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The importance of perceiving heterogeneity at multiple scales in a natural resource context

Thesis for the degree of Philosophiae Doctor

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"Why then is not every geological formation and every stratum full of such intermediate links? Geology assuredly does not reveal any such fine graduated organic chain; and this, perhaps, is the most obvious and serious objection which can be urged against the theory."

Charles Darwin, 1809-1882

Abstract

To analyze, compare and draw conclusions within a resource assessment context based upon parameter values that represent a large range of variability or evaluate their interaction is far from being straight forward. One of the difficulties stems from the non-uniqueness of the process-response system. Quantitative results are interpreted according to the processes that controls inherent heterogeneity within multiple scales. To prove or reject correlations between input parameters and observed responses requires knowledge in each step of the analysis. Obtaining such knowledge has been the motivation of this thesis with a three-folded purpose: (1) To assess how resource parameters are measured, recorded, analyzed and interpreted relative to resource assessment objectives at given scales, (2) to assess parameter variability at multiple scales as part of a process-response system that may include not only the geosciences per se, but can also be enlarged to encompass the societal consequences of natural resource issues, and (3) to use the representative elementary volume (REV) and area (REA) concepts as a backcloth for interpreting the significance of variability at multiple scales. The REV/REA concept has allowed for an explicit evaluation of the behavior of the study parameter within a given volume or area. To produce a representative value, the volume or area must be large enough for the initial random behavior to become continuous. The examples aborded during this thesis cover the interaction of parameter variability and the corresponding REV/REA in a comprehensive fashion only at the reservoir scale. The other examples at the play, basin and national level have only explored the REV/REA properties in a descriptive fashion due to lack of in-depth data.

Different methods have been applied for each of the nine individual case studies presented. For the first case study, at the lithofacies level, a multivariate statistical analysis has been used to decompose heterogeneous populations (e.g grains of a fluvial deposit) into their underlying populations (e.g sand, shale and coal) that can explain both within- and cross lithological effects. A structured principal component (PCA) methodology that only use records selected from separate lithological units has been used to obtain a more precise definition of variability sources than is possible by an unstructured approach that use all the records from the well logged interval. New synthetic variables representing the combination of the original wireline log variables can by this methodology be interpreted relative to underlying geological processes. The second case study using an inverse procedure (the Eckart-Young theorem) permitted the back-calculation of new wireline log responses that now correspond to the specific underlying geological process previously identified. Results from the use of this methodology on a sandstone interval has permitted to separate global sandstone porosity values into individual porosity contributions from different underlying and independent sedimentological processes. In the subsequent third reservoir case study a process oriented numerical modeling tool (SBED) was used for upscaling lithological heterogeneity at mm-scale to lithofacies heterogeneity (cm-scale). A further upscaling to seismic (10m-scale) permitted to include multilayer sub-seismic heterogeneity in the generation of synthetic seismic traces. The resulting workflow shows that very detailed layering can be modelled and synthetic seismic traces can be generated that takes into account the inter-bedded seismic multiples which may be of great importance in thin-layered reservoirs. In the fourth reservoir study a sequential re-burial methodology to compute high-resolution re-burial porosity-depth values was used that allows for stratigraphic interwell correlation. The results show that this methodology can lead to alternative inter-well correlation scenarios based on differentially compacted sediments in the subsurface.

A different operational scale was chosen for the fifth case study where characteristic analysis (CA) was re-implemented in a GIS environment that permitted the disaggregation of a regional fault map and the construction of fault signatures within $1 \times 1\text{km}^2$

related to the accumulation of hydrocarbons. A sixth study focusing on the regional downscaling of fault data was achieved by pre-processing the fault attributes into a cell based ternary coding expressing either favorable or unfavorable conditions or a situation where the controlling effect of an attribute is either unknown or unevaluated. By using a weighted linear combination of these ternary coded attributes, favorability was computed using a probability significance metric for selecting cells and variables to outline favorable cells where further exploration should be conducted. In addition to the CA-GIS hydrocarbon assessment examples, a seventh probabilistic assessment at the sedimentary basin scale was undertaken to show how intra-country (meso-scale) hydrocarbon volumes can be estimated. This assessment used the U. S. Geological Survey (USGS) world petroleum assessment approach to estimate the prospective oil resources of Chad within three types of sedimentary basins. Input parameters derived from published literature and oral contributions from Chad officials were used in this assessment.

An eighth case study at the same operational scale as the previous one was undertaken to investigate the resource management policy options of Chad relative to prospectivity, exploration effort and the endemic risk for conflict from post-colonial to the present time. The result shows that exploration (and later production) and severe conflicts in Chad have co-existed in a symbiotic way, where the government and the extractive industry has sought to increase their reserve base and maintain production volumes, whereas those opposing the government has tried to get a just share of the revenue derived from these activities. The revenue management plan crafted by the World Bank in relation to oil revenues intended to distribute that wealth justly but failed. A ninth case study this time on a multi-national scale (Sub-Saharan region) and addressing renewable resources was undertaken to investigate the utility of using a newly developed non-state conflict database for a large-N study of non-state conflicts versus the annual variations in the access to renewable resources, such as food with precipitation as a proxy. A standard regression analysis was carried out using the spatial proxy data for testing non-state conflicts and their relation to various theoretical hypothesis of lack of access to renewable resources and the origin of such conflicts. The result of the analysis showed no statistically significant

correlations as could be expected from the REA evaluation that indicated only partly to inadequate spatial and temporal representativity of the input parameters. More efforts need to be conducted e.g. regarding the homogeneity of the sub-types of non-state conflicts and the spatial and temporal categorizations of the input data used.

This thesis with operational focus ranging from lamina scale to multi-national scale, has shown that the interpretation of a given phenomenon depends on the required scale appropriate for the quantification of this phenomenon. The thesis further attempts to show that there is an unredeemed potential for using the REV/REA concept in all studies that have a spatial or temporal operational scale for problem solving. In the non-reservoir examples, still more work has to be carried out in order to prove the utility of the REV/REA concept outside its established proven domain within reservoir characterization.

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I had the privilege to attend the 2008 CIOME (Chad International Oil, Mining and Energy) conference in N'Djamena, Chad. Thanks to the CIOME'08 participants and especially Almahadi Mahamat Gamar, the Production Division Manager of the Ministre du Petrole, Chad, for the private discussion related to future oil exploration in Chad. The

people at this conference gave me valuable insight into the socical and professional life in Chad that no textbook can offer.

I would further like to express my gratitude to Jan Ketil Rød for introducing me to GIS and to the VIP group at Department of Sociology and Political Science, NTNU, especially Halvard Buhaug and Ole Magnus Theisen, for given me insight into different aspects of how they look upon natural resources and armed conflicts. The commenting performed by Ole Magnus Theisen including the personal discussions related to quantitative/qualitative social science methodology was vital for this thesis as it resulted in a refined approach for the better.

I appreciated the accommodating attitude from Statoil and its licensees for accepting me to publish data and results from the Heidrun Field case studies. The unselfish help from Arve Næss and Mali Brekken gave me a deeper understanding of the challenges related to fluviodeltaic deposits. I am grateful to the Geomodeling Tech Inc., especially Renjun Wen, for providing me with SBED licenses. I would further like to express my gratitude to the GeoEnhance consortium project for allowing me to use and publish results from the consortium work.

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Last but not least, I wish to thank my wife Marthe and my two daughters, Thora and Eir, for their encouragement and tolerance to my absence during numerous evenings and weekends.

Executive summary

Recent results from the literature have shown that traditional averages of core plugs in upscaling will generally underestimate vertical permeability or overestimate horizontal permeability. However, the representative elementary volume (REV) analysis has been shown applicable to consistently upscale core plug data. The emphasis of this thesis has therefore been on using the REV and representative elementary area (REA) concepts as a backcloth against which the variability studies presented as individual cases could be evaluated. The REV/REA evaluation ranges from quantitative to qualitative when proceeding from the reservoir to the multi-national scale reflecting the immature applicability of this concept beyond the reservoir scale.

The industrial and resource management importance of this thesis resides in the following recommended actions.

1. An explicit quality assessment of observational data relative to the REV/REA concept will ensure reproducible and reliable results when these data are used in reservoir, play or basin modelling or serve a basis for developing resource management policies.

2. Implementation of a multivariate approach to data interpretation using structured and inverse recalculation procedures will permit the detection of higher order variability effects that normally are concealed by first order heterogeneity.

3. A strategic choice of using GIS as the standard tool for pre-processing and analysis of resource and social science data will enhance productivity and enable the effective

use of relevant proxies necessary for solving complex problems at multiple spatial and temporal scales.

Nine case studies categorized into three parts, all within a natural resource context, show that the REV/REA concept can help to frame complex problems related to the derivation and use of parameter values that are representative for a given volume or area.

The results from two studies at the lithofacies scale using multivariate statistical analysis allowed for identifying individual populations from a mixture of heterogeneous populations (fluvial deposits) that correspond to underlying geological processes. Specially a separation of porosity contributions from different underlying and independent sedimentological processes were achieved. This result permits in-depth interpretation and prediction of porosity variability in producible horizons. The successful upscaling of small scale lithological heterogeneity from lamina to lithofacies scale and further to seismic scale (10m) made possible the comparison of synthetic seismic traces with seismic traces that allowed for differencing between plausible depositional scenarios. This result illustrates that the quantification of geological knowledge in terms of interpreted scenarios can be incorporated into an operational workflow. The example showing the computation of reburial porosity-depth values based upon differentially compacted sediments showed that this procedure can lead to alternative inter-well correlation scenarios that can enhance the quality of reservoir zonation mapping.

The identification, quantification and application of representative parameter values in resource assessments is essential for obtaining reliable results. Pre-processing of data reflecting the operational objective relative to the study purpose is therefore a prerequisite. This was exemplified by using GIS to disaggregate a regional fault map into fault signatures representative of $1 \times 1\text{km}^2$ cells that expressed a favorable/unfavorable/unevaluated state for the presence of fault related hydrocarbon accumulations. Effective pre-processing of the data capturing the essential discriminating power of the information useful for evaluating prospectivity has successfully been demonstrated in the Halten case study and represents a workflow that currently is operational and can be used both for play and prospect

assessment.

Within a natural resource management framework, the availability of natural resources and conflicts related to such resources may interact on multiple scales: Just as exploration and exploitation of non-renewable resources has been shown to trigger conflicts, restricted access to renewable natural resources like water have also provoked conflicts. The reason behind such conflicts are complex and can be observed at multiple scales. To observe, map and quantify such conflicts and to identify their causal mechanisms is tedious but rewarding and has great implications for conflict prevention. The post-colonial non-renewable resource management history of Chad has shown that the exploration and exploitation of non-renewable resources has co-existed with severe conflicts in a symbiotic way where all stakeholders may benefit from a large and undisruptive natural resource revenue stream. This case reveals that conflicts are not religious or ethnic motivates and that oil revenues can be said to directly contribute to keep Deby Itno in power-by financing his fight against rebellions and the bribing of rivals with positions/and or money. The last case that unfortunately was not conclusive addressed the challenge of identifying global quantitative causal mechanisms between non-state conflicts and the access to renewable natural resource within the Sub-Saharan region. This non-conclusive result is no surprise as the the REA requirements were not met due to partly inadequate disaggregation of input parameters into $100 \times 100\text{km}^2$ cells derived from much larger and irregular administrative units. A large preprocessing effort needs therefore to be undertaken if one shall have hope to unveil causal mechanisms between non-state conflicts and renewable resources.

The thesis shows that in quantitative analysis of complex problems across scales and disciplines there is an unredeemed potential for using the REV/REA concept in all studies that have a spatial or temporal operational scale for problem solving.

The recommended solution is that preprocessing and proper upscaling or downscaling that honor the REV/REA concept is needed if one wants to obtain successful quantitative interpretation of reservoir and socio-political problems.

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Chapter 1

Introduction

1.1 General introduction

One of the key themes within the non-renewable resource initiative of the International Year of Planet Earth (IYPE) stated the following question (de Mulder et al., 2006): - *How can our improved knowledge of geological resource endowments, promote better planning, governance, social stability and advancement, in a climate of sustainable development?*

The current thesis, ranging from reservoir characterization to the study of natural resource induced conflicts, contain examples showing how natural resource information at different scales interacts within its own geological context as well as with the human dimension and as such represents a contribution to the IYPE 2007-2009.

Even though scientific research has improved our knowledge of geological resource endowments, the understanding of the inherent geologic variability is still a challenge. Transformation of geological knowledge into a representative form where strategic decisions, spanning from those made by natural resource exploration and production managers to governmental officials, can reliable be made is not yet fully achieved and represent a great untapped potential. The impact of the natural resources on the economies of many countries is so dominant that understanding their technological, social and geoscientific constraints commands broad interest for the world community (e.g. Le Billon, 2007b;

Ross, 2008). To analyze, compare and draw conclusions within such a complex environment based upon quantified parameter values that represent a large range of variability or evaluate their interaction is far from being straight forward (Le Billon, 2001; Ewert et al., 2006). One of the difficulties stem from the non-uniqueness of the process-response system defined to explain such environments. Quantitative results are interpreted according to the processes that controls inherent heterogeneity within multiple scales (Keogh et al., 2007). To prove or reject correlations between input parameters and observed responses requires knowledge in each step of the analysis. Obtaining such knowledge has been the main motivation behind this thesis.

For centuries, scientists have attempted to understand heterogeneity developed by earth processes at multiple scales (Craig et al., 2001). In the biological world much effort was devoted to express linkages that eventually led to the evolutionary theory of Darwin. His theory was founded on observations of different animal species, where he realised and presented compelling evidence that all species of life have evolved over time from common ancestors, through the process he called natural selection (Darwin, 1859). As earlier quoted, Darwin indicated that the most obvious and serious objection against his theory was that no continuous organic chain could be identified within geological formations and processes. During the time Darwin published his "Origin of Species", knowledge of the geosciences was limited, and a representative scale for explaining geologic processes and their species linkages was not understood.

Using Darwin as an example, his measurements were based on analysis of multiple fossil observations from different stratigraphic layers from where he tried to explain geologic layering. Darwin observed heterogeneity within analysed fossils, however only fossil analysis cannot explain phenomenon related to stratigraphic layering. His approximation from measurement scale to an operational scale from where the selected phenomenon was to be explained was therefore not completely successful. This Darwin example includes several aspects related to explaining a phenomenon: Not only is the definition of the phenomenon to be explained important, but also the available data need to be at a representative format when explaining this phenomenon. However, the most important aspect when trying to find processes that can link heterogeneous variables and a given phenomenon is probably the issue of scale.

An example can be cited from our current climatological debate about warming or cooling of the Earth. The analysis of the development of the average annual temperature anomalies over the northern hemisphere for the last millennium, Fig. 1.1, illustrates the importance of the size of the selected time window when analyzing time series (Olsen et al., 2008).

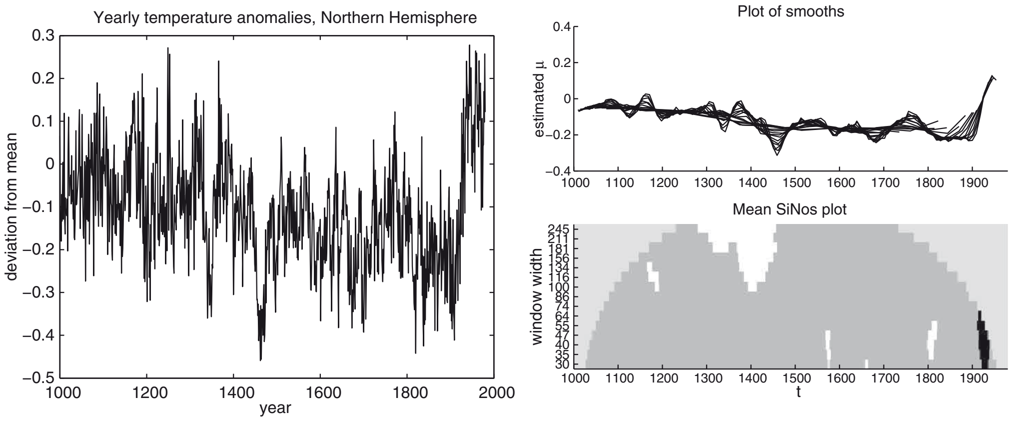

Figure 1.1: Taken from Olsen et al. (2008), the left figure displays temperature anomalies from the northern hemisphere covering the 1902 to 1980 yearly averages over the last millennium derived mainly from temperature measurements of ice cores from Greenland. Curves with most variations are smoothed with a window width of 30 years (upper-right), whereas the smoothest curves represents a width of 245 years. A Significant Non-stationarities (SiNos) analysis of the significant deviation from the mean of the temperature data are shown in the lower-right. A temperature increase is marked with black and a decrease in white.

The short window widths on the vertical scale from 30-64 years in Fig. 1.1, lower-right, capture the temperature increase (black signatures) that started around 1900, whereas those with more than 100 year window widths capture a temperature decrease (white signatures) that started around the end of 1300^{th} century. This was the beginning of the "Little Ice Age", a period of low average temperatures (1400-1850). If only window widths of 74 or 86 years had been applied, non of these variations would have been captured (gray areas). This example underlines the need for selecting an adequate operational window (scale) that captures the representative changes that one wants to identify.

As both quantified input parameters and response outcomes are affected by the selected representative scale, the processes explaining their correlation is also affected by the selected scale (Griffiths, 1988). This can be illustrated by how the selected scale can affect the relation between oil occurrence responses and the geologic processes making oil generation and accumulation possible. A too detailed or generalized scale can result in no or misleading correlation between responses and input parameters. In other words, the selected scale of the process-response system was not representative. Similar misleading correlations can be identified when selecting scale in systems where e.g. drought is the response to changes in meteorological processes leading to lack of precipitation. Likewise armed conflict is the response to different processes resulting in people picking up guns for fighting (Theisen and Brandsegg, 2007). From this reasoning it can be assumed that the representative scale change accordingly to the analyzed process-response system. According to Griffiths (1988), several types of processes can be integrated as natural resource occurrences can be related to the accumulation processes leading to armed conflicts (Gilmore et al., 2005; Theisen and Brandsegg, 2007), similarly political-technological processes can be related to conflict (Le Billon, 2007a).

The concept of scale has intrigued scholars from many disciplines for centuries, being the cornerstone for understanding and interpreting earth properties (Craig et al., 2001). Following the development of map production, the question of scale and representation arose: How will a location in a map deviate from the complexity of reality, and how is this managed when deciding the size of features that should be included on maps with different cartographic scale? Such issues can be exemplified by a map of non-state conflicts in Africa South of Sahara (Fig. 1.2). The first challenge when generating this map relates to how the non-state conflicts are observed, recorded and given spatial coordinates. The actual fighting occurs often in rural areas and for geographic mapping purposes, it will often be recorded to a known geographic location nearby a village/town. As locations

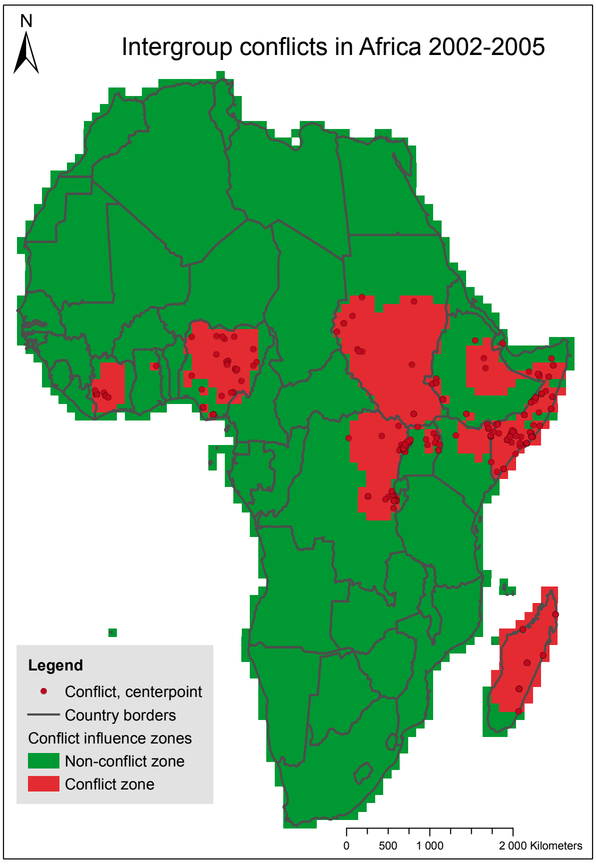

Figure 1.2: Map of influenced zones related to non-state conflicts in Sub-Sahara (2002-2005) taken from Theisen and Brandsegg (2007). Here, non-state conflicts has been defined as a domestic armed conflict between two non-state actors with more than five casualties (Kreutz and Eck, 2005). Chad had no such recorded conflicts in the years between 2002 and 2005.

of similar conflicts are often grouped/aggregated together spatially and/or temporally to suit quantitative analysis, a second challenge arise: How should a grouped conflict location be defined when more than one conflict location is observed within a given time frame? Multiple spatial weighting methodologies can be applied, but the location of the mean value (e.g. center point) is often employed (Theisen and Brandsegg, 2007). Generated influence zones around e.g. mean can therefore represent different coverage area; E.g. number of incidents or casualties (severity) can be represented by a circle with a radius equal to the distance from the grouped conflict center point to the remotest conflict point. A third challenge lies in the choice of how this information should be incorporated into quantitative analysis. On the national level, all defined records are attributed to a specific country without considering the conflict location within the country where the fighting took place. Disaggregation on the other side opens for defining conflicts induced within specific areas, e.g., within a grid cell of $100 \times 100\text{km}^2$ (Fig. 1.2). This example show the complexity of transforming a map into cell based form where the cell values are representative of the cell areas.

Throughout history, observational parameters have been quantified ranging from socio-political themes to a geologist's subjective interpretation of a specific land area or a well measurement recording from a wireline log that measures a petrophysical response related to a geological layer in an oil field. All these parameter values are affected by the scale of measurement and needs to be transformed into an operational scale that reflect the scale that is relevant for solving the stated problem. If a regional map is to be produced, the geologist should interpret rocks with emphasize on the delineation of major rock types, whereas for an outcrop of some 100m a different scale is used in order to observe smaller scale variations, such as different depositional features.

In the current thesis, geological heterogeneity has been related to multiple scales ranging from the macro to micro scale (Table 1.1), where for example the understanding of the micro scale pore distributions in a hydrocarbon reservoir can be essential for predicting the hydrocarbon production potential of a hydrocarbon well at the macro scale. The concept of a representative sample for measuring as diverse properties as petrophysics, hydrocarbon accumulation sizes and the social tension often related to hydrocarbon extraction will in this current thesis be used to emphasize the generality and importance of the representative elementary volume and area (named REV and REA) concepts first introduced by Bear (1972) and Wood et al. (1988), respectively. The difference between REV and

Table 1.1: General spatial scale used in different disciplines: Cartographic scale (Peterson, 2009), remote sensing (Wu and Li, 2009), seismic mapping (Brown, 2004), geologic mapping (Rockaway, 1976), reservoir characterization (Miall and Tyler, 1991; Schatzinger and Jordan, 1999).

Geographical mapping / remote sensing

Scale	Length	Area	Coverage
Micro	$1m - 1km$	$1m^2 - 1km^2$	local
Meso	$1km - 100km$	$1m^2 - 1km^2$	regional
Macro	$100km - 10000km$	$100km^2 - 10000km^2$	continental
Mega	$10000km$	$10000km^2$	global

Seismic mapping

Scale	Length	Area	Coverage
Micro	$1m$	$1m^2$	lithofacies
Meso	$10m$	$10m^2 - 1m^2$	lithofacies
Macro	$100m$	$100m^2$	sequence stratigraphy
Giga	$1km$	$1km^2$	basin

Geologic mapping

Scale	Length	Area	Coverage
Micro	$1cm$	$1cm^2$	rock type
Meso	$10m$	$10m^2 - 1m^2$	lithology
Macro	$100m$	$100m^2$	rock groups
Giga	$1km$	$1km^2$	nappe

Reservoir Characterization

Scale	Length	Area	Coverage
Micro	$1\mu m$	$1\mu m^2$	pore
Meso	$1m$	$1m^2 - 1m^2$	bedsets
Macro	$10m - 1km$	$10m^2 - 1km^2$	lithofacies
Giga	$1km$	$1km^2$	reservoir

REA resides in a volumetric or areal support respectively for the corresponding representative values. Theoretically, this concept implies the possibility to replace a heterogeneous property field (e.g. porosity measurements) with a hypothetical homogeneous one. This is often referred to as the effective medium approximation (Bear, 1972). Essential to this approach is the notation of a representative elementary volume (REV) or area (REA) which denotes the volume or area size of the property field that will yield a value representative

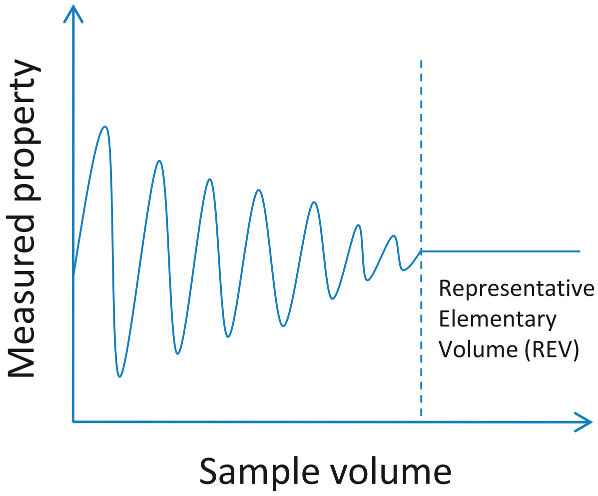

Figure 1.3: Schematic graph of how a measured property varies with sample volume and the domain of the Representative Elementary Volume (REV) (based on Bear, 1972).

of the whole (Bear, 1972). Instead of considering specific core plug measurements with large individual variations in porosity, Bear introduced average porosities at a coarser scale in which the studied interval could be seen as homogeneous regarding porosity. The three advantages of this REV continuum approach was according to Bear and Bachmat (1984): (1) no knowledge of the microscale pattern is required if a representative value is available at hand; (2) the continuous medium is differentiable; and (3) the continuum represents measurable quantities. The REV/REA concept represents therefore a systematic effort of looking at spatial variability as function of scale using a sampling window in which numerous measurements of a highly-variable property (e.g, porosity, permeability) can be averaged by an appropriate methodology into a single representative value of statistical and physical significance (Nordahl, 2004). A too low sample size tend to oscillate, whereas this oscillations begins to dampen out with larger sample size (Fig. 1.3). The upper and lower limits of the REV/REA are closely related to the geostatistical terms local homogeneity and local stationarity (Corbett et al., 1998).

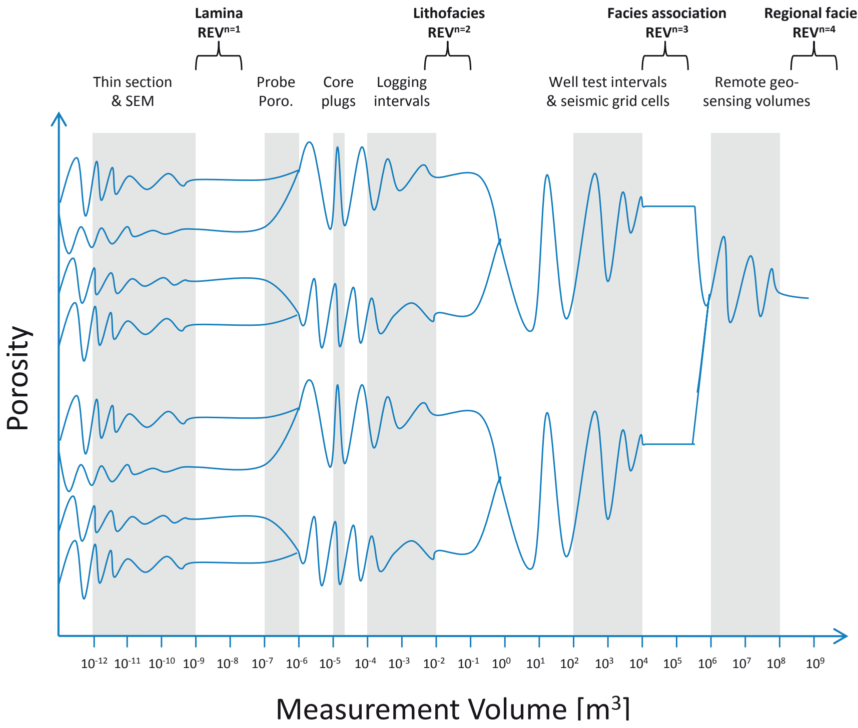

Figure 1.4: A conceptual sketch of different scales ($n = 1, 2, 3, 4$) of REV related to sedimentological porosity heterogeneities and the scales of measurement (modified after Nordahl and Ringrose (2008)). In this illustration there are eight lamina types (REV$^{n=1}$) that combine into four lithofacies (REV$^{n=2}$) that further combine two facies association (REV$^{n=3}$) which again are combined in a regional facies association (REV$^{n=4}$). The approximate ranges in sample parameter values for typical measurements are shown in relation to the volume of influence and indicate that these parameter values have high variability below the appropriate REV$^{n=x}$ statistical support.

The applicability of the REV concept for reservoir characterization in Nordahl et al. (2005) showed that traditional averages of core plugs in upscaling would generally underestimate vertical permeability or overestimate horizontal permeability. Nordahl and Ringrose (2008) further showed how a nested structure of scales can give different REV's in the reservoir and how these scales are related to scales of measurement. Fig. 1.4 enlarges the results of Nordahl and Ringrose (2008) and shows a conceptual sketch of how porosity measurements has multiple REV's according to the operational scale that a phenomenon needs to be explained. Measurements from thin sections ($< mm$) to remote geo-sensing ($> m$) scale include four different REV's. A reasonable separation of geological length scales is required as shown in the figure if a multi-scale REV method is to be used.

In the present thesis, the research related to natural resource information and the human dimension has been hampered by the fact that the REV concept involving such disciplines have not been fully developed. However, representative elementary area (REA), introduced by Wood et al. (1988) defines the optimal elementary measurement size for water catchment areas from where the distribution of catchment behavior can be represented without the apparently undefinable complexity of local heterogeneity. Further both VandenBygaart and Protz (1999) and Lin (2003) applied the study of heterogeneity in quantitative soil micromorphology to show that the REA concept is facilitating multi-scale bridging when connecting pedology (soil study), soil physics and hydrology to link such phenomena at multiple scales. Likewise, Jia and Lin (2010) used the REA concept to estimate a best-fitting cell size for specific lineament densities when mapping fractured rock aquifer. An example of such multi-scale bridging of REAs (Fig. 1.5) shows that a representative elementary value of REA at 1×1 cells can be included for explaining a new phenomenon with representative elementary values of REA at 5×5 cells. A proper upscaling routine must be applied to find this new representative elementary parameter value.

Lam (1992) showed that the concept of scale has in a wide sense both a temporal and a spatial aspect, often with emphasis on one or the another. The current thesis considers both multiple temporal and spatial scales. Four common uses of the term scale have been outlined within the spatial domain according to Lam (1992) (Fig. 1.6) and these names are retained for use in the thesis:

1. The *cartographic* or *map* scale refers to the ratio between the measurements on a map and the actual measurement on the ground.

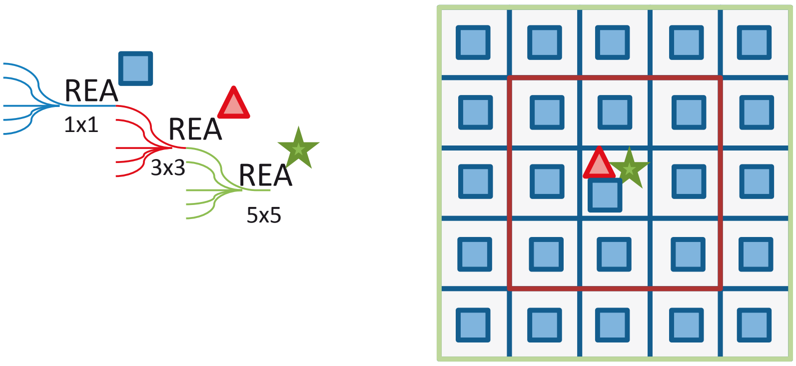

Figure 1.5: A sketch of different scales of REA. In this illustration there are 9 1×1 cell values (REA^{box}) that combine into one 3×3 cell value (REA^{triangle}). The 5×5 cell value (REA^{star}) includes 25 (REA^{box}) cell values or just partly four of the (REA^{triangle}) cell values.

2. The *geographical* scale refers to the spatial extent of the study or the area of coverage.
3. The *measurement* scale, or commonly called resolution, is the scale from where measurements are recorded.
4. The *operational* scale refers to the scale where the analysis need to be performed.

Traditionally, the concern of scale has been confined to issues of units of analysis, rather than the more fundamental problem of what determines the representative volume or area for a given parameter. In particular, this thesis concentrates on demonstrating the importance of knowing the appropriate REV/REA when a problem needs to be solved with representative values for a voxel volume or cell area. A similar approach is also relevant for the social science research component that addresses how the human sphere of interest relates to the spatial resolution of natural resource information. If one wishes to define and explain the interaction between social and non-human systems, then it is of

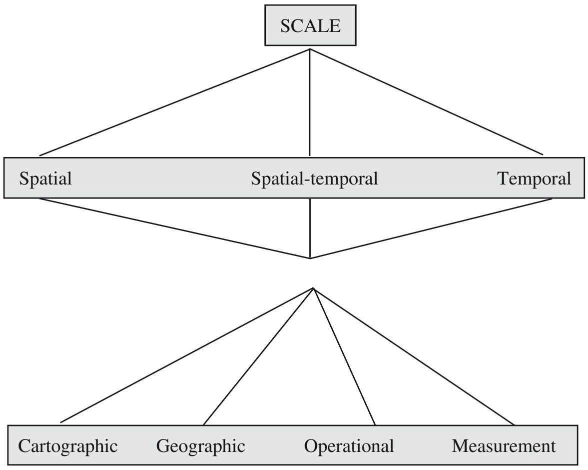

Figure 1.6: Sketch of the structure and definitions of scale, based on Lam (1992).

vital importance to understand the scale of the interaction as well as the scale of different environmental and social processes (Ewert et al., 2006; O'Lear and Diehl, 2007).

The REV/REA examples outlined above have indicated that a parameter can be recorded on different measurement scales have multiple REV/REA's according to the operational scale where the phenomenon needs to be explained. This concept can be adopted to other datasets to bridge micro scale and macro scale information and thereby enhance the understanding of process-response systems in many disciplines.

Earth process-response systems involves several subsystems that is highly heterogeneous at multiple spatial and temporal scales (Fig. 1.7). E.g. the atmosphere, oceans, hydro- and cryosphere, including the solid earths upper crust (Christopherson, 2005). One possibility to categorize such information is by hierarchical systems that can be used to explain primarily the organization of geologic information or, secondary in a wider sense, both to the socio-political and the biological organization.

When moving within one hierarchical organization exemplified by the geosphere, the

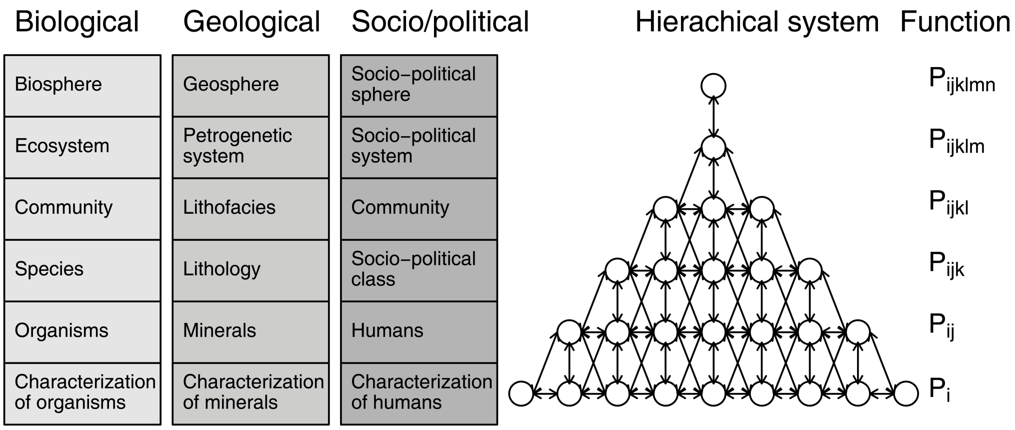

Figure 1.7: Schematic representation of biological, geologic and socio-political hierarchical systems with their nested sub-systems (based on Ewert et al., 2006). A hierarchical system concept allows for the investigation of systems that operates on multiple spatial-temporal scales, where the focus on such systems is on levels of organization and issues of scale. The observer of the system plays an important role (Weston and Ruth, 1997). In their organization, structured as the shape of a pyramid, each row of objects is related to the objects below. Thus, at a given level of operational scale, a system is composed of interacting objects/components and is itself an object/component of a larger system. Proper scaling may reduce the nested detail.

representative spatial and temporal scales also change (Fig. 1.8). This figure portrays the changing spatial zones of influence when focus varies from leads/prospects or other drilling targets to the petroleum system or up to the global scale. Similarly, the time needed to deplete a producing well is short compared to the depletion of a whole play or producing sedimentary basin. The discrete levels in Fig. 1.8 displays the interaction of these scale dependent influences at the discrete scales ($n = 1, 2, 3, 4$) of REV related to the hydrocarbon pore volume heterogeneities explained in Fig. 1.4.

The natural resources itself have no relation to the human dimension as it has only geologic characteristics (Griffiths, 1978). However, the human dimension play a crucial role when such natural resources are developed and extracted, as it is the current economic status of the given resource that decides if it is economic or not. The natural resource

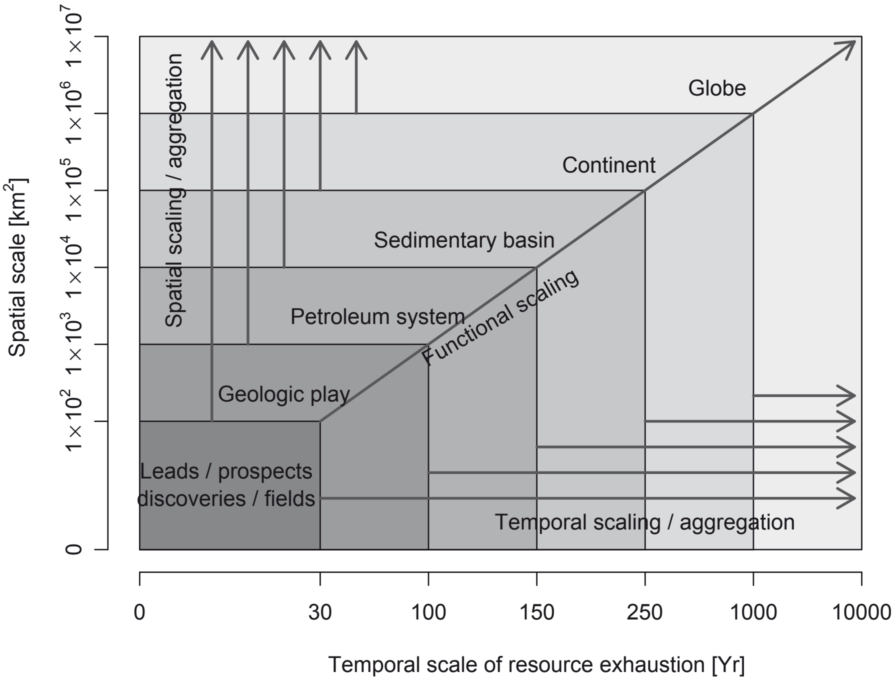

Figure 1.8: Schematic representation of scales and levels of generalization in a petroleum exploration setting (based on Ewert et al., 2006). Geologic play, petroleum system, sedimentary basin etc. represents different levels of generalization and changes from one level to another and are discrete, whereas changes in temporal and spatial scale are continuous.

endowment is therefore influenced by the political-economical pressure to produce the endowment (Griffiths, 1978). This can be included in the modeling of natural resource management (NRM) options, expressed in a process-response system. NRM options consist of complex problems that require integration of information across multiple scales and disciplines (Weston and Ruth, 1997). In the latest years, as the number of processes and degree of added organizational information has increased following the extended range of spatial and temporal scales, models have become very complex to approximate the given system reality. One particular challenge is the ambition to assess system behaviour simultaneously at several levels of organization. Therefore, understanding correlation within process-response systems, both understanding input parameter characteristics and the appropriate measurement and operational scales are of vital importance. Several other approaches have been outlined for explaining and evaluating such highly complex, heterogeneous and multi-scaled systems, such as multilevel modelling and hierarchy theory (Evans et al., 2002).

Conflict research is a branch of social science that aims to identify the causes of conflict from local to multi-national scale. The latest achievements in both qualitative and quantitative approaches of conflict research have resulted in an improved knowledge of the conflict mechanisms (Cederman and Gleditsch, 2009). With the increasing popularity of coupling geographic information systems (GIS) with armed conflict models and geologic databases for diverse armed conflict applications (Gleditsch et al., 2002), the demand for natural resource information has increased significantly in recent years. The lack of spatial and temporal data precludes the ability to perform robust time series analysis, hindering the ability to look at the dynamic nature of geological, biophysical and social processes (Evans et al., 2002; Keogh et al., 2007). The primary challenge facing researches now is in addition to disaggregating country or county level data to develop spatially explicit models that elegantly handle dynamic relationships and human decision making (Evans et al., 2002). This includes taking into consideration the recorded scales of a phenomenon (O'Lear and Diehl, 2007).

To obtain representative parameter values according to an appropriate scale is a multidisciplinary challenge known to sociologists as the ecological fallacy (King, 1997), to geographers as the modifiable areal unit problem (MAUP) (Openshaw and Taylor, 1979) and to earth scientists as the upscaling or change of support problem (Chilés and Delfiner, 1999) embedded in the REV/REA concept (Bear, 1972; Wood et al., 1988; Nordahl and Ringrose, 2008). Despite the different names of the appropriate phenomenon scale change between scientific disciplines, they cover similar problems.

With examples from different scientific disciplines, this introduction has shown that more or less all disciplines strive to achieve solid analytic results that can prove or reject correlations between input parameters and observed responses that is important for evaluating a given specific hypothesis. In addition to the scale issue and the importance of considering the problem solving within a process-response system context, this introduction has shown that the selection of an adequate representative scale is of vital importance for achieving quantitative results that can serve as a basis for within and between disciplinary research.

1.2 Purpose of thesis

The purpose of the current study is to:

- assess how resource parameters are measured, recorded, analyzed and interpreted relative to resource assessment objectives at given scales.
- assess parameter variability at multiple scales as part of a process-response system that may include not only the geosciences per se, but can also be enlarged to encompass the societal consequences of natural resource issues.
- use the representative elementary volume (REV) and area (REA) concepts as a backcloth for interpreting the significance of variability at multiple scales.
- show the importance of using a representative scale and data that are combined with a proper framing for explaining specific phenomenon.

By using REV/REA concept as a backcloth, this thesis aims to emphasise the importance interpreting the significance of variability influencing natural resource related issues at multiple spatial and temporal scales.

1.3 Outline of thesis

This thesis consists of three major parts. The first part after the introduction (Chapter 2) is devoted to the study of small scale geologic heterogeneities, the second part (Chapter 3) is related to meso scale heterogeneities ranging from reservoir to sedimentary basin scale, and the last part (Chapter 4) is devoted to large scale political-sociological heterogeneities in a natural resource context. All the three parts consider the previous outlined research questions. The different papers in Appendices A-I have their own aims and results and contributes as case studies to the specific parts of this thesis. In this thesis, these case studies are expressed in a wider sense enlighten by the research questions. This structure has made it possible to merge different case studies that rarely are identified to have any coherence. Finally, general results, conclusions and recommendations for further work are outlined, followed by an appendix where the individual papers are presented. A summary of the papers and their relation to the different parts of this thesis is outlined in Table 1.2.

1.4 Contributions of papers in Appendix

Several of the papers in Appendix are written in cooperation with others and in the following my contribution to these papers are outlined.

A comparison of Unstructured and Structured Principal Component Analysis and their Interpretation

Brandsegg, K.B., Hammer, E. and Sinding-Larsen, R., 2010
Natural Resources Research 19 (1), 45 - 62.

Brandsegg performed most of the interpretation and writing of this paper (Appendix A)(Brandsegg et al., 2010). Hammer contributed with wireline log interpretation, lithological classification into units and matching core and wireline logs. Sinding-Larsen gave important feedback on methodology, interpretation and writing. Both co-authors contributed to reading corrections and discussions of the organization of the paper.

Table 1.2: The relation of the observational scale of the three parts that makes up this thesis, including all papers presented in Appendix.

Part	Appendix	Paper	Scale	Level	Process-response system
2	A	A comparison of unstructured and structured principal component analysis and their interpretation	$mm - m$	lithology / lithofacies	Fluviodeltaic depositional system
	B	Refined lithological description through structured multivariate analysis	$mm - m$	lithology / lithofacies	Fluviodeltaic depositional system
	C	A novel workflow for 3D integration of geological and geophysical heterogeneity signatures at the reservoir scale	$cm - m$	lithofacies	Turbiditic depositional system
	D	Reconstruction of heterolithic reservoir architecture based on differential decompaction in sequence stratigraphic backstripping	$cm - km$	lithofacies	Fluviodeltaic depositional system
3	E	Characteristic analysis -GIS and petroleum exploration risk	km	geologic play	Hydrocarbon accumulation system
	F	Where should we explore in the Halten Terrace? -GIS and Characteristic analysis applied to a mature play in the Norwegian Sea	km	geologic play	Hydrocarbon accumulation system
	G	Yet to find oil resources in Chad	km	petroleum system	Hydrocarbon accumulation system
4	H	Non-renewable resources and conflicts within a Chadian resource management framework	km	sedimentary basin / mineral provinces / regional	non-renewable natural resource exploration related to conflicts
	I	The Environment and Non-State Conflicts in Sub-Saharan Africa	km	regional	environment variables related to conflicts

Refined lithological description through structured multivariate analysis

Brandsegg, K.B., Hammer, E. and Sinding-Larsen, R.
In manuscript

Brandsegg has performed the calculations, generation of tables and figures and most of the writing and collection of literature of this paper (Appendix B). Both Hammer and Sinding-Larsen contributed by adding ideas and reading through drafts and commenting on the organization of the paper. Sinding-Larsen also gave important feedback on methodology, whereas both co-authors contributed with result interpretation.

A novel workflow for 3D integration of geological and geophysical heterogeneity signatures at the reservoir scale

Sinding-Larsen, R., Stovas, A., Landrø, M., Brandsegg, K.B., Johnsen, S.O., Lippard, S.J., Mørk, M.B.E. and Vik, E., 2006.
In: International Association for Mathematical Geology. University de Liege - Belgium, p. 4.

Brandsegg compiled this paper (Sinding-Larsen et al., 2006) (Appendix C) including generating figures and writing. Sinding-Larsen defined the approach, co-wrote and commented on the organization of the paper. Stovas carried out the calculations of synthetic seismic and generating the seismic related figures. All authors commented drafts of the paper.

Reconstruction of Heterolithic Reservoir Architecture based on Differential Decompaction in Sequence Stratigraphic Backstripping

Hammer, E., Brandsegg, K. B., Mørk, M-B. and Næss, A.
Submitted to Petroleum Geoscience

Hammer performed the review of the methodology, wrote and performed most of the geological interpretations the paper (Appendix D). Brandsegg performed most of the programming and the generation of the figures. He also carried out perusals of the paper and contributed with general comments and discussions of the results. Næss defined the scope of the study and assisted with ideas for the backstripping methodology. Mørk performed perusals and comments of the paper.

Characteristic analysis -GIS and petroleum exploration risk

Sinding-Larsen, R. and Brandsegg, K.B., 2005.
In: Cheng, Q., Bonham-Carter, G. (Eds.), The Current Role of Geological Mapping in Geosciences. Vol. 1 of Proceedings of IAMG. The Geomatics Research Laboratory, York University, Toronto, Canada, pp. 187 - 192.

Brandsegg contributed by generating figures, writing, adding ideas and commented on the organization of the paper (Sinding-Larsen and Brandsegg, 2005) (Appendix E). Sinding-Larsen defined the approach and wrote most of the paper.

Where should we explore in the Halten Terrace? -GIS and Characteristic analysis applied to a mature play in the Norwegian Sea

Brandsegg, K.B. and Sinding-Larsen, R., 2005.
In: Cheng, Q., Bonham-Carter, G. (Eds.), The Current Role of Geological Mapping in Geosciences. Vol. 1 of Proceedings of IAMG. The Geomatics Research Laboratory, York University, Toronto, Canada, pp. 580 585.

Brandsegg wrote, coded the method and generated the figures of this paper (Appendix E) (Brandsegg and Sinding-Larsen, 2005). Sinding-Larsen contributed by reading through drafts, adding ideas and commented on the organization of the paper.

Yet to find oil resources in Chad

Brandsegg, K.B. and Sinding-Larsen, R.
In manuscript

Brandsegg wrote, calculated the assessment volumes and generated the figures of this paper (Appendix G). Sinding-Larsen contributed by reading through drafts, adding ideas and commented on the organization of the paper.

Non-renewable resources and conflicts within a Chadian resource management framework

Brandsegg, K.B.
In manuscript

This paper, (Appendix H), is single-authored by Brandsegg.

The Environment and Non-State Conflicts in Sub-Saharan Africa

Theisen, O.M. and Brandsegg, K.B., 2007.
Paper presented at 48th Annual Convention of the International Studies Association,
Chicago, 28 February - 3 March 2007

Brandsegg performed the GIS operations in the preprocessing of data and the generation of figures in this paper (Theisen and Brandsegg, 2007) (Appendix I). He also contributed by adding ideas and commenting on the organization of the paper. Theisen performed the review of the methodology, wrote most of the paper and performed the statistical interpretations.

Chapter 2

Small scale heterogeneities at reservoir compartment scale

Through time the traditional scale of rock analysis has been related to a hand specimen, where rocks have been characterized by appearance and by their physical behavior. The introduction of microscopy, chemical analysis and others have established new scale levels from where separate mineral characteristics that constitute the rock can be determined. This has resulted in a new set of measurements and observations that can identify the inherent variations of the hand specimen to give an improved characterization of the previous visually observed rock properties.

This example of a rock hand specimen illustrates how measurements differ according to the defined operational scale. The selection of operational scale is therefore not self-explanatory or pre-defined as it must reflect the study objective. It is obvious that identifying the inherent variations of e.g density of a rock sample by only visual observations at hand specimen scale without additional measuring tools are ineffective and can result in inappropriate densities that cannot fully explain the characteristics of the rock.

Similar challenges are observed in reservoir characterization where the early models of fluvial reservoirs using interpolation techniques failed to produce geologically correct models for yield prediction (Keogh et al., 2007). In recent studies the philosophy of the

”pore-to-field” scale modelling approach aims to include the small scale heterogeneities of fluvial depositional systems at several scales in order to preserve the fluvial heterogeneity characteristics during upscaling (Keogh et al., 2007). In other words, it is important to integrate the variability in parameter values at various measurement scales, from the microscopic to macroscopic scale, derived from the interaction of many depositional processes to obtain reliable representative result at a given operational scale (Nordahl and Ringrose, 2008).

2.1 Introduction

This chapter considers scales in the context of geologic process-response systems that can be broken down according to the measurement scale. Studies within this chapter range from lithofacies types at intra-reservoir scale to characterization of different minerals at the microscopic scale. These studies encompass the four lowermost levels in the previously outlined geological hierarchical system expressed in Fig. 1.7 and use the REV concept (Fig. 1.4) for an explicit evaluation of the behavior of the study parameters within a given volume and represent examples of the ”pore-to-field” scale modelling approach.

As introduced in the previous chapter, the conceptual population framework of Griffiths (1988) allows different populations across multiple scales and levels of organizations to be explained by five factors (E.q. 2.1):

$$P = f(m, s, sh, o, p) \tag{2.1}$$

where P is a unique index representing the specific population and is a function of the kinds and proportions of the different elements (m_i, or $m_1, m_2, \ldots, m_k$), their sizes (s_i), shapes (sh_i), and arrangement. The arrangement is subdivided into two substitute properties of the elements; their individual position in space (o_i), and their position relative to the neighbouring elements (p_i). The index aims to represent elements of different kinds. These five properties are fundamental in defining P as a unique index, where any other property is dependent on variants in these five; for example, porosity and permeability may be substituted for P. The description of any population begins therefore by defining the kinds (m) of elements and often followed by a statement of their proportion. The expression of the sizes and shapes of each kind of element gives increased knowledge of the element, but suffers from explaining its relation to the other elements in the population. The location of each individual element ($o = orientation$) and its relation to other elements ($p = packing$) are the two last relevant factors. All different populations can be explained by this conceptual analysis.

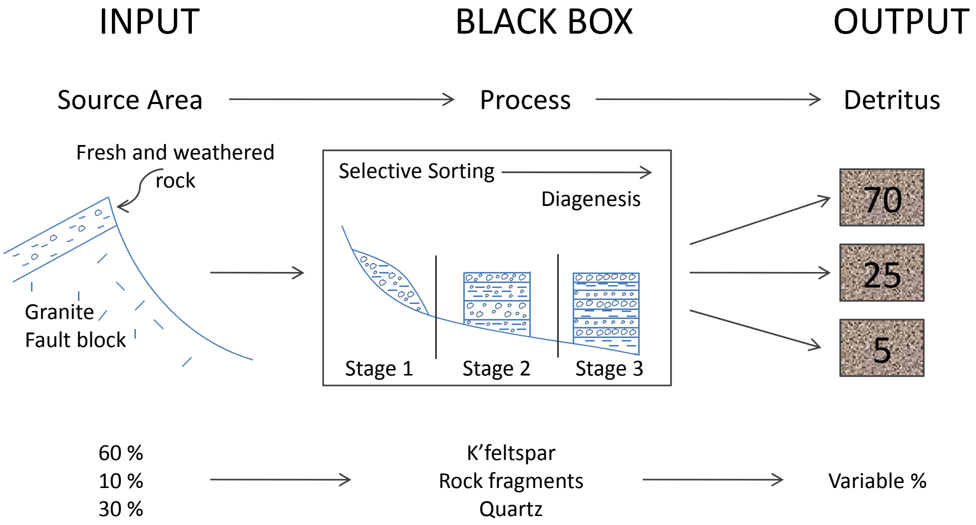

Figure 2.1: Petrogenetic system showing variable output from a single input. Modified after Griffiths (1988).

Griffiths illustrates how different populations (Eq. 2.1) of quartzitic boulders from a scree of a hillside and quartzite pebbles from a gravel pit can be used to indicate the initial composition of the host rock from where both of these populations are derived (Fig. 2.1). The first stage is characterized by the presence of both source material and its weathered (in situ) soil. At the second stage this material is eroded, transported and deposited to form detritus where the sorting process is dominated by fluvial transport that results in a change in density (=composition of elements, m) and the size (s) and shape (sh) of these elements. At the third stage this detritus is reworked and modified by diagenetic processes that are present during and after deposition where the changes in size, size-sorting and shape of the elements and the different aspects related to compaction and cementation modify the arrangement (o and p) of the elements. Whereas the second stage is predominantly expressed by a single selective sorting process, the third stage is mainly a diagenetic process. This system, illustrated by Griffiths in Fig. 2.1, shows how one process can be subdivided into two transforming processes changing the initial source material to the final detritus product. This demonstrates that there are no direct links between the source area (input) and the detritus (output), other than through a process stage that can be considered as poorly defined or representing a black box.

To solve this relation, Griffiths stated that it is essential to know the genetic model of the sedimentary processes that may transform the scree quartzites to the ones found in the gravel pit. This quartzite example, where the Tuscarira scree being a population approximating stage 1 (Fig. 2.1) and the Montourville gravel and Homewood (Pottsville) quartzite being approximation to the third stage (Griffiths, 1966) is exceptional as both the initial step and the final step of a the genetic model is known. If the genetic model explaining this specific sedimentary depositional process-response system is known then predicting one of these two populations from the other can be done. This example can be generalized and used to explain many other populations in various contexts. An example is how crude oil in a refinery can be differentiated into several different cracked products. Based upon this argumentation, it is therefore necessary to examine the entire problem as the solutions to parts of problems are usually inadequate unless actually tied into the entire problem-solving procedure of a process-response system (Griffiths, 1988).

The SBED software (Nordahl, 2004; Wen, 2004; Geomodeling, 2006) represents an example of one of the most sophisticated process-response systems developed for upscaling porosity and permeability from lamina scale to the geomodel scale suitable for input to the operational reservoir simulation scale (typical 100m×100m×10m). Upscaling models must therefore be capable of capturing correlations between measured observations that is essential for identifying factors explaining process-response systems which can be applied for modelling geological processes across scales and levels of generalization up to the appropriate operational scale.

In general, quantification of any population can be performed through either direct or indirect measurements. In direct measurements, records are determined directly. This can be exemplified by thin sections analyzed in microscope, where measurements are accurate observations of the studied rock quantified by point counting, calculated surface area, observations of size and shape as well as the occurrence of the different minerals. Indirect measurements in the geosciences, for example sieving in the aggregate industry (Stanley and Sinclair, 1988) and wireline log measurements carried out in the oil industry (Serra and Abbott, 1982) characterizes the rocks differently. In sieving, the original five factors from the initial rock sample are reduced to only include three factors $P = f(m, s, sh)$ as both packing and orientation is eliminated by the disaggregation of the minerals. In wireline log measurements only the petrophysical characteristics are recorded and do only give a partial explanation of the variation in rock properties along the logged interval. Indirect measurements are often more useful than direct measurements as they are capable of obtaining reliable results on large volume of data within a short time (Doveton, 1994). Still, in indirect measurements, inherent bias can occur as there is a potential for inability to measure accurately and directly the desired phenomenon (Davis, 2002; Bárdossy and Fodor, 2003). It is therefore important to be aware of the potential processes behind a phenomenon and its relations to measurement methods when explaining a specific phenomenon.

Table 2.1: Matrix representation of the petrogenetic model, modified from Griffiths (1988).

Source material	Process	Detrital sediment
A_{ij}	T_{ij}	B_{ij}
n x p	m x n	m x p

Griffiths (1988) expressed this petrogenetic model in a matrix representation indicating that by applying the transformation process T_{ij} to the input source material A_{ij} then the output B_{ij} is obtained (Table 2.1). Several statistical methods, such as principal component analysis (PCA), can be applied to model the transformation process that links the initial state and variability of a system to its final states (Brandsegg et al., 2010).

Multivariate analysis techniques used for mimicking black box processes can be explained as techniques that computes correlation between specific set of variables without considering their nature and origin, where m variables define an $m \times m$ correlation matrix (Davis, 2002). The crucial part is then to determine how good this correlation matrix is in capturing the interrelated black box processes, according to some criteria or aspects. Different multivariate techniques are associated with different aspects of correlation matrices. In multiple regression, for instance, where one variable is predicted from the other variables, the important aspect is the multiple correlation coefficient (Davis, 2002). On the other hand, principal component analysis (PCA) focuses on one or several of the eigenvalues of the covariance/correlation matrix and in many multinormal likelihood procedures the determinant of the correlation matrix is studied (Davis, 2002).

Following the argumentation of Griffiths (1988), Mohan and Rao (1992) successfully applied PCA to evaluate the petrogenesis system of a Lower Pleistocene conglomerate sequence and identified specific principal components separating erosion and transporting processes (size, sorting and shape), composition (quartzite and sandstone grain proportions) and depositional processes (orientation and packing). In another study from the carbonate environment, Ramkumar et al. (2002) proposed a petrographic type recognition and prediction scheme by using multivariate techniques (cluster analysis and discriminant analysis). Their study demonstrated the importance of generating a large database containing well-constrained groups of populations helping to predict the group/population of unknown samples.

Multivariate analysis is the dominant tool used to study scale dependent factors in geosciences (Royer, 1988; Bridge and Tye, 2000), such as in reservoir characterization where seismic, wireline logs, core measurements and physical core examinations are compiled to express effective parameters for optimal exploitation (Schatzinger and Jordan, 1999). The benefits of using such analysis are that the generated separation within the dataset results in various independent factors that can potentially isolate effective properties, such as porosity and permeability (Nordahl and Ringrose, 2008).

Conceptually, a specific phenomenon can either be expressed directly at one scale or by the results of its underlying processes at multiple scales representing different levels of generalization. In a hierarchical system approach, the population at a specific level of organization is composed of other populations from underlying levels (Fig. 1.7). By following the argument of Griffiths (1988), each specific population can be evaluated separately or in a joint population at a higher generalization level incorporating other lower level populations. The joint population variability is therefore dominated by the measurements incorporated in each specific scale.

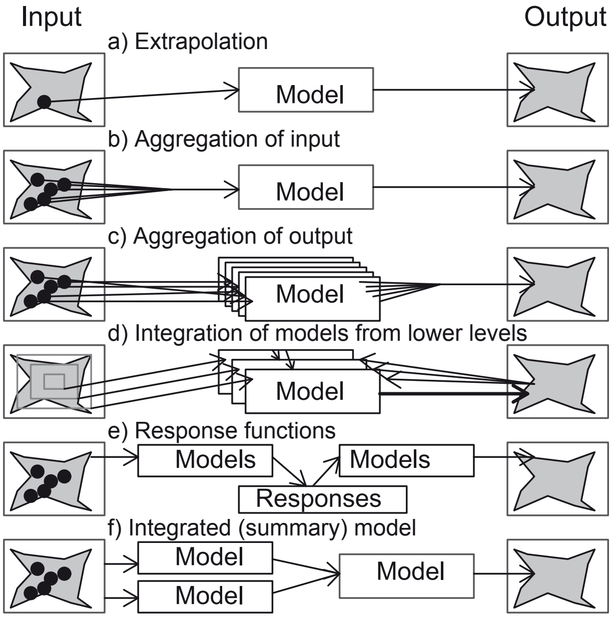

Figure 2.2: Approaches used for upscaling in geosciences and conjugating disciplines (modified after Ewert et al. (2006)). See text for further explanation.

In addition to use mathematical methods to extract hidden information in datasets potentially explaining inherent characteristics, several upscaling methods can be employed to generate new generalized variables at an operational scale suitable for the explanation of specific process-response systems related to a given phenomenon (Ewert et al., 2006). The simplest method is to extrapolate results obtained at a detailed level up to a higher level (Fig. 2.2a). A second approach is when aggregation is performed to project the underlying details up to the next level either by aggregating the input (Fig. 2.2b) or by aggregating the simulated output (Fig. 2.2c). The benefit for using the latter is that it accounts for non-linearity. However, this method has limited use due to lack of available data and the large number of simulation runs needed. Some methods integrate data from different levels of organization (e.g mineral characterization to sedimentary facies), (Fig. 2.2d). This method requires the input of extensive data and sophisticated model parameters that normally is limited for applications beyond the reservoir scale. The ineffective modeling of details from the previous method can be discarded by lower level relationships that can decrease the data requirements and/or simulation runs if this can be justified by the problem context (Fig. 2.2e). The derived parameters from Fig. 2.2e can also be used as input for higher-level models. These pre-derived relationships can lower simulation runs, but are not robust for complex interactions or feedback mechanisms. The last method, aggregate models or integrate models into higher level (more generalized) models in multiple steps (Fig. 2.2f). Such method is depending on the skills of the modeler as structure and details are integrated and depend on the objectives of the model and the understanding of the system under investigation. To avoid unnecessary details, the components or processes that determine the higher-level systems behavior must be understood and modelled in adequate and consistent details. The SBED modelling approach uses elements from both method d and f for modelling the upcaling of permeability in three dimensions.

The selection of upscaling method to be applied on a dataset for obtaining precise and accurate results is not self-explanatory as the method implemented depends on the research question, the behavior of the system, understanding of this behavior including underlying processes, mechanisms and their interactions. Still, the most important factor is the availability of data that can explain a certain response at a given scale as this is the main component from where models are calculated (Ewert et al., 2006).

Nordahl and Ringrose (2008) identified multiple representative scales for measuring vertical and horizontal permeability that can be incorporated in reservoir modelling for optimal hydrocarbon production strategies. By using their approach for upscaling effective reservoir parameters from bedform scale to lithofacies scale, they identified the importance of decomposing the permeability measurements into horizontal and vertical directions important for reservoir characterization. The SBED software used in their study, incorporating fine-scale geological details and upscaled effective properties from lamina to reservoir scales by a process-oriented methodology, has previously shown its capabilities in upscaling across several levels of generalization (Nordahl, 2004; Nordahl et al., 2005; Jackson et al., 2005).

Some approaches have tried to couple models from different levels of generalization ranging from e.g grain composition to lithofacies, where the input data and model parameter requirements are high and their availability often limited for application across multiple regions (Corbett et al., 1998). The underlying variability in response functions and integrated models has shown to be of vital importance, when upscaling a dataset from one discipline to be included in analysis at a higher level from other disciplines, such as the integration of geological and geophysical data (Schatzinger and Jordan, 1999). This includes how property variability can be upscaled into lower resolution without creating bias in the representative value of the upscaled property (Webster et al., 2006).

The approach of Nordahl and Ringrose (2008) followed the representative element volume (REV) concept and is profoundly dependent on the characteristics of the phenomenon analyzed as well as the representative scale from where observations are recorded (Nordahl, 2004). This concept has been further developed since its introduction and has wide applicability (Keogh et al., 2007).

In the literature, several methods have been published to identify and evaluate small scale heterogeneities ranging from how populations are measured (e.g Griffiths, 1988) to upscaling techniques important for incorporating the significant small scale heterogeneities into higher levels of generalization (e.g Ringrose, 2008). In the following, four separate case studies are presented to illustrate the importance of knowing small scale heterogeneities related to geologic phenomena and how these can be used in the "pore-to-field" scale modelling approach. By extending the conclusions of Nordahl and Ringrose (2008) which indicated the need to evaluate representative scales related to geological heterogeneity, the subsequent sections give study examples of how the REV concept can be applied to ensure reproducible and reliable results at the reservoir scale. The driving force behind the studies presented stem from the great industrial importance of being able to predict the effect of small scale heterogeneities upon reservoir fluid flow.

2.2 A comparison of unstructured and structured principal component analysis and their interpretation

The quantification of heterogeneity in sandstone reservoirs is often challenging as the magnitude and type of geological heterogeneities are normally not known beforehand (Schatzinger and Jordan, 1999). In reservoir characterization, often very few wells are available to obtain representative reservoir parameters that are important for well planning and exploitation of the reservoir. Core samples are assumed to be the best for the identification of heterogeneity in reservoirs and for defining effective parameters for fluid flow (porosity and permeability) as both direct measurements (e.g thin section analysis and porosity and permeability tests) and indirect measurements (e.g rock physics that among others can estimate pressure and share velocities and bulk and share modulus) can be performed to characterize reservoir parameters. However, a complete core of the entire well section is rarely available, due to intervals of no interest for exploration and that coring increase the drilling time and costs. Wireline logs, on the other hand, give measurements of the entire well and are quite inexpensive compared to core samples. Wireline log responses give quantitative recordings that can be used for fast interpretation of intra-well characterization as well as for lateral correlation between wells (Doveton, 1994).

Each wireline log response represents one or more specific rock properties (e.g. density, radioactivity, porosity), where several of these responses are needed to express the lithofacies characteristics of a given sample interval. Manual methods for characterization of such responses into lithofacies groups are often slow, highly labor-intensive, inconsistent and expensive (Doveton, 1994). Although several automatic methods have been developed to indicate both intra-well and inter-well correlations, human interaction is still needed to omit correlations that are not related to geological processes (Doveton, 1994). One of the most applied techniques for studying dependencies is multivariate data analysis (e.g principal component analysis, PCA) can visualize the data in a more comprehensive way than by visual inspection of raw data cross plots and thereby ease the interpretation of heterogeneity (Davis, 2002).

One goal of PCA is to reduce the dimensions of a specific dataset without losing information. Linear combinations of the original variables created through PCA can define a smaller set of variables that successively extract the maximum variability (Jolliffe, 2002). Another goal can be to seek the most representative multidimensional structure according to a given problem. This implies seeking an appropriate variance-covariance matrix as input to the PCA. The general objectives may therefore be twofold; data reduction and interpretation (Davis, 2002). In wireline log characterization, the challenge when applying PCA is to isolate specific process signatures, expressed by the principal component (PC) loadings that mimic geologic processes. These geologic processes can be, among others, depositional features explaining vertical sandstone successions or, transformed into a reservoir characterization context, explaining effective porosity or permeability variation. Multivariate analysis, in particular PCA, has traditionally been applied under the assumption that the first PC is the most important one and that it can separate different lithofacies types (Moline and Bahr, 1995; Scheerens et al., 1995; Yang et al., 2006). Without considering the differential selection of input variables or the selection of a specific study interval expressing the given research aims, such research is of limited value as the first principal component will be randomly data dependent explaining the major variability without considering the relevance of the PC loadings that makes up the weighting mechanism for generating the PC responses (scores). It is of crucial importance for ob-

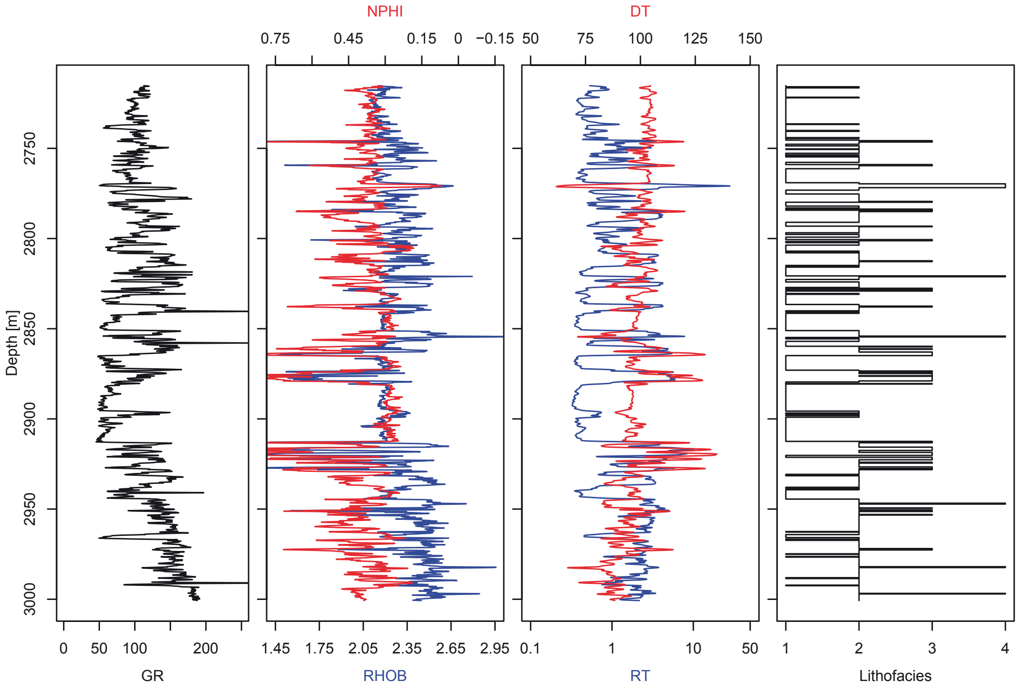

Figure 2.3: Five wireline logs (gamma ray, neutron porosity, density, resistivity and sonic) that show a clear indication of vertical heterogeneity form the basis for the multivariate analysis. The lithofacies log derived from interpretation of cm scale core samples and the original wireline logs has the following notation: (1) sand, (2) shale, (3) coal and (4) cemented layers.

taining interpretable results to exclude outliers that can mislead interpretation and results due to the inclusion of correlation between geologic process variables.

The following case presents the main findings in Brandsegg et al. (2010) (Appendix A) where PCA is used in a non-standard form including both an unstructured and structured approach for the characterization of fluviodeltaic reservoir heterogeneity from inferred wireline logs. The benefits of using a modified structured PCA approach to decompose petrophysical wireline log responses reflecting different orders of variability is emphazised.

From a well in the Norwegian Sea, indirect measurements of five wireline log responses are used to demonstrate the importance of defining different populations that portray small scale heterogeneities (Fig. 2.3). The wireline logs are taken from a specific geologic formation, the fluviodeltaic Upper Triassic to Lower Jurassic Åre Fm. (Dalland et al., 1988) and PCA is introduced to evaluate the joint information from the five wireline log responses (gamma ray, neutron porosity, bulk density, resistivity and sonic log). Principal components (PC) are used to identify independent correlations that can be related to specific geologic processes. PCA has the potential to show relationships not previously suspected, and thereby uncover fluviodeltaic associations that are not readily seen from the initial wireline log responses. The lithofacies classification used corresponds to the definition presented by Serra and Abbott (1982), where lithofacies is defined as *a characterization of collective associations of wireline log responses that are linked with geological attributes*. Two lithofacies types, representative of two different processes are used. The first process is associated with the deposition of rock types (sandstone, shale, coal and cemented layers), whereas the second lithofacies classification is adopted from Kjærefjord (1999) expressing the depositional environment of the Åre Fm. (fluvial channel, floodplain fines, sandy bay-fill and muddy bay-fill).

In PCA, the data can be standardized values or not. Whereas a PCA using non-standardized values is based upon the covariance matrix, a PCA in which the values are divided by the standard deviation is based upon the correlation matrix. This study follows the recommendations of Davis (2002), who stated that a correlation matrix is most appropriate when analyzing variables that are measured and expressed by different units.

A two step methodology is applied to identify and interpret both gross and intra lithological variations. The first step seeks to identify the gross variations. Univariate analysis is performed in a preprocessing mode to interpret the shape of the individual frequency distributions, where the most prominent populations of log responses can be revealed by probability plots (Stanley and Sinclair, 1988). Polymodality within the five wireline log distributions might be caused by processes expressed by specific variations within the different lithofacies types. The number of modes or populations is determined by the selection of inflection points for each of the probability plots (Stanley and Sinclair, 1988), where the calculated percent overlap between each population indicates the separation between each population.

Subsequent multivariate analysis is structured according to the univariate analysis results. Eigenvectors representing orthogonal directions in space permit the viewing of data from a variety of perspectives (Davis, 2002). In this case study (Appendix A), the modified structured PCA approach is not applied to reduce the dimensionality of the data, but rather to work on subsets of the wireline log. These subsets only include those samples in the correlation matrix that capture particular heterogeneity effects related to specific lithological units. Two calculations are performed, firstly, a total unstructured analysis of all well records from all wireline log variables and, secondly, a structured subset of separate well records according to the lithofacies classification given in Hammer et al. (2010). Four lithofacies classified rock types are identified within the total wireline log interval based upon core analysis and wireline log responses; sandstone (ss), shale (sh), coal (co) and cemented layers (cc). The loadings from these structured subsets are used to calculate PC scores that can be used to extrapolate a specific lithological signature to the totality of the well records. The signatures of both the univariate and the two multivariate approaches are compared with each other to identify both similarities and differences. These results are visualized by interpreting the PC loadings in table form and as star diagrams (Wegman, 1990), whereas the univariate results and PC scores are displayed as probability plots (Davis, 2002) and crossplots.

The univariate analysis identified several populations within each of the wireline log responses. The most significant populations were identified, such as the populations of radioactive enriched samples in the GR variable, cemented samples in the RHOB variable and in the coal component of the NPHI variable (Fig. 2.4). The identification of the most prominent variability in the data outlined large difference in the measurement wireline log response magnitudes ranging from neutron porosity, NPHI, (0-1) to gamma-ray, GR, (1 - 300). Such large differences in response magnitudes and the skewness of the distributions would impose an unequally weighting of the different responses if a standardization of each of the five wireline logs was not performed to ensure equal weights for the wireline log responses. The standardization procedure applied to all variables is consisted in the

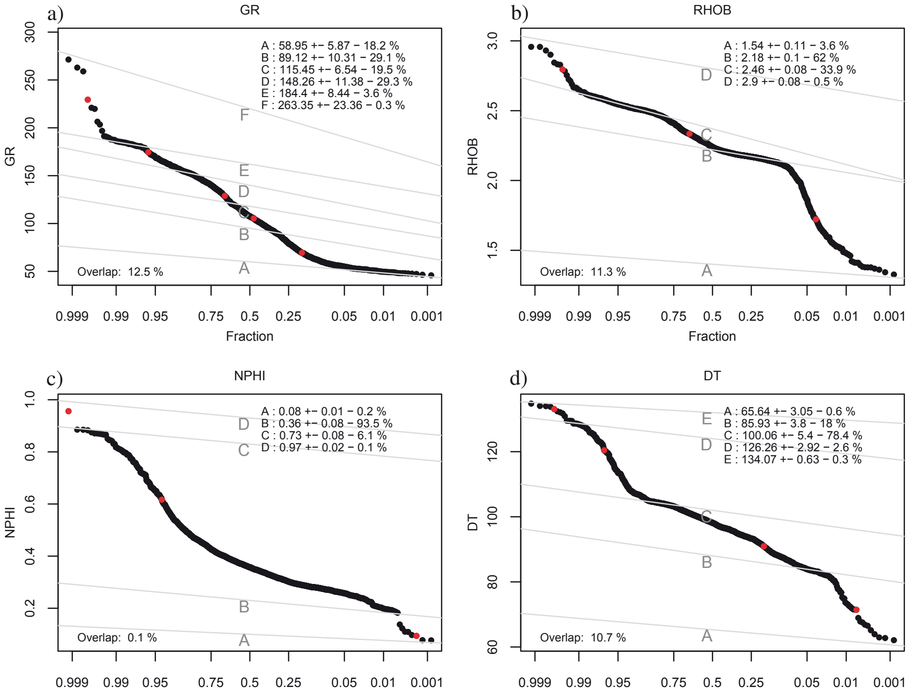

Figure 2.4: The cumulative probability plots, represented by four of five wireline responses, indicate polymodal distribution. The mean and standard deviations for each distribution are specified including the percentile of the total records within each population. The red circles specify the inflection point between two populations and the lines crossing the cumulative distribution indicate the average value for each population.

subtracting for each record variable mean from the measurement value followed by a division by the standard deviation.

The first PCA, performed on all samples of the studied interval as one population, named unstructured PCA by Stanley and Sinclair (1988), outlined the major lithological contrast between sand and shale. However, the interpretation of specific PCs in terms of discovering specific geologic processes was found to be intricate due to non-specific loadings representing interacting geological processes. Despite this, the unstructured PCA crossplot of the first two unstructured PCs still permits a more precise separation of the lithological units than can be obtained from the crossplot of the NPHI and RHOB wireline logs (Fig. 2.5).

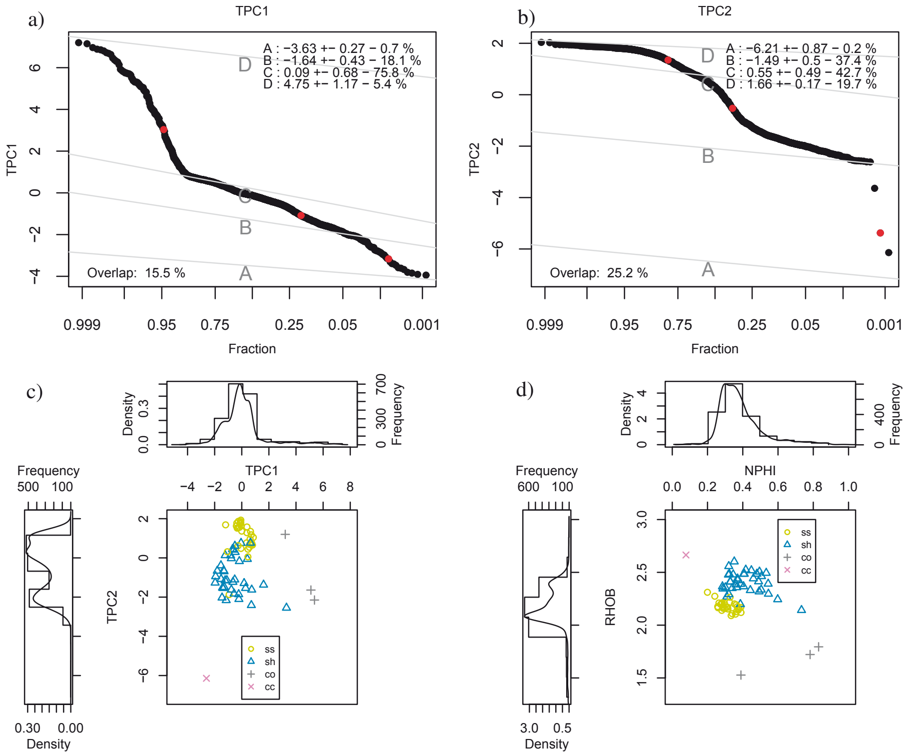

Figure 2.5: Analysis of the unstructured PCA. Polymodal distributions are indicated for the two first PCs. For visualization purposes only every fifth point is plotted in the crossplots. (a) TPC1 has 4 populations, where the B and C populations comprise 94% of the records. (b) TPC2 also indicates four populations. (c) The TPC1-TPC2 crossplot illustrates that the TPC1 could not resolve all the major lithofacies variations as the sand-shale variations are discriminated only by the TPC2. (d) The crossplot of RHOB and NPHI wireline log variables has less discriminating power than the TPC1-TPC2 crossplot. In the crossplots, only every twentieth record is displayed.

As a supplement to this standard approach, each of the lithofacies are calculated separately to explain within lithofacies variations without the interference by the other lithofacies responses. Stanley and Sinclair (1988) introduced the term structured PCA for the analysis using a specific subset of variables in a geochemical survey in order to better outline mineralized zones. Their results showed that the PCA using all the elements that were related to rock forming minerals outlined the major lithological units, whereas the mineralization was not delineated due to variations dominantly reflecting lithological contrasts. Different modes in the polymodally distributed variables related to trace elements from a mineralization could be identified and was used to select the variable that should be included structural approach pin-pointing the mineralized zones. This interpretational philosophy is extended to wireline log interpretation with some important modifications. Where Stanley and Sinclair (1988) selected a subset of the variables to characterize mineralized zones separately in a R-mode fashion, this study is not reducing the variables, but splits the sample points into four categories from where the structured analysis in a Q-mode fashion is executed. This results in an unbiased version of the within lithofacies variations, that can be expressed by the probability plots of each of the five separate lithofacies as well as separate binary cross plots that can identify specific within lithology contrast. All principal components outlined polymodal populations indicating different within lithofacies contrasts (Fig. 5 in Appendix A).

The interpretation of these polymodal populations clearly indicates the importance of interpreting the principal component loadings from where the principal component scores are calculated. Subsequently, the individual lithofacies crossplots of the two first principal components illustrate how the different principal component loadings affect the distribution within each specific lithofacies (Fig. 2.6). The PC crossplot of the sandstone records can outline coal, GR enriched and shale influence records that was not evident in the unstructured analysis. The crossplot of the shale lithological units indicate that PC1_sh separate sand-shale variations and the low PC2_sh scores outline coal influenced shale. Through extrapolation of the specific lithofacies PCs by calculating the specific lithofacies loadings to all wireline records, all wireline records are visualized by the specific lithofacies signatures.

The difference in loading values (Table 2 in Appendix A), including their ability to explain the total data variability, is distinct when comparing unstructured PCA and the

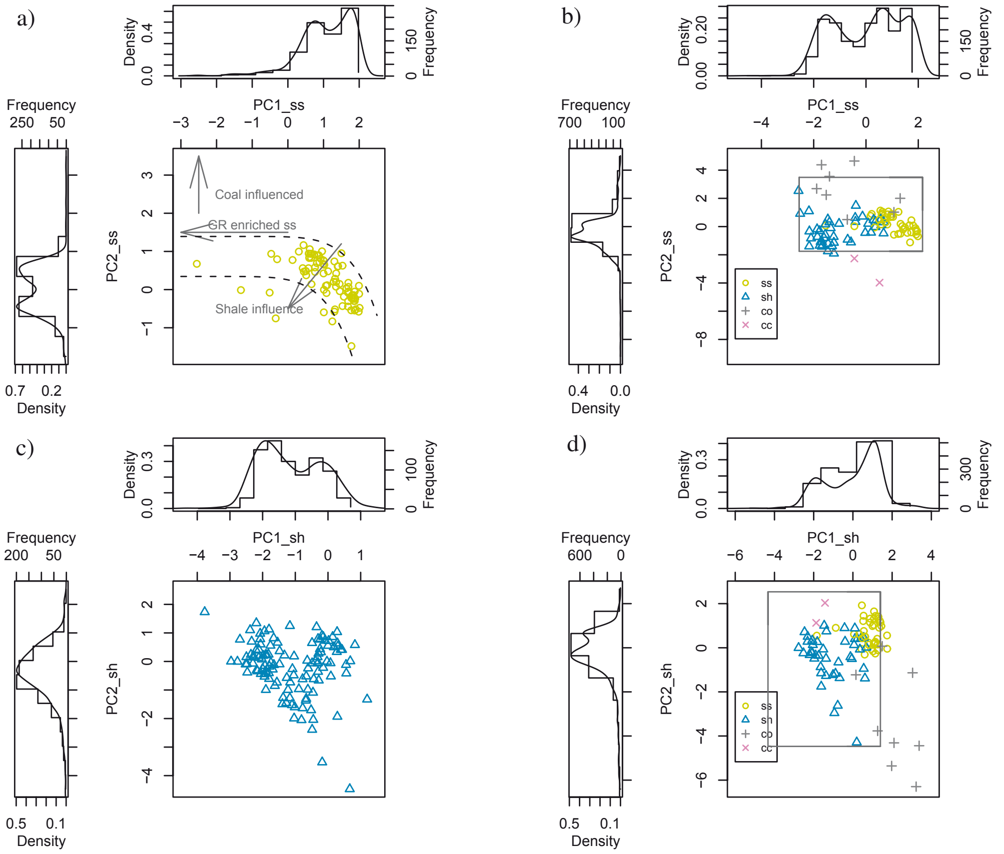

Figure 2.6: Crossplots of the first two PCs of the (a) sandstone and (c) shale lithological units, including crossplots where the loadings of each specific lithological unit are applied to the entire study interval (b and d) to illustrate the difference between the structured PCAs. In (a and c) only every tenth record is displayed, whereas (b and d) display every twentieth record.

four separate structured PCAs (Fig. 2.7). The bar plot shows that the first two PCs of the unstructured PCA explain less of the total variability than the structural PCAs. This implies that unstructured PCA uses a correlation matrix that has less strong correlations due to a larger part of heterogeneity from inter-lithological variations. The star diagrams and Chernoff faces show that the PC1_ss has about identical loadings as TPC2. This

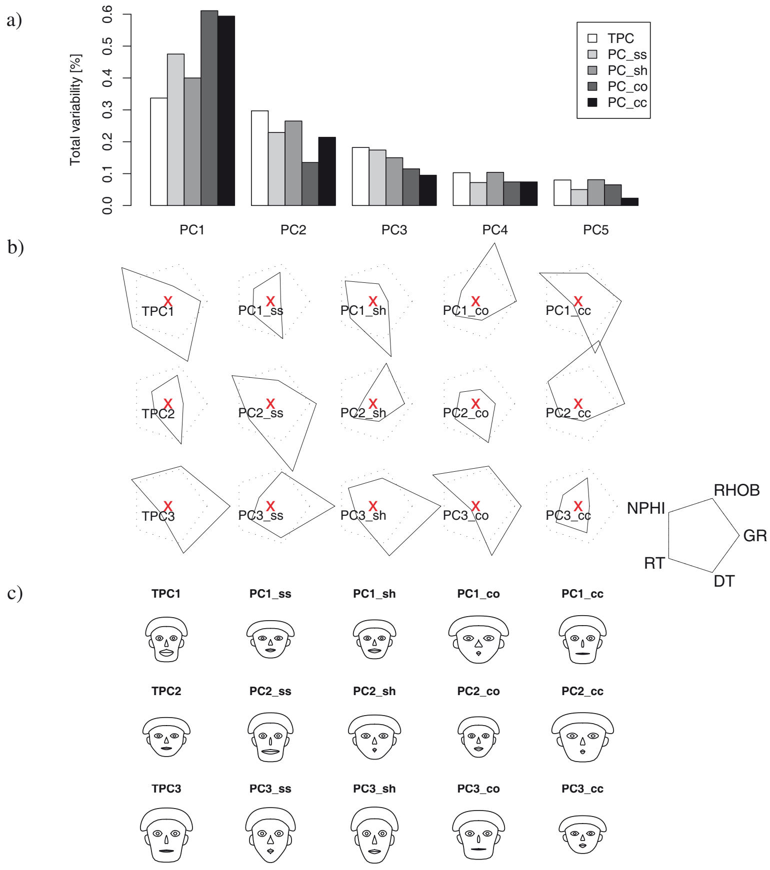

Figure 2.7: Separate plots displaying and comparing unstructured and structured PCA loadings and their magnitude of variability. (a) The bar plot explains the total variability of each PC both for unstructured and structured PCA. (b) The star diagrams (Wegman, 1990) show that each PC loading has its own specific signature that can be compared to other loadings. The most prominent loadings are easily identified by their high negative or positive values confirming that similar loadings have different PC rank. Zero loading is plotted at the dotted line and high negative loading is at the center point. The dotted line of the diagram is where PC loadings are zero. (c) Another visualization of the PC loadings is Chernoff faces (Chernoff, 1973), which use faces to display five variables in one plot; GR - height of face, RHOB - width of face, NPHI - shape of face, RT - height of mouth, DT - width of mouth.

indicates that TPC2 represents the residual sandstone variability due to internal sandstone variations after the major lithofacies variability has been removed by TPC1. The similarity between PC2_ss and TPC1 shows that the residual variability once the intra-lithological sand variability is removed contains much of the same heterogeneity as shown in the totality of the well records. This indicates a sort of fractal behaviour (definition see Emerson et al. (2005)) of the lithological mix at the Åre Fm. scale (300m) and the scale of the combined sandstone layers (130m).

The comparison of the unstructured and structured PCA scores, expressed by the percent overlap of populations, identified some significant results: While the unstructured PCA shows an increase in population overlap with increasing PCs, the structured PCA has an opposite trend. The unstructured PCA has little overlap between populations as it incorporates all data samples including the end-members. It therefore explains the interpopulation variability with only limited variability remains to explain the intra variability. The structured PCA on the other hand expands the intra-population variability in the respective lithofacies units without interference from other lithofacies variations. This permits to break the apparent uniform unstructured population into sub-populations reflecting local petrophysical contrasts related to specific lithofacies units. Through comparison of unstructured and structured PCA by displaying probability plots and binary cross plots of the PC scores as well as table analysis, spider diagrams and Chernoff faces of the PC loadings, this intensive evaluation has increased the knowledge of the importance of understanding the input data prior to multivariate analysis. It has also identified how within population contrasts can be identified by stepping down one level of organization from analyzing gross lithofacies type to analyze the inherent variability within specific lithofacies types.

In contrast to the initial study performed by separating the samples into four lithofacies types derived from rock types, a second lithofacies characterization explaining depositional features, fluvial channel (FCH), flood plain fines (FF), sandy bay-fill (SBF) and muddy bay-fill (MBF) was applied. The two major principal component scores of the sandstone lithofacies, plotted with the labelling of the new lithofacies grouping, showed

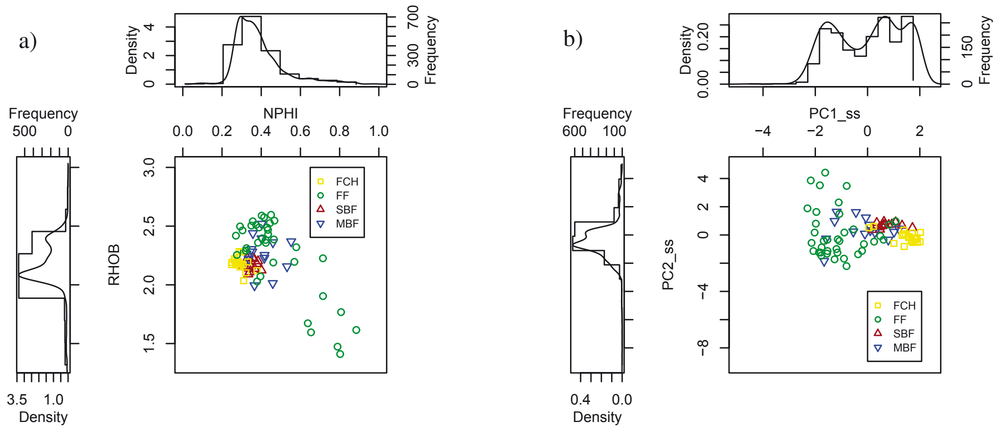

Figure 2.8: Comparison of initial wireline logs, NPHI and RHOB, and the two first PC scores, PC1_ss and PC2_ss, calculated by the structured sandstone intervals with a lithofacies types classified according to Hammer et al. (2010). There is more distinct separation between the fluvial channel (FCH) and sandy bay-fill (SBF) when structured PCA is applied. Only every tenth record is displayed.

a more distinct separation between FCH, SBF and MBF than the initial RHOB-NPHI crossplot (Fig. 2.8). This confirms the expectations of using the structured PCA of sandstone grouping to accentuate the variations within sandstone depositional features. The structured PCA crossplot is therefore superior to the initial wireline log responses when focusing on specific variations within a specific depositional setting. The calculations and graphical visualization of data using loadings expressing variations in the sandstone population has enhanced the differentiation between the different depositional environments without interfering with the other specific lithologies, such as coal and cement influenced intervals.

Capturing small scale heterogeneities in a reservoir by indirect measurements, such as wireline logs, are shown not to be straight forward. In terms of scale, taking into considerations the petrophysical responses and their sampling rate and influence distance, are all important when correlating direct measurements of core samples. In this study, the 15 cm sample rate of measurement scale contained sufficient details to express within lithology contrasts.

These results show the importance of the pre-processing of the data before input to multivariate statistical analysis. Cumulative probability plots of each wireline log allowed the identification of polymodality that in most cases represented specific lithological populations.

This study has shown that there is a vast potential to apply separate loadings derived from structured PCA for expressing specific lithological contrast, both between and within lithofacies units, to other locations with similar geologic setting and/or deposition environment. This result contradicts the work of those who blindly defines the first PC as the most important one, as the selection of study interval is crucial for the exclusion of undesirable significant end-members. The analysis of specific lithologies and their decomposed wireline log signatures can express underlying geologic processes that often are classified as noise. The comparison of the unstructured and structured PCA loadings and their explained variability permits a detailed understanding of the relationship between geologic processes and the PC loadings and scores. By recalling the REV conceptual sketch (Fig. 1.4), this study is related to lithofacies, whereas the underlying processes are related to the lamina level. The structured sandstone PCA showed evidence to express underlying processes not seen when using univariate analysis or the unstructured PCA approaches. This study coincides with the REV concept as the unstructured PCA identified representative values for each of the lithofacies types. At the same time the structured PCA extracts representative values for the underlying variability of the given lithofacies types at lamina level.

This study has opened for a more detailed understanding of the PC loadings and their importance for indicating signatures that can express specific lithological processes. It is of crucial importance to understand the input variables, its measurement and operational scale and how these parameters can be applied for achieving representative values that can increase the correlation of wireline log responses to different rock types and/or upscaled to specific depositional environments. However, more work need to be performed in lithofacies classification, in the lithofacies type identification of the representative parameter values, how this is related to the geological processes forming these lithofacies types and how all these interacts with the change in measurement and operational scales.

2.3 Refined lithological description through structured multivariate analysis

In reservoir characterization, the interpretation of wireline logs for defining lithology types and investigating lithological variability is challenging (Schatzinger and Jordan, 1999): Wireline log responses are indirect measurements and various log responses are needed to portray special lithological signatures. Generally, the wireline log responses can been decomposed into three different types; gross lithology contrasts, within lithology contrast and noise. The relative magnitude of these types of contrasts is strongly dependent on the geological variations on one side and how the well was drilled and the quality of the wireline log responses on the other side (Shelly, 1998). The geologic variations affecting the petrophysical wireline log signatures can among others be a result of grain-size variation, grain sorting and grain orientation (Martinius et al., 2005). Small scale heterogeneities within specific lithological units, whose contrasts are minor compared to gross lithological contrasts, can be of great importance as input to reservoir modeling for explaining effective reservoir properties (Nordahl and Ringrose, 2008). The magnitude of noise compared to the within lithological variations depends on the geologic heterogeneity and the quality of the wireline log responses. Even though, numerous attempts to isolate different geologic variations and noise have been tried, no published method have completely separated these contrasts and evaluated them against core sample studies. E.g. the study of Moline and Bahr (1995) used PCA as a pre-processing tool before lithofacies clustering and concluded that the use of PCA reduced dimensionality of the wireline log space and increased the separation between gross lithology effects for facies clustering. However, their study did not consider if the remaining PCs explained small scale geologic variations or noise.

Other previous studies of wireline logs have outlined capabilities to invert principal component scores to rescaled versions of the initial wireline log responses. Doveton (1994) showed how a PCA model can invert the first principal component into a specific wireline log response, exemplified by the gamma-ray (GR) log, by computation of Eq. 2.2,

$$G_i = u_{11} z_{1i} \tag{2.2}$$

where G_i is the first principal component estimate of the gamma ray reading of the i-th sample, the u_{11} coefficient is the loading of the first principal component with respect to the GR log, and z_{1i} value is the first principal component score for the i-th zone. As the principal components were computed from the correlation matrix, the reconstructed logs are in units of standard deviation with an origin at the mean. Therefore the rescaled GR in API units can be calculate by

$$G_i = u_{11} z_{1i} s + \bar{G} \tag{2.3}$$

where $\bar{G}$ is the mean and s is the standard deviation of the original GR log (Doveton, 1994). The residual value that represents the combined contribution of the remaining principal components, expressing both minor geologic variations and noise, can then be calculated by subtraction of the rescaled GR based on the first principal component from the initial GR response.

Despite several studies have indicated the advantages of using only the first principal component for lithofacies classification while the remaining components are neglected (e.g Moline and Bahr, 1995; Elek, 1990; Lim, 2003), other study results, such as Zhang et al. (2007), successfully showed the importance of evaluation of the specific principal components by applying minor PCA variability to detect hydrocarbon bearing sands on satellite images. Still, this procedure has not yet been adopted to wireline logs or litho-classification in general.

Following the findings in the previous section (Section 2.2), where specific lithofacies analysis were found to be essential for indicating small scale heterogeneities, the present study evaluates the performance of two separate multivariate techniques for the characterization of fluviodeltaic reservoir heterogeneity from wireline logs (Appendix B). The benefits of using structured PCA approach in conjunction with the Eckart-Young theorem (Eckart and Young, 1936) demonstrates how petrophysical wireline logs can be decomposed into different orders of variability and differentially interpreted to provide additional insight into fluviodeltaic heterogeneity. This study also emphasizes how the second, third and subsequent PCs, previously often classified as noise, contain information of small scale heterogeneities that can be important for e.g. defining representative effective parameter values in reservoir characterization. It is further shown that standardized PC scores, by the use of Eckart-Young theorem can be decomposed into signatures expressed by the initial wireline log units. The PC loadings expressing a refined lithological fingerprint can be used to portray separate processes that influences porosity e.g. grain size, sorting and packing. The interpretation and use of these loadings will uncover additional information from the initial wireline log responses.

A case study, analyzing a fluviodeltaic section of the Late Triassic - Early Jurassic Åre Fm. (Dalland et al., 1988) from a well in the Norwegian Sea, offshore mid-Norway, was carried out. This well section (Fig. 2.9) has previous been classified into the following four lithofacies groups that have been separately evaluated (Brandsegg et al., 2010): Sandstone, shale, coal and cemented influenced lithofacies types. In the present study, structured PCA of the sandstone lithofacies group is compared with structured PCAs of two 10m subsections (zone 1 and 2), interpreted to be two pointbar successions. The results are correlated with core interpretation that is documented with core photos.

As Doveton (1994)'s study used the mean and standard deviation for calculating rescaled versions of a wireline log response, the present study uses the Eckart-Young theorem to decompose the specific wireline log responses into wireline log responses related to each of the calculated principal components. Further these principal components can be back-calculated to portray their individual contribution to each of the initial wireline log measurements.

Prior to applying the Eckart-Young theorem, an intensive evaluation of structured PCAs are performed to investigate how the PC loadings are influenced by changing the

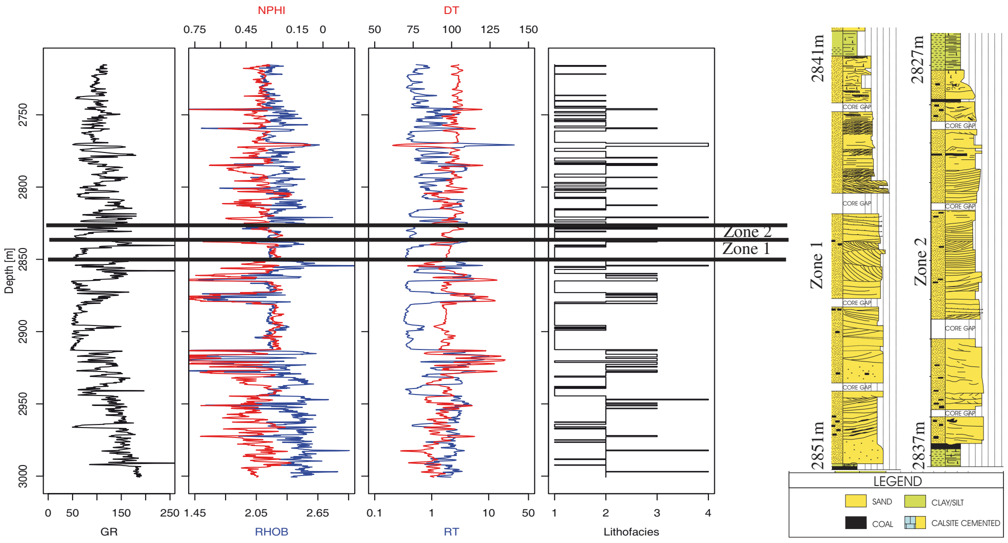

Figure 2.9: Five wireline logs (gamma ray, neutron porosity, density, resistivity and sonic) that show a clear indication of vertical heterogeneity form the basis for the multivariate analysis. The lithofacies log derived from interpretation of cm scale core samples and the original wireline logs has the following notation: (1) sand; (2) shale, (3) coal and (4) cemented layers.

focus from one sandstone interval (Zone 1, z1) to another (z2) as well as a composite sandstone representing the sum of all sandstone intervals. The remarkable stability of the loading from each of these subsets of data indicates the intrinsic sandstone fingerprint of these heterolithic sandstones interpreted to be point bars (Brandsegg et al., 2008, 2010). The results of the pre-processing study is illustrated by spider diagrams and the PCs independent signature is summarized in table form outlining the dominant and opposing wireline variables that express different lithological variations within the sandstone lithofacies type that may be linked to specific depositional processes (Tab. 3 in Appendix B). These PC loadings are used as input to the Eckart-Young theorem for back-transforming standardized PC scores into the original wireline log unit responses .

The Eckart-Young theorem is the cornerstone of several multivariate techniques (Davis, 2002). The theorem expresses the interrelationship between a data matrix and the eigenvalues and eigenvectors of the correlation matrix. It states that any real matrix, X, can be decomposed into two orthogonal matrices, V and U, and a matrix, Λ, containing the square rot of the non-zero singular values, λ, where the positive elements are along the diagonal and off-diagonal elements equal to zero (Davis, 2002). That is,

$$X = V\Lambda U^T \tag{2.4}$$

where Λ is defined as

$$\Lambda = I\sqrt{\lambda} \tag{2.5}$$

where I is the identity matrix. The initial wireline log responses are placed as column vectors into an $n \times m$ matrix, X, where n is the number of samples in each wireline log and m is the number of wireline logs. The first step is to compute the V and U matrices using the standardized wireline log variables. The columns of the $n \times m$ orthogonal matrix V and the $m \times m$ orthogonal matrix U contain the eigenvectors associated with eigenvalues of the major and minor product matrix of X, respectively. Λ is an $m \times m$ diagonal matrix containing the square root of the eigenvalues, $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4 \geq \lambda_5$. This use of eigenvalues are possible as the initial matrix, X, has zero empirical mean. The matrix Λ can be decomposed such that

$$\sum_{i=1}^{5} \Lambda_i I_{ij} \tag{2.6}$$

where Λ is the 5×5 identity matrix, I is the Kronecker delta function, $j = 1, 2, \ldots, 5$ and $i = 1,2,\ldots,5$. By performing this decomposition and then recalculate the X matrix for each eigenvalue, five separate signatures for each of the wireline logs are produced related to the five eigenvalues of the matrix X. Each of the five separate versions of the original data set contains isolated first to fifth order effects which when summed together equal the original. The procedure above can be used in a total mode, where the entire wireline log is used to calculate the correlation matrix or in a structured mode where specific intervals of the wireline log can be selected to focus on specific lithological variability or a particular type of samples within the study interval. The use of total or structured mode will normally result in some degree of difference in weights illustrating the inherent variability within these samples. The wireline log samples of the structured mode are placed as column vectors into an $s \times m$ matrix, $X_{section}$, where s is the number of samples in each wireline log section and m is the number of wireline logs. The section of the X matrix is defined as

$$X_{section} = V_{section} \Lambda_{section} U_{section}^{T} \tag{2.7}$$

where the notations are similar to Eq. 2.4. The weights from this specific section can be applied to the entire wireline log, X, mimicking the specific sectional variations. The refined decomposition of the entire wireline log can be defined as

$$X_{refined} = V_{refined} \Lambda_{section} U_{section}^{T} \tag{2.8}$$

where $V_{refined}$ is similar to the Eckart-Young theorem defining $V = XU\Lambda^{-1}$ that in this case can be written as

$$V_{refined} = XU_{section} \Lambda_{section}^{-1} \tag{2.9}$$

where X is the initial wireline log responses. $V_{refined}$ is now the new decomposed wireline log mimicking the five signatures of the selected interval.

Further is the isolated first to fifth order effects of each wireline response scaled to show the percentile contribution of each effect on the wireline response. The direction of the specific eigenvectors is undetermined and can therefore be changed to suit the problem at hand. This makes it possible to ensure that the loadings of a specific wireline variable are positive. The positive loadings for this variable make it possible to calculate the percentile contribution of each of the first to fifth order PCs for this specific wireline variable. The individual contribution can represent inherent petrophysical variations that are intricate and may not be perceived by core inspection or the original wireline log.

The results of the structured PCAs, prior to applying Eckart-Young theorem, indicate that the first principal components of all three analyses (sandstone lithofacies and the two point bar successions) have close to identical signatures, whereas the remaining PCs have different loadings according to their rank of variability (Fig. 2.10). A more detailed comparison between the sandstone lithofacies and the two point bar successions are given in Appendix B.

The decomposed NPHI wireline log (Figure 2.11) calculated over the 10m fluviodeltaic section (zone 2) provides a clear example of the existence of different small scale heterolithic lithology effects. These lithology effects could be verified by core interpretation and core photos of the point bar sequence and indicated the presence of sandstone including coal fragments in the upper part, succeeded by shale. The separate decomposed NPHI variables can also be expressed as a ratio. E.g. the NPHI [%] indicates the percent contribution for each of the five decomposed NPHI variables relative to the total NPHI at that specific depth interval. The PC4 contributing only about 1% of the total variability is of particular interest as the NPHI scores (expressed as % contribution to the total NPHI) outlines three sandstone successions, possibly cyclic, within the point bar. These successions have been interpreted to reflect change in sand transport rate. In addition, the analysis permits to identify two thin coal layers not detectable from the initial wireline response.

As a supplement to the 10m point bar sequence, a crossplot of the individual decomposed NPHI variables and the initial RHOB variable expressing isolated effects and that it is superior to the initial NPHI variable (Fig. 2.12): NPHI1 scaled express GR enriched records, whereas the NPHI4 scaled variable indicates where the three sandstone successions are terminating.

The results show that a mapping of contrast components by the use of PCA and Eckart-Young theorem can be used to enhance our ability to characterize small scale reservoir heterogeneities. Through the decomposed variables mimicking specific within-lithology contrasts by means of percentile contribution of the initial wireline log responses, the interpretation is suitable for non-multivariate experts as the percentile values give more comprehensive understanding than the traditional principal component scores. The use

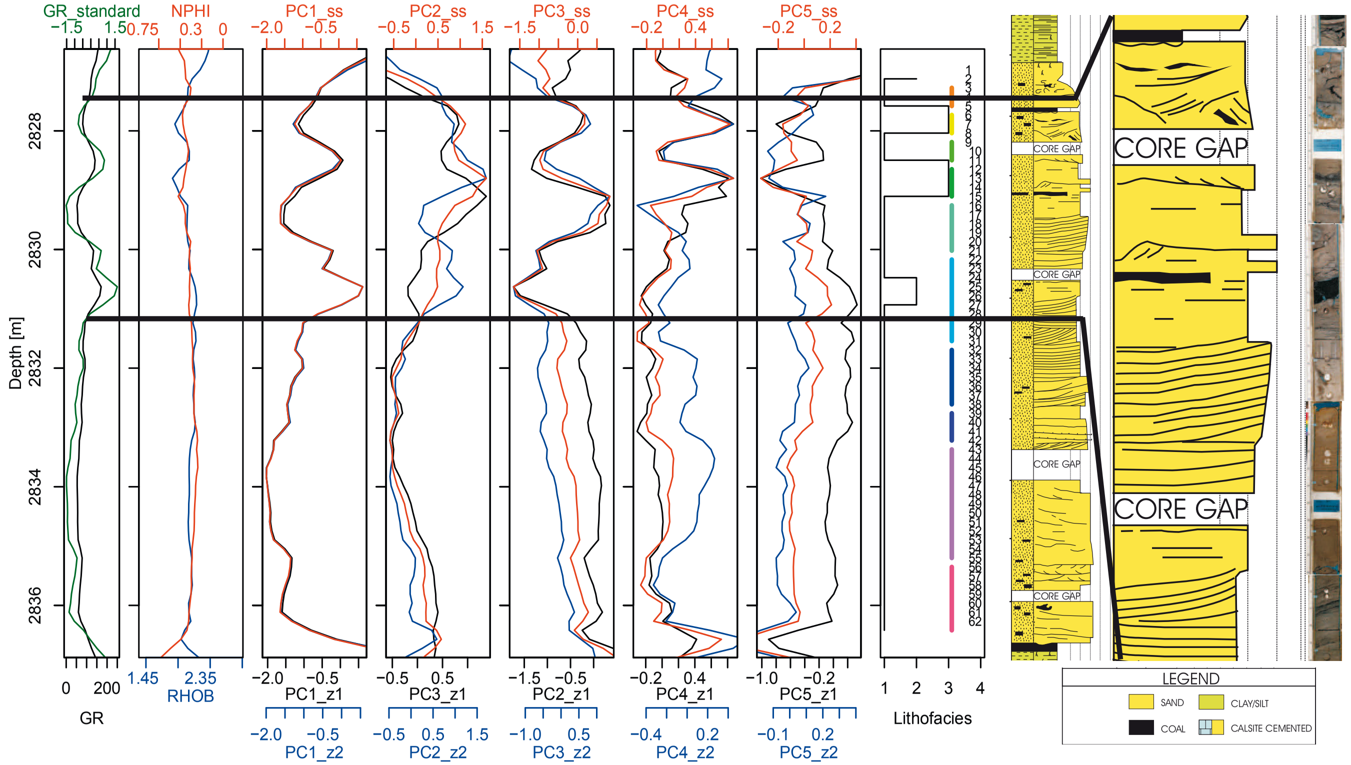

Figure 2.10: Variations between scores using loadings of point bar 1 and point bar 2 and the sandstone lithological unit variables, PC1_ss-PC5_ss, visualized by the point bar 2 sequence. The first, third and fifth plots have close to identical responses, whereas the second and fourth responses do not correspond solely to the other response. The fourth plot of zone 2 diverges particularly at the PC4_z2 response indicating three sandstone successions.

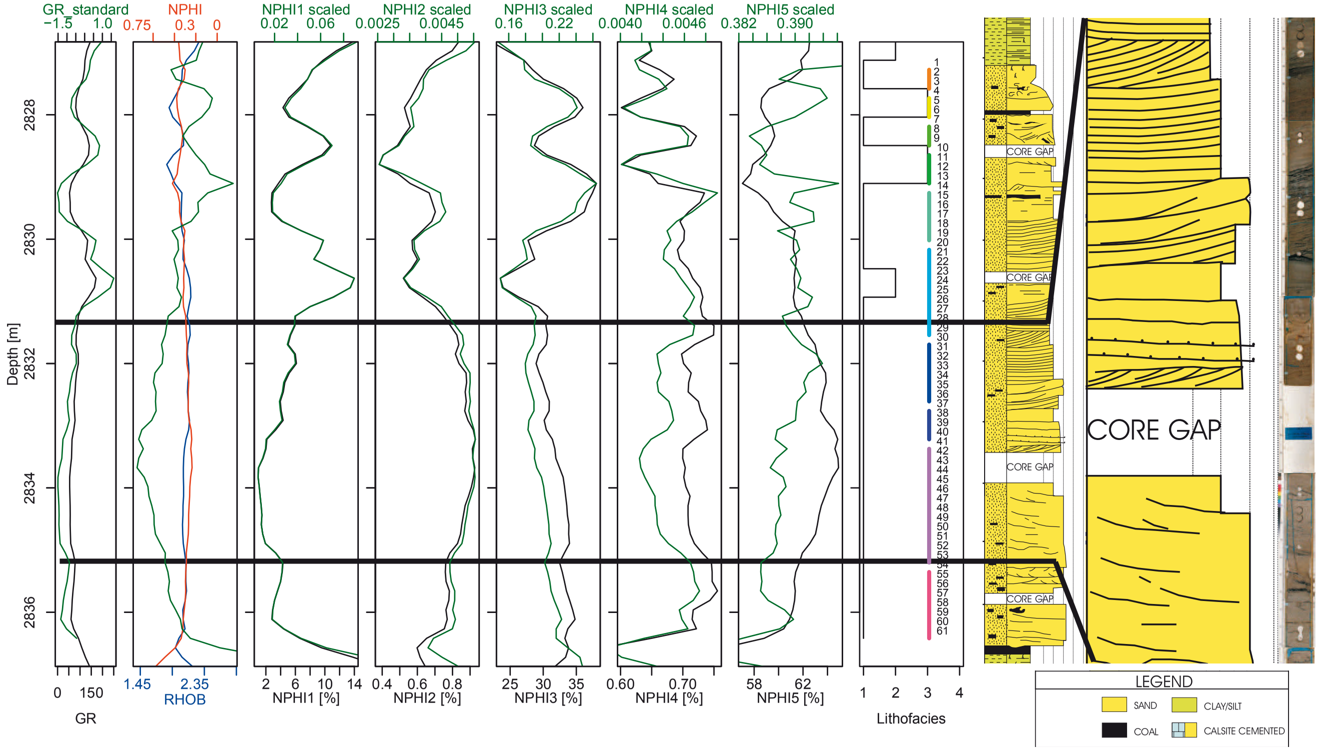

Figure 2.11: The plot of Eckart-Young derived scores constructing new responses first scaled to show their contribution to the standardized wireline log response and secondly the percentile contribution for each variable of each sample point.

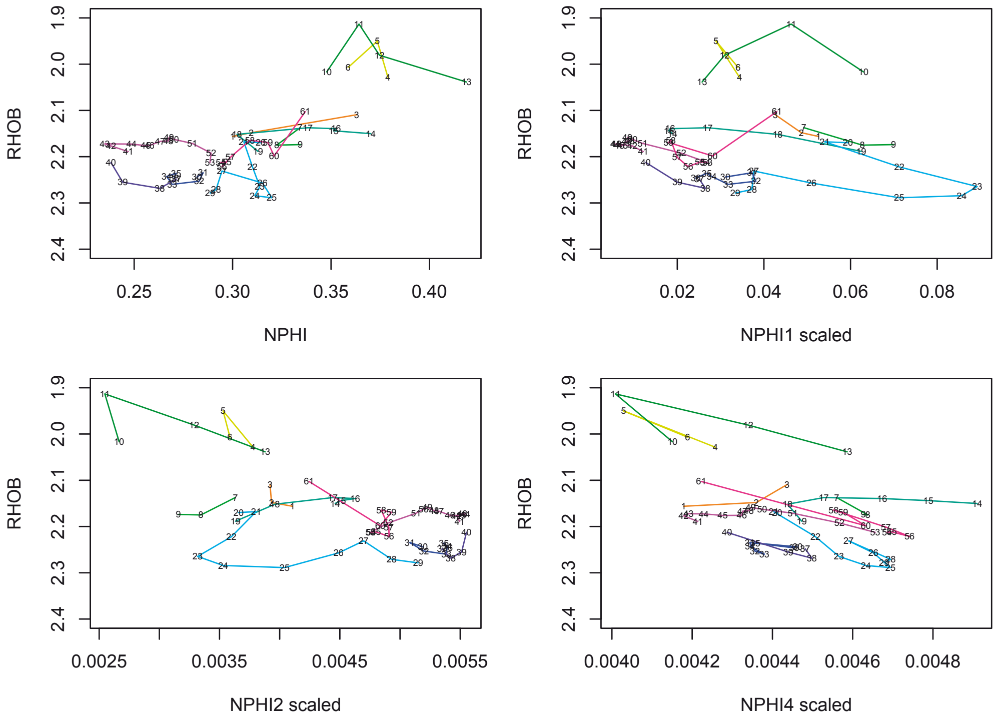

Figure 2.12: The plots of Eckart-Young derived scores constructing new responses first scaled to show their contribution to the standardized wireline log response and secondly the percentile contribution for each variable of each sample point. This can ease specific lithology trend interpretations based upon specific decomposed wireline log variables without interpreting the traditional PC scores.

of Eckart-Young theorem also enables to merge two or more principal components into a combined component that explain a specific lithologic phenomena that is not possible in a standard PCA as each principal component is independent on each other and have independent (scaleless) scores (Fig. 2.13).

Within the present study, a change in the operational scale related to the study area was performed. Firstly, it evaluated all the sandstone lithofacies samples, followed by two separate point bar sequence. The point bar sequences expressed similar gross variability with deviating within lithology contains as the two point bars contained different composition

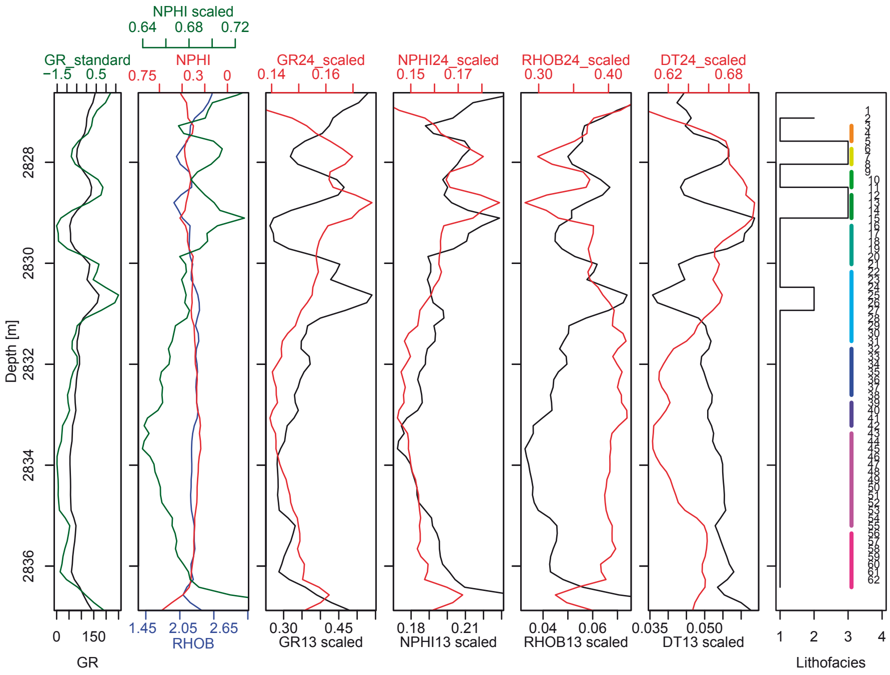

Figure 2.13: The plots of joined Eckart-Young derived scores constructing new responses can be fine-tuned to explain specific lithology trends.

of sand, shale and coal. These contrast in the point bars were illustrated by the deviations from the sandstone lithofacies loadings (Table 2 and Fig.2 in Appendix B). There is also a difference in the PC loadings between each of the point bars interpreted sections. This is most probable related to the number of records within the PCA, counting 66 for each of the analysis. If a more general expression of point bars are to be assessed, several intervals with similar depositional characteristics need to be incorporated in the analysis. Based upon this argument, when explaining within lithofacies contrast that is to be related to depositional processes, more sample points with similar depositional history need to be incorporated in the analysis. Here in this study, the selected sandstone lithofacies outlined specific within lithological contrasts related to the aim of this study that was to isolate within lithological contrast related to effective parameter value signatures. This presented study follow the REV concept (Fig. 1.4) and the process-response concept for identifying the appropriate scale for extracting representative responses explaining specific geologic processes that can ultimately increase the accuracy when upscaling to overall reservoir characteristics. The analysis of the sandstone interval has permitted to separate global sandstone porosity values into individual porosity contributions from different underlying independent sedimentological processes.

The introduction of addition wireline logs, especially geochemical logging tools, estimating concentrations of mineral elements by measurements from several nuclear logging devices (Wendlandt and Bhuyan, 1990; Lofts et al., 1995), can enhance the characterization of small scale heterogeneities and reduce the deviation between petrophysical log and core measurements. However, if these or other tools (e.g electrical imaging methods, induction logging and total gamma and spectral gamma) are to be used, an increased effort to understand the inherent variability of the new wireline log responses is needed in order to understand the result of the application of Eckart-Young Theorem.

The results presented here hold great promise, but additional work remains in order to explain the sedimentological processes that underlie the use of the Eckart-Young theorem. One option is to include more variables in the analysis and a second option is to fingerprint specific PCA signatures (loadings) that are known to express specific geologic processes that are present in heterolithic environments.

2.4 A novel workflow for 3D integration of geological and geophysical heterogeneity signatures at the reservoir scale

Following the two previous sections that identified the importance for recognition of underlying processes recorded by wireline logs, this section is devoted to the inclusion of small scale heterogeneities in a seismic reservoir characterization workflow from lamina to facies association scale (Fig. 1.4). The present study relates to reservoir characterization where various reservoir signatures are described using all the available data at multiple scales to generate reliable reservoir models for precise reservoir performance prediction (Schatzinger and Jordan, 1999). The ultimate goal of seismic reservoir characterization is to identify reservoirs, delineate them and determine the distribution of their effective properties, such as porosity and permeability, and model and determine the hydrocarbon yield of a given reservoir. The reservoir characteristics affecting porosity and permeability include pore and grain size distributions, facies distribution and depositional environments. During field production, repeatable seismic is often performed to monitor the production and to delineate undrained areas where additional production wells need to be placed for maximizing the recoverable reserves (Brown, 2004). A typical reservoir characterization project using seismic data and well data is subject to continuous assessment process of mapping, calibrating and interpreting data and is often refined through iterations over each of them (Ringrose, 2008). Proper selection and application of representative information derived from various tools contributes to the accuracy of property determinations and to the success of the project (Keogh et al., 2007).

The most important data for describing reservoir characteristics are core data, well logs, well test data, production data and seismic survey (Allen and Allen, 2005). Normally, the available data for reservoir characteristics is only fragmented, e.g. core samples and wireline logs give only cm lateral knowledge of a reservoir that are several km wide. It is therefore essential to extract as much information from the available data and incorporate this data for generating realistic reservoir models (Brown, 2004). Especially, wireline log data gives valuable petrophysical information about mineralogy, texture, sedimentary structure and fluid content of the reservoir layers. By including core samples, direct information can support the wireline log data to improve the determination of specific reservoir properties. As the capture of small scale lateral variations are mainly limited to the cross-comparison of wireline measurements, such reservoir properties can be integrated with information from seismic data. Seismic data provides a more lateral investigation that still has a shortfall of identifying small scale vertical heterogeneities beyond seismic resolution (Brown, 2004). A challenge is therefore to produce a geomodel incorporating small scale heterogeneities of the effective reservoir properties that can be upscaled and related to seismic trace signatures (Keogh et al., 2007).

According to Avseth et al. (2005), rock physics can be the link between seismic data and geology as the rock physics helps to explain reflection signatures by quantifying the elastic properties of rocks and fluids. This contrasts the conventional seismic interpretation that recognizes and map geologic elements and/or stratigraphic patterns from seismic reflection data from where hydrocarbon prospects are defined and drilled. Seismic resolution is normally characterized by a voxel size of 15-25 m (both horizontal and vertical). From 3D seismic data, top and base of thin reservoirs can often be distinguished and interpreted, whereas the internal variations within the reservoir often needs to be based on well bore information that can capture this heterogeneity at lamina and lithofacies scale. These intra-reservoir variations can contain internal boundaries that often are neglected in synthetic seismic generation from wireline logs (Stovas and Landrø, 2005). Avseth et al. (2005) indicated that geological software packages can represent very detailed geological models, but these still have significant uncertainty at the sub-seismic scale.

For both reservoir characterization and in general, the demand for integration of geology and geophysical data has resulted in an intensive literature stretching from basin scale, via reservoir characteristics and to small scale heterogeneities (e.g. Keogh et al., 2007; Hantschel and Kauerauf, 2009). Their united aim is to incorporate geologic and geophysical heterogeneity for the characterization of effective reservoir parameter values. Previous research in sedimentary deposit modelling as well as seismic modelling (Janbu et al., 2005; Nordahl, 2004; Stovas et al., 2004; Stovas and Landrø, 2005; Stovas et al., 2006) have identified problems related to characterize a reservoir model acute in geologically complex and heterogeneous reservoirs.

As a contribution to reservoir characterization methodology, a novel workflow is introduced to improve integration of geologic and geophysic data that can be used to enhance the importance of geology knowledge in constructing realistic reservoir models and validate industry-standard geomodels both for hydrocarbon exploration and production

(Appendix C). This workflow focus exclusively on integrating geological and geophysical heterogeneity signatures on sub-seismic scale that are upscaled to seismic scale.

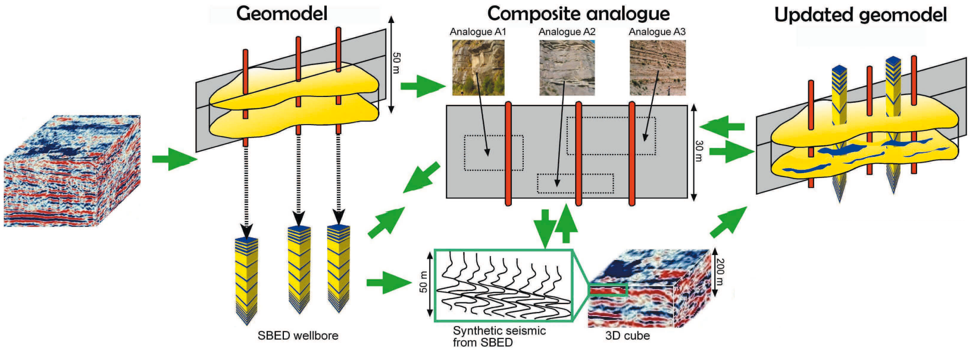

Figure 2.14: Representation of the workflow. The initial geomodel is based on regional 3D seismic and wells. A composite geological analogue is created and calibrated with wellbores and relevant geological outcrops. Hypothetical wellbores are then positioned and modelled by SBED. SBED modelling gives output for seismic modelling, which can in turn be compared with the 3D regional seismic cube. Hypothetical infill wells and existing wells generated with SBED are constrained with seismic data through modelling and used to update the existing geomodel.

The presented novel workflow is based upon improving an existing geomodeling derived from 3D seismic, wireline logs and other sources by quantified hypothetical well at cm scale derived from cores, wireline logs or composite analogues (Fig. 2.14). Further, these ultra-slim one-dimensional digital hypothetical wells are used to generate synthetic seismic traces which are later correlated to the existing 3D seismic. By introducing hypothetical wells in undrilled areas, different depositional scenarios can be tested in relation to the existing 3D seismic and an updated geomodel reflecting all available data is achieved. From the latter analysis, geologists can verify if a given hypothetical well corresponds to relevant facies from borehole data, outcrop analogues or imaginary wells, through quality control of the petrophysical parameters. The hypothetical well bores, introduced to test different reservoir depositional scenarios, are evaluated in relation to a given seismic trace at the specific hypothetical well site that enables to quantify which estimated depositional scenario is the most plausible.

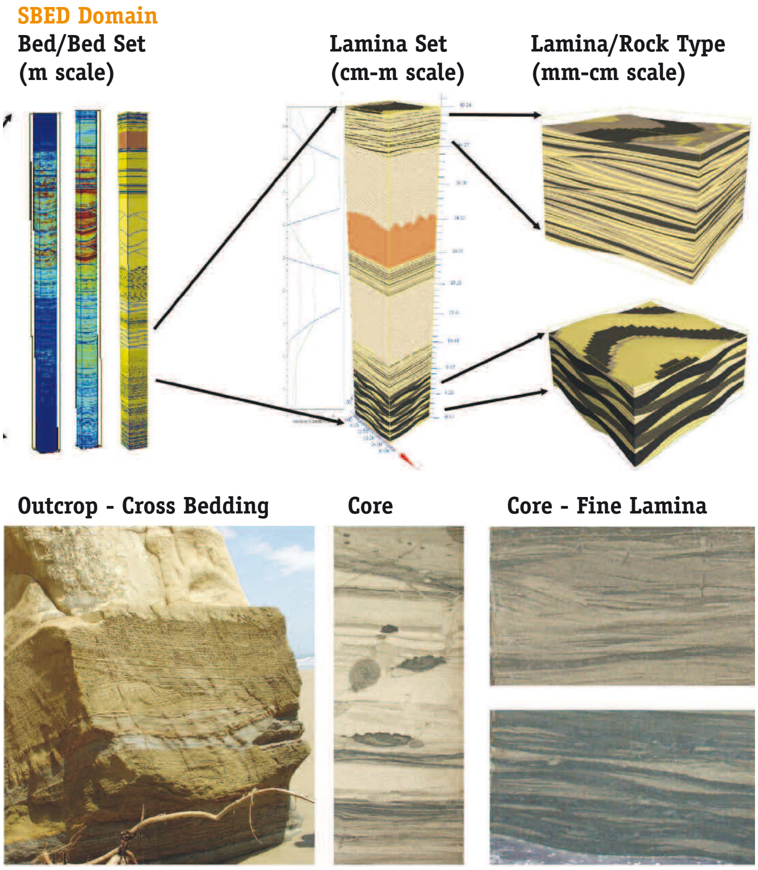

Figure 2.15: The SBED domain operates from lamina rock type (mm-cm scale), via lamina set of cm-m scale to bed sets of m scale (Geomodeling, 2006). These scales can be correlatable with the representative element volume (REV) scales outline in Fig. 1.4.

To generate hypothetical wells, the SBED software (Geomodeling, 2006) from Geomodeling Technology Corp. are applied. This software represents the state of the art in quantifying petrophysical properties from sedimentary complexity described by depositional environments and is capable to quantify stratigraphic architecture of reservoirs that, here, are used as input for seismic modeling (Nordahl et al., 2005). The SBED software is based on manipulating sine-functions, creating surfaces representing incremental sedimentation (Nordahl, 2004; Wen, 2004). The displacement of the surfaces generates a three dimensional image mimicking bedform migration and depositional environments, which can be used to model intrinsic properties such as porosity, permeability and net-to-gross ratio based upon customized Gaussian distributions (Nordahl et al., 2005). This SBED methodology generates realistic 3D lithofacies models that are able to span the geological length scales from lamina to bedset (Fig. 2.15). This upscaling is important for obtaining representative bedset data that are input for seismic inversion.

In this case study, a small turbiditic offshore field in the North Sea is investigated from 1cm resolution core samples and 15cm resolution petrophysical logs. These input parameters are used by SBED to model the geological complexity in and between existing vertical wells. The output parameters (porosity and net-to-gross) are the key parameters used in the following synthetic seismic modeling.

First, the methodology is tested on two vertical wells, from where two SBED depositional models are generated. At the modeling time, turbiditic depositional templates was not available in SBED, therefore several templates was applied to generate a realistic depositional model. The building block for thicker turbiditic sandstones are modeled based upon the flat lying, parallel bedding SBED template. The sub-model "no mud lamina, thinning upwards" provided the best fit form large depletive turbidity currents, which becomes weaker with time and therefore depositing gradually finer sediments like the typical normal graded beds of the Bouma sequence. The flaser bedding SBED template is selected for thin turbiditic sandstones interbedded with thin turbiditic mud. With some modification, this model could be adapted to represent deposition from weak turbidity currents, producing sequences of thin sandstones (commonly with small ripples) interbedded with thin (silty) mudstones. The separate fine-tuned template models are further used to generate a stacked geomodel representing the observed data.

After the different depositional templates are selected, their parameters (bedform,

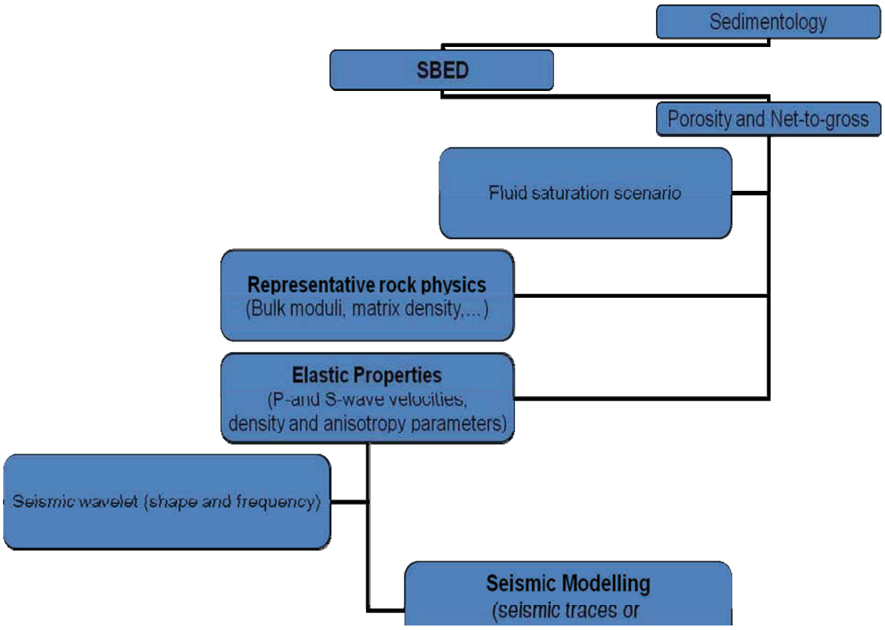

Figure 2.16: Forward modeling scheme from quantifying reservoir sedimentology by SBED for generating porosity and net-to-gross values, to create seismic traces by incorporating fluid saturation scenario, representative rock physics, elastic properties and seismic wavelet information.

migration, sand and mud petrophysical parameters) are fine tuned to mimic the exact deposition and petrophysical signature indicated by the input data. The input parameters for the SBED modeling are predominantly given with a mean value with a possibility to add linear trends, periodic variations or random fluctuations. The former represents the mean value of the parameters that together describe the bedform, while the latter three add different forms of deterministic and stochastic variability to the mean pattern. The output from the SBED modeling is porosity, permeability (lateral and vertical) and net-to-gross ratio at mm scale which is possible to upscale using the the incorporated SBED upscaling routine evaluated to be precise (Nordahl and Ringrose, 2008). The upscaling technique incorporated in SBED has successfully be incorporated in several published studies, such as (a) representing small-scale sedimentological heterogeneity in full-field reservoir models (Elfenbein et al., 2005; Ringrose et al., 2005; Scaglioni et al., 2006; Nordahl and Ringrose, 2008), (b) re-scaling well data (Nordahl et al., 2005), and (c) to evaluate two-phase flow performance (Pickup et al., 2000).

The SBED model generations of two wells, named well 1 and well 2, are used to create input for synthetic seismic trace generation and to analysis the results with 3D seismic trace in their given locations. The well 1 model is 80m long and consists of 37m of three cored intervals. The remaining non-cored zones are modeled from wireline log interpretation. Deposition pattern, wireline responses and porosity for both sand and shale intervals are used as input parameters for SBED modeling. The basic to the understanding of SBED is that each cell represents both a compositional element, two types of sand and mud, and a homogeneous and isotropic petrophysical property.

The seismic traces are generated from several different input parameters (Fig. 2.16): The porosity and net-to-gross parameters are derived from SBED modelling and the remaining parameters, fluid saturation, representative rock physic, elastic properties and seismic wavelets were taken from a related study of the wells (Avseth et al., 2001).

Seismic interpretation, matching of well log-data with seismic data and seismic modeling requires relating measurements of wave velocities at a scale of tens of meters with measurements of velocities at a scale of centimeters. As stated above, borehole logs can capture sedimentary layering on all length scales down to a few centimeters. Whereas thick layer models use blocking and ray tracing procedures assuming no internal multiples, thin layer models are more realistic for, among others, deep water turbiditic deposits as they includes stacking of thin sediment layers. By using a matrix propagator method that includes multiples and having frequency dependent AVO responses, thin layer models need no preliminary interpretation and blocking (Stovas and Landrø, 2005). Previous studies have indicated that wave propagating through finely layered medium, such as cm thick turbiditic layers, is dispersed and attenuated (O'Doherty. and Anstey, 1971) and that the limit of infinite wavelengths in finely layered media can be regarded as an effective homogeneous medium (Backus, 1962). The wave propagation velocity depends strongly on the ratio λ/d of the dominant wavelength to the typical layer thickness. When the wavelength is large compared to the layer thickness, the wave velocity is given by an average of the properties of the individual layers (Backus, 1962) and waves behave as if propagating in an effective anisotropic homogeneous medium. Based upon these arguments, Stovas and Ursin (2001) outlined a methodology for the purpose of generating synthetic seismic based on only the velocity from the Backus averaging technique in terms of reflection coefficients. A more detailed geophysical explanation of the seismic trace generation are expresses in e.g Stovas and Ursin (2001); Ursin and Stovas (2002); Stovas (2002); Stovas and Landrø (2005).

Synthetic seismic traces of well 1 and 2 were derived from both SBED and wireline responses (Fig. 2.17). From the wireline response P and S waves including density were used to generate synthetic seismic traces. The correlation of these synthetic seismic responses to seismic are performed by a moving-window approach and a higher correlation is indicated by the synthetic seismic responses based upon SBED models than the synthetic seismic based solely on wireline derived responses.

To infer the heterogeneity in areas between wells, two different scenarios are constructed as input to the SBED modelling. These scenarios are based upon a superposition of turbiditic reservoir analogues and nearby well information, where Model 1 is assuming thick homogeneous turbiditic sands interbedded with thin shales, the Model 2 has a varying sand thickness assuming change in distance to feeder channel and general sand influx. Separate synthetic seismic traces are generated from these two scenarios (Fig. 2.18). The likelihood for the reality of these two given heterogeneity scenarios are evaluated against the center and 8 surrounding 3D seismic traces. Only the heterogeneity within the reservoir has been correlated against 3D seismic as the overburden is not modelled. Model 1 displays within the reservoir interval a decrease in amplitude with depth, where model 2 displays the opposite (Fig. 2.18). Fig. 2.19 shows that the model 1 scenario has a higher correlation coefficient than model 2 and therefore represents the most plausible heterogeneity setting of these two.

The results, based upon the presented novel workflow, show that core analysis and

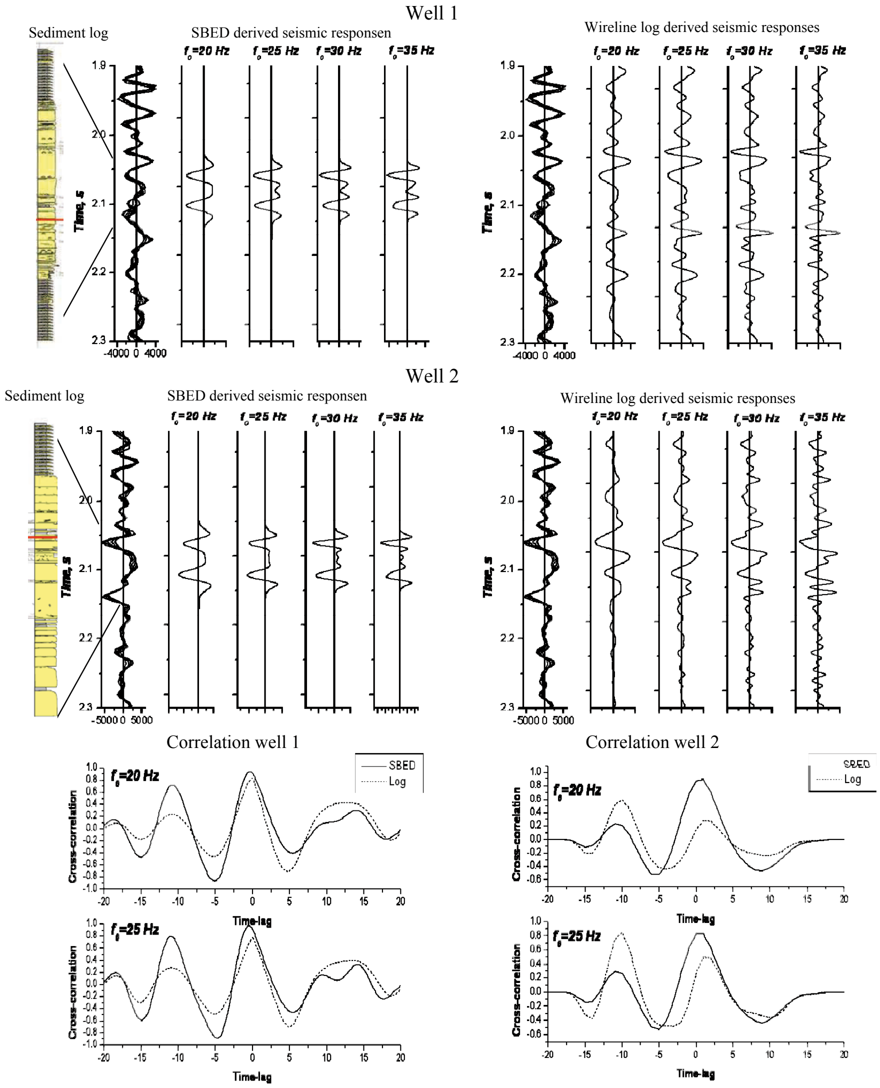

Figure 2.17: Synthetic seismic traces of well 1 and 2 derived from both SBED (left) and wireline (right) responses. The correlation of these synthetic seismic responses to seismic are performed by and indicate that the SBED results give a higher correlation than the wireline derived responses.

wireline log responses supported by the SBED software can be used to generate ultra-slim wellbore with a resolution of 1cm corresponding to lamina / lithofacies scale (REV in

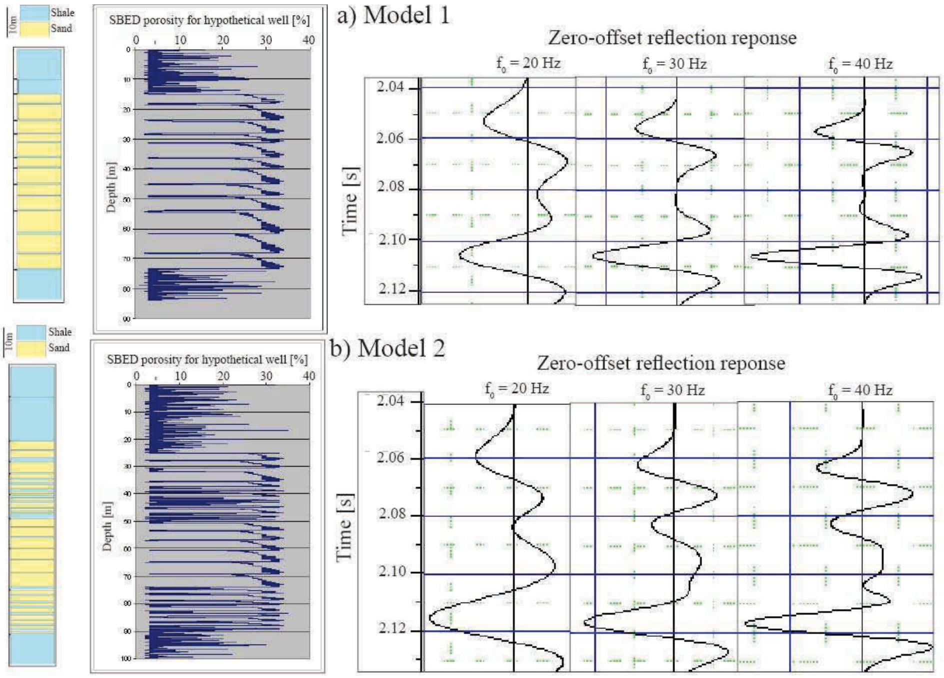

Figure 2.18: Two separate hypothetical wells are constructed based upon nearby well information, reservoir analogues and depositional history for generation of different synthetic seismic traces. Both scenarios have alternating shale and sand, where (b), model 2, have thinner sand bodies and more shale than model (a), model 1.

Fig. 1.4), where effective reservoir parameters, such as porosity and net-to-gross (NTG) fractions, are expressed at similar scale. By including lithofacies scale rock physics, elastic properties and seismic wavelets, these small scale variations can be incorporated in generation of seismic traces. The cross correlation of 3D seismic traces and the synthetic seismic traces can be applied to test different deposition scenarios both at existing and hypothetical well locations.

The advantage of this method is that very detailed layering can be modelled and synthetic seismic can be generated that takes into account the inter-bedded multiples which are of great importance in thin-layered reservoirs (Stovas and Landrø, 2005). Different depositional scenarios can subsequently be evaluated against 3D seismic indicating the

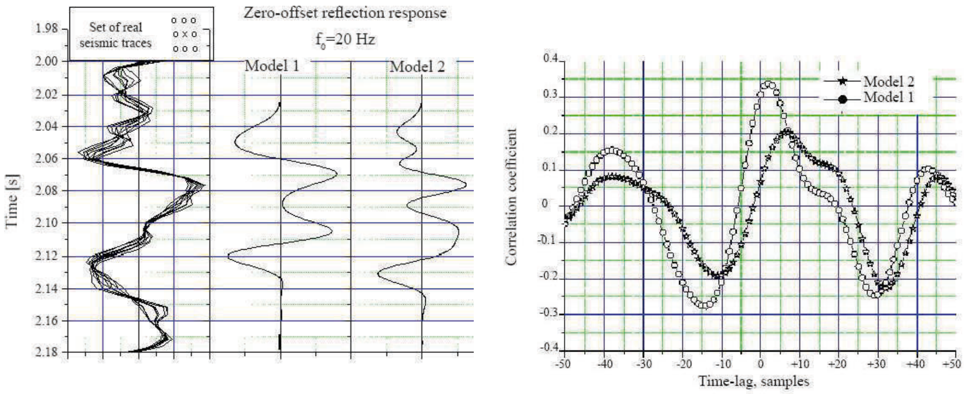

Figure 2.19: Cross correlation between 3D seismic and synthetic seismic based on hypothetical wells from two depositional scenarios; model 1 and model 2. The trace with the highest match, model 1, is more plausible due to its correspondence to 3D seismic compared to the depositional scenario for model 2.

probability of match. The most likely scenario can be found among several relevant composite analogues. In this study the collection of appropriate parameters, both geologic and geophysics, has been important foundation for successfully show the applicability of the novel workflow. The preprocessing of geological data in relation to SBED modelling was performed by the incorporation of how turbidity reservoirs are deposited. The reservoir parameters related to rock physics was adopted from Avseth et al. (2001), with one value for sand and one value for shale. These values were defined as constants throughout the study without consideration of variations within the sand and shale at lamina scale. This presented workflow is incorporating several sub process-response systems to express how small scale heterogeneity geomodels can be upscaled to an operational scale where the data is representative for the generation of seismic responses. The results in this study corresponds to the REV concept outlined in Fig. 1.4 as small scale parameter values at mm scale are upscaled into representative parameter values at sub-seismic scale from where synthetic seismic traces are generated to differentiate facies associations. This outlined workflow and its applicability is a contribution to the pore-to-field approach (Keogh et al., 2007).

A potentially further improvement of the seismic trace generation can be to link sedimentary micro-structures quantified by geomodel software, such as SBED, with appropriate rock physics models related to specific depositional scenarios. In addition to the improvements in the preprocessing to obtain representative data, one potential direction for further work can be to optimize the novel workflow by means of testing different realizations including multiple depositional scenarios and rock physics parameters. One possibility is to modify the method of Schaaf et al. (2004), who introduced an optimization workflow: Through a single objective function evaluation, refinement indicators were computed and these indicated which realizations that might improve the iterative geological model in a significant way. The performed workflow of Schaaf et al. (2004) integrated data by a linear combination of gradually deforming a set of multimillion grid geostatistical realizations during the optimization process, where the inversion parameters are reduced to the number of coefficients of this linear combination. However, this optimization need to be anchored within the parameter variability defined in the geomodel so that it obtain its representativeness of the geologic understanding.

2.5 Reconstruction of heterogeneous reservoir architecture based on differential decompaction in sequential re-burial modelling

Whereas the previous sections have indicated the importance of spatial geologic heterogeneity in present day recordings, this section includes how spatial heterogeneity can evolve through time (Appendix D). Knowledge of the subsidence history is important for understanding the development of a sedimentary basin as it has implications on, among others, reservoir characteristics. In quantitative analysis, present day stratigraphic thicknesses, a product of cumulative compaction through time, is investigated and correlated with present day depositional patterns for interpretation of the deposition at specific time

(Allen and Allen, 2005). The common method for decompaction of these stratigraphic units is to apply variations of porosity with depth relationships for identified sedimentary units (e.g. Sclater and Christie, 1980). This can, for normal pressured sediments, exhibit an exponential relationship of the form

$$\phi = \phi_0 e^{-cy} \tag{2.10}$$

where ϕ is the porosity at any depth y, ϕ_0 is the initial porosity and c is a lithology dependent coefficient describing the rate of the exponential decrease of porosity with depth. While some, more sophisticated methods incorporate corrections for variations in water depth through time and for absolute fluctuations of sea level relative to present sea level datum, other methods consider burial pressure, sediment density and sediment overburden load (Allen and Allen, 2005).

For lateral correlation, such as linking top of correlative units, geologists trace the structure and thickness changes of formations through correlations profiles and maps of surfaces across fields or basins (Schatzinger and Jordan, 1999). Although several automatic methods are developed and proposed, still human interactions are essential for extracting lateral correlations (Doveton, 1994). Compared to automatic methods, manual methods for correlation are often slow, highly labor-intensive, inconsistent and expensive. The decisions performed by human operators in stratigraphic correlation require pattern recognition skills of a geologist. Still, correlations made by geologists often differ substantially. Therefore, geologists apply a set of procedures and criteria for the practice of correlation (Doveton, 1994). These procedures and criteria can be applied to computer methods for result consistency. However, these methods need to be adjusted for each case study analyzed to produce, not only a consistent, but accurate and precise result.

In a reservoir perspective, the problem of correlating wireline logs between wells is generally complex (Hammer, 2010). Some beds are laterally continuous over great distances and maintain essentially constant log characteristics, while others display marked lateral variability, or even pinch out completely. Cyclic repetitions of lithologies also challenge

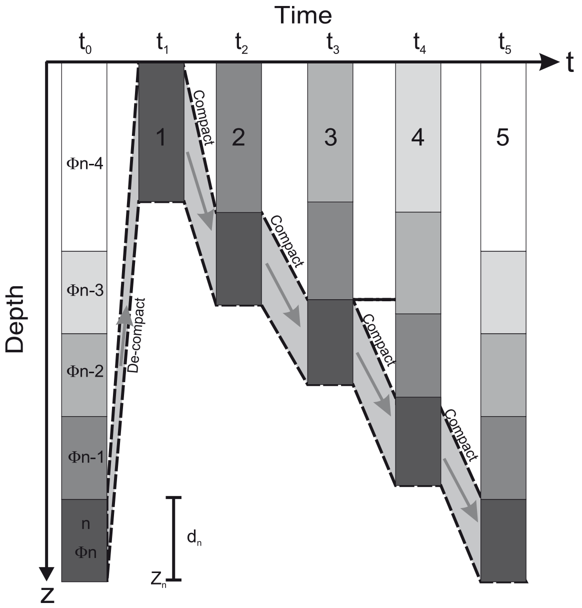

Figure 2.20: A conceptual sketch illustrating the backstripping procedure. Stepwise re-burial comprising progressive compaction, beginning with decompaction of the lower most unit (1) after removing the overburden (2-5). This is followed by a stepwise burial (compaction) in time steps (t_1-t_5), determined by flooding surfaces (FS), of each unit and subsequent reduction in porosity following calculated porosity-depth-trends for each interpreted lithofacies within each unit (modified from Bond and Kominz (1984)). t_0 corresponds to the present day scenario.

the interpretation of correlatable units. Other features, such as unconformities, hiatuses, faults, can also disturb correlations significantly (Schatzinger and Jordan, 1999). The inclusion of several new wireline logs and new interpretation methods have improved the correlatability between the indirect measurements performed by the wireline logs and the direct measurements on subsurface cores.

Whereas backstripping and decompaction of stratigraphic units have normally been analyzed on seismic stratigraphic units (facies associations) with a scale of measurement of 15-25m or larger, wireline logs captures smaller scale heterogeneity due to its sampling

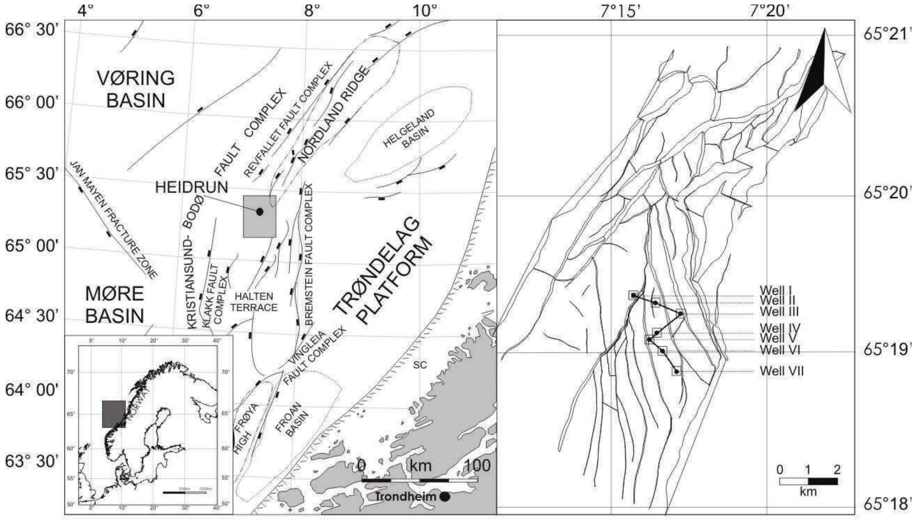

Figure 2.21: Left: The structural elements of the Mid-Norwegian continental shelf (modified from Gabrielsen et al. (1984); Koch and Heum (1996)) and the location of the Heidrun Field (shaded rectangle). Right: Top Åre reservoir structure (after Svela, 2001) and the location of studied wells and cross-section.

rate around 15cm (See REV sketch in Fig. 1.4). The results presented here show that different lithofacies types at wireline log scale can be incorporated into a quantitative decompaction methodology for stratigraphic correlation of sedimentary units by using a re-burial technique (Appendix D).

Seven wells from the Heidrun Field (Fig. 2.21), offshore mid-Norway, were used as a case study, where eight lithofacies groups are determined from core data and specific wireline log signatures for each lithofacies type. In addition, two lithofacies types were introduced, fault and sea water, with constant porosity of 0 and 1, respectively, to counter the effect of water depths and assumed fault throws. An exponential porosity-depth relationship was defined for each lithofacies (Eq. 2.10). Each of the lithofacies ϕ_0 and c values were derived from published literature and performed calculations.

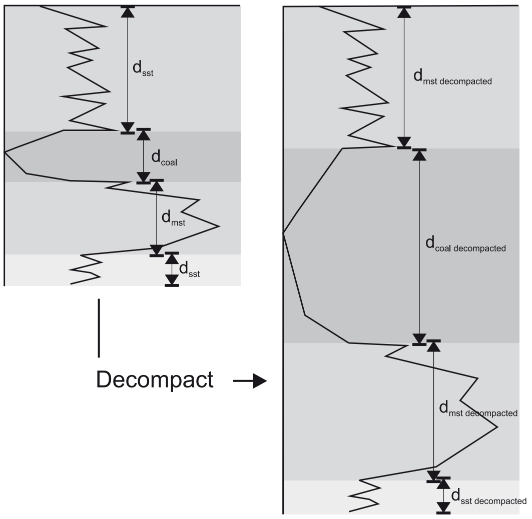

Figure 2.22: A conceptual sketch illustrating the principles of signal stretching. The sample interval is increased in relation to the added porosity due to decompaction, whereas the sample value is retained.

The methodology used here calculates differential compaction for selected depths anchored to the specific sample points (Figs. 2.20 and 2.22). This allows, not only for decompaction based upon predefined horizons, but can also easily incorporate new identified surfaces by changing the sample points which represent the depth to these new surfaces. This flexibility allows for testing different interpretations of lateral correlation challenging the present interpretation of the Åre Fm. (Dalland et al., 1988) sequence stratigraphy (e.g Leary et al., 2007; Thrana et al., 2008). Each of the applied lithofacies types has separate porosity-depth curves, which will change the thickness of the lithofacies units depending on the lithofacies present and the depth of burial at the time of interest (Appendix D).

The results, plotted as correlation panels including specific horizons, decompacted lithofacies types and petrophysical signatures, shows how early compactions affect the different lithofacies types (Fig. 2.23). The decompacted sequence stratigraphic interpretation contributes to increase the robustness of the present Åre geomodel and can strengthen the general knowledge of the Åre depositional system by mapping and correlating the lateral and vertical distribution of depositional units on a decompacted reservoir architecture. Differences in compaction thicknesses and lithofacies composition are assumed to affect the lateral correlation of highly heterogeneous and highly compactible sediments, such as the Åre fluviodeltaic deposit.

This can be exemplified by the reservoir architecture interpretation of the lower Åre units (Fig. 2.24) that is based on published and identified correlatable surfaces. The decompacted intra Åre 3.1 coal suggests a possible re-interpretation of the Åre 2.2 incised valley fill. As shown in Fig. 2.24 the incised valley is in fact rather a zone comprising more abundant channel sandstones occurring as lateral and/or vertical amalgamated in some wells. This may suggest that there was no base level fall, but probably more a reduction in base level rise and that the upper part of the Åre 2 reservoir zone corresponding to a late highstand deposit, rather than a lowstand as inferred by the presence of an incised valley. This example shows that this methodology enables re-interpretation of stratigraphic surfaces/units and interpretation and correlation of depositional units between known correlatable surfaces from where different depositional scenarios can be evaluated (Fig. 2.25).

Measurements of lithology at 15cm wireline log scale can be combined with other decompacted thickness techniques to yield more accurate lithological description. However, the results here show that adding the 15cm scale of lithofacies information to the reburial routine is particularly helpful when interpreting heterogeneous reservoir units that include different lithofacies types with differentiated early compaction development. This coincides with the REV concept shown in Fig. 1.4 as the result presented here showed the importance of using an appropriate scale from where representative parameter values can give reliable input parameters. The approximate ranges in sample volume for typical reservoir measurements are shown and indicate large variabilities within certain scale intervals. Parts of this variability, such as variability within the core plug scale used in this study, may relate to the inherent small scale heterogeneity of the core plug. This can be accounted for by selecting and grouping plug samples related to specific interpreted

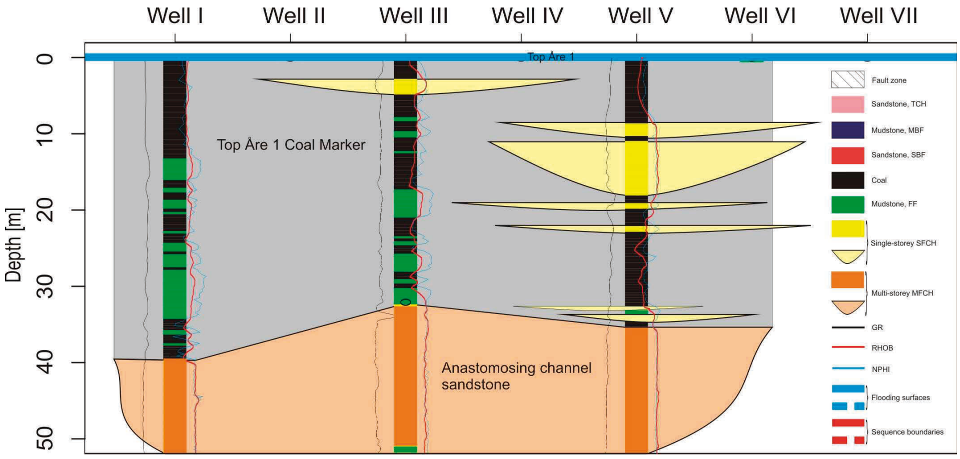

Figure 2.23: This cross-section comprising the Top Åre 1 Coal Marker. A correlation of MFCH deposits in wells I, III and V is suggested. The cross-section is interpreted as parallel to palaeoflow direction (south east) as these sandstones are suggested to represent anastomosing channel deposits indicating limited channel widths.

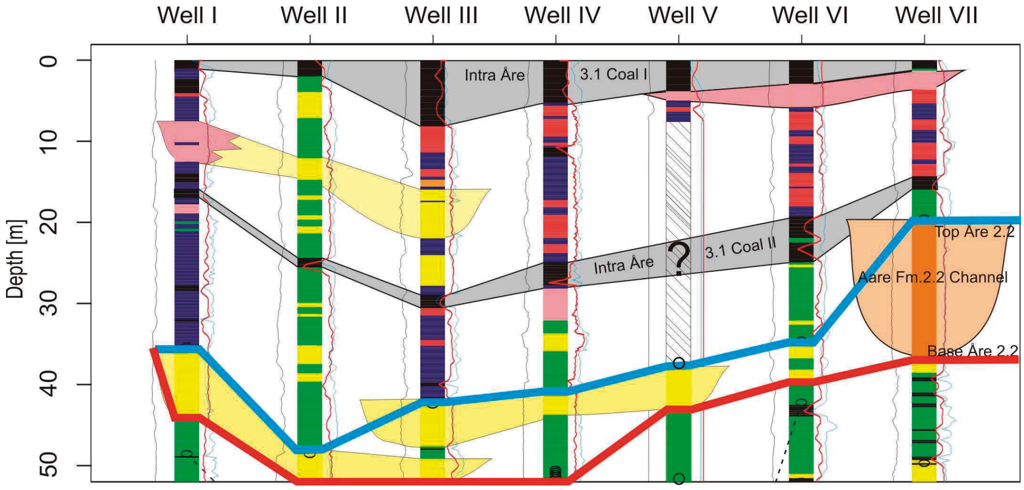

Figure 2.24: This cross-section showing 50m decompacted reservoir underlying the intra Åre 3.1 Coal I suggests several correlatable channel sandstones in addition to intra Åre 3.1 coal II approximately 20 m below the intra Åre 3.1 coal I.

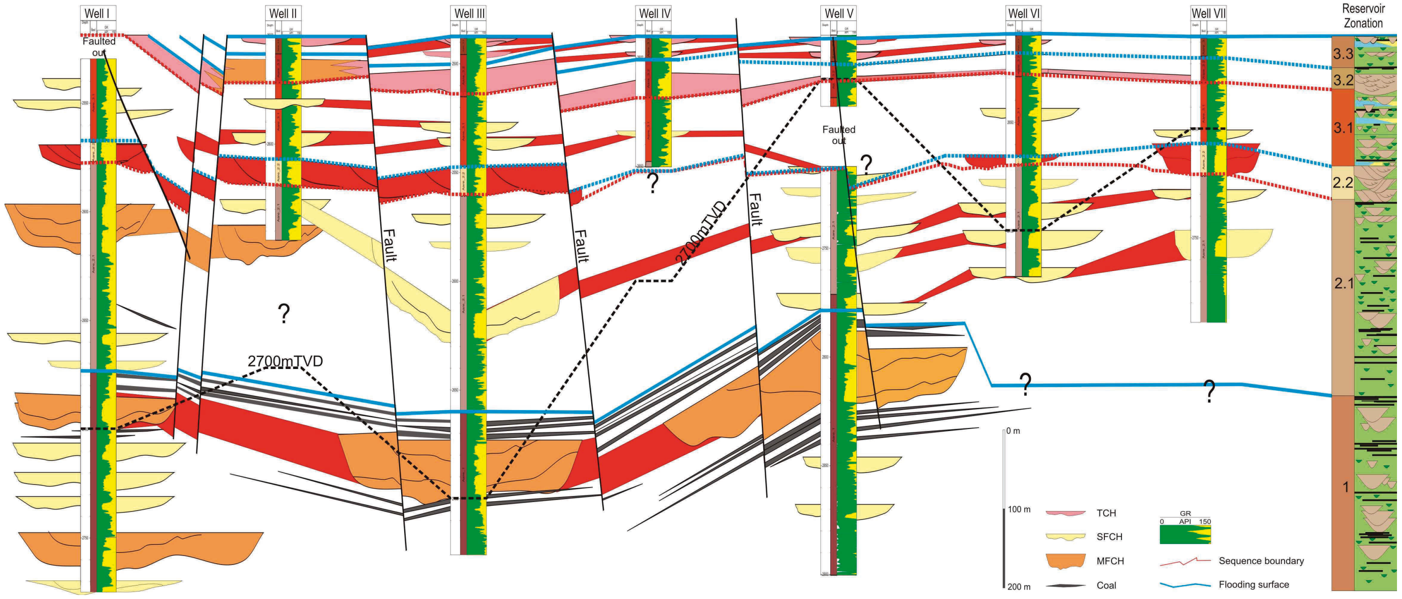

Figure 2.25: Updated correlation (red color) of the Åre 1. 2 and 3 reservoir zones in the seven studied wells based on correlation on decompacted reservoir sections. Published surfaces together with interpreted flooding surfaces, seen as correlatable coals, enable identification of correlatable channel sandstone units within top Åre 1, Top 2.1 and Åre 2.2, Intra Åre 3.3 and top Åre 3.3. Note the Åre 2.2 unit comprising several individual channel sandstone units.

lithofacies classes, such as plug data from sandstone intervals not affected by significant diagenetic alteration (REV). This is an example of the importance of preprocessing data when incorporating small scale reservoir heterogeneities into reservoir interval correlations. These results expressed here show how a basin scale method can be adopted to express within lithological contrast. Recalling the process-response system outlined by Griffiths (1988), the study here has included representative input parameters derived from analysis of small scale variations. These parameters are further processed through the general exponential porosity-depth relationship, to generate time-dependent small-scale output that focus on small-scale variations in a intra-reservoir scale context.

The results presented in this section show some promise, but much work remains in order to better utilize small scale heterogeneity into backstripping/re-burial routines. Lithofacies classification is very scale-dependent, and the unity of the defined lithofacies through depositional time is important for determining their specific representative c-value in the exponential depth-compaction (Eq. 2.10). One option is to include a sedimentological approach to refine reservoir architecture from an improved litho-classification (e.g. Section 2.4 and Hampson et al. (2004)) and combine this result with the backstripping procedures from where the assumed geologic horizons can be evaluated. A second option is to include multivariate analysis to evaluate compaction of sedimentary rock, as exemplified by, Tewari (2008) using PCA to evaluate net subsidence and evaluation of coal swamp compaction. His study concludes that the total thickness of sandstone and number of sandstone beds are largely responsible for variation in net subsidence in coal measures. A third option is to apply structured PCA (see Sections 2.2 and 2.3) to outline more representative effective parameters that can e.g. improve the values expressing each of the lithofacies types i.e. improve discrimination between lithofacies types. A fourth option is to used the SBED routine presented in the previous section (Section 2.4) for upscaling pore plug measurements to representative porosity parameter values for each lithofacies type. A fifth option is to include wireline scale seismic inversion and rock physics into basin modelling, such as indicated in Avseth et al. (2005), to close the gap between geology and geophysics. The common interest of these five options, including the study expressed in this section, is a thorough appreciation and representation of the variability and uncertainty of the system at multiple scales. This is required if a full understanding of this system is to be achieved (Keogh et al., 2007). This section shows that the selection of scales and the type of data to be included into the selected methodology is important for obtaining representative results answering a desired question.

2.6 Results and conclusions

This first part has considered lamina to reservoir scale heterogeneities and has shown the importance to assess how reservoir related parameters are measured, recorded, analyzed and interpreted relative to reservoir analysis objectives at given scales. Further by using a process-response system approach, the interaction of parameter variability from lamina to reservoir scales have been comprehensive assessed and related to the corresponding REV. The REV concept is shown to be vital both mapping representative parameter values from underlying variability into integrated models and when upscaling a dataset to be included in analysis at a higher / more generalized level.

The major results of this chapter studying reservoir related heterogeneities are:

- A structured principal component (PCA) methodology that only use records selected from separate lithological units has been used to obtain a more precise definition of variability sources than is possible by an unstructured approach using all the records from the logged well interval. This methodology decomposed heterogeneous populations (e.g grains of a fluvial deposit) into their underlying populations (e.g sand, shale and coal) that can explain both within- and cross lithological effects. This coincide with the REV concept as the unstructured PCA identified representative parameter values for each of the lithofacies types, the structured PCA uncovered the underlying population at lamina scale.

- Results from the use of an inverse PCA statistical analysis procedure (the Eckart-Young theorem) on a sandstone interval has permitted to separate global sandstone porosity values into individual porosity contributions from different underlying and independent sedimentological processes.

- The results of using a process oriented numerical modeling tool (SBED) methodology for upscaling lithological heterogeneity at mm-scale to lithofacies heterogeneity (cm-scale) and a further upscaling to seismic (10m-scale) shows that very detailed layering can be modelled and synthetic seismic traces can be generated that takes into account the inter-bedded multiples which are of great importance in thin-layered reservoirs. This study showed also how different high resolution depositional scenarios can be upscaled and evaluated against 3D seismic traces indicating the probability of match.
- The results using a sequential re-burial methodology to compute high-resolution re-burial porosity-depth values based on wireline log interpretation can lead to an alternative inter-well correlation scenario in hydrocarbon reservoirs based on differentially compacted sediments in the subsurface. This study showed also how a sedimentary basin scale methodology can be adopted to express within lithological contrast of reservoir zones if the data is properly preprocessed and incorporating small scale reservoir heterogeneities.

The implication of considering small scale geologic variations is that it can give a thorough appreciation and representation of the variability and uncertainty of the system to be analyzed at multiple scales that is required to achieve a full understanding of this system. This can lead to enhanced well placement and drainage strategies over field life cycles and ultimately more efficient hydrocarbon production. These results presented here contributes also to the philosophy of the ”pore-to-field” scale modelling concept, reviewed by Keogh et al. (2007). Other implications are:

- An explicit quality assessment of observational data relative to the REV concept can ensure reproducible and reliable results when these data are used in reservoir modelling and analysis and has implications on the strategic decisions related to reservoir assessments.

- The PCA methodology can be used to isolate specific variability in other depositional environments.

- The inverse recalculation procedure of Eckart-Young Theorem allows for back-calculation of responses of second order or higher effects that can contain signatures explaining e.g. sedimentological processes. This procedure can most likely be applied in other resource related studies considering hidden effects obscured by the primary/gross effect.

- The process oriented numerical modelling tool (SBED) for upscaling lamina scale heterogeneity to seismic can generate better geological anchored models for sub-seismic reservoir characterization.

- The sample based sequential re-burial methodology using high-resolution re-burial porosity-depth values for stratigraphic inter-well correlation of differentially compacted sediments can be applied in other heterogeneous environments (e.g. turbidites) for the purpose of evaluate alternative inter-well correlation scenarios. By using lithofacies variations at wireline log measurement scale as building block from correlations studies a more confined model can be generated that will increase the depositional knowledge that is assumed to outperform the more generalized re-burial methods when reservoir modeling is in focus. This methodology has the potential to enhance the quality of reservoir zonation mapping.

Chapter 3

Play scale heterogeneities related to basin and reservoir scale

Different natural resources are scattered throughout the world both on the surface and subsurface according to varying densities (Craig et al., 2001). These resources are formed as a result of specific phenomena derived from time dependent processes (Griffiths, 1988). Whereas the non-renewable resources represent phenomena predominantly derived from geological processes evolving over long time intervals, renewable resources are phenomena evolving over shorter intervals controlled mainly by topographic relief and climatic processes (Christopherson, 2005). Our society is heavily dependent on both types of natural resources and their future availability is vital for our society (Craig et al., 2001). The extraction of natural resources are influenced by two types of characteristics (Griffiths, 1978); (1) inherited characteristics from the geological events (processes) that accumulated these resources and (2) acquired characteristics, such as the socioeconomic factors leading to e.g. capital investments and the construction of infrastructure.

This chapter covers the inherited characteristics, whereas the renewable resources and the relationship between natural resources and the human dimension will be discussed in the subsequent chapter (Chapter 4). The focus of this chapter is on reservoir to basin scale heterogeneities and are more generalized than the pore-to-reservoir scale presented in the previous chapter. How geological parameters can be mapped, categorized and combined into representative forms that are suitable for play and sedimentary basin assessment will be discussed relative to the REV/REA concept.

3.1 Introduction

The assessment of non-renewable resources require information across multiple scales. Inherent variabilities and uncertainties related to the underlying geological processes allow hydrocarbons to be matured, generated, migrated and trapped (Hantschel and Kauerauf, 2009). According to Divi (2004) the most obvious uncertainties in hydrocarbon resources assessments are: (1) imprecisely understood geological processes that generate, transport and trap the resources; (2) insufficient geological, geochemical, geophysical and other data for the region under assessment; and (3) unavailable or incomplete existing data on the resources because of proprietary rights. These processes leading to a population of accumulations can be explained, as earlier stated by Griffiths (1988), by five factors expressed within a process-response system. The hydrocarbon accumulations formed can therefore be defined as the end-product of the hydrocarbon forming processes. To quantitatively express an end-product phenomenon, mathematical models mimicking these related geological processes must be constructed.

Before outlining specific resource assessment methodologies, three central concepts need to be defined, sedimentary basin, petroleum system and play. Whereas a sedimentary basin is defined as an area where sedimentary rocks have been deposited, plays are related to the presence of similar types of hydrocarbon accumulations (Allen and Allen, 2005), a "petroleum system" is *a geologic system that encompasses the hydrocarbon source rocks and all related oil and gas, and which includes all of the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist* (Magoon and Dow, 1994). NPD (2009) defines a geologic play as: *"A play is a geographically and stratigraphically delimited area where a specific set of geological factors such as reservoir rock, trap, mature source rock and migrations paths exist in order that petroleum may be provable."*

The selection of an appropriate scale for a given assessment is important as both the operational scale and the measurement scale needs to be known before deciding on the appropriate assessment methodology. Different resource assessment methodologies have been developed to quantify ultimate resources within a given geographic area or to estimate how the quantity of given resource will change over time (Meneley et al., 2003). Whereas the objective of some methods is to give a first indication of the total resources within an area without consideration of where the accumulations are, others are directly related to the location of the remaining resource including their potential yield (Otis and Schneidermann, 1997). For successfully explaining a given resource phenomenon, the selection of input parameters and the transformation of these to a representative form given the operational scale is important. Following the approach in the previous chapter (Chapter 2), the REV concept can also be applied at the play scale level, as spatial maps generated from quantifications of point, line and polygon features can be pre-processed/transformed into the appropriate operational form that are suitable to be included in the resource assessment.

Finding the appropriate measurement and operational scales led to the adoption of the previously outlined REV concept (Bear, 1972) for volumes to that of representative elementary areas (REA)(Wood et al., 1988). The REA concept is related to the spatial area that is large enough to include sufficient data to be statistically meaningful and small enough to be quantified as a mathematical point (Fan and Bras, 1995). The REA concept has been successfully used to analyse spatial heterogeneity and scale-dependent problems in studies of e.g. catchment hydrological responses (Wood et al., 1988) and lineament mapping of fractured rock aquifer (Jia and Lin, 2010). Density maps are also used to explain features related to hydrocarbon resources assessment. The REA density features can, e.g. represent the number of leads, undrilled prospects, dry prospects, discoveries, fields, production units, plays and sedimentary basins within a defined cell of size area (A). All these features may have different methods for calculating a representative elementary value depending on the area (REA) and the phenomenon that produces feature values. In other words, the feature representing the number of sedimentary basins on a continent level scale unit could have a REA of 10000km^2, whereas a representative number for hydrocarbon discoveries at play scale unit may have a REA in order of 1000 km^2 (Brandsegg, 2003).

Adopted from the previous outlined REV concept sketch (Fig. 1.4), a specific sketch of different REA's related to hydrocarbon yield at different scales of measurement is outlined (Fig. 3.1). This conceptual sketch shows how the nested hierarchy of scales needs to be integrated when a representative value needs to be calculated for the REA given the operational requirements. Ideally, a multi-scale model should be used to consistently integrate all available data types to achieve appropriately modelled estimates, rater than using averaging functions based on feature values from lower measurement scales. It is especially important that hydrocarbon yield properties assigned to the prospect, play or sedimentary basin are consistently upscaled to ensure realistic generalized values for REAs at the chosen operational scale. The figure shows that there are different representative REAs according to the features studied and the process-response system that governs how feature values e.g. sub-play/individual play/petroleum system change with the change in areal support. Similarily, the disaggregation of representative feature values for the sub-play/individual play/petroleum system REAs to lower REAs needs to capture the inverse process-response system that can induce feature variability belonging to REAs at a lower level than the original REA.

The quantification of undiscovered hydrocarbon resources in accordance with a standardized protocol is desireable as it results in a quantitative expression of the potential of a specific area that can be used for cross comparison with other study areas having used the same protocol (Meneley et al., 2003). The quantification of undiscovered resources generally needs to consider two separate steps (Griffiths, 1978). The first step is related to the magnitude of the resource itself, and the second step is related to the factors influencing exploration and exploitation of this resource. Whereas some hydrocarbon assessments focus solely on the estimation of resource magnitude, others includes a time threshold defined as hydrocarbon volumes that can be producible within the next 30 years (Charpentier and Klett, 2005). Previous exploration history, earlier regional assessments or previous delineated remaining oil pools are all factors that need to be considered prior

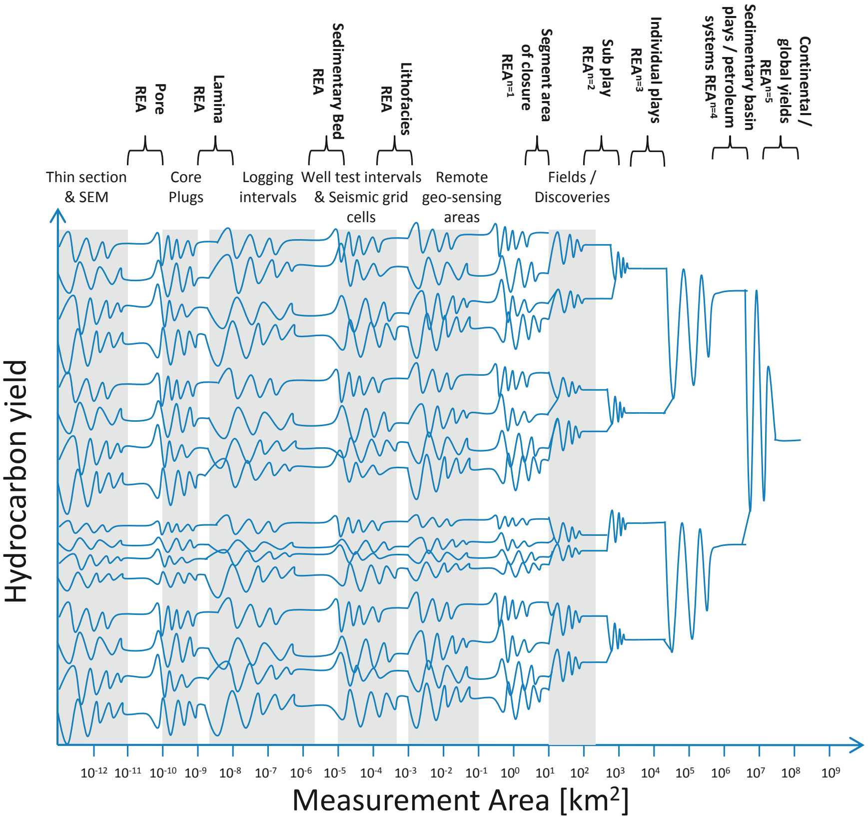

Figure 3.1: A conceptual sketch of different scales ($n = 1, 2, 3, 4, 5$) of REA related to hydrocarbon yield heterogeneities and scales of measurement. In this illustration there are sixteen areal yields at the segment level corresponding to closure area ($REA^{n=1}$) that combine into eight subplay yields corresponding to sub-play area ($REA^{n=2}$) that further combine into four individual play yields ($REA^{n=3}$) which again are combined in two sedimentary basin play / petroleum system yields ($REA^{n=4}$) that finally are combined to include continental / global yields ($REA^{n=5}$). For visualization purposes the segment types are not further disaggregated. According to the trend in scale ($n = 1, 2, 3, 4, 5$), the lithofacies, sedimentary bed, lamina and pore yields corresponding to individual REA's at each scale should have had 32, 64, 128, 256 sub-yields, respectively. The approximate ranges in yield values for typical measurements are shown in relation to the area of influence and indicate that these features values have high variability below successive representative values within the corresponding $REA^{n=x}$ areal support.

to methodology selection (Divi, 2004).

Five major hydrocarbon assessment methodologies are outlined below to show how the various methodologies use different types of input parameters as a function of the study purpose. Each of these methodologies is expressed with a focus on the REV/REA concept, the operational scale, measurement scale and the level of aggregation. This also includes an emphasis on the type of representative data that are needed to obtain accurate and precise results. Both interval analysis and probability theory can be applied to outline the uncertainties related to these methodologies.

Despite the challenges outlined above, hydrocarbon resource assessments are highly appreciated and have been conducted by a variety of organizations at different operational scales, such as global, national, provincial and local, and for wide range of purposes. Such purposes include resource management options for strategic, optimal usage, conservation, planning and exploration decisions (de Mulder et al., 2007). Other uncertainties, not directly related to the resource itself, could be caused by the changing economic and technological issues related to the exploration, exploitation and marketing of the resources (Griffiths, 1978; Meneley et al., 2003). These issues are not considered in this chapter, but is included in the subsequent chapter (Chapter 4).

Basin analogue

In frontier areas, assessments can be made utilizing hydrocarbon occurrence patterns and yields pr. unit volume of rock from analogue areas with similar overall geologic character and tectonic framework (Allen and Allen, 2005). Such assessments are often performed within a given basin, play or total petroleum system (TPS). There are several methods that can be applied. One method is to use the known field size distribution of an analogue area and the accumulation density to calculate the assumed potential within the study area (Divi, 2004). The advantage of this method is that it is based on direct analogy with a known basin providing a yield factor to be applied to the target basin. However, the range of variation of yield factors is large, and as such, the selection of the appropriate factor is very critical for the assessment process and results.

A second method, mass balance, also known as source generation model, has been commonly used to estimate the hydrocarbon resource potential within a study area (Divi, 2004). This deterministic method estimates the amount of hydrocarbon that may have been generated from known or hypothetical source rocks within a basin. A coefficient is used to estimate the fraction of trapped resources. A precise volumetric estimation of the source rock, including its organic content, are necessary for obtaining reliable results (Allen and Allen, 2005). An alternative approach is to use probability theory. Each of the input parameters are then modelled by probability distributions and the quantity of interest is represented as a random variable whose distribution is computed by numerical methods (e.g. Monte Carlo simulations) (Hantschel and Kauerauf, 2009). This allows for computing the probability for instance for a play having a hydrocarbon yield potential larger than a given threshold.

The basin analogue method rely on being able to define similarities within the geological context at an aggregate level corresponding to individual plays REA and petroleum systems REA as outlined in the REA sketch (Fig. 3.1).

Basin play analysis

Play analysis methods are predominantly used when assessing mature to semi-mature areas where hydrocarbons already have been discovered and a reasonably good geological database exists (Allen and Allen, 2005). The study area often consists of a play fairway (Fugelli and Olsen, 2005) where a group of prospects and/or discovered pools have common geological characteristics such as reservoir unit, petroleum charge, regional top seal, petroleum traps as well as an opinion about the detailed reservoir parameters such as prospect area, reservoir thickness, porosity, trap fill and hydrocarbon fraction that are used to estimate hydrocarbon yields (Meneley et al., 2003). The operational scale depends on the aim of study and range from the segment REA to individual prospects REA and plays REA.

Discovery process methods

In semi-mature to mature hydrocarbon provinces, discovery process methods offers some advantages for estimating the remaining resources in terms of both volume and number of fields (Haun, 1975). Discovery process models have been successfully used to assess specific plays (e.g. Sinding-Larsen and Xu, 2005). Both the selection of representative data and the appropriate operational scale need to be considered when using this method. The sensitivity of this method is among others, related to discovery efficiency and exploration maturity affecting the shape of the parent field size distribution which if biased can result in an over or underestimation of a given play yield potential (Chen and Sinding-Larsen, 1994).

In 2003, Meneley et al. (2003) stated that they believe that discovery process modelling in the future will represent a dominant assessment methodology for mature plays. A demonstration of this is shown by Chen and Osadetz (2009), who successfully combined discovery process models with traditional play assessment to estimate the undiscovered number of hydrocarbon pools in the Sverdrup basin, Canada. Their results were cross-validated by assessment results using other methods. This example showed that quantitative estimates of the ultimate play resources can be predicted with increased accuracy when integrating multiple assessment methodologies. The discovery process methods operates best with input data at the segment level REA and with results given at the play level REA.

Direct assessments

Direct assessments are performed by experts that are familiar with the geological setting of a region under study (Divi, 2004). They relate the adequacy of the required geological features within an area to a potential resource yield for this area (Otis and Schneidermann, 1997).

Play scale introduction remarks

Play scale variability has a large impact on the appropriate selection of hydrocarbon resource assessment methodology and the expected reliability of the assessment results. This implies that the study objective and its operational scale needs to be compatible with the measurement scale of available data. Play scale heterogeneity must be expressed at the operational scale by representative elementary feature values often represented by a generalization of the small scale heterogeneities described in the previous chapter (Chapter 2). Each of the REA variables need to represent the pre-processed and upscaled version covering the inherent variability of this specific variable. If the detailed information necessary to properly compute a representative feature value within the desired REA is not available, then proxy features must be created that can mimic the information needed for resolving the problem at hand. A second option is to include an analogue approach to extrapolate information from a mature part of the given play or a separate mature explored play with similar characteristics.

By applying the full range of GIS technologies covering pre-processing of data, such as data capture and data manipulation as well as data analysis of these pre-processed data, it is possible to answer spatial questions that include utilizing the inherent characteristics of the available spatial data. The selection of data analysis methods need to reflect the input parameters, the pre-processing of these parameters into an operational form and the aim of study. The benefit of GIS is that it is time-effective in both data manipulation and calculation and that the results can be quickly visualized by maps, graphics or in a table form (Kumar, 2007).

The need to explicitly know the appropriate process-response system that governs the scale change for a given phenomenon and how to obtain representative values that describes this phenomenon at a given REV/REA has been one of the driving forces behind the theme of this thesis.

3.2 Characteristic analysis - GIS and petroleum exploration risk

The quantification of resource variables can be performed by using GIS software. GIS is built upon knowledge predominantly from geography, cartography, computer science and mathematics and can be applied in any field, directly or indirectly (Rajesh, 2004). The use of GIS in the natural resource industry is widely recognized and has been used extensively for the exploration of natural resources (Kumar, 2007). GIS systems make images and extracted information compatible and provide convenient data modelling and information extraction functionality, which greatly facilitate the integration of data from regionalized variables (Brandsegg, 2003, 2004a,b; Hantschel and Kauerauf, 2009). Raw data will seldom be appropriate for decision making. The relevant information content of the data is often concealed by inherent variability and some filtering is needed to enhance the relevant signature beyond the inherent noise (Broome, 2005). Pre-processing of data prior to analysis is therefore a necessity.

Characteristic Analysis (CA) is a technique originally proposed as a R-mode approach (Botbol, 1971) that has been re-implemented as a Q-mode approach into a GIS environment to facilitate spatial map generation and the characterization of fault trends related to hydrocarbon accumulations (Appendix E and Sinding-Larsen and Brandsegg, 2005). In this GIS implementation, the CA technique is executed in three steps. A hydrocarbon accumulation process model is firstly generated based upon known hydrocarbon accumulations within model cells and then similar cells outside the known hydrocarbon accumulations are added. Models based solely on cells that contain known accumulations may not be optimal in that such models are overly restrictive in their application in other areas. Thus, the model should as stated above include other cells that are similar to cells in the model but that may or may not contain hydrocarbon accumulations. The problem now is the potential to overgeneralize the model by including cells in which the variables match only by chance. A refined generalized model is therefore calculated where only variables with a high significance for being hydrocarbon related are retained and the other being present only by chance are excluded. This refined generalized CA, proposed by McCammon (1983), expands the established model progressively by adding to the statistical base the unknown cells that are most closely related to the initial control cells selected for model identification.

The basic idea of CA is three fold (McCammon, 1983); combining data, interpreting data and identifying prospective areas based upon the two first factors. If used by experienced interpreters, McCammon (1983) concluded that CA is a valuable tool for (1) target selection in exploration, (2) delineation of favourable areas in regional resource appraisal, and (3) evaluation and appraisal of resources. One of the major advantages of CA is, according to Chaves (1993), its simplicity and that it is easily understood by geologists. Another appealing feature of this method is that it consists of quantitative procedures by which different modes of geological data pertinent to exploration for minerals and hydrocarbons can be quantified, integrated, and analysed.

In the initial applications of CA, the data used were transformed into binary form, 1 meaning favourable and 0 meaning unfavourable or unevaluated (Botbol, 1971). In order that the two states represented by 0 could be distinguishable, the data were transformed into ternary form; +1 meaning favourable as before, −1 unfavourable, and 0 meaning unevaluated (McCammon, 1983).

In CA, the favourability f of a given cell is defined as a weighted linear combination of the ternary-transformed variables, that is

$$f = a_1x_1 + a_2x_2 + \ldots + a_nx_n \tag{3.1}$$

where the $a_i(i = 1, 2, \ldots, n)$ represented the weights and the $x_i(i = 1, 2, \ldots, n)$ represented n transformed variables. However, an experienced explorationists commonly has prior knowledge of different logical combinations of variables using AND, OR and NOT combinations that are judged to be favourable (or unfavourable) with respect to particular models. Consequently, the x_is in Eq. 3.1 can be extended to include not only ternary-transformed variables but also logical combinations of ternary-transformed variables. The capacity to construct logical combinations of ternary-transformed variables enhances the result obtained by using CA. A demonstration of the different aspects of variable selections and ternary coding are explained in details in the subsequent section (Section 3.3).

The results outlined here show that CA incorporated into a GIS environment can successfully manipulate and decompose variables related to specific geologic signatures that are favourable for the accumulation of hydrocarbons. The case study in Appendix E demonstrates that the CA significance metric can be used to derive favourabilities for the presence of fault induced hydrocarbon accumulations on the Halten Terrace, offshore Mid-Norway (Fig. 3.2).

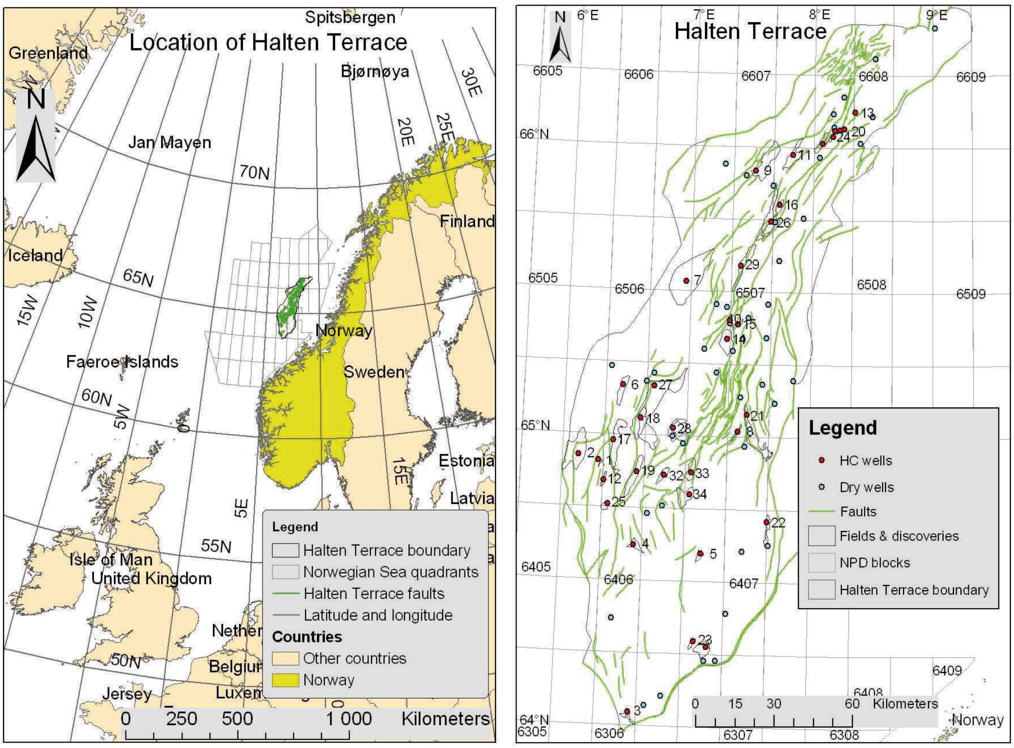

Figure 3.2: Map of the Norwegian Sea showing the location of Halten Terrace with main faults, fields and discoveries. Field and discovery names (census 2005) are given in Table 3.1.

Whereas McCammon (1983) derived mineralization and lithogeochemical models to

Table 3.1: Index of discoveries (census 2005) on the Halten Terrace that is numbered in Fig. 3.2.

No.	Discovery/Field	No.	Discovery/Field	No.	Discovery/Field
1	6406/1-1	13	Falk	25	Ragnfrid
2	6406/1-2	14	Heidrun	26	Skarv
3	6406/11-1	15	Heidrun North	27	Smørbukk
4	6406/5-1	16	Idun	28	Smørbukk South
5	6407/4-1	17	Kristin	29	Snadd
6	6506/11-7	18	Lange	30	Stør
7	6506/6-1	19	Lavrans	31	Svale
8	6407/11-6	20	Lerke	32	Trestakk
9	6407/2-2	21	Midgard	33	Tyrihans North
10	6407/7-13	22	Mikkel	34	Tyrihans South
11	Alve	23	Njord		
12	Erlend	24	Norne		

delineate new areas favourable for massive sulphide deposits, this study, testing CA in a GIS environment, has derived two models related to separate hydrocarbon trapping styles, a rotated fault block model and a horst model (Sinding-Larsen and Brandsegg, 2005). A ternary coding scheme honoring the REA concept related to the publicly available fault data from the Norwegian Petroleum Directorate (NPD, 2005) was defined within the operational scale chosen representing $1 \times 1\text{km}^2$ cells. Initial fault models were each built from groups of 10 cells. Details related to the ternary coding of the input variables in the relation to the REA requirements will be discussed in the subsequent section (Section 3.3). Favourability for the presence of hydrocarbon accumulations were computed by a weighted linear combination of ternary attributes, where the weights were calculated by Eq. 3.1, corresponding to the first eigenvector of the fault model. From the regional cells with high favourability calculated from the initial model, 30 new cells were selected in addition to the 10 cells in the initial model constitute a more robust generalized model. These 40 cells were then tested by the significance probability metric in order to evaluate if the high values could have occurred by chance. Those 20 cells having the highest significance values for not occurring by chance were then selected for the refined generalized model.

In addition the variable with the lowest probability for discriminating between barren and hydrocarbon prone cells was excluded from the final favourability calculations. Through this process, a refined generalized model was generated and expressed by weights in the model tables and used to generate favourability maps.

Table 3.2: Characteristic weights of rotated fault block related variables. The favourability map of cell results are shown in Fig 3.3.

Variables	S1	S2	S3	Variables	S1	S2	S3
Structural $4km$	0.407	0.335	0.340	Structual E-W	0.301	0.318	0.313
Structural $5km$	0.430	0.314	0.416	Complexity sum	0.349	0.277	0.000
Structural NE-SW	0.079	0.297	0.000	Complexity count	0.407	0.279	0.399
Structural N-S	0.267	0.319	0.375	Intensity structural	0.337	0.328	0.416
Logical Structural NW-SW AND Structural N-S	0.013	0.351	0.020	Logical Structural $4km$ AND Complexity count	0.407	0.336	0.416

The CA methodology has been applied twice to model specific trapping signatures of specific hydrocarbon fields, first to characterize the Smørbukk trap model and secondly the Tyrihans North trap model (Fig. 3.2 and Table 3.1). Both models were used to determine the degree of match between the central Halten Terrace area and these specific models. By fine-tuning ternary transformed variables of 8 variables and two logical combinations, specific input variables were generated according these two trapping models. The resulting CA weights from of the rotated fault block model (Smørbukk trap model) in Table 3.2 show that the initial model (S1) has two variables with low weights and in the subsequent significance probability calculations (S2) the first of these two variables has the lowest significance value and is classified as pure chance, whereas the second variable has obtained the highest significance probability and is therefore included in the final model (S3) calculation. The refined generalized model is superior to the initial model as it expands the model to include cells outside the initial model with cells containing close to similar signature (Fig. 3.3).

The example presented in this section outlined and evaluated one geologic factor con-

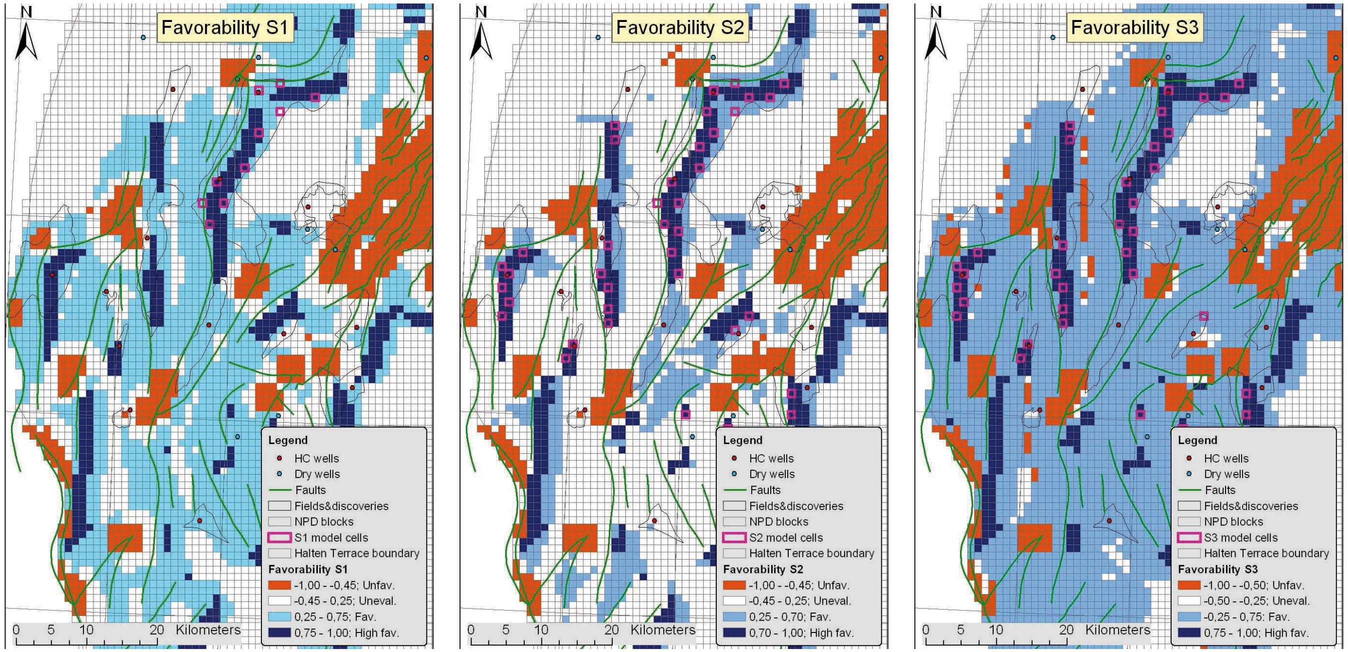

Figure 3.3: Map of the rotated fault block model favourability (derived from the Smørbukk trap model, Table 3.2) for regional cells and model cells indicating the three steps of initial (S1), probability (S2) and refined generalized model (S3).

stituting play analysis to express fault related hydrocarbon accumulations. The applied CA methodology was based on fault variables derived from the disaggregation of one single fault variable. These variables were combined, optimized and generalized to include regional data in the surrounding areas of the calibration points for estimating the presence of prospective fault related hydrocarbon accumulations.

The result shows that CA methodology can be incorporated in a GIS environment to manipulate and decompose variables suitable for expressing specific geologic signatures that are later included in calculating favourability maps for petroleum exploration. When used by experience interpreters, CA has proven to be a valuable tool for (1) evaluating exploration patterns, and (2) delineating favourable areas for use in hydrocarbon play assessment. This case study treated demonstrates that the significance probability metric can be used to derive favourabilities for the presence of fault trapped hydrocarbons and contribute to the evaluation of exploration risk on the Halten Terrace.

The major difficulties relate to the implementation of CA technique is perhaps not in the technique itself, but the need for the pre-processing of data and the ternary coding procedure. After defining a model, including defining the appropriate cell size and the ternary coding of the included variables, the selection of cells to be included in the weighting calculations of the model is of crucial importance. The number of cells in the initial model and location of these affect strongly the weighting calculations.

Determining the number of independent observation cells required to obtain a sample pattern given the number of variables constructed represents a challenge. In the literature, the suggested observation to variable ratio vary predominantly from 2:1 to 20:1, still some indicate the need for as far as 200:1 and beyond in order to have significant and stable results (Guadagnoli and Velicer, 1988). Because the model weights and the derived cell scores are based on samples, the replicability of the results will be affected by sampling considerations. (Velicer and Fava, 1998) concluded that the rules that recommend determining sample size as a function of number of variables are incorrect as it is the design of the study methodology including the quality of the sample selection and input variables that defines the sample size. They also concluded that representative population sampling, variable sampling, and the calculated weights interact in ways that permit compensation for weaknesses in one area by strengths in another area. These results must be seen in relation to the presented case study where the initial model used a ratio of 2:1, 20 samples were selected for 10 variables. The models used here did not include neighbouring cells as these often have strong autocorrelation and do not necessary express the model optimally. Despite this low ratio, it is assumed that the samples used are representative for the model as the operational scale is in accordance with the fault related migration into parts of sub segments which is believed to be at the km scale. The three step methodology corrects for new model cells that are incorporated to create the generalized model. The calculations in the second step, testing the sample cells constituting the generalized model are included due to variable matching by chance, corrects for cells deviating from signature of the fault modelling process. The introduction of this significance probability metric helps to identify cells deviating from the model and the refined generalized model therefore represents a more robust prediction tool. However, knowledge of inherent limitations in the multivariate techniques used and their dependency on pre-processing are important issues for obtaining reliable results.

This study follows with the population definition from Griffiths (1988). The disaggregation of the initial fault map into fault related migration components induced variability at a 100m - 1km scale that could be captured by new input parameters that reflect the hierarchical geologic system (Fig. 1.7). The variability within $1 \times 1\text{km}^2$ cells is related to the REA concept outlined in Section 3.1 as the initial fault data has a different variability and REA (Fig. 3.1) at the $100 \times 100\text{km}^2$ scale than each of the disaggregated REA values of the fault cell maps. The applied operational scale of $1 \times 1\text{km}^2$ corresponds to the study objectives for the identification of sub-segments favourable for fault related migration of hydrocarbons. The results described above could not have been obtained if the fault data used had retained its initial single variable form with an REA corresponding to a larger, say $5 \times 5\text{km}^2$ or $10 \times 10\text{km}^2$ support area (A) as the input data would have been to generalized to capture the variability of the REA related to migration hydrocarbons along fault paths into $1 \times 1\text{km}^2$ segments.

3.3 Where should we explore in the Halten Terrace? -GIS and Characteristic analysis applied to a mature play in the Norwegian Sea

Whereas the previous section (Section 3.2) outlined the methodology of CA in a GIS environment with examples of hydrocarbon trapping styles, this section is devoted to express in more detail how the disaggregation of the information from single faults presented in the previous section was transformed into several fault attributes at a $1 \times 1\text{km}^2$ resolution that made it possible to outline potential fault related migration scenarios related to hydrocarbon accumulations. Fault trapping styles and knowledge of their underlying geological processes are essential when fault attributes needs to be transformed into an operational form that relates the presence of fault induced migration and trapping to the presence of hydrocarbon accumulation.

The ultimate goal in play analysis is to identify hydrocarbon accumulations and several parameters need to be present for accumulations take place (Allen and Allen, 2005). Three of these parameters are the presence of traps, migration of hydrocarbons into the trap and retention. Hydrocarbon accumulations can be classified into several trapping, migration and retention types (Shelly, 1998). As most traps are related to different tectonic processes, the investigation of fault patterns is important for understanding the geological setting leading to the identification of hydrocarbon accumulations (Gluyas and Swarbrick, 2003). The relationship between fault density patterns and hydrocarbon accumulations is complex as faulting and fracturing influence e.g. reservoir geometry were hydrocarbons are accumulated. Vertical fractures may also constitute critical pathways for hydrocarbon migration and spill that are related to matured and expelled hydrocarbons from source rock beds into reservoirs (Hantschel and Kauerauf, 2009). Traps are preferentially charged in the vicinity of fractures and therefore are fracture density and orientation of fractures important factors related to hydrocarbon accumulations.

Seismic interpretation is the classical method for identifying faults and other structural and stratigraphic features of the subsurface for generating structural maps (Brown, 2004). These structural maps can outline faults from where the tectonic development is interpreted. Geological features can be transformed into an operational form by a standardized scheme in terms of area. E.g. lineaments captured from satellite images often provide a crustal clue on the interpretation and analysis of the structural setting within mineral and hydrocarbon provinces (e.g Rajesh, 2004; Zhang et al., 2007, respectively). The main assumption that underlines all lineament analysis is that these features, when properly identified, represent proxy subsurface parameters and that such information can ultimately lead to the identification of mineral zones or hydrocarbon accumulations.

Generally, lineaments are usually characterised by azimuth and length distributions, length density (total length of lineament per unit area), frequency (total number of lineaments per unit area), and intersection point density (total number of lineament intersection points per unit area). Such lineament density maps are hence important for the study especially when they are incorporated with other pertinent maps via GIS integration. The preparation of lineament density map is usually done by segmenting lineaments with squared or circular grids cells. The specific lineament feature is computed for each cell that generates density maps through various interpolation techniques. The choice of cell size in not arbitrary but obtained through a statistical study of specific spatial properties (Wu and Li, 2009). There is therefore necessary to estimate a best-fitting cell size (REA) for the specific lineament densities at the operational scale (Jia and Lin, 2010).

How to calculate a representative value for a process-response system is not trivial and may depend on different algorithmic approaches. In image analysis, local variance analysis, global variance analysis, fractal analysis and variogram analysis is used (Wu and Li, 2009). These methods are applied for evaluating scale effects, but can also be used to analyze the lateral extent of specific fault phenomena at a given operational scale and may include other standard summary statistics, such as total length of feature, total number of features and their geographical orientation within a geographically defined area (Jia and Lin, 2010).

A simple index of spatial complexity can e.g. be a local variance analysis using the standard deviation as an indicator to reflect a moving window with sizes ranging from

3x3 cells up to 7x7 or larger. The results of such local variance analysis help to outline areas with high or low local variability. The different local density maps depends on the measurement scale and need therefore to be transformed to an operational form to mimic the specific process-response system defined by the study objectives.

In the present study (Appendix F and Brandsegg and Sinding-Larsen, 2005), the preprocessing of variables defined to model different fault related trapping styles outlined in Section 3.2. The knowledge of understanding tectonic processes in conjugation with fault mapping and interpretation related to optimal sample selection for defining effective variables explaining such processes and the classification of these processes are therefore of crucial importance to map out such trapping styles. To a large extent, the success or failure of CA of a given set of data rests upon the ability of the interpreter to determine what constitutes favourability for each variable within the defined regional cells (Chaves, 1993).

The present section analyzes the effect of using different ternary coding schemes on the input maps for subsequent generation of favourability for hydrocarbon maps. CA is used to calculate the favourability related to the following trapping models; Rotated fault block traps and horst traps from the Halten Terrace area, Norwegian Sea (Fig. 3.2 and Table 3.1). Vector maps available from the Norwegian Petroleum Directorate containing structural and play information from Upper and Lower Jurassic reservoirs formed as described in the previous section (Section 3.2) the basis for the input attributes (NPD, 2005).

Three major types of new fault related variables were generated describing the; (1) influence distance from faults, (2) intensity of fault manifestations within a specific cell and (3) complexity incorporating fault trends from neighbouring cell. These structural variables were generated by selecting influence distances from the faults without taking into account the analytical cell size. The initial fault variable was further split into three according to the fault line direction that can be related to the geologic history of Halten Terrace: NE faults had a mean fault direction of $25 - 70°$N or $110 - 155°$N, N-S a mean fault direction of $< 25°$N or $> 155°$N and W-E a mean fault direction of $70 - 110°$N. The intensity variables were related to the number of fault occurrences within each specific cell measured by the total number of faults, the total length of faults and the variance of the fault lengths. The local fault contrasts, named complexity, was related to fault records from neighbouring cells. High values of standard deviations (SD) indicate large contrasts within the neighbouring cells, whereas low contrasts can be assumed for low SD values.

Table 3.3: Ternary transformed variables related to the Smørbukk rotated fault block model used to describe exploration data in the Halten Terrace area, Norway. The ternary coded maps are given in Figs. 3.4,3.5,3.6.

Structural 4km		Structural 5km		Structural NE-SW		Structural N-S	
0	At fault	0	At fault	0	At fault	0	At fault
+1	$< 4km$ from fault	+1	$< 5km$ from fault	+1	$< 4km$ SE of fault	+1	$< 5km$ E of fault
0	$> 4km$ from fault	0	$> 5km$ from fault	−1	$> 4km$ NW of fault	0	$> 5km$ W of fault

Structural E-W		Complexity sum		Complexity count		Intensity structural	
0	At fault	0	0 faults in cells	−1	SD > 0.1	0	Sum> 0
+1	$< 4km$ S of fault	+1	$1 - 3$ faults in cells	0	$> 4km$ from fault	+1	0
−1	$< 4km$ N of fault	−1	> 3 faults in cells	+1	SD < 0.1	−1	Sum < 0

Based upon these fault derived variables ternary coding was performed to identify two separate fault related trapping styles: Rotated fault block trap and horst trap. The rotated fault block model was tuned to fit the Smørbukk field and 10 variables were identified, including two boolean variables combining (1) *Logical Structural NW-SW AND Structural N-S* and (2) *Logical Structural* $4km$ *AND Complexity count* (Table 3.3, Figs. 3.4, 3.5, 3.6). The second model, the horst model, was related to the Tyrihans North field and a full decription can be found in the corresponding paper in Appendix F. Based upon the three step CA methodology outlined in the previous section including the variables weighting, specific high favorable areas for fault related hydrocarbon traps are outlined for two trapping style models (Fig. 3.7).

Expanding the results of CA, a third model was identified by Boolean operations of the categorical data; unfavourable, unevaluated, favourable and high favourable. A confusion matrix of the rotated fault block model and horst model outlined the Smørbukk,

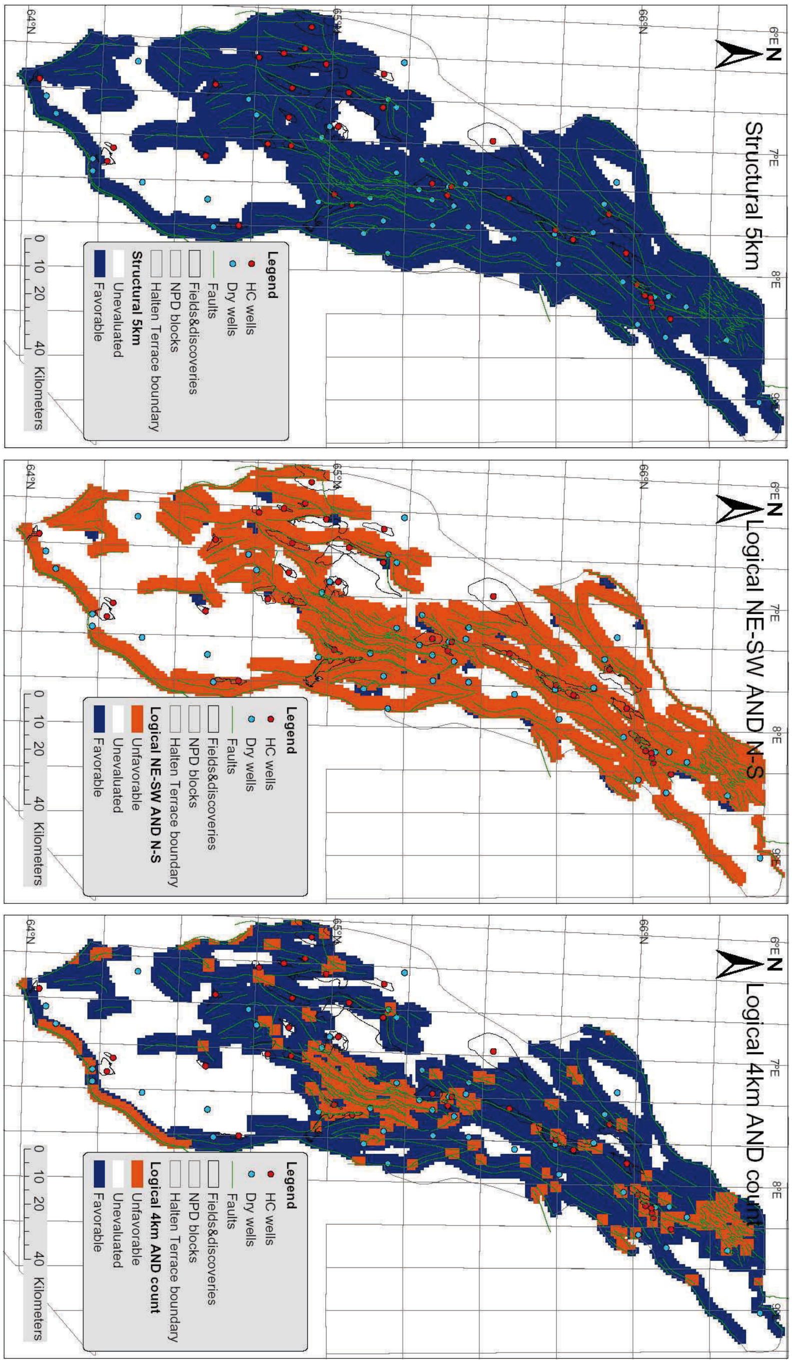

Figure 3.4: Input maps of the rotated fault block model. Structural 5km, Logical Structural NE-SW AND Structural N-S and Logical Structural 4km AND Complexity count.

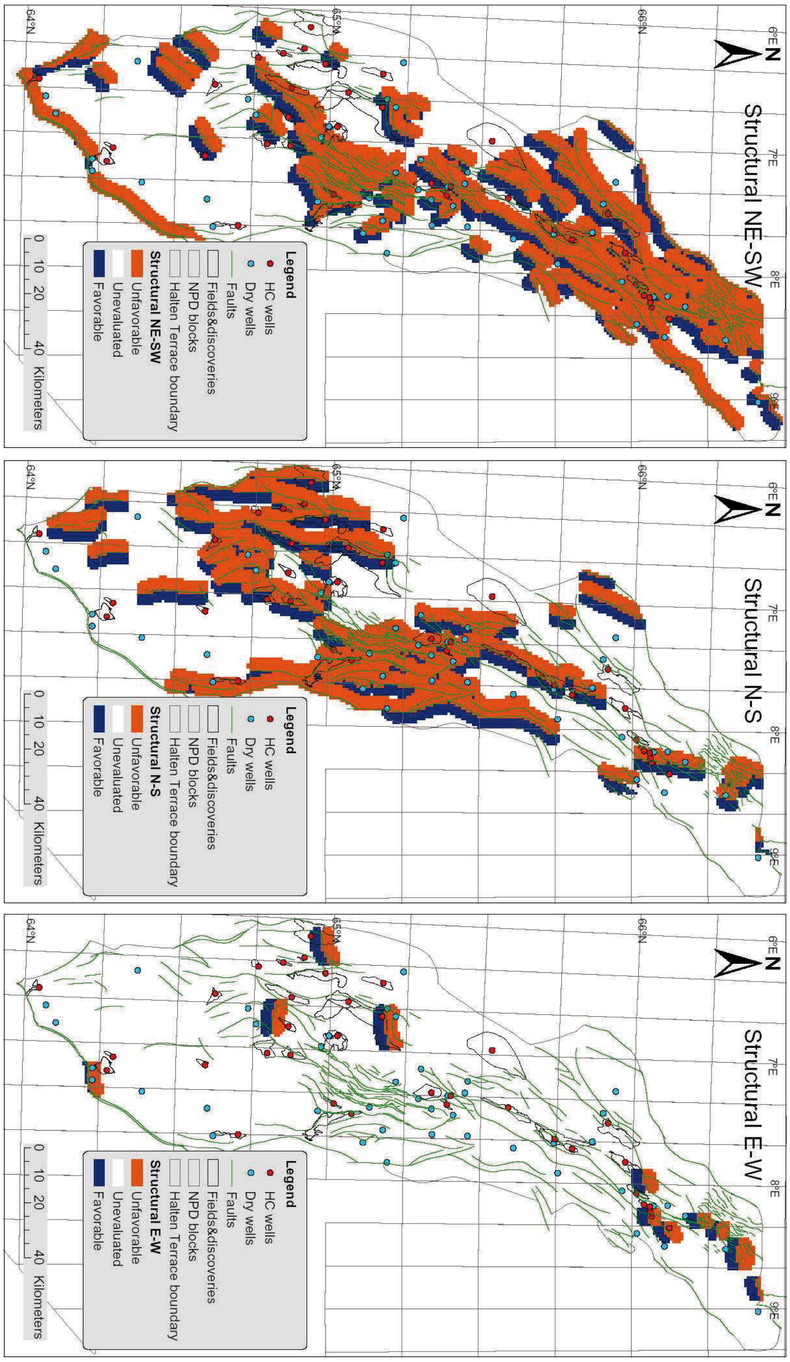

Figure 3.5: Input maps of the rotated fault block model. Structural NE-SW, Structural N-S, Structural E-W.

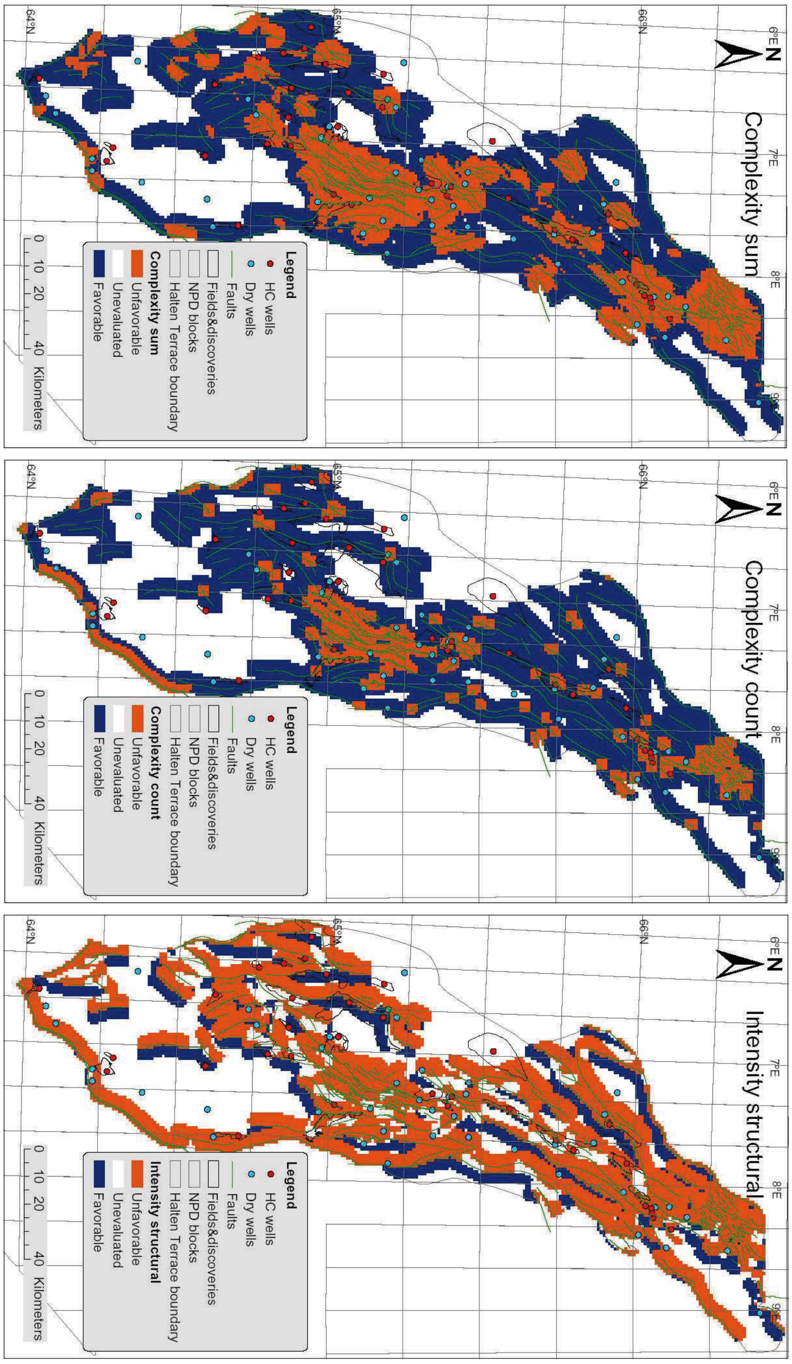

Figure 3.6: Input maps of the rotated fault block model; Complexity sum, Complexity count and Intensity structural.

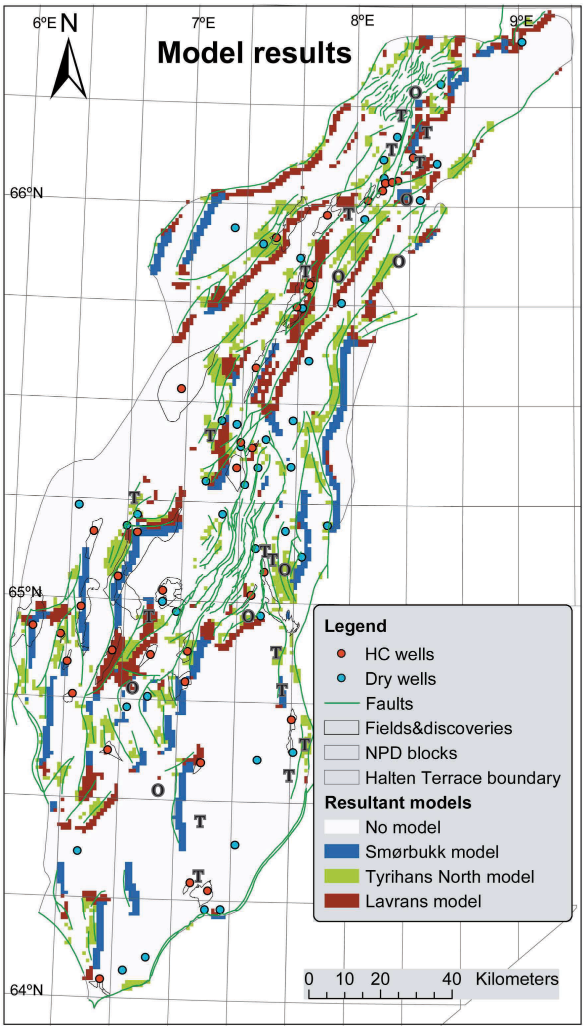

Figure 3.7: Favourability map for indicating high favorable zones for the Smørbukk, Tyrihans North and Lavrans models defined in Table 3.4. 25 exploration wells have been drilled in this play between 2005 and end of 2010 (NPD, 2010). These wells, on the map shown as T (targeted hydrocarbons) and O (dry), resulted in one hydrocarbon well within the Smørbukk model, 9 wells (6 with hydrocarbon) within the Tyrihans North and 6 wells (4 with hydrocarbons) within the Lavrans model. 6 discoveries and 3 dry wells were not within the favorable cells of these three models.

Table 3.4: Definition of the models including some discoveries described by these models.

Model	Rotated fault block model	Horst model	Examples of discoveries described by model
Smørbukk	High fav.	Uneval. & Fav.	Kristin, Tyrihans South, 6406/1-2
Tyrihans North	Uneval.	High fav.	Idun, 6406/1-1
Lavrans	Fav.	Fav. & High fav.	Skarv, Heidrun North, 6507/2-2

Tyrihans North and the new Lavrans models. Whereas the Smørbukk and Tyrihans North models are related to high favourability cells in either the fault block model or the horst model, the Lavrans model is related to favourability cells to both fault models (Table 3.4). The graphical display of the three field models outlines separate areas within the Halten Terrace region where there are a higher probability for the presence of specific fault related accumulations (Fig. 3.7). These three model results are compared to the 25 exploration wells drilled in the play since 2005 and the wells in both the Tyrihans North and Lavrans models have a discovery rate of 1/3. However, the Tyrihans North model has 3 more wells drilled than the Lavrans model. Only one well has target in the Smørbukk model, which can indicate that large drillable structures have already been drilled in the region. This shows that the transform and generation of the third model was superior to the Smørbukk model and appropriate for delineate drillable structures.

The selection of an operational scale consisting of $1 \times 1\mathrm{km}^2$ cells was not arbitrarily but chosen according to the maximization of fault density given the presence of hydrocarbon discoveries related to conjugated faults. A larger cell size, say $5 \times 5\mathrm{km}^2$ or larger, would have made it difficult to differentiate between different trapping styles because each cell would have covered multiple fault patterns. An operational scale corresponding to sub-segment closure areas (REA in Fig 3.1) was chosen. The empirical field-discovery closure areas on the central Halten Terrace have a range of 5-150km^2, with a mode of 25km^2 (Brandsegg, 2004a). Therefore, a discovery generally covers many neighbouring grid cells.

Studies have indicated that the ternary classification of variables using +1 for favourable,

-1 for unfavourable and 0 for unevaluated/unknown outperform the binary classification of $+1$ favourable and 0 unfavourable/unevaluated (e.g Chaves, 1993). However, the introduction of the -1 for the unfavourable state could lead to bias in the dataset, especially in oil exploration as most often there is no method for direct detection of oil and it is risky to conclude that there is no chance for oil in a specific part of a sedimentary basin unless the play element maps clearly indicate no chance e.g. by not having a reservoir due to erosion. The selected representative values for a given feature may not have its significants related to a linear scale and could accordingly have values that are more significant if the feature describing the geological process was thresholded at the more appropriate value. If this thresholding invalidates of the model, then new threshold values and/or new variables need to be evaluated and potentially included to enhance the predicting power of the model chosen to explain the process-response system.

This study has shown that adequate attribute pre-processing is vital for a good result and that image analysis and GIS are ideal tools for performing the necessary tuning of ternary coding that are used for input. The favourabilities obtained show how the CA method can be used to express the favourability for fault related hydrocarbon accumulations. The selection of the individual play (REA) as the geographical study object with an operational scale at the sub-segment closure area level (REA) gave representative results corresponding to the study objectives. The results further show that GIS is an excellent computing platform for building the database, doing the map calculations and visualizing the results that all are required in successful quantitative hydrocarbon assessment. The CA approach with a fault related model provides an example of how a single mappable fault feature can be pre-processed into several new derivative fault features that jointly and weighted properly can predict drilling targets where hydrocarbons could have been accumulated due to fault related migration and entrapment.

3.4 Yet to find oil resources in Chad

Hydrocarbon resources are one of the most income-earning natural resources in the world that also has a strategic position in the world energy supplies (Shelly, 1998). Apart from Antarctica, hydrocarbon resources have been identified within all continents. The presence of natural resources within the borders of a given country represents a major opportunity for the development of that country (Craig et al., 2001). However, several geological factors, such as source and reservoir rocks, trap occurrence, source rock maturity and the timing of these factors needs to be simultaneous adequate for an accumulation to form (Shelly, 1998). The mapping and quantification of these factors are therefore essential for obtaining reliable information that can ultimately indicate a location resulting in a successful exploration drilling result (Gluyas and Swarbrick, 2003).

A national resource assessment is a necessary prerequisite for making strategic decisions about what basin to enter and subsequently the tactical decision about what targets to drill. Russia (Sandvik and Zakharov, 1996), China (Zhao et al., 2008), USA (Ahlbrandt and Klett, 2005) and Norway (NPD, 2007, 2009), assess their hydrocarbon resources regularly as part of their strategy to increase efficiency in hydrocarbon resource management policies. Assessments are updated with new geologic information as the geologic knowledge base increases with ongoing exploration. The development and use of hydrocarbon assessment methods (e.g. Meneley et al., 2003) for such national appraisals are a continuing activity in most oil producing countries. Assessments can be very general, e.g. include only an evaluation of the hydrocarbon potential within a sedimentary basin area solely based upon the presence of a favourable geological setting (Divi, 2004). Whereas other assessments can be related to specific local areas where risk factors, such as political and economical considerations, are incorporated (Otis and Schneidermann, 1997). Both these assessment examples can be included in different decision making processes. Exploration for prospective hydrocarbons is therefore a challenging task that not only includes geosciences disciplines, such as geology and geophysics, but may also includes other disciplines that are involved such as petroleum economy (Gluyas and Swarbrick, 2003) and sociopolitical aspects (Griffiths, 1978).

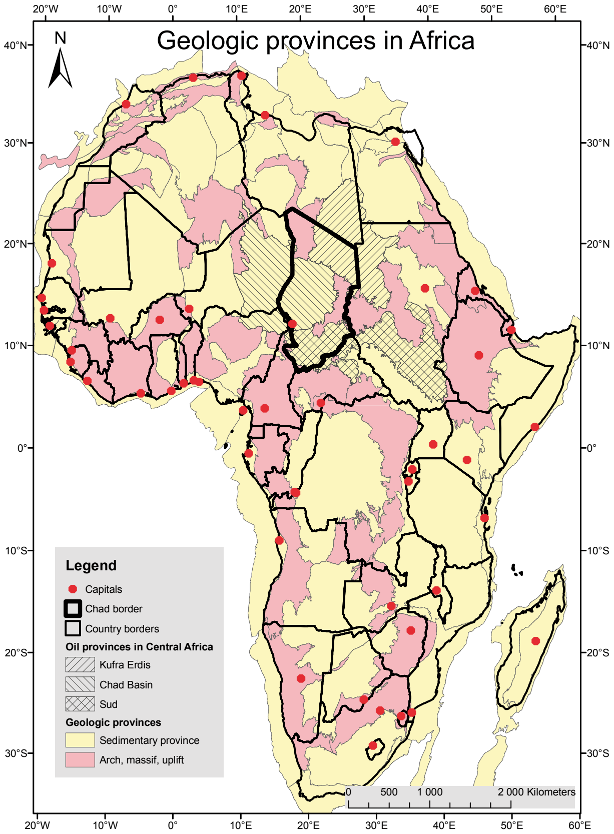

Figure 3.8: According to USGS (Charpentier et al., 2000), Chad can be divided into several structural provinces. The three sedimentary basin provinces within Chad are named Erdis Kufra in north, Chad Basin in central west and Sud in the south.

This national assessment of Chad uses the USGS World Petroleum Assessment 2000 approach (here named USGS 2000 methodology), which is a probabilistic methodology with representative input parameters that ensures an uncertainty range in the final results expressed by the estimated statistical distribution of undiscovered hydrocarbon resources (Klett et al., 2000). Experts' judgments are fundamental for the determination of input parameter values expressed in the form of a range of values, each with a differing degree

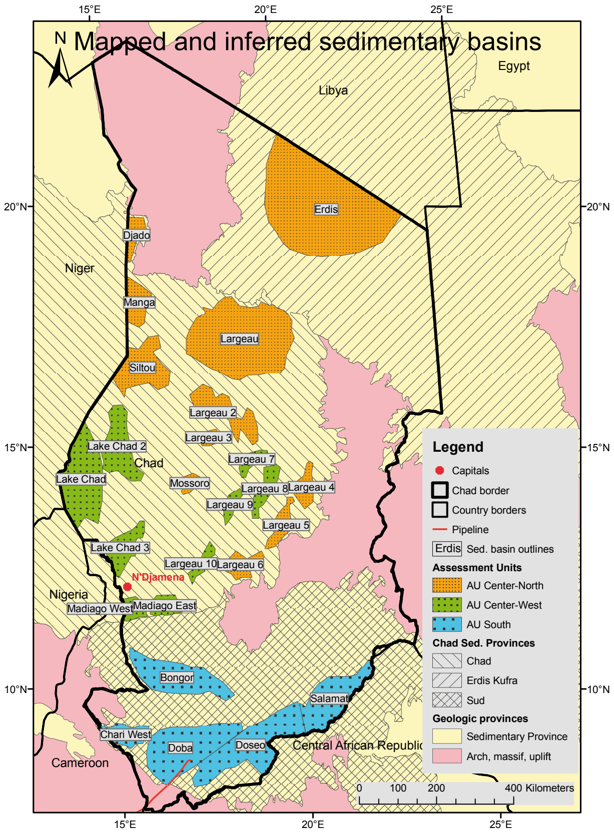

Figure 3.9: The mapped proven and inferred sedimentary basins within the available Chadian licensing blocks (African Petroleum Producer's Association, 2008) are interpreted from the Bouguer anomaly map of Louis (1969, 1970).

of certainty (subjective probability). A single assessment unit can be subdivided into a number of sub-assessment units (AU) each with homogeneous geological characters.

The USGS world assessment hydrocarbon resource approach comply with the REA concept and its operational scale are mostly related to individual plays (REA in Fig. 3.1) with input parameters expressing, among others, a specific minimum accumulation size, the number of expected accumulations that exceeds the minimum size, and the undiscovered accumulation sizes or a field size distribution (FSD). Although this USGS assessment method is geology-driven, exploration and discovery processes are typically included in the definition of the probability distribution of each parameter (Klett et al., 2005).

This national Chad assessment has as its objective to assess the oil potential of all the sedimentary basins in Chad (Figs. 3.8 and 3.9) in support of the Chadian efforts to evaluate all the future resource management policy options. The input parameters for the assessments are based upon the hydrocarbon geology of Chad and its adjacent areas as well as the results of previous exploration efforts conducted within these areas. Until 2010, no published regional hydrocarbon resource assessments had been undertaken before Brownfield et al. from the USGS performed a geology-driven assessment of the Cretaceous-Tertiary total petroleum system of the greater Chad basin that include parts of Niger, Chad, Nigeria and Cameroon (Fig. 3.8). They assessed the following mean amounts of undiscovered, technically recoverable resources: 2.32 billion bbl oil, 14.65 trillion cubic feet of natural gas, and 391 million bbl of natural gas liquids as part of their World Oil and Gas Assessment Project. When assuming equally distributed volumes, the oil volume estimate in Chad is approximately 463 MMBO as approximately 20% of the study area is within Chad. This hydrocarbon potential as well as the reserves discovered to date was in the colonial to post-colonial time considered non-existent and only a historical patchy hydrocarbon exploration effort had been conducted (Azevedo, 1998; Kusnir and Moutaye, 1997). A contributing factor to this patchy exploration effort is the fragile political stability in Chad that several times in the past has stopped exploration or slowed it down in specific regions of the country (Section 4.2). Prior to the assessment of individual sub sedimentary basins as part of the present assessment thesis work, the hydrocarbon exploration history of Chad will be outlined as this background information is important for understanding how the exploration coverage has evolved through time. A more extensive treatment can be found in Appendix G.

The remote location, including dry and hot environment and long distance to port interacting with depressive exploration results in the early stage of exploration resulted in insignificant quantities of hydrocarbons (Klitzsch, 1994). The first major oil discovery was proven in 1975, 15 years after the hydrocarbon exploration was first initiated

(USGS minerals yearbook, 1976). During this period, the exploration effort moved from Northern Chad to the more promising sedimentary basins in S-SW Chad. During the last 30 years the oil exploration effort has been focused upon Southern Chad which is now the preferred area for hydrocarbon development, not only from a geologic point of view, but also when considering political, technical and economic issues. This is dominantly due to the presence in the area of a skilled workforce, better infrastructure and political support from the local government. Development of 1 bill bbl of oil reserves found in the Doba and additional reserves that is now being developed in the Bongor basins have reduced technical and economic risk and thereby prompted several oil companies to restart exploration in the central and northern Chad regions (Younous, 2008). The first oil from the Doba was exported in 2003, almost 30 years after the first oil discovery, and has up to mid-2010 produced 354 mill bbl oil (EssoChad, 2010).

Chad comprises three distinct sedimentary domains, the Palaeozoic-Jurassic intracratonic depression in the North and two rift systems in the S-SW related to Cretaceous-Tertiary rifting (Guiraud et al., 2005). Three major types of hydrocarbon source rocks can be found within these domains; Upper Paleozoic (Silurian) marine source rock (Craig et al., 2009), Cretaceous lacustrine and marine shales (Genik, 1993) and Paleogene lacustrine shales (Genik, 1993; Alalade and Tyson, 2010). Several of the more recent publications (e.g. Brownfield et al., 2010) indicate that many of the large sedimentary basins in Chad can contain significant amounts of hydrocarbon. This is explained by the presence of different types of both source rocks and reservoir rocks in combination with a favorable timing for hydrocarbon generation (Genik, 1993; Lüning et al., 1999; Tawadros, 2001; Mohamed et al., 2002; Guoping and Lei, 2007; Craig et al., 2009).

Based upon these petroleum system elements, three composite assessment units (AU) were defined for the present Chadian assessment: (1) AU Center-North, including only Paleozoic source and reservoir rocks that are assumed to be present in both the Kufra Erdis and the Chad Basin provinces; (2) AU Center-West, includes only Upper Cretaceous to Tertiary source and reservoir rocks that are assumed to be present only within the greater Chad Basin province; and (3) AU South, including only the Lower Cretaceous source and reservoir rocks of the Sud province. These AUs are inline with the USGS 2000 definitions, where AU Center-West is corresponding to the Chadian part of the AU assessed in Brownfield et al. (2010). The mapped and inferred basins outlined in Fig. 3.9 can be categorized into the following three assessment units (AU):

1. AU Center-North: Erdis, Djado, Siltou, Manga and Largeau 1-6 basins
2. AU Center-West: Lake Chad, Madiago, Moussoro and Largeau 7-10 basins
3. AU South: Bongor, Chari West, Salamat, Doseo and Doba basins

Even though exploration drilling have been performed within all these three AUs, proven economic oil accumulations related to effective source and reservoir rocks have only been identified within the Cretaceous-Tertiary strata the S-SW Chadian sedimentary basins of Lake Chad, Doba and Bongor (USGS minerals yearbook, 2009).

Despite the fact that the Chadian government has opened bidding for oil blocks that cover nearly all regions of Chad (African Petroleum Producer's Association, 2008), only technical discoveries (e.g. Doseo and Salamat basins) have been found outside the Lake Chad, Doba and Bongor basins (Table 3.5). Stratigraphically, all the major economic oil reserves in Chad, predominantly high viscous crude, are discovered in Cretaceous strata representing complex and challenging reservoirs with significant vertical heterogeneity (Liangqing, 2008). The Ronier field in the Bongor basin has, however multiple thin oil zones with light-oil suitable for pipline transport to the refinery near N'Djamena (Geosint, 2011). Additionally, the Lake Chad basin has a thin oil zone discovered in Eocene sandstones (Genik, 1993).

When assessing the oil potential of the three AUs of Chad, the information from fields and discoveries and analogue areas are transformed and downscaled or upscaled to individual plays. Based upon the geologic knowledge of the mapped sedimentary basins, an estimation of the total oil resources pr. basin is calculated and aggregated into a estimate of the total AU oil resources.

The discoveries in Doba, Lake Chad and Bongor have area of closure and reserves as

Table 3.5: Oil reserves in Chad and their pool sizes based on USGS minerals yearbook (2000); EssoChad (2002, 2010); Chevron (2008); CNPC (2008, 2009); Geosint (2011); Liangqing (2008)).

Sed. basin name	Field name	Discovery name	Discovery closure area [km^2]	Reserves [MMBO]	Reserves/ closure area [MMBO/ km^2]	Nr. field basin area fields /1000km^2	Reserves/ basin area MMBO /1000km^2
Doba	Doba	Kome	50.8	588	11.6		
	Doba	Bolobo	13.5	135	10.0		
	Doba	Miandoum	22.7	227	11.3		
	Doba	Nya	1.3	11	8.4		
	Doba	Moundouli	15.0	69	4.6		
	Doba	Maikeri	3.2	22	6.9		
Sum Doba basin			106.5	1052	9.9	0.26	46.3
Lake Chad	Sédigui	Sédigui	5.0	15	2.0		
		Kanem/Kumia	2.0	4	3.0		
Sum Lake Chad basin			7.0	19	2.7	0.14	0.9
Bongor	Ronier	Ronier	30.0	243	8.1		
	Mimosa	Mimosa	10.6	86	8.1		
	Baobab	Baobab	5.6	44	8.1		
	Kubla	Kubla	9.4	76	8.1		
Sum Bongor basin			55.6	450	8.1	0.23	26.3
Total:			191.1	1583	8.3		

indicated in Table 3.5. The areal yield from discoveries are calculated from the proven reserves divided by the estimated closure area expressed as MMBO/km^2 and range from 2 to 11.6.

Two of three assessment units have different maximum field sizes and size distributions (Table 3.6), where the AU South and AU Center-West is assumed to have similar field sized and accumulation densities. The intra-cratonic basins of AU Center-North are assumed to have similar field density and higher maximum accumulation size than the rift basins to the South. The results (Table 3.6 and Fig. 3.10) shows that the Erdis, Largeau and Doseo basins have the most undiscovered mean resources.

Table 3.6: Input parameters for the USGS 2000 methodology assessing the undiscovered oil resources in Chad. Sedimentary basins with a area less than 3000 km^2 (ID: 5, 8, 12, 14, 15) are not displayed as their sediment volumes are interpreted to be insufficient for an active TPS. MMBO, million barrels of oil. Minimum field size assessed is the undiscovered field size minimum (10 MMBO). The probability indicates the likelihood of at least one equal to or greater than the MFS.

ID	Basin area [km^2]	Basin name	Assignment Unit	Status	Probability				Undiscovered Fields					
									Number			Size [MMBO]		
					Fluids	Rocks	Timing	Access	min	med	max	min	med	max
1	67994	Erdis	AU Center-North	Drilled	0.8	0.9	0.6	0.7	3	9	18	10	30	600
2	3502	Djado		Undrilled	0.7	0.8	0.6	0.7	1	2	4			
3	5914	Manga		Undrilled	0.6	0.8	0.6	0.8	1	2	4			
4	12667	Siltou		Undrilled	0.6	0.7	0.6	0.9	1	3	5			
6	43942	Largeau		Undrilled	0.5	0.8	0.6	0.8	2	7	11			
7	11007	Largeau 2		Undrilled	0.5	0.7	0.6	0.8	1	3	5			
9	3735	Largeau 4		Undrilled	0.5	0.6	0.5	0.8	1	2	4			
10	4049	Largeau 5		Undrilled	0.5	0.6	0.5	0.7	1	2	4			
11	4354	Largeau 6		Undrilled	0.5	0.6	0.5	0.8	1	2	4			
13	4682	Largeau 8	AU Center-West	Undrilled	0.7	0.7	0.5	0.7	1	2	4	10	30	400
16	20821	Lake Chad		Economic disc.	1.0	1.0	1.0	1.0	1	5	9			
17	11490	Lake Chad 2		Undrilled	0.9	0.9	0.9	1.0	1	3	5			
18	6997	Lake Chad 3		Undrilled	0.8	0.9	0.8	1.0	1	2	4			
19	3206	Madiago West		Undrilled	0.8	0.8	0.7	1.0	1	2	4			
20	3807	Madiago East		Undrilled	0.8	0.8	0.7	1.0	1	2	4			
21	17098	Bongor	AU South	Economic disc.	1.0	1.0	1.0	1.0	1	4	8	10	35	400
22	5178	Chari West		Undrilled	0.9	0.9	0.9	1.0	1	2	4			
23	22698	Doba		Economic disc.	1.0	1.0	1.0	1.0	1	2	4			
24	23676	Doseo		Technical disc.	1.0	1.0	1.0	1.0	1	4	8			
25	15209	Salamat		Technical disc.	1.0	1.0	1.0	1.0	1	2	5			

Table 3.7: Assessment results of the total undiscovered oil resources of Chad using USGS 2000 methodology (Table 3.6). Sedimentary basins with area less than 3000 km^2 (ID: 5, 8, 12, 14, 15) are not displayed as their sediment volumes are interpreted to be insufficient for an active TPS. These sedimentary basins are displayed without any oil resources in Fig. 3.10.

ID	Basin area [km^2]	Basin name	Probability		Undiscovered oil [MMBO]											
			Geo	Geo& access	unrisked				Geologically risked				Geologically and access risked			
					P90	P50	P10	Mean	P90	P50	P10	Mean	P90	P50	P10	Mean
1	67994	Erdis	0.43	0.30	120	328	601	334	52	165	303	169	36	116	212	118
2	3502	Djado	0.34	0.24	22	63	165	84	7	21	55	21	5	15	39	20
3	5914	Manga	0.29	0.23	22	64	166	85	6	18	48	24	5	15	28	20
4	12667	Siltou	0.25	0.23	36	94	219	117	9	24	55	29	8	21	49	27
6	43942	Largeau	0.24	0.19	112	242	461	243	27	58	111	66	22	47	89	53
7	11007	Largeau 2	0.25	0.20	36	91	215	114	8	19	45	24	6	15	36	19
9	3735	Largeau 4	0.15	0.12	22	63	165	84	5	15	40	20	4	12	32	16
10	4049	Largeau 5	0.15	0.11	22	63	165	84	5	15	40	20	3	11	29	15
11	4354	Largeau 6	0.15	0.12	22	63	165	84	5	15	40	20	4	12	32	16
13	4682	Largeau 8	0.25	0.17	21	61	149	77	5	21	36	19	5	21	36	19
16	20821	Lake Chad	1.00	1.00	70	169	316	185	70	169	316	185	70	169	316	185
17	11490	Lake Chad 2	0.81	0.81	36	89	191	105	29	72	155	85	29	72	155	85
18	6997	Lake Chad 3	0.58	0.58	22	61	146	77	12	35	84	44	12	35	84	44
19	3206	Madiago West	0.51	0.41	22	61	146	77	12	31	75	40	12	31	75	40
20	3807	Madiago East	0.51	0.41	22	61	146	77	12	31	75	40	12	31	75	40
21	17098	Bongor	1.00	1.00	68	166	324	184	68	166	324	184	68	166	324	184
22	5178	Chari West	0.73	0.73	25	72	164	87	19	52	119	63	19	52	119	63
23	22698	Doba	1.00	1.00	25	71	165	87	25	71	165	87	25	71	165	87
24	23676	Doseo	1.00	1.00	66	163	308	178	66	163	308	178	66	163	308	178
25	15209	Salamat	1.00	1.00	41	102	212	118	41	102	212	118	41	102	212	118
	Total undiscovered resources							2481				1436				1347

The USGS 2000 methodology uses basin play methods incorporating Monte Carlo simulations to indicate the total petroleum occurrence within a specific area (Klett et al., 2000). The input parameters for this methodology consist of information about the assessment unit, characteristics of the assessment unit, estimates of the number and size of undiscovered fields. The prerequisites for calculating the potential hydrocarbon yield within a study area is based upon several factors; minimal field size, assessment unit maturity, discovery history and assessment unit probabilities. Resources in a field less than the minimum size are excluded from the assessment. Generally, in areas with only small fields, is it preferable to increase the minimum field size threshold as the total number of insignificant small fields will be high. The threshold value was set to 10 million bbl oil [MMBO] to exclude a potentially large number of small fields. In Chad, all mapped basins without discoveries are classified as frontier or hypothetical, where mature is classified if more than 13 discoveries exceed the minimum field size, frontier from 1-13 fields are discovered and hypothetical where no fields are discovered at present time (Klett et al., 2000).

The input parameters for this assessment (Table 3.6) estimated from the published literature are defined in terms of triangular distribution with an estimation of the minimum, median and maximum of both the number of expected fields and resource sizes, in addition to the point estimates of the fractions of geologic risk and accessibility. The results from 50000 Monte Carlo simulations runs of the excel-based program Emc2 (Klett et al., 2000) are outlined in tabular form (Table 3.7) as well as on a map (Fig. 3.10). The assessment units have been aggregated with full dependency within each unit due to a common dependency on a within unit source. Between units (Table 3.8 and Fig. 3.11) no dependency is postulated and the aggregation has been done without any dependency. The estimated risked most likely value (mode) of the undiscovered resources of 1420 MMBO is about one-half of the ultimate most likely resources of 2639 MMBO (Table 3.8). This mode is used to report ultimate resources due to its lack of sensitivity for a highly uncertain upside potential (pers. comm. Sinding-Larsen). Although Chad is generally underexplored in both the intra-cratonic and most of the rift development related basins, they are estimated to contain significant yet to find oil that can potentially lead to field developments and contribute to sustain Chad's oil export. About half of the Chadian total undiscovered resources are expected to be in the Lower Cretaceous strata. The Lake Chad and Erdis basins are the two basins outside the Lower Cretaceous strata (AU South) basins with most expected undiscovered oil resources.

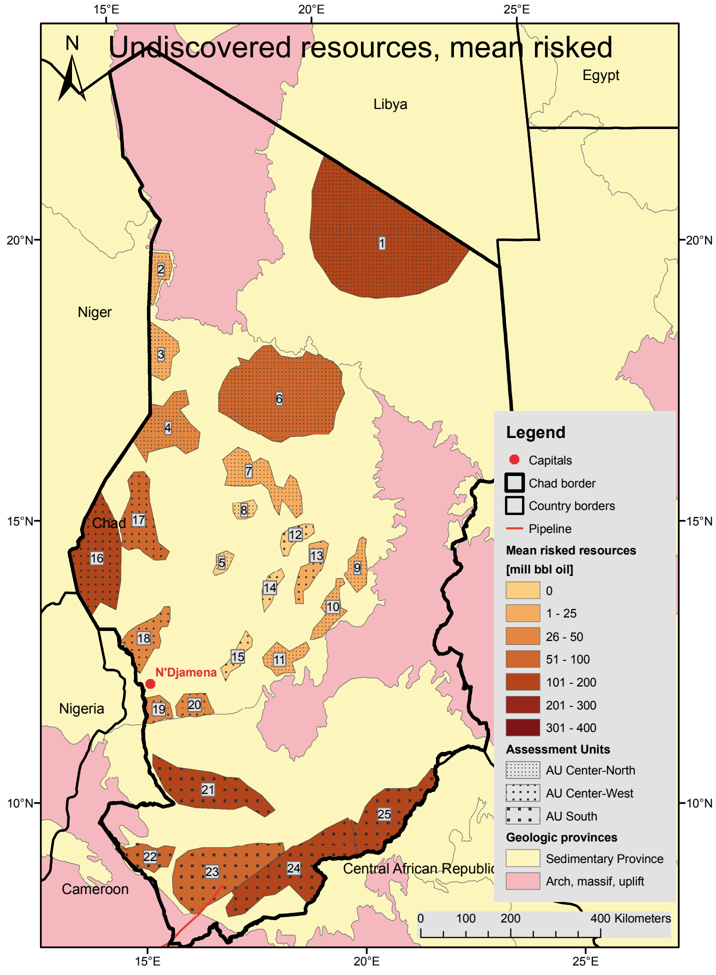

Figure 3.10: Estimated mean risked undiscovered oil resources in Chad using the USGS 2000 methodology. Graphical display of Tab. 3.7.

Table 3.8: Chad ultimate technically recoverable oil are compiled from proven reserves (Table 3.5), cumulative oil production (EssoChad, 2010) and the oil assessment results using the USGS 2000 methodology (Table 3.7). MMBO, million barrels of oil. Results shown are fully risked estimates. P90 represents a 90 percent chance of at least the amount tabulated; other fractiles are defined similarly. The individual basin results are aggregated under the assumption of full interdependency due to the regional uncertainty about the presence and the adequacy of a mature source rock. The AUs have been aggregated assuming independence. AU, assessment unit.

Assessment Unit (AU)	Field Type	Cumulative production	Identified reserves	Original reserves	Total undiscovered Resources Oil (MMBO)					Ultimate resources (mode)
					P90	P50	P10	Mean	Mode	
AU Center-North	Oil	-	-	-	103	285	552	304	240	240
AU Center-West	Oil	-	19	19	139	368	739	413	310	329
AU South	Oil	354	1210	1564	270	699	1002	630	780	2344
Total		354	1229	1583	877	1376	1900	1347	1420	2639

The immediate future of new oil development in Chad will be from the Bongor Basin where the already proven hydrocarbons will be tied to a refinery that is now under construction around the capital N'Djamena (CNPC, 2009). In a longer term, the exploration of the sedimentary basins in western and northern Chad depends on the exploration results in the neighbouring countries as these sedimentary basins extends into Nigeria, Niger, Libya, Sudan, the Central African Republic and Cameroon.

The hydrocarbon assessment results in Table 3.8 show that Chad is composed of many basins without any exploration drilling, but not necessarily without geological information. Exploration for hydrocarbons in the Center-West and South as well as in the neighbouring countries where similar sedimentary basins occur, has given valuable insight into many of the still under-explored basins of Chad.

National borders do often correspond to present day topographical boundaries, such as rivers, mountain chains, lakes and oceans, and do not necessarily follow geologic boundaries (e.g. the intra-cratonic sedimentary basin Kufra/Erdis basin where Chad, Sudan and Libya all have a share).

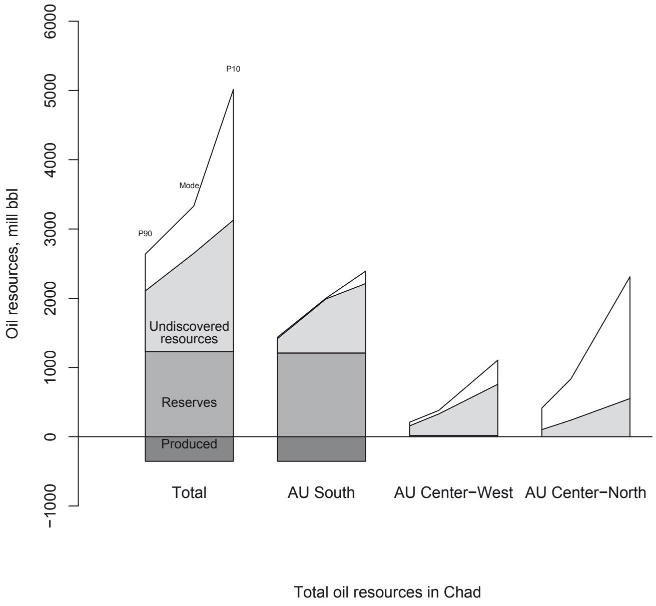

Figure 3.11: Chad ultimate oil resources. Graphical display of Tab. 3.8. The upper non-shaded area of the resource column indicates the magnitude of undiscovered resources given removal of the geological and access risk.

When performing a resource assessment, obtaining full focus on specifying the uncertainties, indicate dependencies between geologic variables and selecting the appropriate values are important for generating accurate and precise results (Schuenemeyer, 2002). His first concludes that uncertainties can be split into two, where the uncertainty inherent in the geologic process can be solved stochastically, the uncertainty associated with lack of knowledge are best solved by expert judgments. Secondly he emphasize that dependencies can occur at several stages of an assessment process, where the failure to consider positive dependencies leads to narrower estimates of uncertainty than could occur if they have been incorporated into the model. The third aspect highlighted relates to the quantification of risk. Whereas failure to risk an assessment will overstate the expected resource, assigning too much risk, such as double risking, will result in understating the expected resource. These uncertainty principles have been taken into account in this assessment.

3.5 Results and conclusions

This chapter has considered play scale heterogeneities related to reservoir and sedimentary basins and emphasized the importance of critical evaluation and necessary pre-processing of resource assessment input parameters. Raw data must be recorded, analyzed and interpreted relative to resource assessment objectives at the suitable operational scale. The interaction of parameter variability between reservoir and sedimentary basin scales can be assessed against changes in the REAs. The REA concept has proved its utility both for understanding the process-response system when upscaling/downscaling a dataset and for quality assurance of variability in integrated models.

The major results of this chapter related to reservoir heterogeneities are:

- The disaggregation of a regional fault map using a GIS environment and the construction of signatures within $1\times1\text{km}^2$ for fault related accumulation of hydrocarbons showed that the fault data needed to be pre-processed into cell based ternary coding expressing either favourable or unfavourable conditions or a situation where the controlling effect of an attribute is either unknown or unevaluated. GIS is an ideal tool to perform adequate attribute pre-processing (tuning) of data into ternary coding which is vital for obtaining reliable results.

- By using Characteristic Analysis for a play assessment, a weighted linear combination of ternary coded attributes was used to compute favourability for hydrocarbons on the basis of a probability significance metric. The outlined favourable cells express where further exploration should be conducted for potentially identifying fault related accumulation of hydrocarbons.

- A Monte Carlo assessment of the Chadian oil potential in the AUs (AU Center-North, AU Center-West and AU South) gave 1420 MMBO as the most likely amount of untapped oil and indicates that approximately half of the national potential has been identified.

The implication of considering play scale geologic variations is that it can give a thorough appreciation and representation of the variability and uncertainty of the regional geological system to be analyzed at multiple scales that is required for obtaining quantitative estimates. This increased knowledge can lead to a more efficient location of natural recourse exploration effort. This knowledge may further enhance the formulation of resource management options within a sociopolitical context. Other implications are:

- An explicit quality assurance of observational data relative to the REA concept can ensure reproducible and reliable assessment results when the input parameter values are representative. High quality resource assessment results has implications for the strategic decisions related to such assessments.
- The GIS environment permits pre-processing of data, e.g. disaggregating of data into operational form to produce representative signatures. These signatures e.g. in terms of boolean variables are of general nature and can be efficiently used for more than explaining fault related hydrocarbon accumulations.
- The CA methodology with GIS supported pre-processing of data into a ternary coding should be used by the oil industry to delineate favourable areas in play assessments.
- National resource assessments estimating the ultimate hydrocarbon resources within a country expressed by probabilistic volumetric estimates within each sedimentary basin has implications not only for identifying the location and potential hydrocarbon volumes important for further prospectivity efforts, but are also important for devising efficient resource management policies and for supporting the international community for political decisions.

Chapter 4

Human dimension of natural resource variability

The human existence is dependent on natural resources and how these resources are available for human consumption. Such resources, both renewable and non-renewable resources, are unevenly distributed around the world both in terms of geologic characteristics (mineralogy, grade, grain size, grain texture, size and depth of a deposit) and economic dependency (profitability dependent on extraction costs and market value) (Craig et al., 2001). The natural resources itself have no relation to the human dimension as it has only geologic characteristics (Griffiths, 1978). However, the human dimension plays a crucial role when such natural resources are developed and extracted, as it is the current economic status of the given resource that decides if it is economic or not (Fig. 4.1).

The quantities of economic resources (named reserves) at any time are well defined, but changes constantly with change in the economic environment (Table 4.1). Due to mineral extraction, the reserve base decrease, but increase as new discoveries are made or as technological advances make the overall extraction cheaper (Griffiths, 1978). An increase in the market value can also turn an uneconomic resource into an economic reserve. The access to natural resources has not only a technical aspect, but also legal and economic constrains defined by political regulations through land ownerships, incorporation of land

Table 4.1: Resources are classified according to geological understanding and economic viability (Craig et al., 2001). The best known and most profitable of the resources fall into the category of reserves and the constitute our present source of mineral commodities. The resources classified as "demonstrated identified resources" are included in the reserve base.

Identified resources			Undiscovered resources
Cumulative production	Demonstrated	Inferred	Probability range (hypothetical / speculative)
Economic	Reserves	Inferred reserves	Hypothetical - speculative
Marginally economic	Marginal reserves	Inferred marginal reserves	
Sub-economic	Demonstrated sub-economic resources	Inferred sub-economic resources	

into national parks or wilderness areas that may exclude otherwise mineable resources from reserve status (Humphreys, 2005). This includes fluctuations in price of non-renewable resources adding extra complexity to the resource classification expressed in Table 4.1. Conflicts over present boundaries and land areas, both non-violent and severe armed conflicts, can also reclassify the mineable reserves to demonstrated resources as the reserves may not be exploitable during a conflict. Even though conflicts are not directly related to natural resources, modern industrialized societies function on the basis of natural resources and strives therefore to obtain its resource base. A deprivation of a nation's natural resource base would rapidly lead to a collapse of the nation's economy and could therefor be worth fighting for access to new resources (Le Billon, 2001; Collier and Hoeffler, 2005; Le Billon, 2007a).

In a global perspective, identifying the major driving mechanisms of conflicts are of importance not only for science itself, but primary to identify potential conflicts before break out. The expenses for ending a running armed conflict is much more expensive for the global community, in terms of e.g. money, time, casualties, than preventing an emerging conflict to start. Conflicts related to natural resources can be identified on multiple scales (Le Billon, 2007b). One example can be onshore hydrocarbon exploration, development

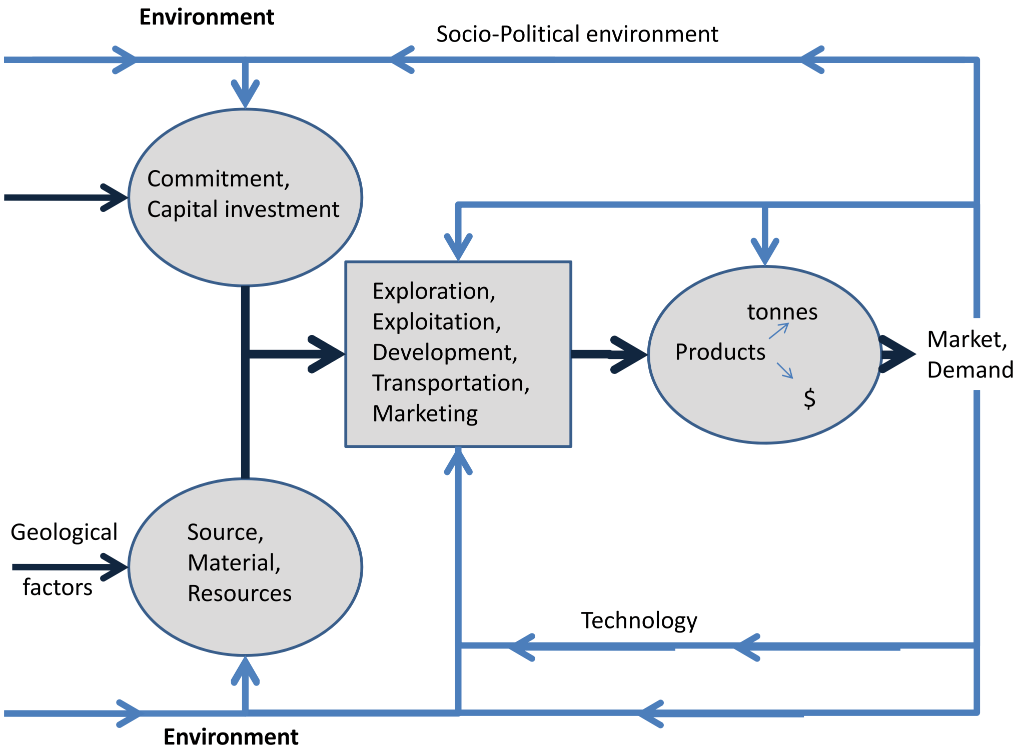

Figure 4.1: Simple cybernetic model of mineral resource subsystem, modified from Griffiths (1978). The exploration phase for natural resources, can be expressed by two kinds of processes; (1) acquired characteristics, such as the socio-economic factors which lead to capital investment and to the construction of infrastructure, and (2) inherited characteristics, the geological events (processes) that formed natural resources.

and exploitation that includes both area and time intensive operations from large regional seismic surveys to infrastructure development and construction of production facilities. Such operations can cause crossing interests, not only on micro (household level) scale as in Chad where farmers loose their possibility to perform agriculture (May and Massey, 2000), and also at meso (community level) scale where e.g. new industry interferes with existing industry (Bridge, 2002), and lastly also at macro (national level) scale where e.g. income taxes from oil production that can increase the national revenue rapidly like in Chad and open for more governmental spending (Hilson and Maconachie, 2009). Contradictory interests can also be identified at a global level as e.g. a hydrocarbon exploration program can be situated in a region sensitive for specific animal eradication e.g. the recent Chevron oil pollution case from Amazonas. The local citizens, the national government and the industry can all be positive for exploration and production, whereas on a global level, it is important to retain the world's diversity if the area contains rare species/animals (IUCN, 2007) as was observed when the Chadian Doba pipeline crossed the tropical forest areas in Cameroon.

Much of the growing quantitative literature on the role of natural resources and conflicts are devoted to geographic distribution of natural resources and its relation to environmental and sociopolitical factors. The intensive increase in available digital geographical data has been utilized to quantitatively assess this role (Cederman and Gleditsch, 2009). The central aspect related to this role lies in the management policy of natural resources (Le Billon, 2007a). Natural resources, renewable and non-renewable, are spatially scattered over a given territory and have a specific economic, political and social value that has varied through time (Craig et al., 2001). From this perspective, is it perhaps intuitive that the management of natural resources could motivate conflict, however, the precise role that the specific natural resource may have in conflicts are less obvious (Collier, 2000; Ross, 2004; Le Billon, 2007a; Di John, 2010).

Whereas the previous chapters, in a wide sense, have been devoted to explain various characteristics of the input parameters for controlling the quality of the process-response systems within the natural resource context, this chapter enlarges the system and concentrates on the human dimension of natural resource variability.

4.1 Introduction

Without including to much or making this thesis too wide, two specific case studies are outlined. These two cases express differently how the human dimension is related to natural resource variability and are devoted to aspects of the natural resource-conflict nexus. The common aim of these case studies is to exemplify how spatial and temporal data are pre-processed to generate representative parameter values at an operational scale that reflects each of the study objectives. These results are discussed in relation to the REA concept to emphasize the representativeness of the input parameter values used in the analysis.

The challenges

Similar to observable geologic processes and how such processes develop specific natural resources, the development of conflicts can be expressed by process-response systems (Griffiths, 1988). E.g. the important step in a conflict is the phenomena where humans pick up arms for fighting (onset of armed conflict). A conflict itself is perhaps easy to identify, however, the underlying processes leading to this conflict is more complex (Le Billon, 2007a). The absolute magnitude or the magnitude variations over time of factors explaining e.g natural resource, political, economical, social and technological processes can be significant for explaining a given conflict phenomenon (Mauro, 2009). Quantifying these multidisciplinary processes to express potential causal mechanisms for conflict is a multifaceted task as observations are mapped and recorded at multiple scales (both spatially and temporally).

The complexity of each conflict on one side and the quantification methodology of conflicts on the other side can result in inconsistent and incomplete sets of conflict data due to inadequate quantification of the underlying processes (Le Billon, 2007a). This can generate misleading results as all interactions in the process-response system are not considered (Di John, 2010). One of the main challenges in quantitative natural resource conflict research using spatially distributed data is therefore to obtain appropriate representative parameter values for all input variables at an operational scale that can explain a certain phenomenon by an appropriate mathematical procedure.

The debate on the quantification of the relation between natural resources and conflicts was initiated predominantly by Collier and Hoeffler (1998) after their econometric study work initiated by the World Bank that presented development economist's perspective on the origins of the post-World War II civil wars. Their results implied that the strongest predictors of civil war onset were, among other factors, oil resources, dependence on primary commodity exports and poverty. The initial excitement about the significance and large effect that natural resources have on risk for conflict has tapered off as other researchers with other methods and model specifications have failed to confirm such relation (e.g. Ross, 2004; Fearon, 2005; Hegre and Sambanis, 2006; Brunnschweiler, 2008). However, as Collier et al. (2009) concludes, the availability of systematic empirical studies have not fully succeeded in providing convincing evidence for a relationship between natural resource abundance and territorial conflicts.

The various outcome of the present results in natural resource conflict studies show no indications that there is a universal scaling law for complex natural resource-conflict phenomena (Cederman and Gleditsch, 2009). Thus, as Openshaw and Alvanides (1999) generally conclude, it is critical to find an appropriate scaling method or a proper combination of scaling methods for different types of processes. The challenge is therefore how to obtain representative quantitative values from available data (Le Billon, 2005, 2007a; Di John, 2010). This implicitly includes being able to derive the REA's of human-natural resource related processes. It is widely accepted that measurement values can change with varying measurement scale (resolution). E.g. the national GDP per km^2 can be different from the county GDP per km^2. In quantitative large-N studies of conflict research, the traditional workflow has been to compare countries against each other using data on the national level to identify causal mechanisms that may cause conflict (e.g. Collier and Hoeffler, 1998).

Finding the appropriate scale for a given data variable can be exemplified by the annual precipitation data of Chad (Fig. 4.2). The Chadian climate zones can be divided into three regions and the spatial variability in % within each region at three different measurement scales were calculated. Whereas the regions with high precipitation (Soudanian and Sahelian regions) had stability in their parameter values across scales, deviated the low precipitation area (Saharan region) with increasing percentwise variability as for an decrease in operational scale from 100 × 100km^2 to 25 × 25km^2. This could be the consequence of locally increasing radom percipitation behavour and therby lack of reliable average values.

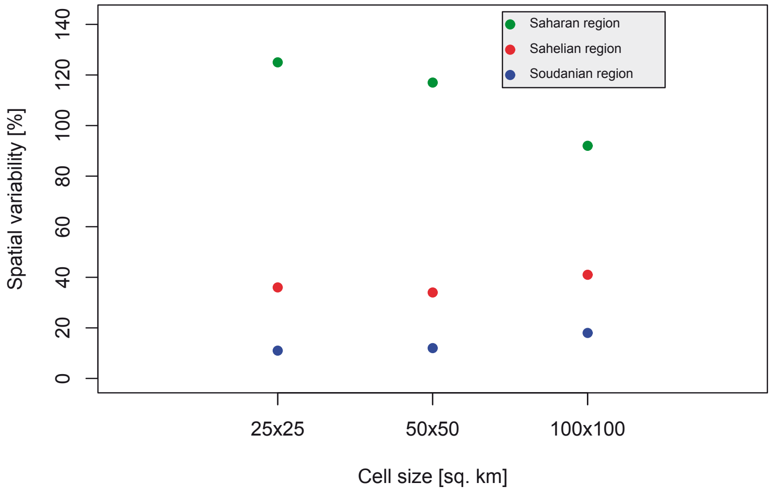

Figure 4.2: The annual precipitation data from CPC (2006) show that the there is stability in the Soudanian and Sahelian region in Chad with different scale, whereas the Saharan region show no stability in the study interval and a scale larger than 100x100 km^2 is assumed to be appropriate. Values are percent difference of standard deviation and mean of the mean value of the specific grid cell.

The importance of obtaining representative datasets must therefore be emphasized. Anselin (1999) outlined three directions how spatial analysis can enhance process-response modelling in the social sciences. The challenges related to these three directions are:

1. *Theory* has three major challenges; firstly how the concept of ”space” is incorporated in statistical models and how it is digitally recorded and stored in a GIS environment, secondly the theoretical concerns related to the theoretical interpretation of

the role of "space" in statistical and economic models, and thirdly is how data models and modelling techniques can handle spatial interaction as well as space-time interactions.

2. *Data* might be split into three parts. The first challenge is the selection of "proper" scale of analysis as the GIS tool can integrate data collected at different scales of observations for one level of analysis that do not necessarily provide useful information about lower levels of analysis. This is also related to the integration of multiple scales of analysis as in hierarchical modelling. The second challenge is the large size of the geo-spatial databases that can constitute a computational (permutation approaches for each observation) as well as conceptual (multiple comparisons) challenges. The last challenge is how spatial sampling is performed. The sampling design need to be corrected for presence of spatial effect (such as spatial autocorrelation), understand and measure the underlying spatial autocorrelation as it is the basis for respectively separating or grouping sampling units. The granularity of the sampling design is important for understanding processes characterized by spatial heterogeneity.

3. *Dissemination* has two major challenges; firstly is the development of a generic spatial analysis software toolbox and secondly is the integration of spatial analysis in the methodological curricula of social scientists.

Anselins research conclude that the developments in the theory and empiricism of the social science will most likely influence the spatial analysis discipline and will be accomplished by a tight interaction between theory, data analysis and computation that require interdisciplinary and multidisciplinary environments where the traditional boundaries are broken down. One decade have passed since the publication of Anselin (1999) and several of these challenges have partly been met. This includes, among others, more disaggregated data from where new theories assisted by GIS software can be tested (Cederman and Gleditsch, 2009). Armed conflicts represents one such example where data need to be disaggregated into several subcategories (Gleditsch et al., 2002; Kreutz and Eck, 2005); Type, onset, duration, severinity, repetition and location, where the representative variables applied in a given analysis can change accordingly to the operational scale.

Several new datasets have been developed to increase the knowledge of the spatial variations of specific natural resources, such as petroleum (Gilmore et al., 2005), diamonds (Lujala et al., 2005), minerals (Taylor et al., 2009) and uranium (IAEA, 2009). In addition to these datasets, other spatial datasets incorporated in present day empirical studies are topographic related datasets such as administration boundaries, rivers, roads, mountains, precipitation (CPC, 2006) and forest cover (FAO, 1999). Spatial datasets related to the human dimension are e.g. population (CIESIN, 2005b), infant mortality rate (CIESIN, 2005a), ethnicity (Buhaug et al., 2008). The spatial non-renewable resource datasets described above have resulted in new knowledge of the spatial distribution of some of the most valuable and disputed non-renewable resources in the world. Such datasets have resulted in a more balanced understanding of the processes leading to conflict and have according to Cederman and Gleditsch (2009) been used both for approving and rejecting stated theoretical hypothesis. Most of these non-renewable resource datasets give no indications of prospective resources in terms of location, type and quality. This also includes no estimation of ultimate potential revenue that can be generated from such resources. Based the lack of data, less quantitative research has been devoted to indicate prospective and hypothetical non-renewable natural resources and analyze how these resources are related to conflicts (e.g. Humphreys, 2005).

The United States Geologic Survey (USGS) has compiled two of the most significant data sets for predicting the future non-renewable resources of the world that are independent of socio-economic factors. Predicting world's prospective hydrocarbon volumes was carried out in the USGS World Assessment 2000 (Klett et al., 2000), whereas mineral quantities was compiled by the USGS Quantitative Global Mineral Resource Assessment Project (GMRAP) (Schulz and Briskey, 2003, 2005). The GMRAP project included information such as deposit name, location, commodity, deposit description, geologic characteristics, production, reserves and resources (Taylor et al., 2009). This project also pointed out interesting areas that most likely will contain world-class deposits. Due to its sensitivity and study objective, only the most prominent world-class deposits was outlined. On global and/or continental scale, these outlined deposits will potentially have an impact on the host country economy. However, for a specific country, a discovery lower than a world-class magnitude that are not outlined can also make huge difference for the government income and its citizens.

The major challenge of these non-renewable resource datasets outlined above is that the reserve and resource volumes are dynamic quantities as they are just a picture of the present knowledge and can vary strongly by, among others, future technological achievements and human consumption (Wellmer and Becker-Platen, 2002; Wellmer, 2008). Other challenges of such datasets are the need to indicate more precisely the exact location of the prospective areas and reliable volumes and monetary value. However, these hypothetical resources can be used by governments, the extractive industry, NGOs, as well as local patriots to estimate a given area's future value that can be used in natural resource management policies to reduce crossing interests related to extraction of these potential resources.

Some of the datasets applied in conflict-natural resource research are widely criticized according to their reliability, among others measurement quality and categorization. One of the most criticized dataset is perhaps the soil degradation dataset of the GLASOD (Global Assessment of Soil Degradation) study by Oldeman et al. (1990). The data consists of 250 expert assessments of soil degradation in their area of expertise. The lack of "cross-expert" comparability and the potential role of incentives which could bias the reported degradation make it hard to validate the representativeness of the data and to use it as a proxy variable for land degradation (Benjaminsen, 2002).

Potential surmounts of these stated challenges

One of the major uncertainty aspects in conflict research is the structure of a study. Local case studies analyzing "isolated" processes and large-N studies analyzing the gross variation within the whole or parts of the world are both important for giving insight to the resourceconflict nexus (Le Billon, 2001). O'Lear (2005) critically argues that such natural resource datasets tend to indicate the location or distribution of natural resource features, but they do not necessarily indicate infrastructure that is critical to the exploitation, use, or transfer of these resources. In his point of view enhancements in these datasets could be, for water resources; attribute and spatial data on water quality, wells, dams and extraction structures, for minerals; infrastructural data such as mining technologies would greatly enhance our understanding of how profitable extraction of such resources could be or the likelihood of a change in control over the given resources. With respect to hydrocarbon exploration and production, the locations and operational factors of pipeline networks, oil rigs, refineries and storage facilities are important (O'Lear, 2005). The efforts by the French company Geo212 (Geosint, 2011) to use geointelligence to asses the extent of development infrastructure for oil development represents a path in the right direction. The ultimate dataset which O'Lear seeks is a joint dataset that can incorporate several underlying datasets, similar to the earlier outlined global ecology approach. Even though the understanding of the underlying processes and their representative measurement and operational scales when express phenomena generating conflicts are of great importance, a joint dataset of O'Lears dimension will contain major complexity. Not only in spatial scale, but also in the temporal scale and suits better to be generated in a local case study within a specific time and area than in a large N-study.

According Buhaug (2007) three complementary directions can be identified to enhance future resource-conflict studies:

1. A sustained blend of case-based and large-N empirical assessments
2. Disaggregation of the subject under study, both theoretically and empirically
3. Increased use of advanced methods, such as GIS, spatial regression, and multilevel modelling

Case-based analysis and large-N empirical assessments are designed to answer different questions and complement each other so that better understanding of a given phenomenon is achieved (Collier et al., 2009). This can be exemplified by how policy makers tend to ask experts on how to end a specific conflict. Such experts use theoretical knowledge, results derived from case-based and large-N analysis combined with local knowledge of the given conflict to indicate possible actions to end this conflict. The second direction is related to the disaggregation of data to avoid explaining lower-order phenomena with higher-order data, known as ecological fallacy (Cao and Lam, 1997). These lower-order phenomena can be explained by generating disaggregated datasets. This turns the focus away from general state-centric analysis and towards more specific disaggregated analysis, e.g. types of conflicts that will require improved and more complete geo-referenced data, not only on armed conflict but also on important environmental and socioeconomic factors. The disaggregation of data opens for testing new theoretical approaches in conflict studies previous unattainable. The third point introduces approaches taken from other scientific disciplines to be included in conflict studies. GIS technology have opened for advanced spatial methods that allow multi-level modeling to test among others hierarchy theories.

The transformation of measurement values into an operational form that is representative for a given phenomenon is intensively discussed in spatial data analysis (e.g. Anselin, 1999). The Modifiable Area Unit Problem (MAUP) indicates challenges resulting from the imposition of artificial units on geographical phenomenon that might be impacted in the generation of artificial spatial patterns (Openshaw and Taylor, 1979). To solve the MAUP, Wrigley (1995) outlined two challenges that need to be overcome: For treating these problems, it is essential to develop an adequate statistical framework with clearly formulated models, and to develop practical method which can be offered to researchers for using spatial data to draw meaningful inferences about level relationships.

The generalization of data from one specific scale to another is one of four key relevant problems identified in spatial data analysis, where the three others are the boundary problem, the measurement scale problem (resolution) and the pattern problem (Barber, 1988; Sheppard and McMaster, 2004).

Boundary problems can firstly affect the interpretation of spatial patterns depending on how the phenomenon is bounded. Arbitrary or inappropriate boundaries can split spatial-temporal social phenomenon (e.g. sub national/international borders splitting a specific ethnic group). Secondly, it can cause "blurred" statements about spatial-temporal social phenomena that are computed for a large area whereas it might be just valid in one particular location/area (e.g. one ethnic group controlling one major city within a county, whereas excluding this city the remaining area is controlled by another ethnic group). On the other hand, measurement scale problems are related to moving from local scale, where homogeneity of phenomenon is maximized and extreme values are noticeable, even though at these scales heterogeneity must be assumed, to regional scale, where conditions might merge towards an average state and correlations become stronger (REA). Knowing the measurement scale when this average-state occur and when the distribution of a given phenomenon potentially becomes exaggerated it therefore essential. The pattern problem is related how similar two datasets are within an analysis and this can be tested by spatial autocorrelation statistics to measure and analyze the degree of dependency among spatial observations (Davis, 2002).

Phenomena can be explained by hierarchical theory which enables a given phenomenon to be separate into distinctive temporal and spatial scales. This implies that different processes are expected to have specific spatial-temporal scale characteristics at which these processes operate (Sheppard and McMaster, 2004). This means that multi scalar analysis can be dramatically simplified. Projecting this into the discipline of resource-conflict studies, the complexity of nature can be tackled by applying the proposition of hierarchy theory that nature can be divided into a hierarchy of spatial-temporal scales of progressively increasing extend. Implicitly, this indicates that conflict causality runs from the bottom up as local scale phenomena and processes provide the initiating conditions for larger scale conflict phenomena.

Political and technological ecology represent another potentially constructive meeting point for the integration of diverse perspectives of scale, in the sense of understanding political and technological as well as biogeophysical processes behind people-technology-economic-environment-conflict relations (Zimmerer and Bassett, 2003). This approach combines information from different sources with different temporal and spatial extent that aims to explain integrated politicized phenomena (Bridge, 2002). The political ecology approach has also been applied in analysis of natural resources and conflicts. Le Billon (2001) outlined how natural resources and conflicts can be expressed by the political ecology of war. He argued that within the historical processes shaping political economies of resource extraction, natural resources and armed conflicts are related to the distortionary effect of societies' dependence on valuable natural resources, the conflictuality of such resources and the spatial distribution and lootability of resources that can be regarded as opportunities for conflict actors at multiple scales to seize or retain control over such resources.

The transformation/pre-processing of geologic maps into an operational form that is suitable for analysis related to the human dimension is a challenge that are now incorporated in natural resource management options (NRM)(Evans et al., 2002; Suteanu, 2010). Such analysis assesses natural resources in relation to economic, political, sociological, technological and infrastructure factors. In social science disciplines, one possible solution to increase the data quality in models is to include the REA concept (e.g Chapter 3.1 or Wood et al., 1988; Jia and Lin, 2010). The initial REA concept can be used as a systematic effort of looking at spatial-temporal variabilities as function of scale. Whereas the hierarchal theory and global ecology concepts are aiming for complete dataset, the REA concept applies representative scales from where records can give essential information. It is therefore not essential to include all inherent variability of a given input data variable if the representativeness is known. However, the representative parameter values need to reflect the operational scale defined by the study objective.

Whereas much of the present literature have validated/invalidated previous propositions, the future analysis will blend the state-centric analysis with new scales and levels of analysis including new theoretical and methodological approaches in a way that can give a more nuanced understanding of the resource-conflict nexus. Especially importance is the collaboration with other scientific disciplines that can supply future studies with more data and theoretical knowledge incorporating the representative scale to identify process-response systems that are included in statistical calculations of natural resource and economic models for evaluating the causal mechanisms of natural resource induced conflicts.

No standardized workflow to generate datasets has been identified within the social sciences or natural resource-conflict research. One potential workflow can be anchored to the detailed explained methodology expressed in Charpentier and Klett (2005) that outlined five philosophic principles when assessing undiscovered natural resources: (1) Robustness, (2) valuable data exists in geology and exploration history, (3) the use of statistical methods without geological analysis can give misleading results, (4) transparency and (5) utility. These five philosophic principles can also be projected into social sciences and conflict research to increase the data quality and the correlatability within and between specific datasets.

This introduction covering challenges related to the human dimension of natural resource variability, exemplified with the natural resource-conflict nexus, has shown that more effort need to be carried out to select variables and to pre-process these variables into representative values explaining a given phenomena. This implies that the study objective needs to be compatible with the operational scale, upscaling/downscaling of parameter values recorded at different measurement scales. Without proper control of these factors, the inherent uncertainties can in worst case totally obscure the results. Several challenges have been expressed in this introduction and probably the most challenging factor in social science is the creation of representative (spatial-temporal) proxy variables that with the available information can be related to the phenomenon problem to be solved. The need to explicitly knowing the appropriate REV/REA at all aggregation levels has been one of the driving forces behind the current thesis and a motivation of the two cases presented below. This includes reflections related to data, methodology and theory with a focus on input parameter's measurement scale and the operational scale of the specific study.

In the following sections, the two examples outlined give additional insight to the human dimension related to natural resource variability. The first section (Section 4.2) is a case study outlining how the resource management framework has been a major factor in the co-existence of non-renewable resources and conflicts in the country of Chad and how these factors can affect Chad in the future. The second section (Section 4.3) is a empirically large-N study evaluating non-state conflicts in Sub-Saharan Africa and how these conflicts are related to annual variations in renewable resources. These sections expressed below give a wider perspective of the independent paper expressed in Appendices H and I.

4.2 Non-renewable resources and conflicts within a Chadian resource management framework

The management of the exploration and exploitation of resources are challenging as the development of a given resource and its economic exploitation revenues can result in crossing interests, ultimately leading to conflict (Le Billon, 2001). The knowledge of a nation's identified and undiscovered non-renewable resources are therefore important for managing the long term perspective economic development of a country (Hilson and Maconachie, 2009). Natural resource management, exploration/exploitation of these resources and conflicts related to such resources may interact at multiple scales (Bridge, 2008). Conflict related to exploration/exploitation of natural resources and the revenues derived from these activities are observed at multiple scales spanning from angry peasant loosing his farmland through e.g. expropriation or land degradation, displaced village citizens due to resource development, local politicians that receive no or marginal revenue of the natural resource exploitation performed within their area, ethnic groups from resource-lean parts of the country that is marginalized by the government and receive no/minimal share of the national revenue, to countries that see the strategic importance of obtaining access to a given resource so vital that it is worth fight for. All these examples can be related to the resource management framework defined by the government as it is the management policies that defined the areas where natural resource exploration (licensing permits) and exploitation are to be performed, the taxation of such activities and the distribution of income and revenues derived from such resources (Davis et al., 2001).

The interaction of resource management framework, exploration/exploitation and conflicts varies from country to country, and create a space for tension between resource-holding states, its citizens and resource-seeking companies (Le Billon, 2001). If the resource management framework policies are in strong favour of collecting revenue for the government (e.g. high taxation rates) then international exploration and exploitation companies will cease its activities and pull out its involvement in the country. This will then result in less income for this country if no other companies are willing to perform activities under such conditions. Similar, conflicts over income derived from the extractive industry can result in outbreak of civil war resulting in termination of such activities that will reduce the governmental income (Hilson and Maconachie, 2009).

In many countries, natural resource exploitation has been an important element of continuity across fault lines of political conflicts, self-sufficient models of development and transitions from authoritarianism to formal democracy (Bridge, 2008). Other countries have not evolved into such blessing, as they have experienced increased poverty, armed conflicts, corruption, economic stagnation and squandering of the national wealth and ultimately increased poverty, political violence and irreparable damage to the environment (Ross, 2008). This tendency, for large natural resources to decrease rather than increase the level of development in a country, is commonly referred to as "the resource curse" (Auty, 1994). The level of development is therefore connected to a country's management of their natural resources endowment which influences both its political economy and type of governance (Auty, 2001). Studies have shown that resource management from good governance is crucial to ensure that the potential wealth from non-renewable resources becomes a benefit to the general population and can lower the risk for armed conflicts (Hilson and Maconachie, 2009).

According to the abundance resource war argument, primary commodities are easily and heavily taxable, and therefore attractive to both the ruling elites and their competitors (Collier, 2000; Le Billon, 2001). Non-renewable resources can be identified spatially as point assets, including estimates of its volumes (tonnes or barrels) or monetary values and are easier to secure and tax compared to the taxation of evenly distributed natural resources or the taxation of citizens (Hilson and Maconachie, 2009). The characteristics of conflict related to the presence of natural resources and the spatial distribution and lootability of such resources are crucial when considering the opportunities of violent acts of war to seize or retain control over resource revenues (Le Billon, 2001).

A country with large non-renewable resources can benefit substantially from them, but the revenues from exploiting these resources can pose challenges. The ultimate goal for any government is to ensure that important social considerations are safeguarded, that the value created from the activities benefits society as a whole, as well as consideration for the external environment, health, working environment and safety plays. By including these considerations, the government aims to maximize the monetary income from natural resources based on a legal and regulatory framework and ensure that income from the extractive industry are maximized at multiple levels along the extractive industry value chain (Le Billon, 2007a). Such legal framework has a resource management plan that aims to encourage national and international actors to perform exploration and exploitation in their country. For the oil companies to maximize the values within a defined area, a legal framework must be in place which provides the extractive industry with incentives to fulfil the states objectives while at the same time meeting their own goals, which is to maximize their profits. In order for the extractive companies to make rational investment decisions, the legal framework conditions must be predictable and transparent (Hilson and Maconachie, 2009).

A resource management framework is normally defined by the government and can be divided into four parts (e.g. NPD, 2010): (1) licensing permits, (2) fiscal policy, such as tax policy, governmental spending, (3) monetary policy (interest rates, income policy, reserve requirements), and (4) national extractive companies.

National fiscal policymakers need to decide how national expenditures can be planned and insulated from revenue shocks arising from the volatility and unpredictability of resource prices. Decisions also need to be made on the extent to which resources should be saved for future generations (Hilson and Maconachie, 2009). Collier and Hoeffler (2005) indicated that possible starting point is transparency in the reporting of oil revenues, to ensure that they actually flow into the budget and to make the expenditure side of the budget transparent. However, in poor governance countries with low institutional capacity, such as Chad, this approach has often failed (Mehlum et al., 2006). In such countries, the concept of the rentier state indicate that governments use abundant resources to buy off opposition or suppress armed rebellion, thereby contributing to political stability and preventing armed conflict (Basedau and Lay, 2009). Such governments use the large resource revenues to maintain internal peace by combining a huge security apparatus with generous distributional policies. On the other hand, the lack of influence on multilateral institutions can also be an advantage of international business corporations and bilateral actors with stakes in resource exploitations (Le Billon, 2007a).

Finding the quantitative causal mechanisms related to natural resource-conflict nexus still have some shortcomings (Collier, 2000; Ross, 2004; Buhaug, 2007) and Di John (2010) concludes that the extent to which non-renewable resource abundance generate developmental outcomes depends largely on the nature of the state and politics as well as the structure of ownership in the export sector, all of which are neglected in much of the research-conflict literature today. Humphreys (2005) looked behind the observed correlations of exploration and exploitation of non-renewable resources and violent conflicts and suggested ways to introduce finer division of the data that can help to chose between plausible underlying causal mechanisms. This study tries to compile conflict evidence and ultimate resource values to help complement some weaknesses in the current information base regarding the potential conflict-natural resource links in Chad.

In this section, the African country of Chad (Fig. 4.3) is used as a case study, where the historical exploration for non-renewable resources is outlined in relation to the evolution of the resource management framework in relation to political fluctuations. The future areas containing potential undiscovered non-renewable resources, such as hydrocarbons, non-fuel minerals and fuel minerals, are outlined and further discussed in the related article (Appendix H) that elaborates how these spatial distributed resources can affect the potential conflicts and the resource management framework of Chad in the future. These presented results can be characterized as an early estimation of Chad's regional value of non-renewable resources and serve as a basis for assessing Chad's future general

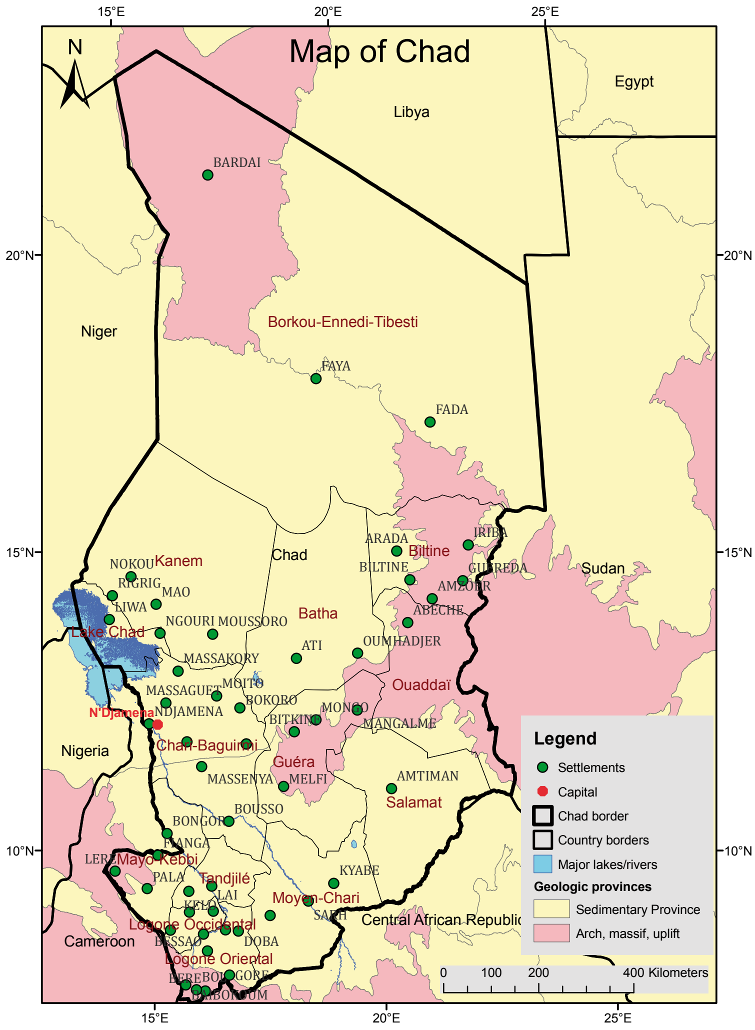

Figure 4.3: Administration boundaries and major settlements in Chad.

development.

Chad is today one of the ten poorest countries of the world, ranking 170 of 179 countries in the United Nation's 2008 Human Development Index, where poverty is a widespread social problem (Frank and Guesnet, 2009). With a per capita income of under $250 a year, and 55% of the population living in poverty, Chad also struggles with low social indicators: more than half of the population over the age of 15 is illiterate and electricity is accessible to only 1% of the population (OECD, 2008). The Human Poverty Index (HPI), focuses on the proportion of people below a threshold level, living a long and healthy life, having access to education, and a decent standard of living, the value is 56.2% for Chad, ranks 133rd among 135 developing countries (OECD, 2008).

This case study involve exploration for non-renewable resources in a political-economic context. Exploration effort conducted in a region will be strongly influenced by not only political and economic decisions arranged by the national government in the form of the legal resource management framework, but also by international actors and multinational companies like CNPC with strong ties to industrialized countries that are seeking to supply their needs for non-renewable resources. The results from Chad illustrate the complexity of the natural resource-conflict within a country that is challenging to upscale into large-N studies finding global causal mechanisms (Appendix H).

This complexity can be recorded on both local (community) scale from where the Doba exploration and exploitation for non-renewable resources has lead to alterations in the working conditions for the locals (EssoChad, 2002), meso scale e.g. where the a rebel group in 1990 (led by current President Deby Itno) overthrew the former regime (May and Massey, 2000), and to large (national) scale e.g. when Libya occupied northern Chad where one of the parameters for occupation was access to the potential large Tibesti uranium deposits (Huliaras, 2001). These and other conflicts can be identified to have a co-existence with the resource management framework in Chad.

In the following three examples from the post-Independence Chad is outlined to show the interaction between exploration/exploitation of non-renewable resources, conflict and resource management are given

During the colonial times, France became aware of the hardship to administer Chad with its huge size, rough topography, geographical disparities, scarce resources and poverty (Azevedo, 1998). The French taxation approach, following the colonial trend of how to best govern Chad in such way that it will benefit France, focused on southern Chad, with

Year	Exploration	Conflicts	Resource management
2010		Bilateral peace accord with Sudan	EITI planned to be adopted in mineral sector
2009	Refinery construction and appraisal drilling in Lake Chad and Bongor		
2008	Bongor economic discoveries	Unsuccessful coup d'etat	SHT established
2007			Autonomy, Chad pay World Bank loan, Petronas/Chevron pay $289 mill to government
2006		Re-election of Deby unsuccessful coup d'etat	WB freeze its accounts. Petroleum Revenue Management Law No.2 Chad reconnect diplomatic ties to China
2005	EssoChad consortium focus only on Doba field. Doba production on decline	Referendum abolishing two-term limit of president election	
2004	Near Doba infrastructure drilling	Unsuccessful coup d'etat	New constitution
2003	Construction finished, oil export starts	Darfur Crisis in Sudan	
1999	Doba construction initiated. Shell & ELF withdrew, Petronas&Chevron in. Exploration in Permit H (south, central west and northeast)		Petroleum Revenue Management Law No.1, 70% to poverty reduction
1997		Government forces kill southern rebels at Moundou	
1996		First pluralist president election	Chad-Cameroon bilateral treaty
1995			New mining code, 45% tax
1994	Appraisal drilling finished in the Doba field. Large volumes discovered	Establishment of Constitutional Assembly	
1992	Consortium (Shell, Esso, ELF)		Democratization process in Chad
1991		Unsuccessful coup d'etat (1990-1997)	World Bank plan: Oil for poverty
1990		Coup d'etat, Deby president, passive French army	
1988	Hunt (US company) explores in Lake Chad basin		Oil agreement between Shell and ELF
1987	Consortium indicate refinery as unfeasible	Aozou strip conflict ended	
1983		Libya backed rebel attacks from northern areas	
1982		Habre president Southern Chad lost influence	
1981		Libya out of central Chad area	New 5 year plan for oil and uranium exploration
1979	No exploration due to civil war	Civil war (1979-1982), Oueddei president (1979-1982)	Refinery plan stop due to civil war
1978	Large Doba discovery		
1977	Consortium (Shell, Chevron, Esso)		
1976	Consortium (Shell, Chevron, Esso and CONOCO)		
1975	First Doba basin oil discovery	Tombalbaye assassinated, Mallum president	Mallum invites for companies exploration
1974	Lake Chad oil discovery		
1972	CONOCO sell a 50% share to Shell	Libya attacks northern Chad	
1970			New mineral code
1969	CONOCO exploration in Lake Chad and Southern areas	Revolt in north, French asked for help	French companies allowed for exploration
1968	National Mineral map published		Chad-Libya bilateral treaty
1966		FROLINAT northern rebel group established	
1965	Negative French exploration in Erdis basin		French are expelled, US and Italian companies in
1962		Conflicts in North	Petrocode, concession contract system
1960	French mineral/oil exploration in BET	Struggle for power by ethic groups	Only French companies allowed in extractive industry

Figure 4.4: Major historical events in exploration, armed conflicts and resource management policy actions in Chad since 1960.

its savannas and rainforests, leaving the northern parts as neglected due to its poverty and lack of significant natural resources (Azevedo, 1998). Azevedo (1998) conclude that the pre-independent Chad was so chaotic and violent at the end of the colonial time as the colonial system by nature was prone to abuse due the unequal power and the marginal supervision of the territories from Chad's capital.

Parallel to Chad's Independence from France, exploration for economic natural resources within the region was carried out by French companies. The systematic exploration in Chad started in the beginning of 1950s as an extension of the exploration of the French occupied Fezzan province (SW Libya) and the primary target was mineral resources as the vast quantities of oil in the African interior were unknown at that time (Klitzsch, 1994).

The first discovery of oil onshore in Libya in 1956 resulted in a massive interest in oil exploration in northern Chad in be beginning of 1960's (Klitzsch, 1994). The exploration for oil that was performed by Petrodar, a company led by a subdivision of the French ELF company, explored for oil in the Erdis basin in northeastern Chad (Borkou-Ennedi-Tibesti county, BET). In 1962, a new petroleum code was introduced based on a concession contract system where royalties and taxes was a function of oil production (Eriksson and Hagstrømer, 2005). The same year, rumors of a substantial oil find in the northeastern Chad caused optimism (USGS minerals yearbook, 1963). Subsequent to this, the tactic of President Tombalbaye to unite all parties by forcing them to collaborate with his own party failed and in 1962 that of the banning of all political parties except the president's own (Azevedo, 1998). Thereafter followed series of arrests from prominent cabinet ministers to regular Christian and Muslim activists. The increased tension following the introduction of a single-party state led to attacks by the opposition with following counter-attacks by government forces (Azevedo, 1998).

The five well exploration campaign of Petrodar concluded in 1965 that there is only sand and water in this region (USGS minerals yearbook, 1965). This disappointed President Tombalbaye, who saw the potential of future oil revenue disappearing and he canceled the 152 000 km^2 Pertrodar concession (Djimrabaye, 2005). Angry with the French exploration effort, Tombalbaye forced the French troops out of BET (Azevedo, 1998) and the sought to United States and Italy for exploration participation. Following this termination, Chad announced an intensive 5-year plan for mineral exploration including hydrocarbons in the Erdis basin, geologic mapping near Abeche and mineralized veins and Uranium in the Tibesti (USGS minerals yearbook, 1965). Now without any French support, the United Nations Special Fund Aid stepped up and financed the mineral exploration resulting in deposit identification in the Tibesti Mountains (BET), Maya-Kebbi and Logone Occidental counties (USGS minerals yearbook, 1968), however all deposits were too small, widely scattered and of too low quality for large-scale exploitation.

The establishment of the National Liberation Front (FROLINAT) in 1966 by northern politicians and nationalists, whose objective was to overthrow the Sara led regime in N'Djamena by force, led to a further escalation of the revolt that proliferated further south into other regions, such as Chari-Bagirmi and Wadai regions (Azevedo, 1998).

The map of the mineral deposits within Chad (Chaussier, 1968; Kusnir and Moutaye, 1997, an updated map of the mineral deposits in Chad is given in Fig. 4.5) that described and located the principal mineral deposits led to an increased tension within the government of Chad as this map indicated prospective national revenues, e.g. Uranium deposits in Tibesti massif (Azevedo, 1998). Before further drilling for oil in the Erdis basin, it was important for the government to secure an Chad-Libyan agreement for a possible pipeline through the most obvious oil transportation route through the Libyan desert (Djimrabaye, 2005). In 1968 the signature of bilateral friendship and technical agreements coincided with a large northern rural revolt, including an increased opposition within the government (Azevedo, 1998). President Tombalbaye had to re-connect to France and ask President Charles de Gaulle to honor the French-Chadian military pact (Azevedo, 1998). The French intervention in 1969 helped to keep the rebels at distance and opened for a reassignment of the lost concessions to the French company Societe Indèpendante de Recherches et d'Exploitation Pètrolières (SIREP) in 1970 after 5 years of minor exploration effort from US and Italian companies. During the first half of 1970s, President Tombalbaye survived several coup attempts as he was facing even more opposition than he were able to prevent and several of these coups was supported from Libya (Azevedo, 1998).

The mentioned map of Chaussier (1968) specified 14 locations potentially containing

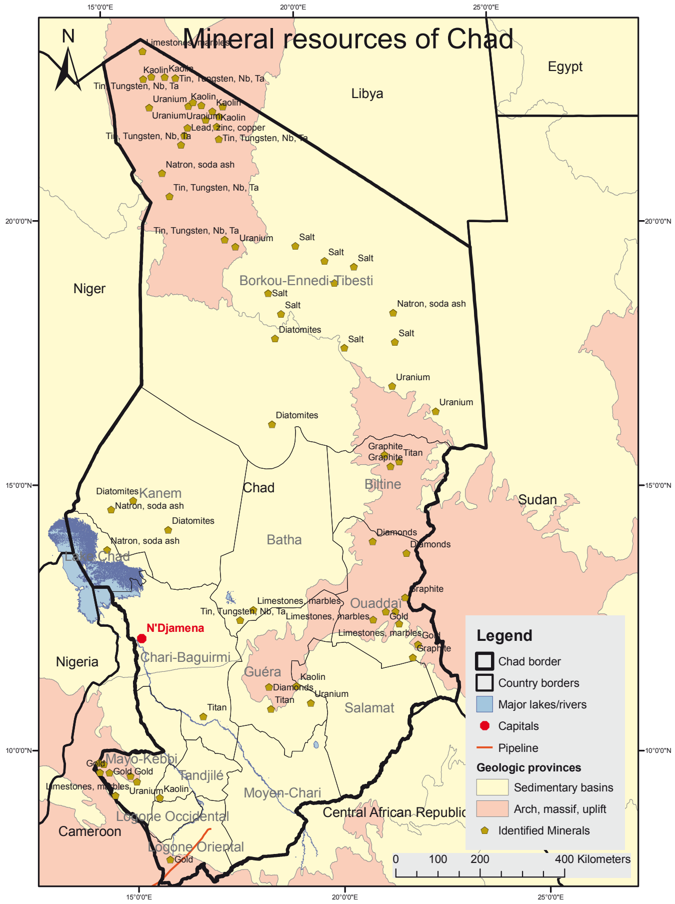

Figure 4.5: The mineral discoveries of Chad including province boundaries. The mineral discoveries are outlined in tabular form in Appendix H. The favourable provinces, known as mining districts, within the Mayo-Kebbi (gold, uranium), Ouiddai (Gold, Diamond) and Tibesti (gold, uranium, tin, tungsten, wolframiite) provinces, having the highest deposit concentrations (Goodell, 1992; Kusnir and Moutaye, 1997; Soo-Young and Se-Jung, 2001; Brinkley Mining, 2008; Mining Weekly, 2009; Signet Mining, 2009; USGS minerals yearbook, 2009). In addition, are several alluvial deposited minerals (gold, diamonds and bauxite) identified near the favorable mining districts and scattered over a large area mainly restricted in the southern half of Chad.

uranium deposits in the Tibesti region and these resources were one of the reasons why Libya, in 1972, occupied the Aouzou strip of Northern Chad (Huliaras, 2001). The military intervention in Chad was undoubtedly Libya's most significant external involvement, as Chad was the center piece of Colonel Qaddafi's Libyan dream for a large Muslim central African cooperation. Libya spent important financial resources with an intense anti-imperialism in supporting Coup d'Etats and radical governments all over sub-Saharan Africa to give support to this ambition (Huliaras, 2001).

This exemplifies that the resource management policy chosen under President Tombalbaye have influenced the exploration effort and the conflicts related to the oppositions aspiration to power. Tombalbaye started in 1960's with a democratization process and openness aiming for exploration of non-renewable resources that could boost the national revenues. This lead within few years to a brutal single-party state due to armed conflicts with opposition rebel groups and an international actor interested to get a share of the resource base.

In late 1969, the government of Chad granted a 5-year permit for hydrocarbon exploration to Continental Oil Co. (CONOCO) covering a 600 000km^2 area of the Lake Chad Syncline and Chari Depression in the central and southern Chad (USGS minerals yearbook, 1969). During the fist years CONOCO performed only magnetometric and photogeologic surveys over their concessions (USGS minerals yearbook, 1971), followed by drilling 28 exploration wells with 11 discoveries between 1969 and 1986 (Djimrabaye, 2005). This was the first oil exploration within the southern areas.

In 1972, the same year as Libyan forces attacked Chad, CONOCO sold 50% of its concession to Chad Shell Exploration and Development Corp. CONOCO and Shell stepped up their seismic campaign in Mondou, Doba and Sarh; south of Bousso; Kanem northeast of Lake Chad. Both oil exploration and mineral activities in the south were hampered by local unrest, still exploration continued (USGS minerals yearbook, 1973). This includes the UNPD (United Nations Development Programme) 10 000 km^2 geologic survey program that resulted in evidence for the presence of gold, nickel, uranium and complex sulfide ores in Mayo-Kebbi and Ouaddai regions (USGS minerals yearbook, 1976, 1979). The first economic oil discovery in Lake Chad region was hit in September 1974 (USGS minerals yearbook, 1974). This opened for full exploration in the Lake Chad and Doba areas. The subsequent year, in 1975, oil was discovered near the town Doba (USGS minerals yearbook, 1976). The assassination of President Tombalbaye during the successful coup d'etat in 1975, where the opposition, led by Malloum, a Sara ethnic, blamed the president for dividing the country, putting the tribes one against the other, and for humiliating the military (Azevedo, 1998).

The opposition against President Tombalbaye increased in the beginning of 1970's due to the pressure from the war against Libyan forces that occupied central and northern parts of Chad together with armed conflicts against and within the government of this brutal single-party state. Despite the conflicts in the northern and central parts of Chad, Tombalbaye maintained a pro-company resource management policy that permitted CONOCO to make the economic discoveries in the Lake Chad and Doba basins. The military takeover of the Government in 1975 by assassinating President Tombalbaye, did not change the Government's position towards mining and petroleum ventures (USGS minerals yearbook, 1975). This therefore favoured for more exploration.

The French was expelled from Chad in 1975 after the new head of state, Malloum, discovered that the French government had directly negotiated with the northern rebel groups in the 1974 capture of a French German group (Azevedo, 1998). This misstep coincided with the build up of the Chadian Civil war where the southern Chad population lost their influence and paved the road to N'Djamena for the northern rebels and for the French army to return to Chad in 1978. Oueddei (from the Teda tribe in BET) that was president during the civil war was overthrown by Habrè (from the Toubou tribe, Faya, BET) in 1982.

In the late 1980s civil unrest escalated as President Habrè could not control the ethnic tension amongst government troops serving in the south as well as disaffection in the capital (Azevedo, 1998). Beyond military superiority and clever negotiation, Habrè relied on the twin support of the United States and, in particular, France (May and Massey, 2000). These assumptions did not materialized and following the successful coup d'etat led by Dèby, a Zaghawa ethnic from eastern Chad (May and Massey, 2000), started the long presidential rule of Deby. The previous attempts for exporting or refining the discovered hydrocarbons in Lake Chad and Doba basins had failed and President Deby Itno now sought help from the World Bank through the oil for poverty plan to materialize oil export (Eriksson and Hagstrømer, 2005). The new government started a more democratic rule and strengthened their systematic prospection for mineral and energy resources by encourage investors to carry out research and exploit known mineral resources that would diversify the energy sector (Frank and Guesnet, 2009). In this regard, a new mining code (law No. 011/PR/1995 of 1995) was adopted (Frank and Guesnet, 2009). The appraisal drilling in the Doba field was finished in 1994 with large quantities of oil reserves (about 1 mill bbl oil)(EssoChad, 2002). President Dèby Itno constant under the treat of coup d'etat, both from southern and northern rebel groups. After the Chad-Cameroon bilateral treaty was signed in 1996, the last obstacle before exploiting the Doba oil reserves, was to end the opposition near the Doba field. This was terminated at Moundou in 1997, where the most dangerous armed rebels were liquidated (May and Massey, 2000).

The new petroleum code (Law No. 001/pr/99 of 1999) was dictated from the World Bank and was a prerequisite for the World Bank supported construction of the Doba field (World Bank, 2000; Frank and Guesnet, 2009). This new code was based on a production sharing agreement, where 70% was to be used on provety reduction within Chad. The main development objective was to strengthen the capacity of Chad to manage the development of its petroleum resources in an environmentally and socially sound manner, beginning with the Doba Petroleum Project in southern Chad (World Bank, 2000).

The code stated that (World Bank, 2000): 10% goes to a future generations fund invested on long-term abroad and 90% goes to domestic accounts in private banks and shall be used as following: (i) 80% of the royalties and 85% of the dividends goes to five poverty reduction sectors: education, health and social services, rural development, infrastructure, environment and water resources. (ii) 5 % of the royalties goes to the oil producing regions local government (Doba). (iii) During the first five years the residual 15% will go to governments operational needs. After that, it will go to the poverty reduction sectors. (iv) Revenues that can jeopardize macroeconomic stability or cannot be used efficiently shall be sterilised.

The oil from Doba started to flow in 2003 after three year development that included the construction of a 1070km long pipeline, including pumping stations and production facilities to transport oil from the Doba field in southern Chad, to the port of Kirbi, Cameroon (EssoChad, 2010). In the beginning of 2004, president Dèby Itno resisted political instability after the amendment of the constitution that abolished the limitation of the number of re-elections. President Dèby Itno found quickly that that he was unable to prevent the coup d'etat attempts without having a larger share of the oil revenue accumulated in WorldBank accounts (Pegg, 2006). The President announced in 2005 a desire to re-negotiate the oil revenue management plan with a raise in the non-priority sector from 13.5% to 30% and inclusion of new priority sectors such as justice, security and territorial administration (Frank and Guesnet, 2009). The abolition in late 2005 by the Chadian parliament of the future generation funds displeased the World Bank and resulted in a freeze of its accounts to Chad (Pegg, 2009).

In Spring 2006, an unsuccessful Coup d'etat was performed by rebel groups supported by Sudan as a result of the rebel growth in eastern Chad, relating to the Darfur crisis in Sudan (Frank and Guesnet, 2009). The following month President Dèby Itno, who threatened to expel 200000 Darfur refugees from Chadian Territory, came to an agreement after talking with France and the US that he would receive 10% more of the oil revenue by lowering the poverty reduction percentile (Pegg, 2009). The next step of President Dèby Itno was to create a national oil company (SHT), whose aim was to have an ownership of 60% in the oil industry (Acyl, 2008). The welcoming of the Chinese investments in the oil industry changed the Chadian commitments to France and US (Pegg, 2009). After getting a larger share of the oil revenue income, President Dèby Itno, accused Petronas and Chevron for failing to pay taxes and threatened to expel them from the country, but came to an agreement were Petronas and Chevron had to pay Chad 289 million dollar (Pegg, 2009). At the end of 2007, after the Dèby Itno regime had first replaced the commitment of the 5 percent fund of royalties paid to the oil-producing region by his own hand-picked government appointees and secondly, dissolved the national coordination for the oil project, the World Bank realized that their position in the pipeline project was not sustainable (Pegg, 2009). The World bank ended the involvement after conveying its concerns to Chad about the 2006 Memorandum of Understanding the breach of Chad answered by respondly fully paying all outstanding World Bank loans (Pegg, 2009).

Both in 2006 and 2008 have eastern multi-ethnic rebels that also include the same ethnic group as Dèby Itno, have attacked the capital, where the Dèby Itno regime defeated the opposition with minor help from France (Pegg, 2009). Despite the coup d'etat, the exploration of non-renewable resources are still ongoing and the development of the oil refinery near N'Djamena using the oil from the Bongor and Lake Chad basins will be completed in 2011 (CNPC, 2009), the year before the next presidential election. Dèby Itno has now also begun reinstating the environmental monitoring agency, increasing investments in productive sectors and mooting its candidacy to EITI(Gerin and Houdin, 2010). This will probably include more companies in the exploration and exploitation for non-renewable resources.

The Dèby Itno regime has now retained governmental power the last 20 years, where as the last 8 years as a oil producer. Despite the challenges with armed conflicts and large oil resources discovered, he has used its resource management efforts cleverly as he has stayed in power despite multiple coup d'etat.

This section has provided an assessment of undiscovered non-renewable resources in Chad and addressed how the perception of resource wealth and conflict dynamics at the local and national level has influenced the resource management policies of Chad. The result show that exploration and exploitation of non-renewable resources together with conflicts have coexisted in a symbiotic way. Chad's resource management policy has always aimed to maximize the national resource revenues regardless of violent changes in regimes. Changes of Presidents have in the past not created difficulties for the extractive industry compared to conflict.

The causes of conflict are many and complex but may in the case of Chad not be readily explained by religion or ethnicity. Hansen (2011) argues that both President Oueddei and the man who toppled him, Habre, as well as Dèby Itno were from minority ethnic groups (Toubou and Zagawa) representing only 5% and 2% of the population respectively and doubt that such small and divided groups could use ethnic politics to stay in power. The religious explanation for conflict is also difficult to substantiate in view of the fact that the major rebel movements are being led by muslin leaders that all of them have been central political players in President Dèby Itnos government or in state-run business. Hansen (2011) therefore concludes that: ”Personal greed and aspiration to power seems to be more relevant as explanation of the conflicts in Chad than in most other African countries”.

Based on the resource estimates of the USGS (Brownfield et al., 2010), the national Chadian yet to find oil assessment (Section 4.2) and the brief evaluation of prospective uranium and non-fuel minerals in Chad (Appendix H), Chad will most likely continue to receive money from non-renewable resources also throughout the next decades year period. The prospective non-renewable resources in Chad are geographically scattered both in terms of type and quality and the regions that can contain producible quantities of such resources represent windfall economic opportunities. The most likely areas for future oil are in the Bongor and Lake Chad area, as well as the Erdis basin. The other prospective non-renewable resources (e.g. gold, diamonds, uranium, REE) in the mineral district of Tibesti (BET) and the district in the East are geographically located in other regions of Chad than where the current oil production is. Similar as oil revenue is important for the current Chadian government, the government will apply effort to obtain revenue from new oil discoveries and/or potentially other non-renewable resources (Younous, 2008; Moutaye, 2008). Such new discoveries can in the future both destabilize and strengthen the Dèby Itno regime as the current oil production facilities are under strong governmental protection, it is likely that new locations of extractive resources need to have identical control of the government. E.g. the BET county has a long distance from the capital with marginalized control from the government with historically low level for local unrest.

Some rebel groups might see the oil wealth as an additional incentive to seize state power. Due to the negative socio-economic and environmental consequences of oil exploitation and their unsatisfactory mitigation, multifaceted conflict potential in the oil producing region exists. Nevertheless, the outbreak of violent conflict is unlikely as violent crackdowns of previous rebellions will avert new violent conflict.

Oil revenues can be said to directly contribute to keep Dèby Itno in power-by financing his fight against rebellions and the bribing rivals with positions/and or money. The wealth from non-renewable resources may accordingly contribute to the national and regional stability and permit the current government to implement the EITI initiative taken by the president and accelerate the development of institutional capacity (Gerin and Houdin, 2010).

The quantitative (large-N) analysis has limitations imposed by data constraints and can not uncover the causal natural resource-conflict mechanisms. These mechanisms are not simple and need explanations with finer grain, such as public policy responses that require stories about who is doing what and why. The use of prospective non-renewable resources has delineated geographic areas within Chad that can have a high potential for conflicts in the future hydrocarbons (heavy and light oil), fuel minerals (uranium) and other minerals important for export that consequently can generate future government revenues.

More effort needs to be performed for mapping and estimating the Chad's prospective natural resources and further quantify them by means of volumes or economic value. In this way a more comprehensive analysis of Chad's non-renewable resource base can be estimated and used as input parameters for sociopolitical analysis related to both identified and unproven resources. The analysis of multiple non-renewable resources coincide also with the unit regional value concept (urv) of Griffiths (1978) that allows for transforming the geologic information of a map into diagrams expressing the ultimate economic potential geographical area. The implications of this work is that the information of proven and estimated prospective non-renewable resources in terms of geographic location, magnitude and type, can be made suitable for decision making by local communities, national governmental entities to the world community, eg. NGOs, UN and other stakeholders.

4.3 The environment and non-state conflicts in Sub-Saharan Africa

Pressure on renewable resource is frequently referred to as an important driver of armed conflicts (Homer-Dixon, 1999). Several case studies have suggested that the role of resource scarcity is more prominent in small-scale conflicts than in international conflicts or large-scale civil conflict (e.g. Kahl, 2006). Some studies have also suggested that conflicts are due to change in access to resources than to the absolute level of resources available (e.g. Bächler, 1999).

Whereas the previous section (Section 4.2) showed how the resource management framework influence the exploration and exploitation of non-renewable resources and conflicts in Chad, this section moves from case study approach to a large-N approach that considers short term renewable resource variations and its impact on non-state conflicts.

In the following the effect of environmental and demographic factors on the incidence of inter-group conflicts is tested (a complete and more detailed version of this study is given in Appendix I / Theisen and Brandsegg (2007)). In order to perform this study, the traditional scarcity concept needs to be refined, since it incorporates both environmental and demographic issues (Homer-Dixon (1999) and Section 4.1). Given the analytical problems, the operational definition of scarcity of a renewable resource is "a low access to a renewable resource of which decrease absolute and/or increased demand leads to absolute scarcity".

A common topic in the scarcity literature is African drylands, allegedly undergoing desertification due to anthropogenic activity such as overgrazing by herds and firewood consumption (Bächler, 1999). Recent research of dryland areas has weakened these arguments, by indicating that human activity has very little impact on where the Sahara begins, as variations in rainfall is seen as the main determinant of how far the desert stretches (Benjaminsen, 2006). This coincide with the assumption scarcity of a renewable natural resource is driven by precipitation. The following question is then, who will fight over such resource? Goldstone (2001) argues that environmental degradation mostly takes a form that strengthens elites and states and/or the relation between them, thus decreasing the opposition against the degradation is strong. Therefore a large-scale conflict is not likely to occur. As fighting a government army requires a considerable amount of organization and resources, is it here assumed that non-state conflicts are more affected by environmental scarcities than conflicts between a given group and the government of a state. A second question emerges: If there is scarcity, why will there be violence? Homer-Dixon (1999) argues that rural-to-rural migration, motivated by the scarcity in the place of departure, leads to further ecological and economic decline at the place of arrival. This process has been labelled environmental marginalization and is argued to have caused deprivation conflicts e.g in the Brazilian Amazon forest, where the scarcity-related process has fueled conflicts over land, although rarely violence with large death tolls (Lopez, 1999).

Based upon this theory, three propositions are outlined:

1. A lower absolute amount/level of renewable resource available in a country increase the risk of internal conflict incidence.

2. Negative change in people's access to renewable resources increase the risk of internal conflict incidence more than absolute amount/level of renewable resources available in a country.

3. Marginalized areas within one country experiencing pressure on renewable resources are more prone to armed/violent conflict than better of areas.

In the empirical assessment testing these propositions the dependent variable used is the incidence of armed non-state conflicts within quadratic 100 × 100 km grid cells. Since the current study only has four years of information on the dependent variable using an incidence design is the only defensible option. Here, development, population density and growth, and precipitation variables are used to try to explain where non-state conflicts break out on a sub-national level. This reduces the problem of ecological fallacies drastically, as a sub-national approach is much more fit to test whether the theorized local fact is an empirical local fact (Buhaug, 2006). For the sake of comparability an operational scale of 100x100km grids are used, just as Buhaug (2006).

In this study, a non-state conflict is defined as "the use of armed force between two organized groups, neither of which is the government of a state, which results in at least 25 battle-related deaths" (Eck, 2004, p.4). Here, a cross-sectional analysis is performed in the time-period 2002-05 for Sub-Saharan Africa, where the conflict data are taken from the Uppsala Human Security Project (Kreutz and Eck, 2005), covering non-state conflicts for the 2002-05 period. Each non-state conflict location has been coded by the conflict midpoint from each conflict event on a standard approach where all events are weighted equally. Here, a circular radius similar to the longest event distance from the conflict centre point rounded upwards to the closest 50km are used, consequently the most distant event is within the conflict zone and not located exactly on the rim (Fig. 4.6). Each conflict zone within a country is set to not exceed neighbouring country borders and the variable contains therefore no spill-over effects. First and second order spill-over variables are generated separately by recording the number of conflict cells within the surrounding 8 cells for the first-order spill-over variable, and the 24 cells for the second spill-over variable.

The population data are downloaded from Center for International Earth Science Information Network (CIESIN, 2005b) of the Earth Institute at Columbia University, which has gathered the Gridded Population of the World, version 3 (GPWv3). The population estimates are available for each five years covering from 1990 to 2005, in addition to future population estimate predictions for 2010 and 2015 and the population estimate values were defined at each national or sub-national administration unit. In this study population estimates from 1990 to 2005, adjusted to match UN totals, persons per km^2, are applied (Fig. 4.7). Population change is measured as the percentage change from 1995 to 2000 of this density estimate. Both these measures are derived from the mean calculated population density within each 100x100 km grid cell.

Precipitation data were downloaded from the Climate Prediction Center, US National Weather Service (CPC, 2006). Annual precipitation data in the time interval 1995 to 2000 were acquired by the algorithm RFE1.0 (Rainfall Estimates 1.0) followed by RFE2.0 from 2001 to 2005 Fig. 4.6). Three precipitation variables are used: (i) the average precipitation for the period 2001-05; (ii) the percentage change in precipitation for the period 2001-05 as compared to 1997-2000; (iii) the standard deviation of rainfall within the 2001-05 period. The measure for mean precipitation has been log-transformed, and the measures for average precipitation and percentage growth in precipitation have been reversed so that higher values reflect more resource scarcity.

In this study, the measure of development (infant mortality rate) is produced by the Columbia University Center for International Earth Science Information Network (CIESIN). The Global Subnational Infant Mortality Rates, hereafter IMR, consists of estimates of infant mortality rates for the year 2000 and single values were defined at each national or sub-national administration unit (CIESIN, 2005a). The IMR is defined as the number of children who die before their first birthday for every 1000 live births (Fig. 4.7).

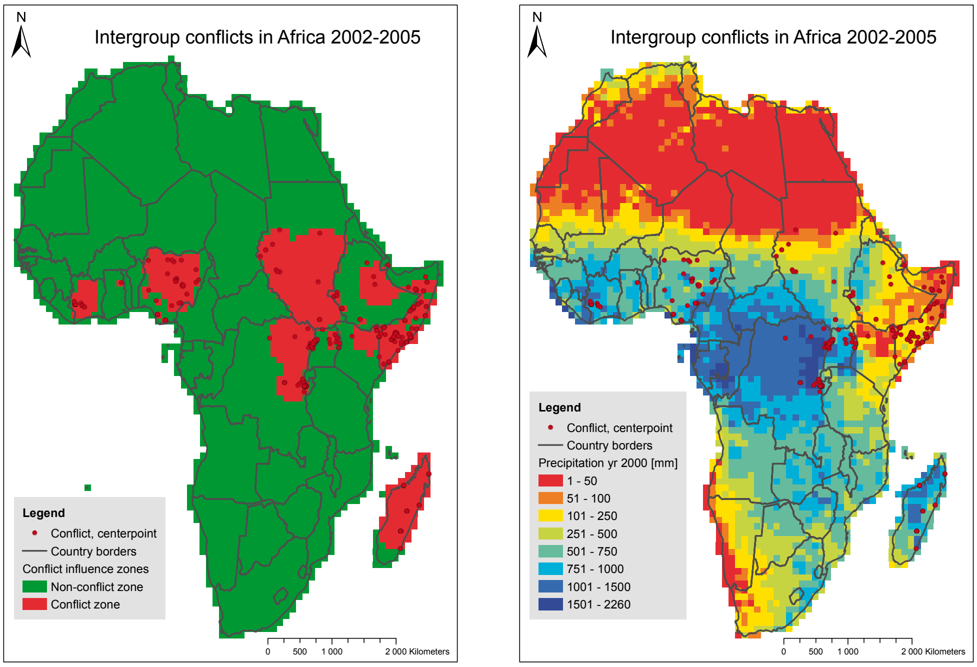

Figure 4.6: Map of influenced zones related to non-state conflicts derived from Kreutz and Eck (2005) and a map of the year 2000 total precipitation derived from CPC (2006).

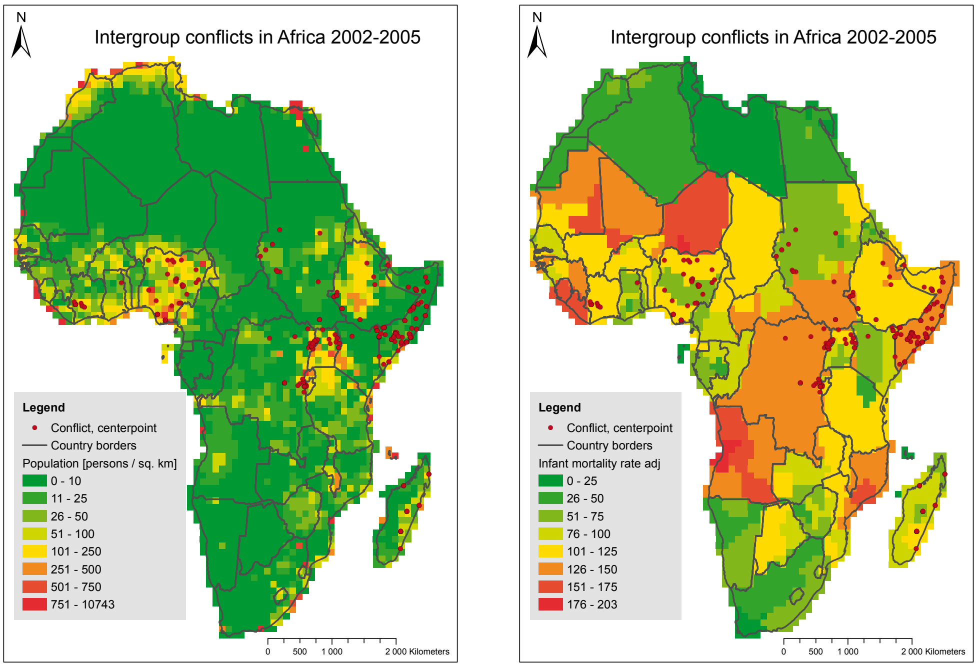

Figure 4.7: Map of the 2000 population estimates of CIESIN (2005b) and a map of the estimated infant mortality rates of CIESIN (2005a).

In order to see whether state capacity affects the risk of conflict, one variable measuring the distance to the national capital for the centerpoint of each 100x100km cell is included. This is based on the assumption that the control capacity of a state is strongest in its capital and diminishes as the problem is removed farther from the capital.

The raster data used are defined by the earth's latitude and longitudes measured in decimal degrees in a geo-referenced coordinate system. The area of each raster pixel will therefore differentiate from regions around equator where the pixel area is largest, to regions different to equator with less area per degree. Using geo-referenced coordinate system is therefore not optimal when statistics applied to varying pixel closure areas. The solution is to use a projected coordinate system, here World Eckert VI. The strength of a standard block with fixed closure area is that is independent to latitude. The resolution problem when transforming from polygon data to pixel data, such as international borders, is adjusted so that each pixel only can be assigned to one country. The method used is if a pixel intersects several countries, then the country position that is at the centre of the unit is given the pixel. Transforming and applying raster data with values recorded at 5 and 10 km units to lower resolution, such as 100km unit squares involves choosing an aggregation type. In this study, the mean value for all of the study grid covariates is applied.

In addition to these variables, national control variables have been applied in a such way that the results can be related to other large-N studies. Since there are no previous large-N studies of non-state conflicts, the choice of control variables are to a considerable extent borrowed from studies of civil conflict. These variables are size of a country, national infant mortality rate (IMR), state-capacity, democracy and political instability (Complete explanation is given in Theisen and Brandsegg, 2007). All variables have been centered to reduce potential collinearity problems, as well as to facilitate interpretation. Robust standard errors and cluster on country are used in order to reduce the potential impact of within-state dependence between units.

The results show that for bivariate analysis the democracy seems to be negatively, but not significantly related to conflict. In the bivariate analysis, it is a general trend that quite few variables are significant. The only robust local predictor of conflict is the number of neighbouring cells with conflict which significantly and substantially increases the risk of conflict with a huge impact on the marginal risk of conflict. The variables proxying for pressure on renewable resources are only to a limited extent in line with the study's expectations. In the bivariate analyses, only population density increases the risk of conflict significantly, while the reversed measure of level of precipitation reveals that the dryer a cell is the safer it is.

When controls for conflict in neighbouring cells are introduced, all the grid-level covariates except for the conflict in neighbouring cell control turn insignificant. This is also the case for the multivariate analyses. Thus proposition 1, 2 and 3 gets little support. As outlined in proposition 3, marginalized areas with increasing scarcities were expected to be more prone to experience non-state conflicts the interaction effects reveals that this is not supported by the current analysis.

An important caveat for these results concerns the homogeneity of the sub-types of non-state conflicts. Since the dataset on these conflicts contains all conflicts not involving official forces, the degree of similarity between the different conflicts is one thing that should be kept in mind. However distinguishing for example between what is a conflict between militias and what is a conflict between tribes could be quite futile as most armed conflicts of a substantial magnitude follow ethnic boundaries. Another limitation of the applied data relates to the temporal category. Four years is not a complete time series when it comes to conflict studies. In order to be more certain about what way the causal arrow runs, a longer time-span should be investigated.

The results of this analysis have lent limited support to the eco-scarcity argument, implying that the arguments that pressures on renewable resources is a security threat do not gain support. One very important caveat has to be noted. This study is assumed to be the first cross-national study of non-state conflicts, so further empirical and theoretical studies is needed to get better modelling of the conflict dynamics and contextual effects.

This paper expressed above shows a clear evidence of the challenges outlined by e.g. Anselin (1999), not only is the theoretical assumptions widespread in low-intensity non-state conflicts, the challenge to include appropriate data expressing the process-response systems of these theories, both when it comes to the dependent variable identifying armed conflicts with more than 25 battle deaths (Kreutz and Eck, 2005) and to the explanatory variables expressing the annual variations in the access to renewable resources, such as food with precipitation as a proxy. The data incorporated in this study is within one of the most harsh and remote areas of the world, Sub-Saharan Africa, where local knowledge and information is sparse for the teams assembling these datasets. This is especially evident for the non-state conflicts, both the identifying the conflict location and the number of casualties. Some of the variables, such as used in this study are proxies and can be classified as indirect measurements.

The operational scale used in this study is defined as a $100 \times 100\text{km}^2$ grid to which all variables are upscaled or downscaled to. For instance the precipitation grid already rasterized with a higher resolution, was generalized into the operational scale. Both the population and the IMR data within the Sub-Saharan countries were on sub-national administrative scale that often covers large areas (the BET county, Chad, is an example (Fig. 4.3)) resulting in no heterogeneity variations within the downscaled area units. Similar, the smoothing from upscaling parameter values defined for small sub-national administrative units into the operational scale can level out essential variability.

After assessing the input parameters in more detail, the non-conclusive result presented in this section is expected as the REA requirements were not met due to partly inadequate disaggregating input parameters in the operational scale of $100 \times 100\text{km}^2$ cells. A large pre-processing effort needs therefore to be undertaken if one shall have hoped to unveil causal mechanisms between non-state conflicts and renewable resources.

One possibility to obtain representative elementary values of the input variables is to follow the REV/REA concept outlined in the previous chapters. Just as the fault lineament analysis in Sections 3.2 and 3.3 transformed the raw single value fault lineament feature into disaggregated fault features representative for calculating favourability for fault related hydrocarbon accumulations, the spatial explanatory variables here can be preprocessed into spatial-temporal maps with representative elementary values that expresses a process-response system at a given operational scale.

Whereas the measurement scale of the precipitation variable was upscaled from approximately $25 \times 25\text{km}^2$ grid cells to $100 \times 100\text{km}^2$ using standard averaging technique, other mathematical or modelling techniques can give other values that can harmonize more with the operational scale. Another transformation can be applied on the population grid values that were defined within each administrative unit and expressed by a single value of population pr km^2. These values are representative for each specific administration unit, but will most likely be inappropriate for a different operational scale, such as grid cells, if a average technique is applied. The transformation of population values into grids can be carried out by introducing new variables that can be combined with the initial population values at a given measurement scale. To disaggregate the single value administration unit into smaller units can be performed by using e.g. forest cover map when assuming there is a function between forest cover and population. Similar, remote sensing maps of e.g. buildings can be used to disaggregate the administration units population values if a relation between population and presence of buildings are assumed.

Understanding the inherent variability in non-state conflicts is in line with Le Billon (2001), where the political ecology of war was outlined. Understanding the local commanders in non-state conflicts and the processes leading to conflicts can increase the knowledge of identifying the appropriate scale of the phenomenon. Similar the pre-processing of input parameters into representative elementary values reflecting the process-response systems involved are vital. This study of non-state conflicts has shown that it is a multifaceted challenging task involving both theoretical challenges and challenges related to data. Further analysis involving more precise data is essential for testing both previous and new theoretical propositions of the phenomena of disaggregated conflicts. This includes knowing each datasets scale of measurement and how to aggregate/disaggregated data into representative elementary values at the operational scale from where the scarcity phenomenon is to be tested. The REV/REA concept has therefore the potential to be applied to find the representative values at the appropriate operational scale of a given scarcity phenomenon as well as other spatial-temporal phenomena.

4.4 Results and conclusions

This chapter has considered natural resource heterogeneities related to the human dimension and emphasized the importance for critical evaluation and necessary pre-processing of natural resource parameters related to society. Raw data must be recorded, analyzed and interpreted relative to the study objectives at the suitable scales. The interaction of parameter variability from community to multi-national scales can be assessed against changes in REA. The REA concept has the potential for both mapping representative parameter values from underlying variability into integrated models and when upscaling/downscaling a dataset to be included in the analysis at a more generalized / disaggregated level.

The major results of this chapter studying the human dimension of natural resource heterogeneities are:

- The result of the investigation of the resource management options of Chad relative to prospectivity, exploration effort and the endemic risk for conflict show that exploration (and later production) and severe conflicts in Chad has co-existed in a symbiotic way. On the one side the extractive industry has sought to increase their reserve base and production volume, and on the other side, the government is dependent on the revenue derived from these activities and both those in power and those that take power will benefit from an undisruptive revenue stream. Oil revenues can be said to directly contribute to keep Deby Itno in power-by financing his fight against rebellions and the bribing of rivals with positions/and or money. The wealth from non-renewable resources may accordingly contribute to the national and regional stability and permit the current government to implement the EITI.
- The standard regression analysis result of an investigation of the utility of using a newly developed non-state conflict database for a large-N study of non-state conflicts versus the annual variations in renewable resources analysis at a multi-national scale (Sub-Saharan) showed no statistically significant correlations as could be expected from the REA considerations due partly to inadequate representativity of the input parameters. More effort need to be conducted when using spatial proxy data for testing non-state conflicts and their relation to various theoretical hypothesis of renewable natural resources and the origin of such conflicts. E.g. the homogeneity of the subject matter sub-types of non-state conflicts and the spatial and temporal category of the applied data.

The implication of considering human dimension of natural resource variability is that it can give a thorough appreciation and representation of the variability and uncertainty of the societal consequences of natural resource issues to be analyzed at multiple scales that is required for obtaining quantitative estimates. This can lead to increased knowledge in determination of the relationship between natural recourse endowments and societal factors, but such information can also increase the precision in natural resource management options and political ecology approaches important for sociopolitical context decisions. Other implications are:

- An explicit quality assessment of observational data relative to the REA concept can ensure reproducible and reliable results when these data are representative input parameter values in quantitative methodologies assessing societal relations to natural resources and has implications on the strategic decisions related to such assessments.
- The implications of the results of resource management option history of Chad showing a co-existence relative to prospectivity, exploration effort and the conflict is that even if Chad (or any other country) will experience severe conflicts in the future, exploration and exploitation of non-renewable resources will be conducted if possible continue undisrupted.
- The implications of considering the input data in large-N regression analysis is that more effort need to be conducted when using spatial proxy data for testing conflict occurrences and their relation to various theoretical hypothesis of natural resources and the origin of such conflicts. E.g. the homogeneity of the specific sub-types of conflicts and the spatial and temporal category of the applied data.

Chapter 5

General results, conclusions, implications and further work

5.1 General results and conclusions

Using REV/REA concept as a backcloth has sought to emphasise the importance of interpreting the significance of variability at the operational scale relative to the variability of raw data at the measurement scale. The research has covered multiple disciplines ranging from analysis of small scale hydrocarbon reservoir heterogeneities of core and wireline data, to how the distribution of identified and unidentified non-renewable resources on regional scale are related to the possibility for efficient resource management by the Chadian government. The thesis has identified similar patterns related to heterogeneity and scale across different scientific problem assessments.

This thesis comprises of nine case studies, grouped into three parts, where all parts in a wide sense are enlightened by the REV/REA concept. The most important results presented in the current thesis are:

- A structured principal component (PCA) methodology that only use records selected from separate lithological units has been used to obtain a more precise definition of variability sources than is possible by an unstructured approach that use all the records from the well logged interval. This methodology decomposed heterogeneous populations (e.g. grains of a fluvial deposit) into their underlying populations (e.g sand, shale and coal) that can explain both within- and cross lithological effects.

- Results from the use of an inverse PCA statistical analysis procedure (the Eckart-Young theorem) on a sandstone interval has permitted to separate global sandstone porosity values into individual porosity contributions from different underlying and independent sedimentological processes.
- The results of using a process oriented numerical modelling tool (SBED) methodology for upscaling lithological heterogeneity at mm-scale to lithofacies heterogeneity (cm-scale) and a further upscaling to seismic (10m-scale) shows that very detailed layering can be modelled and synthetic seismic traces can be generated that takes into account the inter-bedded multiples which are of great importance in thin-layered reservoirs.
- The results using a sequential re-burial methodology to compute high-resolution re-burial porosity-depth values based on wireline log interpretation can lead to an alternative inter-well correlation scenario in hydrocarbon reservoirs based on differentially compacted sediments in the subsurface.
- The disaggregation of a regional fault map using a GIS environment and the construction of signatures within $1 \times 1\text{km}^2$ for fault related accumulation of hydrocarbons showed that the fault data needed to be pre-processed into cell based ternary coding expressing either favourable or unfavourable conditions or a situation where the controlling effect of an attribute is either unknown or unevaluated.
- By using Characteristic Analysis for a play assessment, a weighted linear combination of ternary coded attributes was used to compute favourability for hydrocarbons on the basis of a probability significance metric. The outlined favourable cells express where further exploration should be conducted for potentially identifying fault related accumulation of hydrocarbons.

- The USGS 2000 methodology gives a credible indication of the remaining potential for oil as it can include uncertainty in the upscaling from discovery/field information to basin scale and apply these values to other sedimentary basins that can be considered as representative.

- The result of the investigation of the resource management options of Chad relative to prospectivity, exploration effort and the endemic risk for conflict show that exploration (and later production) and severe conflicts in Chad has co-existed in a symbiotic way. On the one side the extractive industry has sought to increase their reserve base and production volume, and on the other side, the government is dependent on the revenue derived from these activities and both those in power and those that take power will benefit from an undisruptive revenue stream.

- The standard regression analysis result of an investigation of the utility of using a newly developed non-state conflict database for a large-N study of non-state conflicts versus the annual variations in renewable resources analysis at a multi-national scale (Sub-Saharan) showed no statistically significant correlations as could be expected from the REA considerations due partly to inadequate representativity of the input parameters. More effort need to be conducted when using spatial proxy data for testing non-state conflicts and their relation to various theoretical hypothesis of renewable natural resources and the origin of such conflicts. E.g. the homogeneity of the sub-types of non-state conflicts and the spatial and temporal category of the applied data.

Based on these results, the major conclusions presented in this thesis are:

- An explicit quality assessment of observational data relative to the REV concept will ensure reproducible and reliable results when these data are used in reservoir, play or basin modelling and analysis as well as a basis for resource management policies.

- Implementation of a multivariate approach to data interpretation using structures and inverse recalculation procedure will permit the detection of higher order variability effects that normally are concealed by first order heterogeneity.

- A strategic choice of using GIS as the standard tool for pre-processing and analysis of resource and social science data will enhance productivity and enable the effective use of relevant proxies necessary for solving complex problems at multiple spatial and temporal scales.

5.2 Implications of work

In closing, I turn to the implications of this work. Given the conclusions outlined above, the following are among the overall implications of the results from the work presented in this current thesis:

- An explicit quality assessment of observational data relative to the REV concept can ensure reproducible and reliable results when these data are used in reservoir, play or basin modelling and analysis as well as a basis for resource management policies and has implications on the strategic decisions related to reservoir, play assessment and resource management options.
- The PCA methodology can be used to isolate specific variability in other depositional environments.
- The inverse recalculation procedure of Eckart-Young Theorem allows for back-calculation of responses of second order or higher effects that can contain signatures explaining e.g. sedimentological processes. This procedure can most likely be applied in other resource related studies considering hidden effects obscured by the primary/gross effect.
- The process oriented numerical modelling tool (SBED) for upscaling lamina scale heterogeneity to seismic can generate better geological anchored models for sub-seismic reservoir characterization.

- The sample based sequential re-burial methodology high-resolution re-burial porosity-depth values for stratigraphic inter-well correlation of differentially compacted sediments can be applied in other heterogeneous environments (e.g. turbidites) for the purpose of evaluate alternative inter-well correlation scenarios. By using lithofacies variations at wireline log measurement scale as building block from correlations studies a more confined model can be generated that will increase the depositional knowledge that is assumed to outperform the more generalized re-burial methods when reservoir modelling is in focus.

- The GIS environment permits pre-processing of data, e.g. disaggregating of data into representative operational form, into representative signatures and can most likely be successfully applied on proxy data in other resource assessments beyond explaining fault related hydrocarbon accumulations.

- The CA methodology with GIS supported pre-processing of data into a ternary coding can be applied to delineate favourable areas in play assessments.

- National resource assessments estimating the ultimate hydrocarbon resources within a country expressed by volumetric estimations within each sedimentary basin has implications not only for identifying the location and potential hydrocarbon volume important for further prospectivity effort to be conducted, but also important for national officials and the international community for political decisions.

- The implications of the results of resource management option history of Chad showing a co-existence relative to prospectivity, exploration effort and the conflict is that even if Chad (or any other country) will experience severe conflicts in the future, exploration and exploitation of non-renewable resources will be conducted.

- The implications of considering the input data in large-N regression analysis is that more effort need to be conducted when using spatial proxy data for testing conflict occurrences and their relation to various theoretical hypothesis of natural resources and the origin of such conflicts. E.g. the homogeneity of the subject matter specific sub-types of conflicts and the spatial and temporal category of the applied data.

5.3 Recommendations for further work

This thesis has documented the importance of interpreting variability in natural resource related issues at multiple scales and the importance of pre-processing measurement records prior to analysis. However, more research is needed to fully understand such variations. A way to achieve an increased overview is by reassessing other works to determine if the selected scale and data is appropriate for explaining any given phenomenon. Just as the REV concept is now starting to be implemented in reservoir characterization, the REV/REA concept into play, sedimentary basin, national and multi-national level need to be carried out in a comprehensive fashion to fully identify its capabilities.

Even though the importance of considering the REV concept is known when upscaling geologic heterogeneity to reservoir modelling units in a pore to field approach, still there is more work to be carried out for relating direct geologic measurements of outcrops and core with indirect wireline logs, rock physics and geophysics into effective parameters. Avseth et al. (2005) argues that the connection between geology and geophysics lies in rock physics. Even though there has been much research on rock physics related to geophysics, less effort have focused on the gap between geologic processes and rock physics. The development of a process-response database of different geologic processes and its relation to rock physics can significantly help closing the gap between these two disciplines.

More work need also to be carried out to fully explain the structured PCA loadings and scores in terms of relating lithofacies type signatures and their potential geological processes. Similar, the interpretation of Eckart-Young Theorem derived second and higher signatures need to be related to sedimentological processes. The capabilities of the outlined high resolution re-burial routine is not fully known, but improved differential compaction functions and improved lithofacies definitions that are tested on multiple heterogeneous depositional systems can identify its unredeemed potential in inter-well correlations.

The successful re-implementation of CA into a GIS environment to outline fault related hydrocarbon accumulations has showed that ternary coding is capable to be applied, not only assessing a specific input variable in exploration for hydrocarbons, but can also be applied in other assessments where it is important to outline specific favourable/unfavourable conditions. The pre-processing of the input data in a representative form is essential for obtaining reliable results and such pre-processing includes the appropriate selection of ternary coding threshold values that also should be considered in future works.

Future efforts in quantitative socioeconomic research should ensure that additional key information is collected to improve the chances of validating possible cause-effect hypotheses. As Buhaug (2007) argues, there is three main directions for environmental conflict studies in the future; (1) a sustained blend of case-based and large-N empirical assessments, (2) disaggregation of the subject under study, theoretically as well as empirically, (3) increased use of advanced methods, such as GIS, spatial regression, and multilevel modelling. The common of these directions is to consider the representativity of the input parameters explaining the dependent variable (the phenomenon to be explained) using a specific method explaining their correlation. More research need therefore to be performed in the preprocessing of data, such as considering the appropriate upscaling (aggregation) and/or downscaling (disaggregation) of parameters and transforming these into representative proxy variables. This includes knowledge of how data parameter values might change both in spatial and temporal scale.

The mapping of world's natural resources has improved significantly the last decades following the availability of remote sensing incorporated with GIS software. More research needs to be performed to outline both known reserves and prospective areas and volumes of future natural resources important both for sustainable development of renewable and non-renewable natural resources. Based on mapped and estimated natural resources collected in a database, analysis of these resources can be performed. Such database can be included in conflict research to achieve a more complete evaluation of the causal mechanisms in natural resource related conflict. This database can also be included in natural resource management options to evaluate the overlapping interests in natural resource endowments.

E.g. mapping out different stakeholder's interests in an area which is essential for critical political decisions. The unit of analysis should not be isolated to separate countries or administration counties as a nation borders and sub-borders are neither fully related to the extent of natural resource presence nor without influence from other factor such as political processes.

While the scope and niche areas of natural resource management are yet to be further defined and accepted by the general geosciences and study of civil war communities, the promotion of natural resource management offers a renewed perspective and a more integrated approach to the study of people-technology-economic-environment-conflict interactions across spatial and temporal scales.

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Appendix A

A comparison of unstructured and structured principal component analysis and their interpretation

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Appendix B

Refined lithological description through structured multivariate analysis

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Refined lithological description through structured multivariate analysis

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Abstract

Estimation of reservoir heterogeneity from well logs is an important yet difficult task encountered in geophysical formation evaluation and reservoir engineering. This paper presents a workflow for mapping petrovariability through a structured multivariate analysis of a well from the Upper Triassic to Lower Jurassic Fluviodeltaic Åre Fm., offshore mid-Norway. Traditionally, principal component analysis (PCA) is run by analyzing the entire wireline log and using PCA scores to characterize variability within and between lithologies. In this paper we propose a workflow using only selected segments of the wireline log and specific variable responses to quantify reservoir heterogeneity due to second order rock property contrasts, in addition to more standard approaches for lithological segmentation. This paper demonstrates first the potential of structured PCA analyzing specific lithofacies sequences to portray within-lithofacies variations. Secondly, it shows that the petro-normalization obtained by using the Eckart-Young theorem can separate the initial wireline responses into specific litho-variability components that reflect different rock property contrasts. A mapping of these contrast components can be used to enhance our ability to characterize reservoir heterogeneity. Deviating from traditional PC scores, the Eckart-Young derived results can decompose the initial wireline log responses into fractions, that can ease the interpretation performed by petrophysics or geologists. The application of this workflow in the Heidrun case study provides additional insight into the variability of a complex fluviodeltaic heterolithic sequence that poses great challenges for development.

Key words: Eckart-Young theorem, reservoir heterogeneity, lithofacies classification

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1. Introduction

The interpretation of wireline logs to investigate lithological changes poses a variety of problems: Wireline log responses are indirect measurements and various log responses are needed to portray lithological variations. The increase in the number of wireline log variables have resulted in enlarged data sets that are too complex to manage and to draw conclusions from. Several automatic well log facies classification algorithms have consequently been developed to interpret these datasets more comprehensively. Multivariate analysis method includes e.g. principal component analysis (PCA), discriminant analysis, cluster analysis, regression analysis (Tang and White, 2008). Although artificial neural network represents a flexible and robust method, training the network requires considerable parameter tweaking, which is strongly based upon interpreters' experience (Saggaf and Nebrija, 2000). Convergence is often both unreliable and slow and do not explicitly describe the link between wireline log responses and lithofacies. The more classical multivariate statistics methods, on the other hand, are flexible and provide a clear mathematical expression of the relationship between wireline logs and lithofacies (Doveton, 1994).

Wireline log responses can been decomposed into three different types; gross lithology contrasts, within lithology contrast and noise. The relative magnitude of these contrasts are strongly dependent on the geological variations on one side and how the well was drilled and the quality of the wireline log responses on the other side (Shelly, 1998). Small scale heterogeneities within specific litholog-

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ical units, whose contrasts are minor compared to gross lithological contrasts, can be of great importance as input to reservoir modeling for explaining effective reservoir properties (Nordahl, 2004). The magnitude of noise compared to the within lithological variations depends on the geologic heterogeneity and the quality of the wireline log responses. Numerous attempts to isolate these problems have been tried. A study of Moline and Bahr (1995) used PCA as a preprocessing tool before clustering concluded that the use of reduced dimensionality of wireline log space increased the separation between gross lithology effects for facies clustering.

PCA has been widely used to evaluate geological processes ranging from extracting structural elements from regional satellite images (Zhang et al., 2007b) to applying PCA to 3D seismic data for reservoir property estimation (Scheevel and Payrazyan, 2001). Traditionally principal component analysis (PCA) is only used for reducing the dimensions a data set (Davis, 2002), and assumes that only the first principal compoents (PCs) include sensible variability, whereas the remaining PCs are interpreted to be variability due to data noise. This tradition is in contrast with the experience of Zhang et al. (2007a), who successfully applied minor variability PCAs to detect hydrocarbon bearing sand through remote sensing. The higher dimension PCs were used to outline different hydrocarbon-induced zones to decide the prospecting area for oil-bearing sand exploration without the influence of the major data variability explained by the first PCs.

Obtaining lithological variations from wireline responses via applying the Eckart-Young theorem (Eckart and Young, 1936) avoids the need for differencing and bypasses many of the above mentioned associated problems. The process of Eckart-Young theorem is a mathematical operation for decomposing a matrix into the sum of several individual matrices which when summed together is equal to the original (Davis, 2002). The significant implementation of Eckart-Young theorem related to geosciences has been widely demonstrated previously in geophysical prospecting. E.g. Reid et al. (2005) enhanced the 4D time-laps signal to gain confidence in areas where traditional differencing fails and Liu et al. (2005) explained that the Eckart-Young theorem can be applied on the combinable magnetic resonance (CMR) tool to enhance the determination of the formation total porosity, free fluid porosity and formation permeability. The lithological variations recorded from wireline responses can express specific geological-driven processes as petrophysical responses are influcenced by mineral composition, texture, grain size and sorting. These parameters affects the strongly the most inportant effective parameters in reservoir characterization, porosity and permeability (Martinius et al., 2005; Beard and Weyl, 1973). By using the experimental work results of Fraser (1935) that provided the basin concepts of how grain size, sorting and grain packing affect porosity, and (Graton and Fraser, 1935) who showed that porosity is independent of grain size, but decreases significantly with poorer sorting.

The present study evaluates the performance of two separate multivariate techniques for the characterization of fluviodeltaic reservoir heterogeneity from wireline logs. The objective is to describe and evaluate the benefits of using structured PCA approach in conjunction with the Eckart-Young theorem to show how petrophysical properties can be decomposed into different orders of variability and differentially interpreted to provide additional insight into fluviodeltaic heterogeneity. This also includes evaluation of transforming scaleless PC scores by the use of Eckart-Young theorem into decomposed wireline log responses related to each of the PCs and inversely how the PCs can be back calculated to portray their individial contribution to each of the initial wireline log responses.

2. Method

2.1. Study Area, Wireline Data and Software

Lithofacies	ID	Description	Counts
Sand	1	Fine to medium grained sandstone	867
Shale	2	Shale and clay to very fine siltstone	830
Coal	3	Organic rich coal to silt influenced coal	149
Cemented layer	4	Cemented layer	28

Table 1: Summary of the lithofacies description of the studied fluviodeltaic well interval.

The present study was carried out over a 300m zone of the Upper Triassic to Lower Jurassic fluviodeltaic Åre Fm. (Dalland et al., 1988) of the Heidrun Field, offshore mid-Norway. A vertical water saturated well was selected where both core and petrophysical parameters have been thoroughly studied relative to five wireline logs (gamma ray, neutron porosity, bulk density, resistivity and sonic logs). The computations have been performed within the R Language, a free and open source software, with facilitates for data manipulation, calculation and graphical display (Dalgaard, 2008). Univariate evaluation of the wireline logs has been earlier performed by Brandsegg et al. (2010) where the major variations within the study area are outlined. The Åre Fm. can be subdivided into three major lithofacies, sandstone (ss), shale (sh) and coal (co), in addition to cemented lithofacies layers (cc) (Table 1). Their differences are detectable at the 15cm interval wireline log sampling (Fig. 1).

Facies 1, sandstone, is relatively clean poorly to well-sorted sand characterized by low values of gamma, density and velocity, while the resistivity and neutron porosity are more variable. Thickness of the sand varies in the range 0.5-7m. Facies 2, shale, is a material consisting of clay to fine-grained silt. The log responses are more variable than in the sands, depending on the clay content and are characterized by high gamma, density and velocity, and generally low resistivity. Coal layers (Facies 3) are, in general, characterized by low density and velocity with a distinct peak of very high values of neutron porosity. The cemented layers (Facies 4) are diagenetic effects predominantly occurring in sandstone intervals where porosity is replaced by minerals (Hammer et al., 2010; Hammer, 2010). The characteristic log responses are high density and velocity, while neutron porosity and resistivity is low.

2.2. Principal component analysis

PCA of the five wireline logs was performed to outline specific lithology contrasts, both between lithologies and within lithologies. The eigenvectors representing orthogonal directions in space permits the viewing of data from a variety of perspectives (Davis, 2002). Previous studies have shown that the calculated PC loadings and scores can be used to enhance the separation of multiple populations in a data set that reflect geologic heterogeneity (Brandsegg et al., 2008, 2010). This is the reason for the introduction of structured PCA. The PC signatures obtained via analyzing separate lithological unit types using the structured approach showed substantial improvement compared with unstructured PCA where the whole well log was analyzed at once (Brandsegg et al., 2010). The aim of the modified structured PCA used in this study is not to reduce the dimensionality of the data, but to work on subsets of the wireline log responses and use the specific variance-covariance matrices that capture particular heterogeneity effects within different lithological units. PC loadings and scores are calculated first from a structured subset including only sandstone intervals, secondly only subsets of specific sandstone dominated sequences are selected. Through these structured approaches a refined reservoir heterogeneity analysis permits the quantification of the higher order effects of petrovariability by means of the Eckart-Young theorem.

2.3. Echart-Young theorem

The analysis is performed through a normalization transform of the original logs followed by a decomposition of variability due to differing rock properties before a new log response is reconstructed by inverse PCA processing using the Eckart-Young theorem (Eckart and Young, 1936). The Eckart-Young theorem is the cornerstone of several multivariate techniques (Davis, 2002). The theorem expresses the interrelationship between a data matrix and the eigenvalues and eigenvectors of the correlation matrix. It states that any real matrix, X, can be decomposed into two orthogonal matrices, V and U, and a matrix, Λ, containing the square rot of the non-zero singular values, λ, where the positive elements are along the diagonal and off-diagonal elements equal to zero (Davis, 2002). That is,

$$X = V\Lambda U^T \tag{1}$$

where Λ is defined as

$$\Lambda = I\sqrt{\lambda} \tag{2}$$

where I is the identity matrix. The initial wireline log responses are placed as column vectors into an $n \times m$ matrix, X, where n is the number of samples in each wireline log and m is the number of wireline logs. The first step is to compute the V and U matrices using the standardized wireline log variables. The columns of the $n \times m$ orthogonal matrix V and the $m \times m$ orthogonal matrix U contain the eigenvectors associated with eigenvalues of the major and minor product matrix of X, respectively. Λ is an $m \times m$ diagonal matrix containing the square root of the eigenvalues, $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq \lambda_4 \geq \lambda_5$. This use of eigenvalues are possible as the initial matrix, X, has zero empirical mean. The matrix Λ can be decomposed such that

$$\sum_{i=1}^{5} \Lambda_i I_{ij} \tag{3}$$

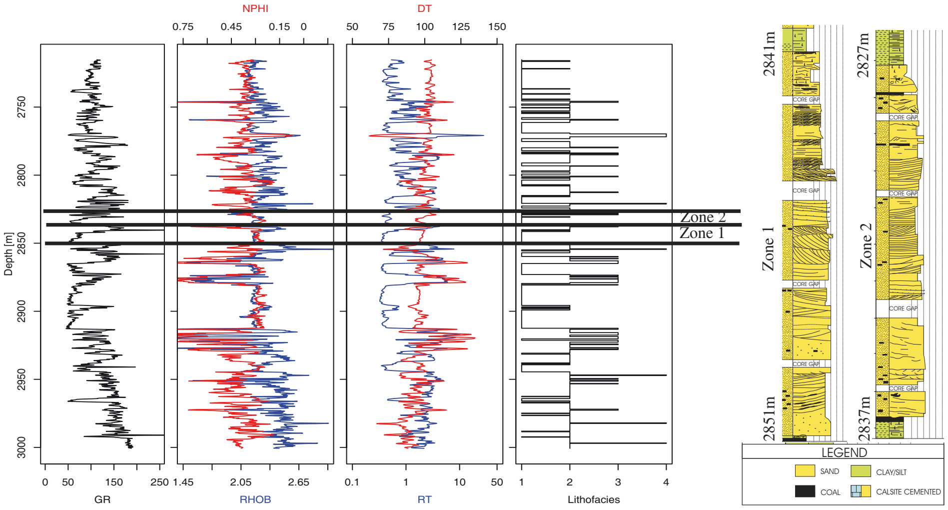

Figure 1: Five wireline logs (gamma ray, neutron porosity, density, resistivity and sonic) that show a clear indication of vertical heterogeneity form the basis for the multivariate analysis. The lithofacies log derived from interpretation of cm scale core samples and the original wireline logs has the following notation: (1) sand; (2) shale, (3) coal and (4) cemented layers.

where Λ is the 5×5 identity matrix, I is the Kronecker delta function, $j = 1, 2, \ldots, 5$ and $i = 1, 2, \ldots, 5$. By performing this decomposition and then recalculate the X matrix for each eigenvalue, five separate signatures for each of the wireline logs are produced related to the five eigenvalues of the matrix X. Each of the five separate versions of the original data set contain isolated first to fifth order effects which when summed together equal the original. The procedure above can be used in a total mode, where the entire wireline log is used to calculate the correlation matrix or in a structured mode where specific intervals of the wireline log can be selected to focus on specific lithological variability or a particular type of samples within the study interval. The use of total or structured mode will normally result in some degree of difference in weights illustrating the inherent variability within these samples. The wireline log samples of the structured mode are placed as column vectors into an $s \times m$ matrix, $X_{section}$, where s is the number of samples in each wireline log section and m is the number of wireline logs. The section of the X matrix is defined as

$$X_{section} = V_{section} \Lambda_{section} U_{section}^{T} \qquad (4)$$

where the notations are similar to Eq. 1. The weights from this specific section can be applied to the entire wireline log, X, mimicking the specific sectional variations. The refined decomposition of the entire wireline log can be defined as

$$X_{refined} = V_{refined} \Lambda_{section} U_{section}^{T} \qquad (5)$$

where $V_{refined}$ is similar to the Eckart-Young theorem defining $V = XU\Lambda^{-1}$ that in this case can be written as

$$V_{refined} = XU_{section} \Lambda_{section}^{-1} \qquad (6)$$

where is the initial wireline log responses. This is now the new decomposed wireline log mimicking the five signatures of the selected interval.

Further is the isolated first to fifth order effects of each wireline response scaled to show the percentile contribution of each effect on the wireline response. The direction of the specific eigenvectors is undetermined and can therefore be changed to suit the problem at hand. This makes it possible to ensure that the loadings of a specific wireline variable is positive. The positive loadings for this variable makes it possible to calculate the percentile contribution of each of the first to fifth order PCs for this specific wireline variable. The individual contribution can represent inherent petrophysical variations that are intricate and may not be percieved by core inspection or the original wireline log.

2.4. Visualization and interpretation methods

The calculated loadings derived from PCA are traditionally shown in table form and biplots. The relationship between each input variable loading is complex to interpret when several input parameters are used. In particular is the importance of identification of loading contrasts. An additional graphical plot is introduced to visualize the variations of loadings. Star diagrams (Wegman, 1990) visualize the loading signatures for each PC, where high negative loading is plotted at the center point and large positive loading is plotted furthest distance from the center point. Each PC loading will have its own specific signature that can be related to other loadings. The most prominent loadings are easily identified with their high negative or positive values.

To visualize the relationship between the initial wireline logs and both calculated PC and Eckart-Young derived scores, their values are plotted against depth and related to core photos of the identical depth interval. The combination of wireline log traces and core photos enhances the interpretation of both major lithological contrasts and within lithology small scale heterogeneities.

To visualize the difference between separate wireline responses, crossplots are introduced to improve the interpretation from sample point to sample point. Several crossplots can be generated based upon the aim of investigation: The possibility to identify differences between initial wireline log responses and specific PC scores can identify lithological constrasts that diverge from the initial wireline log response.

3. Results

3.1. Structured principal component analysis

Initially an independent structured PCA, based on the correlation matrix, was executed to portray the internal variations within the interpreted sandstone lithology unit of the 300m study interval. Two point bar sequences (zone 1 and zone 2) were separately analyzed to study the spatial variations of the heterogeneity within these zones (1). Table 2 shows the PC loadings for the structured PCAs, the sandstone unit (named PC_ss) and the two 10m point bar sequences (named PC_z1 and PC_z2). All are computed from the standardized values of the original wireline logs. The separate sandstone lithofacies grouping is introduced to enhance the internal variations within the sandstone grouping, where as the analysis of two sand-dominated sequences are performed to outline the difference between them and relate these results to all sandstone intervals. A PCA of all records is not performed here as Brandsegg et al. (2010) concluded that the structured PCA was superior compared to unstructured PCA when within-lithology contrasts are in focus.

The star diagrams, visualizing the relation between structured PC loadings in Table 2, show that the PC1_ss has about identical loadings to the PC1_z1 and PC1_z2 indicating that the primary component of all three analysis are close to identical (Fig. 2). This PC is interpreted to separate sand and shale as the dominant variables are GR, NPHI and RT. In zone 1, the PC1_z1 is explaining 75.3% of the variations compared to only 44.1% of PC1_z2 in zone 2 indicating that zone 1 consist of more homogeneous sandstone. The PC1_ss, explains 47.5% of the total variability, has similar magnitude of variability as PC1_z2. This indicates that the overall variability of all sandstone lithological units, 867 records, are similar to the 10m sequence of the second point bar with only 62 records.

The PC2 signature of the sandstone grouping, PC2_ss, and PC2_z2 of zone 2 show similar variance (22.9%), while the corresponding signature of zone 1, PC3_z1, has a variance of only 5.4% (Table 2, Figs. 2 and 3). This indicates that the signatures explaining a specific heterogeneity type, interpreted to be coal with dominant variables of DT and NPHI and an opposing RHOB, is less important in zone 1 as can be seen from the change in order of the PCs from PC2_z2 to PC3_z1 expressing similar signatures, but varying presence of variance explained. The PC3_ss loading corresponds with PC2_z1 and PC3_z2, explaining 13.7% and 20.5% of the total variability, respectively, with NPHI and RT as dominating variables and an opposing GR interpreted to differentiate between GR-rich sand and shale. The PC4_z2 of zone 2, explaining 7.2% variance, portrays three sandstone successions within the point bar not visible from the initial wireline logs and is verified by the sedimentology log and corresponding core photos (Fig. 3). The PC4_z2 is marginal different compared to PC4_ss with lower RHOB and DT loadings including the identical NPHI loadings in

	PC1_ss	PC2_ss	PC3_ss	PC4_ss	PC5_ss
GR	0.741	0.171	−0.645	0.066	0.023
RHOB	0.221	−0.373	0.076	−0.860	0.258
NPHI	0.461	0.226	0.632	0.235	0.530
RT	0.435	−0.320	0.394	0.063	−0.741
DT	−0.011	0.823	0.148	−0.443	−0.322
Variability	47.5%	22.9%	17.4%	7.2%	5.0%

	PC1_z1	PC2_z1	PC3_z1	PC4_z1	PC5_z1
GR	0.720	−0.674	−0.164	−0.024	−0.019
RHOB	0.206	0.223	−0.018	−0.579	0.757
NPHI	0.507	0.442	0.294	0.639	0.228
RT	0.425	0.521	−0.145	−0.419	−0.593
DT	0.037	−0.172	0.930	−0.283	−0.153
Variability	75.3%	13.7%	5.4%	3.6%	1.9%

	PC1_z2	PC2_z2	PC3_z2	PC4_z2	PC5_z2
GR	0.709	0.033	−0.697	0.039	−0.097
RHOB	0.299	−0.521	0.203	−0.729	0.258
NPHI	0.473	0.383	0.428	0.258	0.616
RT	0.418	0.054	0.532	0.021	−0.734
DT	−0.093	0.760	−0.084	−0.633	−0.077
Variability	44.1%	22.9%	20.5%	7.2%	5.3%

Table 2: PC loadings for the structures PCA of all sandstone records (PC_ss) and two sandstone zones (zone 1 - zone 2). The loadings are calculated from the standardized wireline logs. The percentage of the total variability accounted for by each PC i shown in %.

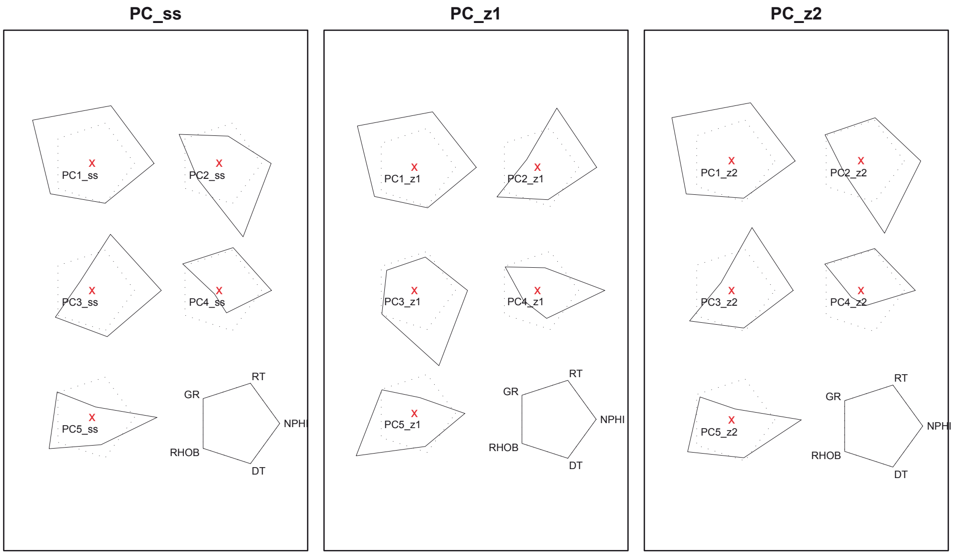

Figure 2: The star diagrams graphically illustrate the PC loading interactions for the structured PCA and the two separate 10m zones shown in Table 2. The dotted line indicates zero loading and the center point represent a -1 loading. The z1 to z2 are loadings calculated from separate 10m heterogeneous sand dominated lithological sequences, where z1 and z2 are interpreted to be two channel point bars, have signatures also found in the structured PCA of all sandstone units.

which gives the pronounced sandstone successions. The PC4_z1 has less variability (3.6%) and do not outline these successions. The last PC, PC5, explains about 5% variability for PC5_ss and PC5_z2 and only 1.9% for PC5_z1. The opposition between the positive NPHI and RHOB and the negative RT is assumed to express internal sandatone variaonts. The PC5 signatures of the three structured approaches in Fig. 3 have deviating signatures within the sandstone interpreted intervals. The PC_z2 has the most deviating signature and is not captured by either the zone 1 analysis or all sandstone interval analysis.

The results of structured PCAs including the star diagrams are summarized in Table 1 and show the dominant opposing wireline variables of each of the PC loadings. The difference between each zone, illustrated by both the loading values in Table 3, and the plot of the 10m sequences of zone 2 in Fig. 4, indicates that zone 1 has less sandstone impurities with fewer coal and silt intervals than zone 2. The similarity between PC1_ss and PC1_z2 show that the mixing of all sandstone intervals in terms of shale is similar to a study sequence with fewer records, and indicate that zone 2 is a representative selection of the variations within all sandstone interpreted records.

In addition, the responses of the 10m point bar sequence in zone 2, accentuate the heterogeneity of the three sandstone successions (PC4_z2). The interpretation of each of the structured PCA results gives a more detailed knowledge than the evaluation of the initial wireline log responses.

3.2. Refined characterization using the Eckart-Young theorem

Following the structured PCA, the subsequent analysis performed is a refined structured PCA using an inverse PCA transform by decomposing each of the loadings representing separate lithological effects that back calculate refined estimates of the initial wireline log variables by means of the Eckart-Young theorem. Firstly, all five initial wireline log responses are divided into new values transformed in correspondence with the response of each of the PC scores. These new synthetic values for the wireline log variables contain sum of separate effects explaining the different sources of petro-variability.

In order to investigate the effect of five decomposed wireline variables, the neutron porosity (NPHI) variable was selected as an example and evaluated and related to the 10m sequence of zone 2 (Fig. 4). The initial wireline NPHI variable is plotted with its standardized values (NPHI standard). This NPHI standard response is decomposed by using the Eckart-Young theorem into five separate NPHI resonses (NPHI1 standard - NPHI5 standard) reflecting the NPHI contribution of each PC. The NPHI [%] response indicates the percent contribution for each of the five decomposed NPHI variables relative to the total NPHI at that specific depth interval. The Eckart-Young derived NPHI values has different values than the PC scores and is related to the impact magnitude for each of the records, which is assumed to be related to the wireline log responses explaining geological variations.

The strongest contribution to the total NPHI response is NPHI3 and NPHI5 response with about 30% and 60%, respectivily. This is in strong contrast to the total variability in PC3_z2 and PC5_z2 which only express 20.5% and 5.3% , respectivily. Eventhough the NPHI loading of PC1_z2 is significant (0.473), the NPHI contribution has only marginal influcence on the PC1_z2 score response as the response is mainly expressed by the other wireline log variables.

The NPHI loading of NPHI2 and NPHI4 have also high PC loadings, still they contribute marginally to the total NPHI response. It is notable that the earlier identified three sandstone successions outlined in PC4_z2 only contributes with about 1% of the total reponse. As sandstone successions are mainly affected by sorting as a result of various sediment transport energy, this process has only a marginal constrbution of the total reponse.

As earlier stated, the strongest contribution to the total NPHI response is NPHI5 response with around 60%. This show that the majority of the NPHI variability is captured by the lastest eigenvector. Whereas the NPHI standard response has a near constant value of 0.40 within the sandstone interval (records 16-60), its relative response (NPHI5 [%]) shows a varying reponse with depth that can be related to geologic properties (e.g. sediment packing).

The Eckart-Young derived NPHI values, explained above, are further displayed in crossplots to illustrate the different impact of each of the new NPHI values (Fig. 5). First is the intial NPHI response plotted against the initial density response, RHOB, which is the traditionally way of displaying their covariations (Fig. 5a). The crossplot of initial RHOB and NPHI wireline logs for the 10m sequence of zone 2 shows that the sandstone units

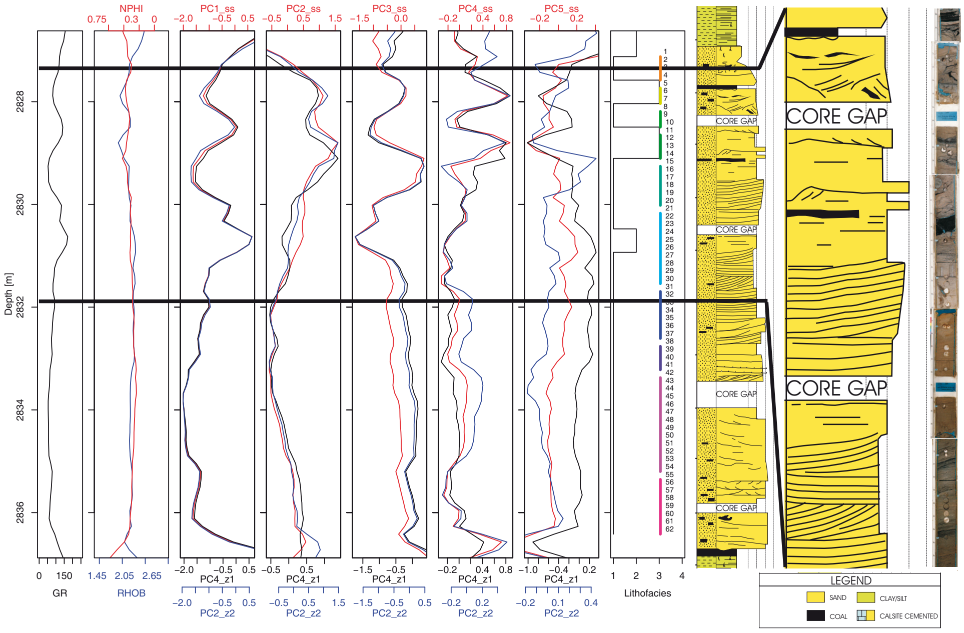

Figure 3: Variations between scores using loadings of point bar 1 and point bar 2 and the sandstone lithological unit variables, PC1_ss-PC5_ss, visualized by the point bar 2 sequence. The first, third and fifth plots have close to identical responses, whereas the second and fourth responses do not correspond solely to the other responses. The fourth plots of zone 2 diverge particularly at the PC4_z2 responses indicating three sandstone successions.

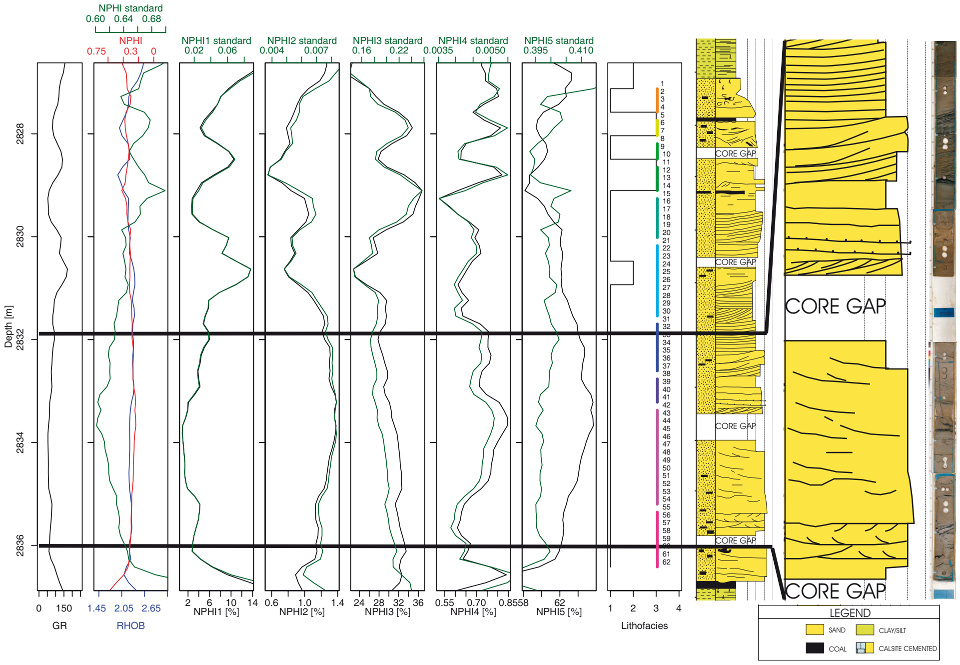

Figure 4: The plots of Eckart-Young derived scores constructing new responses first scaled to show their contribution to the standardized wireline log response and secondly the percentile contribution for each variable of each sample point. This can ease specific lithology trend interpretations based upon specific decomposed wireline log variables without interpreting the traditional PC scores.

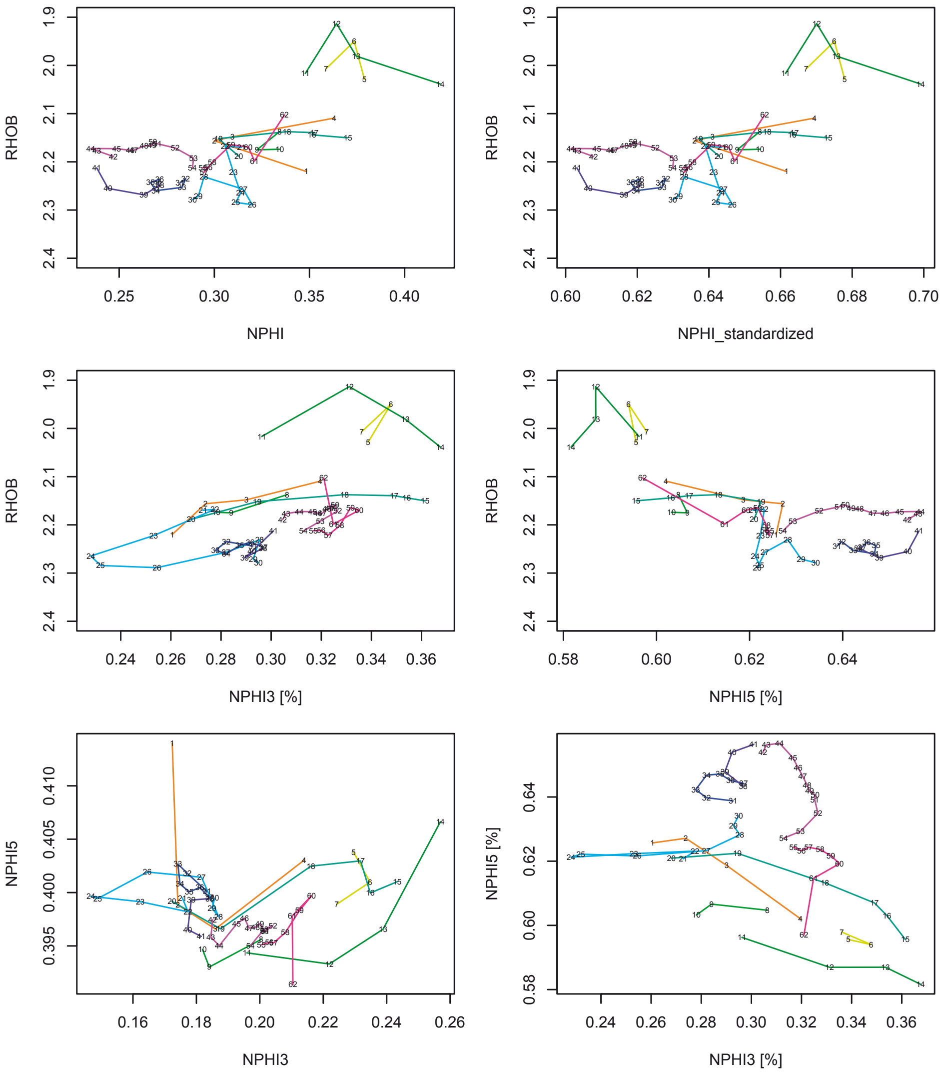

Figure 5: The crossplots of Eckart-Young derived responses in relation to intial wireline log responses show that the Eckart-Young derived responses can isolate effects that in not visable by the initial wireline log responses. This can ease specific lithology trend interpretations based upon specific decomposed wireline log responses without interpreting the traditional PC scores.

are plotted in the lower left and the coal influence sand in the upper right. The NPHI standardized values show identical results as the initial NPHI values (Fig. 5b).

The crossplot of initial RHOB values and the NPHI3 [%] has GR-enriched sandstone intervals in lower left and coal influenced records in the upper right (Fig. 5c). The intial RHOB values and NPHI5 [%] crossplot outline clean sand with the largest grain size in the right area (Fig. 5d). The crossplot of the NPHI3 and NPHI5 responses (Fig. 5e) outline GR-enriched sand and coal influcenced records. This is also outlined in the crossplot of the percentile contribution of these responses (NPHI3 [%] and NPHI5 [%]), as well as a more distinct view of the clean sand (records 30-50) (Fig. 5f).

The decomposed transformed scores show that both scaled values and fractions of the initial wireline variables are easier to identify and interpret than the original PC scores as they correspond to the magnitude of the initial wireline log values.

4. Discussion

As shown by the case study analyzing a specific fluviodeltaic sequence, we have improved the interpretation performance of multivariate analysis from applying structured PCA to evaluate specific within-lithofacies variations to enhanced interpretation capability obtained by the introduction of the Eckart-Young theorem. From the case study presented here we showed that the performance is related to the methods used to collect data and that the data need to be anchored to geologic features. The contrasts in the facies properties and their statistical distribution are the main limitations of the study, as the selected study interval is water filled with close to horizontal layering without varying well diameter.

We have demonstrated the application of the Eckart-Young theorem for evaluation of one specific out of four lithofacies using five wireline log responses in a case of real data. There is, however, no limitation to the number of wireline log responses that can be applied to distinguish between the lithofacies. The characterization of real data is challenging since the lithofacies were initially defined by visual inspection of cores, and thus not fully compatible with the wireline log responses which detect different physical properties and have a coarser spatial sampling. The main obstacle in using petrophysical responses is the resolution of log responses related to the geologic layering, especially in heterolithic deposits (Doveton, 1994). Lithofacies, defined as specified units distinguished on the basis of lithologic features, are in this study identified at the wireline log scale of measurement of 15 cm. Nordahl and Ringrose (2008) discussed the concept of representative element volume (REV), indicating that the lithofacies variations of wireline logs (dm scale) are averaging out the lamina scale variations (cm). However, small impurities within specific lithofacies types can be recorded resulting in a slightly change of the log response. Analyzing separate 10m intervals of a sandstone zone interpreted to be point bar sedimentary features resulted in differences in the loading signatures compared to all sandstone records. This can indicate that the optimal REV, or representative elementary scale of wireline log analysis should include more that 66 sample points.

In this work we have focused on characterizing higher order lithological heterogeneity within a fluviodeltaic deposit and the result portrays heterogeneity within lithological intervals in terms of wireline log derived variability. Several papers have discussed the use of PCA to indicate variations in wireline log responses (c.f. Moline and Bahr, 1995). Although PCA is a robust and powerful method for both visualizing and manipulating the multidimensional representation of wireline data, it cannot be used as a black box, and should be carefully designed in order to obtain significant interpreted results. If violation of these principles leads to a strong bias, a loss in power will inevitably result, because any recognized lithology association will be effect by a strong instance of bias. There are some general limitations in PCA, such that the statistical significance provided by the first few principal component axes are no guarantees to have the best subset of features (Nadler and Smith, 1993). This is due to the fact that PCA uncovers feature combinations that model the variance of a data set, but these may not be the same features that separate the different lithology changes. In other words, the PCA components that model the largest contributions to the data set variance may work poorly for pattern recognition. This is the reason why the structured PCA approach should be taken.

The use of Eckart-Young theorem to decompose the wireline log responses makes it possible to transform the PC scores into decomposed values of the initial wireline log responses that can ease the interpretation performed by petrophysicists or geolo-

PC_ss	PC_z1	PC_z2	Dominant (+) or opposing (-) variables		Dependent on lithofacies variations	Process variable
PC1_ss	PC1_z1	PC1_z2	+GR +RHOB +NPHI +RT		Lithofacies separation of sand/shale	V1
PC2_ss	PC3_z1	PC2_z2	+DT +NPHI	-RHOB	Lithofacies separation specifies coal	V2
PC3_ss	PC2_z1	PC3_z2	+NPHI +RT	-GR	GR rich sand	V3
PC4_ss	PC4_z1	PC4_z2		-RHOB -DT	Internal sand variations	V4
PC5_ss	PC5_z1	PC5_z2	+ RHOB +NPHI	-RT	Internal sand variations	V5

Table 3: Summary of the relations between the most prominent loadings derived from the structured PCAs as indicated by the PC loadings, spider diagrams as well as PC responses. The rank of the PC loadings is varying according to the magnitude of variability explained by each loading. The variables explain contrasting types of lithologic heterogeneity and are grouped into variable numbers (V1-V5) according to variables signatures used to explain the lithofacies variations in PC_ss.

gists. The mathematical decomposition of Eckart-Young theorem allows also to merge two or more variables for constructing new responses. This is now performed in the present study, however, it can be a powerful tool to visualize combined lithofacies signatures not achievable from a standard PCA. Still, it need to be arranged cautiously and anchored to geologic reasoning as inaccuracy can lead to delusion of the results.

5. Conclusions

We have described a new workflow using separate PCAs derived from different lithological intervals to detect and correct for higher order heterogeneity that explicitly models internal lithological differences and gives a clearer and more comprehensive interpretation of the data. A case study analyzing higher order lithological effects from the fluviodeltaic deposit of the Heidrun Field, offshore mid-Norway, has indicated an improved fluviodeltaic reservoir heterogeneity description based upon wireline logs and the structured PCA approach. The structured PCA method and the method using Eckart-Young theorem outperforms the prevailing unstructured method on initial wireline log data sets and can easily be applied to isolate other depositional environments, particularly in studies involving heterolithic deposits. The back calculation of wireline log values by the use of the Eckart-Young theorem permits the effective removal of variability due to gross lithological effects and allows for differential interpretation of heterogeneity. The study can differentiate shale and GR rich sand and indicate sandstone successions within sandstone intervals not visible on the initial wireline logs. PCA mapping within lithological intervals provides a statistical method for precise positioning of the core versus the wireline log and can be used to predict reservoir heterogeneity in wells that have not been cored. Finally, the use of separate PCAs from different lithological intervals has been effective in the portrayal of petrophysical variability of reservoir properties within different reservoir facies at sub-seismic scales and the the decomposed values of the wireline log responses can ease the interpretation performed by petrophysics or geologist.

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C Appendix C

A novel workflow for 3D integration of geological and geophysical heterogeneity signatures at the reservoir scale

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A Novel Workflow for 3D Integration of Geological and Geophysical Heterogeneity Signatures at Reservoir Scale

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ABSTRACT : The main focus of the workflow is to exploit a methodology that can be used to enhance the importance of geology in constructing realistic reservoir models and validate industry-standard geomodels both for hydrocarbon exploration and production. Reservoir characterization is enhanced by means of a geology-driven tool, allowing us to model the high frequency information content of the seismic signal. Composite mosaics of geological analogues are used to derive realistic acoustic impedances from plausible geological scenarios. Synthetic seismic generated from hypothetical wellbores can be used to calibrate the spatial variations of subsurface properties. The method is tested on a North Sea turbidite field. Integrating geological and geophysical information from wells and composite analogues, in order to portray the heterogeneity of reservoirs, both at seismic and sub-seismic scales, is of fundamental importance for the forecasting of future hydrocarbon production.

KEYWORDS : Sub-seismic description, Reservoir heterogeneity.

1. Introduction

Hydrocarbon reservoir characterization comprises the process of creating an interdisciplinary understanding of reservoir complexity as input to the evaluation of recoverable volumes. For most modern hydrocarbon reservoirs, 3D seismic is used to characterize depositional geometries and fluid saturations and to generate the initial reservoir geo-model. Well data that is available after a discovery represents isolated sampling points that laterally only hold a few cm of geological information. Seismic resolution is normally characterized by a voxel size of 15-25 m (both horizontal and vertical). From the 3D seismic data top and base of thin reservoirs can be interpreted, wheras the internal boundaries in the reservoir needs to be located based on well bore information. These intra-reservoir boundaries are then interpolated between well locations. Geological software packages can today represent very detailed geological models, but these still have significant uncertainty at the subseismic scale (Avseth et al. 2005). The findings presented in this paper is a result of the integration of modelling environments in geology and geophysics at NTNU, from a long record of projects in sedimentary deposit modelling as well as seismic modelling (Janbu et al., 2005; Nordahl, 2004; Stovas, Landrø and Avseth, 2006; Stovas and Landrø, 2005; Stovas and Ursin, 2004; Wen, 2004).

2. Methodology

The SBED software (Geomodeling, 2006) from Geomodeling Technology Corp. represents the state of the art in quantifying petrophysical properties from sedimentary complexity described by depositional environments. The stratigraphic architecture of reservoirs can be digitally quantified and used as input for seismic modelling. The SBED software is based on manipulating sine-functions, creating surfaces representing incremental sedimentation (Nordahl, 2004; Nordahl et al., 2005; Wen et al., 2005). The displacement of the surfaces generates a three dimensional image mimicking bedform migration and depositional environments, which can be used to model intrinsic properties such as porosity, permeability and net-to-gross ratio based upon customized Gaussian distributions. Each hypothetically generated well bore represents an ultra-slim one dimensional digital well bore with a vertical resolution of 1cm. Geologists can verify that the hypothetical well bore corresponds to relevant facies from real borehole data, outcrops or imaginary wells, through quality control of the petrophysical parameters (Fig.1).

The advantage of this method is that very detailed layering can be modelled and synthetic seismic can be generated that takes into account the inter-bedded multiples which are of great importance in thin-layered reservoirs (Stovas and Landrø, 2005). Different depositional scenarios can subsequently be evaluated against 3D seismic indicating the probability of match. The most likely scenario can be found among several relevant composite analogues. The similarity of 3D seismic traces and the synthetic seismic traces are evaluated by cross correlation.

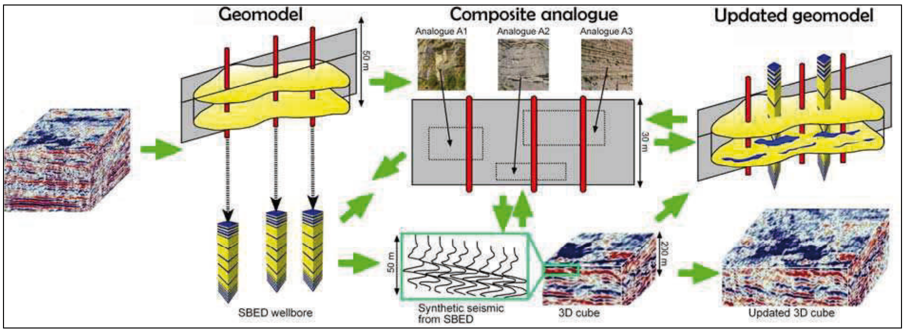

Fig. 1. Representation of the workflow. The initial geomodel is based on regional 3D seismic and wells. A composite geological analogue is created and calibrated with wellbores and relevant geological outcrops. Hypothetical wellbores are then positioned and modelled by SBED. SBED modelling gives output for seismic modelling, which can in turn be compared with the 3D regional seismic cube. Hypothetical infill wells and existing wells generated with SBED are constrained with seismic data through modelling and used to update the existing geomodel.

3. Case study

Studies of a small 9.6 km^2 turbiditic offshore oil field located in the North Sea, with estimated total recoverable resources of 46 mill barrels oil has served as a basis for this evaluation. The reservoir is situated in a Palaeocene submarine fan complex. The fan has a high net-to-gross sandy submarine lobe abandonment facies and a number of thin shales forming important heterogeneities not visible on the seismic data (Avseth et al. 2001). The reservoir has been studied from 1cm resolution core samples and 15cm resolution petrophysical logs. These input parameters are used by SBED to model the geological complexity in and between existing vertical wells. The output parameters (porosity and net-to-gross) are the key parameters used in the synthetic seismic modelling.

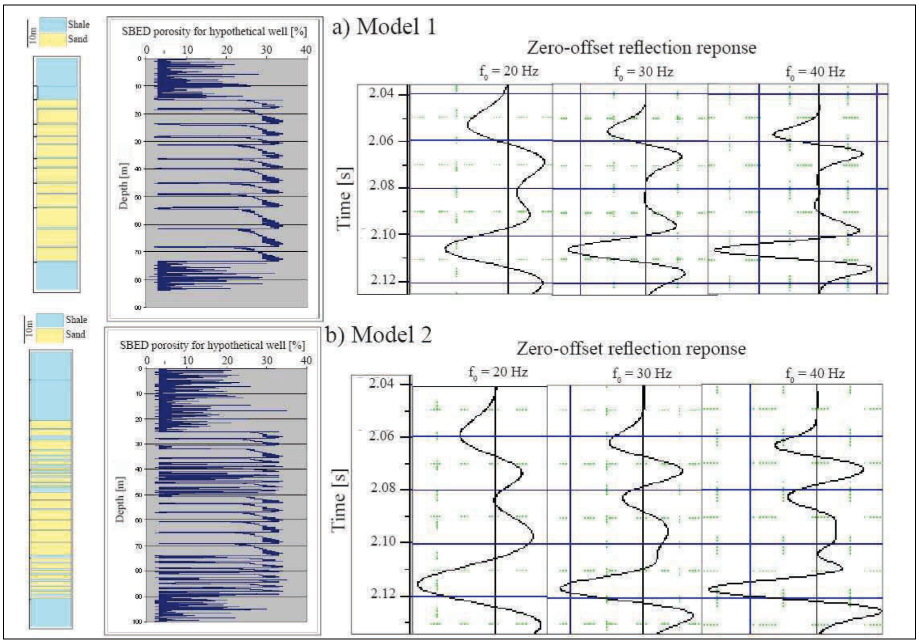

Fig. 2. Two separate hypothetical wells are constructed based upon nearby well information, reservoir analogues and depositional history for generation of different synthetic seismic traces. Both scenarios have alternating shale and sand, where (b), model 2, have thinner sand bodies and more shale than model (a), model 1.

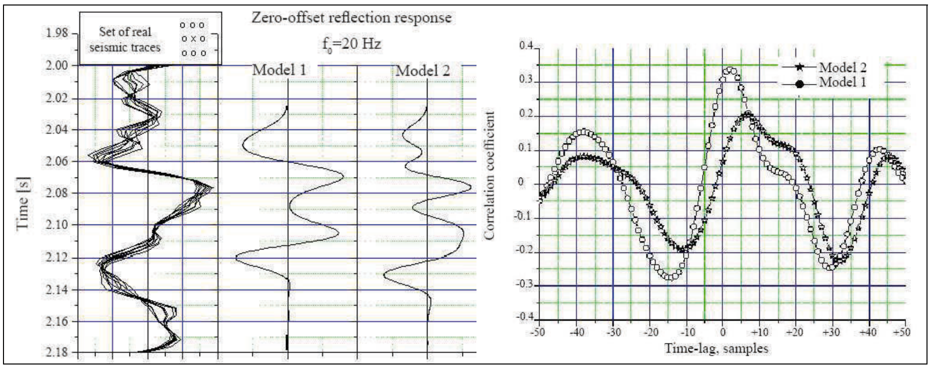

Fig. 3. Cross correlation between 3D seismic and synthetic seismic based on hypothetical wells from two depositional scenarios; model 1 and model 2. The trace with the highest match, model 1, is more plausible due to its correspondence to 3D seismic compared to the depositional scenario for model 2.

To infer the heterogeneity in areas between wells different types of composite analogues have been used. Two different scenarios are constructed as input to the SBED modelling. These scenarios are based upon a superposition of turbiditic reservoir analogues and nearby well information. Separate synthetic seismic traces are generated from these scenarios (Fig. 2). The likelihood for the reality of a given heterogeneity scenario is evaluated against the center and 8 surrounding 3D seismic traces. Only the within heterogeneity of the reservoir has been correlated against 3D seismic. Model 1 displays within this interval a decrease in amplitude with depth, where model 2 displays the opposite (Fig. 3). From fig. 3 it can be seen that the model 1 scenario has a higher correlation coefficient than model 2 and therefore represents the most plausible heterogeneity setting of the two.

4. Conclusions

- This study presents a novel workflow for the integration of geological and geophysical heterogeneity signatures at the subseismic scale that may influences the amount of recoverable hydrocarbon resources from a turbiditic field.
- The method enables us to determine and quantify how probable one heterogeneity scenario is compared to another.
- SBED modelling of hypothetical wells calibrated against 3D seismic can improve the understanding of undrilled areas.
- The proposed workflow includes information from hypothetical wells and can be used to portray reservoir heterogeneity that may influence both exploration and production decisions.

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Appendix D

Reconstruction of heterolithic reservoir architecture based on differential decompaction in sequence stratigraphic backstripping

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Reconstruction of Heterogeneous Reservoir Architecture based on Differential Decompaction in Sequential Re-burial modelling

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Abstract

A new methodology for robust, high-resolution correlation of reservoir sandstones in highly compactable depositional sequences is proposed. Quantitative sequential re-burial modelling has been successfully applied on real data from seven wells covering the heterogeneous fluviodeltaic Åre Fm. in the Heidrun Field, offshore Mid-Norway. The methodology is based on ten interpreted lithofacies classes derived from core descriptions and wireline logs signatures, in addition to interpreted sequence stratigraphic surfaces, i.e. flooding surfaces. Analysis of decompacted sedimentary columns, with emphasis on studies of shallow compaction effects tied to uniquely calculated compaction curves, has revealed several new correlatable horizons within the Åre Fm. These include laterally extensive coals and several laterally correlatable fluvial sandstones enabling a re-interpretation of parts of the Åre stratigraphy. The results from the present study demonstrate the benefits of correcting for the effects of differential compaction in well-to-well correlation of heterogeneous reservoirs comprising highly compactable sediments. The methodology outlined here has widespread applicability to other stratigraphic successions and could potential help in the correlation of highly compacted sediments in the subsurface.

Key words: Re-burial, sequence stratigraphy, compaction curves, decompaction, porosity, correlation

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1. Introduction

Depositional systems are generally thought of as a product of the interactions of three main allogenic controls - basin floor subsidence, base-level change and sediment supply (Posamentier et al., 1988; Posamentier and Vail, 1988; Van Wagoner et al., 1990, 1988). In addition, local factors, such as climate, topography and sediment compaction, define major autogenic controls. Heterogeneities in the sedimentary architecture at many scales can affect reservoir performance by differential compaction. Subsidence analysis of wells and core sections based on decompaction of the sediment column (e.g. Bond and Kominz, 1984; Sclater and Christie, 1980; Van Hinte, 1978) is a standard method for investigating sedimentary basins (Allen and Allen, 2005; Leeder, 1999; Miall, 1999). The restored sediment thicknesses based on the backstripping technique (Sleep, 1971) allow for the calculation of sedimentation rate and basement subsidence, and is the standard method for basin reconstruction (Bond and Kominz, 1984). In this study we introduce backstripping as a tool also for reservoir scale reconstruction based on high resolution (cm scale) wireline- and core data. The correlatability of reservoir units in heterogeneous deposits can be improved by applying decompacted sedimentary columns in the correlation process and taking into account and correcting for the effect of differential compaction. Robust correlations are a fundamental prerequisite in refined reservoir models used as a decision tool in optimizing drainage solutions.

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2. Background; correlation challenges in fluvial deposits

The Åre Fm. (Dalland et al., 1988) in the Heidrun Field (Koenig, 1986) comprises strongly heterogeneous sediments deposited in a fluvial to lower delta plain environment (Pedersen et al., 1989; Gjelberg et al., 1987; Svela, 2001; Leary et al., 2007; Thrana et al., 2008). Due to the lateral and vertical heterogeneous nature and architecture of the deposits, including isolated channel fills and highly compactable lithologies (i.e. muds and coals), large reservoir correlation difficulties are encountered. A reservoir model also taking into account differential compaction was therefore desired in order to counter this effect and hence, increasing the correlatability of sandstone reservoir units. Based on a backstripping technique that is using interpreted flooding surfaces as backstripping surfaces, we suggest that the effect of differential compaction can be accounted for by stepwise correlation on decompacted reservoir sections (Fig. 1).

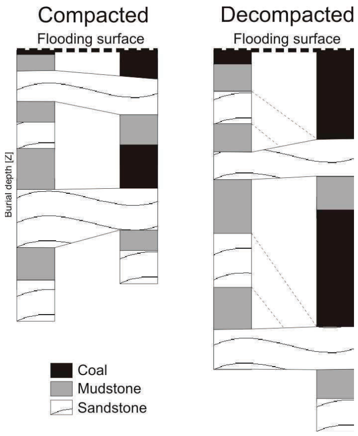

Figure 1: Sketch comparing correlation of two artificial lithological columns illustrating the effect of differential compaction. Correlation of reservoir sands in the columns presented to the left is very different from the decompacted columns presented to the right.

2.1. *The Åre Fm. reservoir zonation*

The Åre Fm. is about 300-500m thick and has been subdivided into seven reservoir zones by Thrana et al. (2009); Leary et al. (2007). The present study focuses on the lower fluvial dominated/fluvial influenced part of the stratigraphy, i.e. Åre 1 to Åre 3 (Fig.2). This interval contains abundant, highly compactable sediments (FF and coals) which are thought to have influenced reservoir architecture significantly during burial due to differential compaction. Åre 1-2.2 are interpreted as entirely fluvial deposits comprising fluvial channel sands, flood plain fines and crevasses. Åre 3 is a transition zone from fluvial to deltaic depositional environment, including sediments deposited in distributary, occasionally tidally influenced, delta channels and interdistributary bay areas. The studied interval is terminated by a regionally interpreted flooding event at top Åre 3.3. Depositional direction has been interpreted to be towards the south-southeast from the first appearance of marine influx in the southeast and from FMI dip data indicating a south-southeast palaeocurrent direction (Thrana et al., 2009).

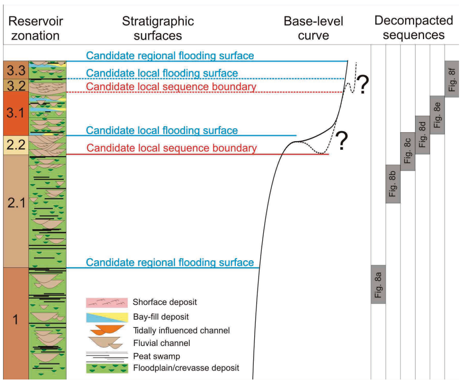

Figure 2: Statoil's revised reservoir zonation scheme modified from (Thrana et al., 2009). Interpreted flooding surfaces used in the present study as backstripping horizons as well as base-level changes interpreted for the selected Åre interval are displayed. Stippled lines indicates local (field-wide) surfaces, whereas continuous lines are correlatable in a larger area, i.e. to neighbouring fields. Interval coverage of presented decompacted sequences (c.f. Figs. 8 a to h) are displayed on the right.

3. Backstripping calculation

To account for the effect of differential compaction, especially where considerable early differential compaction occurs, a correlation exercise

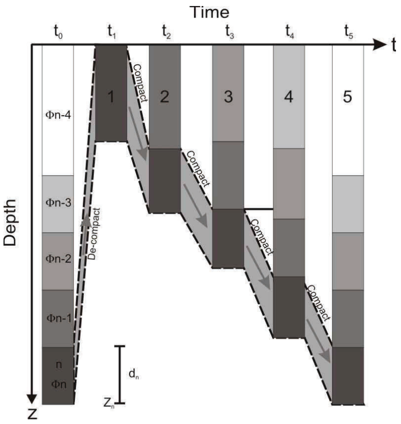

Figure 3: A conceptual sketch illustrating the backstripping procedure. Stepwise loading comprising progressive compaction beginning with decompaction of the lowermost unit (1) after removing the overburden (2-5). This is followed by a stepwise burial (compaction) in time steps (t1-t5), determined by flooding surfaces, of each unit and subsequent reduction in porosity following calculated porosity-depth-trends for each interpreted lithofacies within each unit (modified from Bond and Kominz, 1984). t_0 corresponds to the present day scenario.

performed on decompacted sediment columns is suggested. This challenge is solved by applying the technique of backstripping in a reservoir scale, although in this study a more precise definition would be reverse backstripping or sequential reburial (reloading). Backstripping, a technique developed by Sleep (1971), was first explored in detail by Watts and Ryan (1976). The technique is generally used to estimate tectonic subsidence by accounting for and removing the effect of other causes of subsidence, such as loading due to the sedimentary column (Bond and Kominz, 1984; Steckler and Watts, 1978), or in a basin in which the tectonic subsidence history is simple, allowing to model sea-level changes (e.g. Bond et al., 1989; Kominz and Pekar, 2001). Where tectonic subsidence can be estimated, the backstripping approach can be used to calculate palaeobathymetry and reconstruct the stratigraphy through time (Steckler et al., 1999, 1988). The process of reconstructing the development of a sedimentary column consists of several steps (Bond and Kominz, 1984). The procedure starts with the division of the stratigraphic column into increments, usually formations or groups, or as suggested here, at higher resolution, such as lithofacies, if stratigraphically correlatable surfaces are available, for which the thickness and age range can be accurately determined. Age is not considered in this study, except relative age, as the increments represent relatively small time periods (in the ∼100.000 yrs range). These "time slices" are added to the basement one by one, calculating the original decompacted thickness and bulk density and placing its top at a depth below sea level corresponding to the average depth of water in which the unit was deposited (palaeobathymetry). The isostatic subsidence caused by the weight of this sediment can then be calculated, and the depth to the surface on which the sediment was deposited is calculated with only the weight of the water as the basement load. For fluvial deposits (as for the Åre Fm.), no water is present as overburden. The second unit is then added and adjusted accordingly. The thickness and bulk density of the first unit are adjusted in accordance with the depth of burial beneath the second unit, and so on up the column (Fig. 3). Age controlled stratigraphic surfaces, such as sequence boundaries and flooding surfaces, are the ground pillar of backstripping. If available, high-resolution, biostratigraphic and/or chronostratigraphic markers are excellent surface markers to be applied in a backstripping reconstruction of a sedimentary basin. A simple model, where decompaction is a mechanical, non-reversible process, is here assumed, despite the results of Hammer et al. (2010) indicating some alteration of the grains due to diagenesis. These effects are however accordingly accounted for where they effect the compactability of the lithofacies class (see below). In a mechanical decompaction process initial porosity and compaction gradients for each lithology are necessary input data and discussed in turn below. We "restore" all the stratigraphic units in a sequence for each time step - decompacting the younger units and compacting the older ones. The calculations of the new depths for each step for each unit can be expressed as:

$$Z_n = \sum_{n}^{i=1} d_i \tag{1}$$

where

$$d_i = d_n \left[\frac{\phi_i + S}{\phi_n + S} \right] \tag{2}$$

and

$$\phi_i = k + (\phi_0 + k) e^{-CZ_i} \tag{3}$$

Z_n is the calculated burial depth of the n'th layer, d_n is the thickness of the n'th layer at depth Z_n. ϕ_0, ϕ_n and ϕ_i are initial porosity, primary porosity and porosity at depth Z_i, respectively. As shown in Fig. 4 secondary porosity, if present, must be subtracted from the porosity measurements. S is the solid grain fraction and is calculated by s = 1-ϕ_0 for each lithofacies class. ϕ_n is derived from compaction curves calculated for each lithofacies expressed by Eq.3 (Sclater and Christie, 1980) and are discussed in more detail below. C is a lithology-dependent constant calculated for each lithofacies class using Eq.3 with present burial depth, present burial porosities and initial porosities as input values. If no porosity data is available from the reservoir, C can, according to Ramm (1992), be estimated from least-square regression methods or, according to Wood (1989), be approximated from estimates of the initial porosity (ϕ_0) and the depth to half-porosity, $Z_{1/2}$. k is a correction constant for coal and equals 0.15 which is the lower limit for coal compaction. For other lithofacies classes k = 0. This correction is due to the rapid porosity decrease in peat to coal compaction where the thickness of coal (d_{coal}) would approach zero for relatively shallow burial depths (∼100m). The stepwise reconstruction of sedimentary units to the time of interest in the presented model is based on the reduction of porosity with burial depth. Numerous authors have published porosity-depth-curves for silisiclastic sediments (e.g. Athy, 1930; Baldwin and Butler, 1985; Gluyas and Cade, 1997; Hedberg, 1936; Houseknecht, 1987; Mondol et al., 2007; Paxton et al., 2002; Sclater and Christie, 1980; Velde, 1996; Wilson and McBride, 1988). Depth is, however, a poor indicator for compaction (Schmoker and Gautier, 1988), but acceptable for sediments not subjected to overpressure or to extensive chemical diagenesis. Normally pressured sediments, unaffected by diagenetic effects such as cementation and dissolution, display an exponential decrease in porosity vs depth (Sclater and Christie, 1980). This relationship, first presented by Athy (1930), has later been modified by accounting for effective stress, time and temperature (Bjørlykke et al., 1989; Ramm and Bjørlykke, 1994; Schneider et al., 1996; Walderhaug, 1996; Walderhaug et al., 2001) assessing the effect of mechanical and chemical compaction. In the present case study of the Åre Fm. in the Heidrun area with a burial depth of no more than ∼3000m and with most rapid burial during the last 3 million years (Ottesen, 2006), pure mechanical compaction is assumed, discarding the effect of chemical compactional processes. According to Hammer et al. (2010) diagenesis within the Åre Fm. in the Heidrun Field occurred locally during initial and late stages of burial. Early diagenesis resulted in variable dissolution of feldspar and mica grains from meteoric leaching in fluvial channel (FCH) or sandy bay fill (SBF) facies associations, and local early siderite precipitation in muddy bay fill (MBF) facies association. The leaching of labile grains amounts in some places up to 10% porosity units, with fluvial sandstones (FCH) being more affected than the marginal marine facies (SBF). Eogenetic siderite cement was found to represent on average 10% of the bulk volume of MBF sediments, although only a few samples are recorded from this facies association. These effects are eogenetic in origin, however, they are not considered to have influenced significantly on differential burial compaction, although it has local influence on porosity. Any effect of differential compaction would decrease in magnitude as the difference in compactability between SBF and MBF decrease. Secondary porosity may be accounted for by subtracting average values of secondary porosity from modal analysis, for the FCH and SBF sediments, respectively. For cemented layers the average volume fraction of cement is added to the average measured porosity e.g. in the MBF deposits. In many cases modification

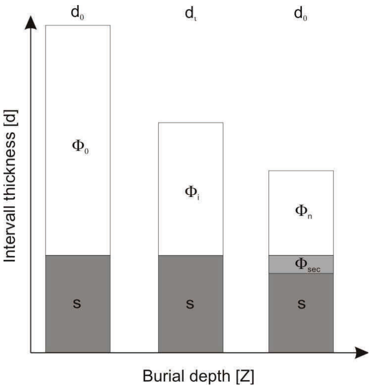

Figure 4: Sketch illustrating the interval thickness change (d) related to porosity changes with burial. Secondary porosity is not related to the mechanical reduction of pore-space and must be quantified and corrected for.

of porosity-depth trends are performed by replacing depth with effective stress that accounts for the effect of overpressure (e.g. Ungerer et al., 1990) and corrections using intergranular volume (IGV) values (e.g. Lander and Walderhaug, 1999). The use of IGV values from the sandstones of the Åre Fm. is disfavoured by the variable replacement of framework grains in cases of cementation (c.f. Hammer et al., 2010). In the fine-grained sediments, however, approximately 10% cement is corrected for in the MBF deposits. Regarding overpressure, minor pressure gradients have been identified across some flooding surfaces in the Heidrun Field, but probably not sufficient to contribute significantly to preservation of porosity.

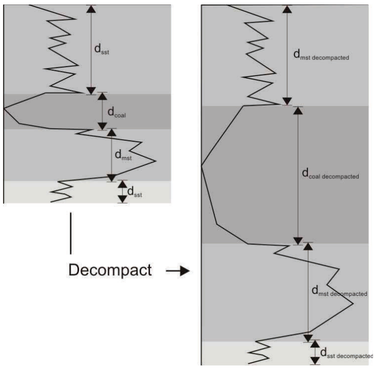

Figure 5: A conceptual sketch illustrating the principles of signal stretching. The sample interval is increased in relation to the added porosity due to decompaction whereas the sample value is retained.

4. Interactive, sample based model

The presented model is sample based, i.e. the backstripping calculation is performed for each sample in the database (15cm interval). In the present study a sample is defined as the petrophysical sample recorded at 15cm intervals which have been manually interpreted and classified according to ten identified lithofacies classes for all the seven analyzed wells. This allows us to create an interactive dataset, where surfaces can be picked at any desired sample point and decompacted accordingly. This also allows us to tie the initial sample to petrophysical wireline log data values (gamma, density, neutron porosity etc.). These values are connected to the sample point through the backstripping procedure. As the length of the sample interval is modified according to the porosity variation vs depth function (Eq. 3), the wireline data remains constant for each sample. The signal signature is thereby stretched, but with measured values retained (Fig. 5). This method thereby allows for interpretation of decompacted depositional sequences between known surfaces and in uncored intervals. The backstripping modelling process is iterative and may be repeated using additional new identified surfaces as new backstripping surfaces.

5. Application

The applicability of our model has been tested on data from the Late Triassic - Early Jurassic Åre Fm. in the Heidrun Field, offshore Mid-Norway (Fig. 6). These sediments consist of heterogeneous, fluvial to lower delta plain (fluviodeltaic) deposits comprising fluvial and tidally influenced channel sands, floodplain fines, sandy and muddy bay fill deposits in addition to coal units. Some thin (∼dm- to a few m) carbonate cemented intervals are also observed throughout the studied interval. The present study uses the Åre Fm. as a case study, due to experienced large reservoir sandstone correlation challenges. Having established a relative age model with correlation between wells based on a sequence stratigraphic framework (Leary et al., 2007; Thrana et al., 2009; Hammer, 2010), the thickness of the sediments up to surface level was reconstructed using the backstripping model (Eq. 1-3). Relative sea level changes and palaeobathymetric data have not been incorporated since the basin sediments are predominantly continental deposits.

5.1. Database

The primary data from the Heidrun Field used in the present study were obtained from petrophysical wireline logs; gamma ray (GR), density (RHOB) neutron density (NPHI) sonic (DT) and resistivity (RT), as well as core sections from four wells (Wells II, III, IV and V). These data form the basis for facies interpretation and porosity vs depth calculations in addition to identifying suitable flooding surfaces used as backstripping horizons. Flooding surfaces are here considered to represent a relatively flat landscape making them excellent datums for sequential re-burial modelling. For the backstripping procedure in the present study, ten lithofacies

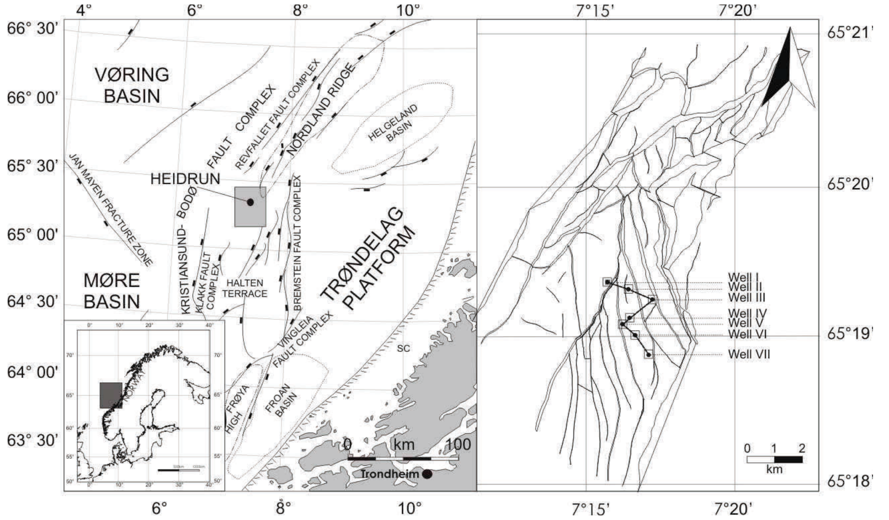

Figure 6: Left: The structural elements of the Mid-Norwegian continental shelf (modified from Gabrielsen et al. (1984); Koch and Heum (1995)) and the location of the Heidrun Field (shaded rectangle). Right: Top Åre reservoir structure (after Svela, 2001) and the location of studied wells and cross-section.

classes are introduced (Table 1). These include five facies associations identified within the Åre Fm.; fluvial channel sand (FCH), floodplain fines (FF), tidally influenced distributary channel sand (TCH), sandy bay fill (SBF) and muddy bay fill (MBF), in addition to coal and coaly units (COAL). Cemented intervals are also classified, however, due to the limited amount and occurrence within sandy intervals, these are defined as FCH. Regarding the overburden (post-Åre Fm. deposits), the sediments have been classified as undifferentiated sandstone (Undiff.sst) or undifferentiated mudstone (Undiff.mst) using the parameters specified for FCH and FF, respectively. Fault zones, recognized in well I and V, are treated as incompressible rock (ϕ=0) for the purpose of reconstructing the fault throws within the reservoir formation. Each identified fault is treated separately to take into account the respective throws. The calculation of faults is discussed further below.

5.2. Data preparation and input to decompaction calculations

As a prerequisite for facies interpretation on wireline logs, the continuous wireline logs first have to be segmented into discrete zones with similar properties (electrofacies (c.f. Serra and Abbott, 1982)) representing each of the identified lithofacies. These electrofacies constitute the elementary units of reference for inferring a correlation between wells and they are equivalent, but not identical to the lithofacies interpreted from core data. Log data are the result of indirect measurements of petrophysical responses to lithology, whereas lithofacies classification from cores are defined directly from the visible features of the rock samples. Manual interpretation of facies from well logs and core data is a labor-intensive process that requires a considerable amount of time by an experienced log analyst (Doveton, 1994). For this reason, computerized numerical procedures have thus been introduced for pattern recognition in facies determination (e.g. Moline and Bahr, 1995; Bhatt and Helle, 2002; Brandsegg et al., 2010). Facies interpretation from log data is influenced by rules that are difficult to represent by simple algorithms (e.g. tool variability, stratigraphic context, overlap of measurements, diagenetic effects etc.). For this reason, manual interpretation of combined log and core data is essential within the present study in order to achieve the necessary resolution in the model.

Table 1: Calculated and measured values for the identified lithofacies classes included in the study

Lithofacies class	C-value	Initial porosity	Burial porosity (∼2.5km)
FCH/TCH/Undiff.sst	0.000188	40	25(29)[a]
SBF	0.000239	40	22(29)[b]
FF/Undiff.mst	0.000481	60	18
MBF	0.000232	50	28[c]
COAL	0.001156	90	5
Fault	N/A	0	0
Seawater	N/A	100	100

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[a] 4% average secondary porosity
[b] 7% average secondary porosity
[c] 10% average cement

5.3. *Sandstone compaction (FCH, SBF, TCH, Undiff.sst)*

The sandstones of the Åre Fm. are relatively loose and sometimes appear unconsolidated in core sections, despite a burial depth of up to 3000m. Average porosity values from plug data representing FCH, TCH and SBF are calculated to 29% (+/- 6%). Modal analysis reveal average secondary porosity amounting to 4% in FCH/TCH and 7% in SBF, although up to 10% secondary porosity in FCH has been counted (Hammer et al., 2010). Hammer et al. (2010) concluded that only minor diagenesis has occurred in the sandstones, in most intervals limited to authigenic kaolinite precipitation due to meteoric flushing and subsequent feldspar dissolution, and eogenetic siderite cementation associated with thin (mm scale) mica and organic rich lamina. Massively carbonate cemented intervals occur in decimeter and up to a few meters thick zones in rare cases. However, these cemented intervals are thought to have little influence on the calculations due to the limited occurrence and the timing as late diagenetic precipitation (Hammer et al., 2010). Backstripping procedures are dependent on the initial values of porosity for each identified lithofacies class to be able to calculate porosity reduction during burial. Variation in porosity is a function of sorting, grain shape, and depositional processes. Many authors have published porosity data on freshly deposited sands (c.f. Table 1 in Atkins and McBride, 1992), from field measurements on sands deposited in river point bars, beaches and eolian dunes, and from sands deposited in laboratory experiments. These studies display average porosity values ranging from 39-49% for point bars, 41-47% for beaches, 39-51% for eolian dunes, and 37-45% for laboratory experiments (Atkins and McBride, 1992). Based on these data 40% initial porosity is usually assumed for moderately to well sorted sandstones (e.g. Houseknecht, 1987; Wilson and McBride, 1988), however Ehrenberg (1989) argued that their value of 40% is an unnecessary oversimplification based on the correlation between the decrease in sorting and initial porosity as demonstrated by Beard and Weyl (1973). Nevertheless, in this study 40% initial porosity is applied for the moderately to well sorted Åre Fm. reservoir sandstones.

5.4. *Fine-grained sediment compaction (FF, MBF, Undiff.mst)*

Concerning argillaceous sediments, a wide range of porosity-depth trends are published in Mondol et al. (2007). Sediments comparable to the muddy siltstones of the Åre Fm. at burial depth porosities similar to reservoir depth display values of about 18% and average initial porosity values of ∼60%. Some of these authors present initial porosities lower than 60%, which is explained by the presence of sand that reduces initial porosities. The siltstones in the fluvial part of the Åre Fm. (FF) are observed to be relatively free of sand, whereas the sediments comprising MBF deposits are more heterogeneous including both more muddy and more sandy successions. The MBF are also found to be more preferable for eogenetic siderite cementation, amouting up to 10% in some samples (Hammer et al., 2010). Initial porosity is set at 60% for FF, whereas MBF is defined lower (∼50%) and with more preserved burial porosity (∼28%) due to the early stage siderite cements compared to FF (18%).

5.5. *Coal compaction*

Peat-to-coal ratios are defined as the ratio of thickness before compaction to thickness after com-

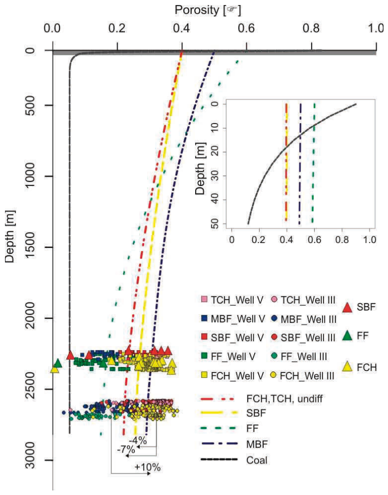


Figure 7: Compaction curves calculated for each of the main interpreted lithofacies. The calculations are based on initial and burial porosities from published and measured (plug and modal analyses) data, respectively. Note that burial porosities for curve calculations have been corrected for diagenetic effects and therefore do not match the measured porosities directly. Plug porosities from Well III and V are plotted in small symbols, porosity from modal analyses from well V are plotted in large symbols. Inset figure displays compaction trends of the first 50m of burial. At present the Åre Fm. in the Heidrun Field is interpreted to be at maximum burial depth between 2200-2900m. See Fig.6 for location of wells III and V.

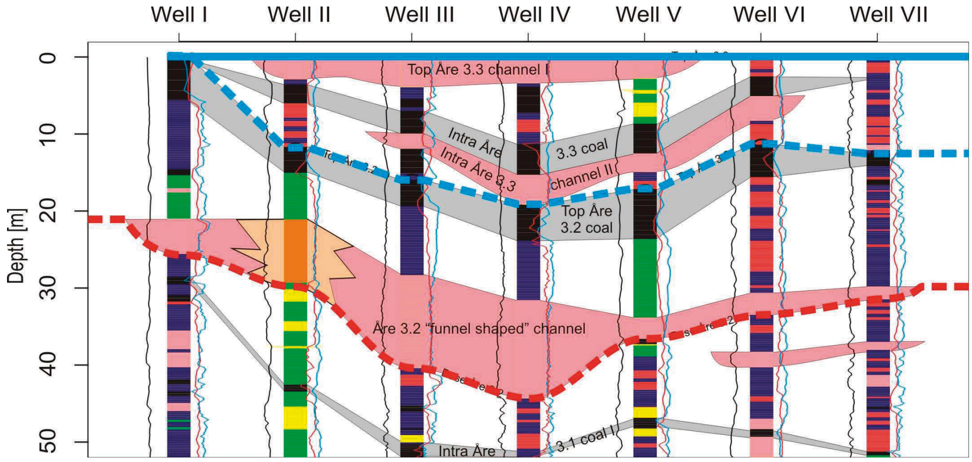
paction (e.g. Ryer and Lange, 1980). Based on a comparison between the thickness of vertical aggraded channel fills and the underlying peat deposit, a peat-to-coal ratio of 6:1 (i.e. a 83,3% volume reduction) is applied for the coals in the Åre Fm. The coals of the Åre Fm. are interpreted as high volatile bituminous coals (TOCs varying from 20% to 50% in the true coals) (Leith, T.L. pers.comm. 2009), which are reported to have a porosity of ∼5% (Rodrigues and Lemos de Sousa, 2002). The peat-to-coal ratio and a present burial porosity of 5% reveals an initial porosity value of 90% when assuming predominantly mechanical compaction has taken place during burial. This peat-to-coal ratio has been calculated by assuming that peat compaction created the accumulation space for the channel sand. This has previously been proposed by Rajchl and Ulicný (2005) for the Neogene, Most Basin, Czech Republic. Using the decompacted thickness of the sand as a measure for the original peat thickness and comparing this result to the present thickness of the coal provides an initial peat-to-coal ratio. This can, however, lead to an overestimation of the ratio based on the fact that the channel can and may have eroded parts of the underlying peat. The coal zone also displays a large variability in composition, from mudprone organic rich intervals to pure coals, and this must be taken into consideration when relating the decompacted thickness of the coal to the decompacted thickness of the sand. Concerning the timing of peat-to-coal compaction, a large part of the volume reduction is thought to occur shortly after burial, i.e. within the first meters or tens of meters of burial (Nadon, 1998) as indicated from Eq. 3 for low C-values. Based on these observations, compaction of peat is in the current study represented by an exponential decrease of porosity down to a cut-off value of about 5% related to the peat-to-coal-ratio of 6:1. In the following sections the coals are termed peat where they are discussed in the context of decompacted deposits and coals for compacted intervals. Porosity-depth-curves for different lithology composition are presented in Fig. 7.

6. Interpretation of a decompacted reservoir

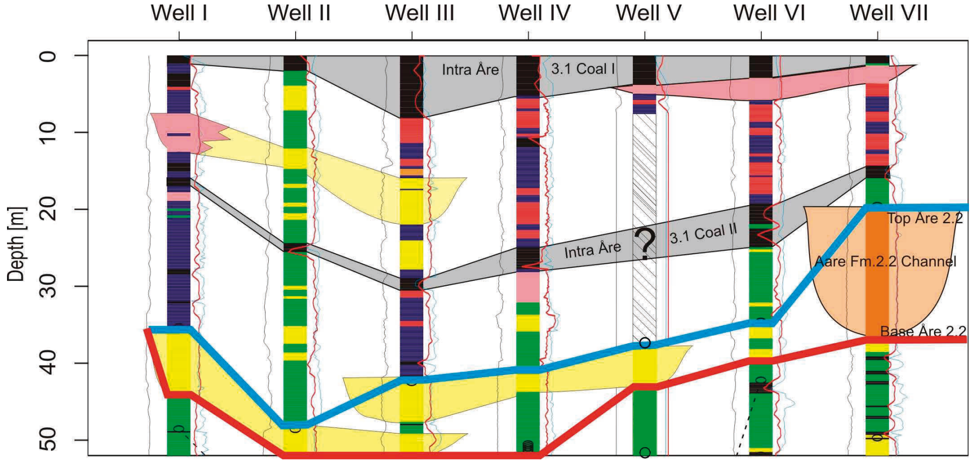
In this section a refined sequence stratigraphic interpretation, as compared to the model presented by Thrana et al. (2009) of the Åre Fm., is suggested based on correlations of six decompacted reservoir cross-sections (Fig. 8a-f), corresponding to time steps selected at known correlatable surfaces (flooding surfaces). The reconstructed units are presented in 50m thick interpreted decompacted sections representing the upper part of the decompacted sequence. The stretched wireline log data are also shown for inter-well comparison of gamma ray (GR) and neutron-density (NPHI-RHOB) log signatures. Interpretation on decompacted reservoir architecture reveals additional (inter-zonal) correlations of lithofacies, which are not part of the current sequence stratigraphic model enabling a refined sequence stratigraphy of the Åre Fm., Heidrun Field.

6.1. Correlation of Åre 1 and 2

Wells I, II, III, V and VI penetrate into the Åre 2.1 interval, whereas wells I, III and V also penetrate into Åre 1. Comparison of present and up-

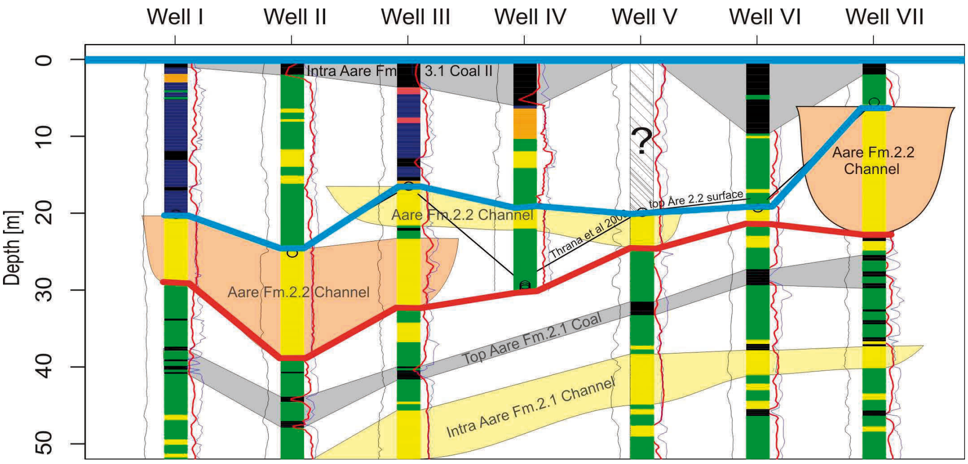


(a) Cross-section 1 showing 50m section of decompacted reservoir underlying the top Åre 3.3 flooding surface. The section suggest five correlatable units; Åre 3.2 "funnel shaped" channel sand, Intra- and top Åre 3.3 channel sandstones top Åre 3.2 coal and intra Åre 3.3 coal. GR = Black line, RHOB = Blue line and NPHI = Red line. See Fig. 6 for well locations and 8(f) for legend.

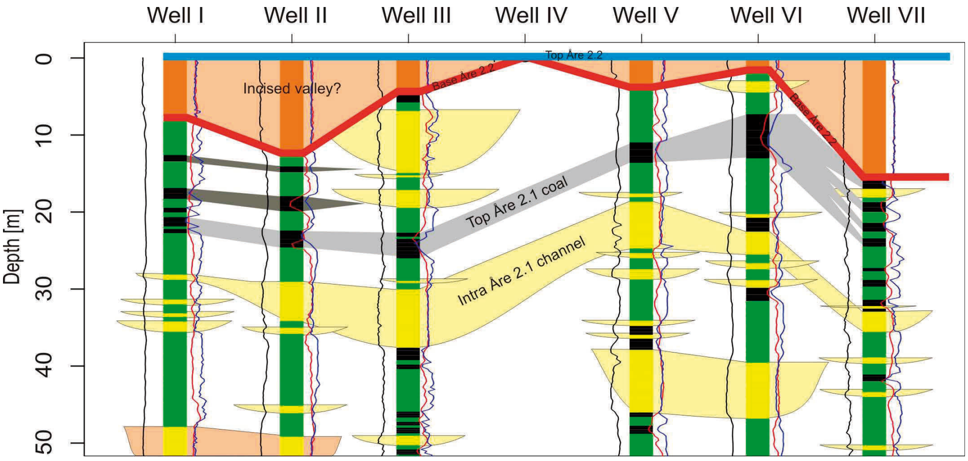


(b) Cross-section 2 showing 50m decompacted reservoir underlying the intra Åre 3.1 Coal I suggests several correlatable channel sandstones in addition to intra Åre 3.1 coal II approximately 20 m below the intra Åre 3.1 coal I.

Figure 8: continued

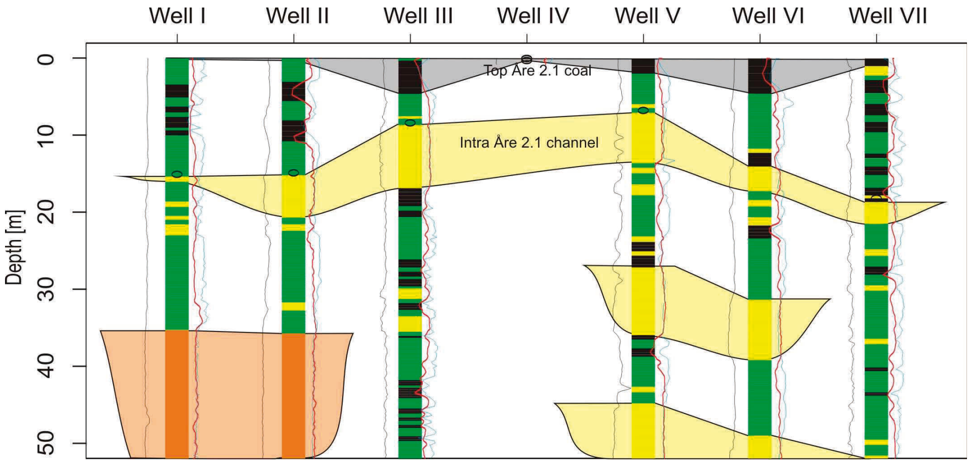


(c) Cross-section 3 showing 50m decompacted reservoir underlying the intra Åre 3.1 Coal II. The channel sands corresponding to the Åre 2.2 incised valley fill of Leary et al. (2007) is here suggested to represent a zone of increased occurrence of channel sandstones represented by several individual channel units, in contrast to one single valley fill.

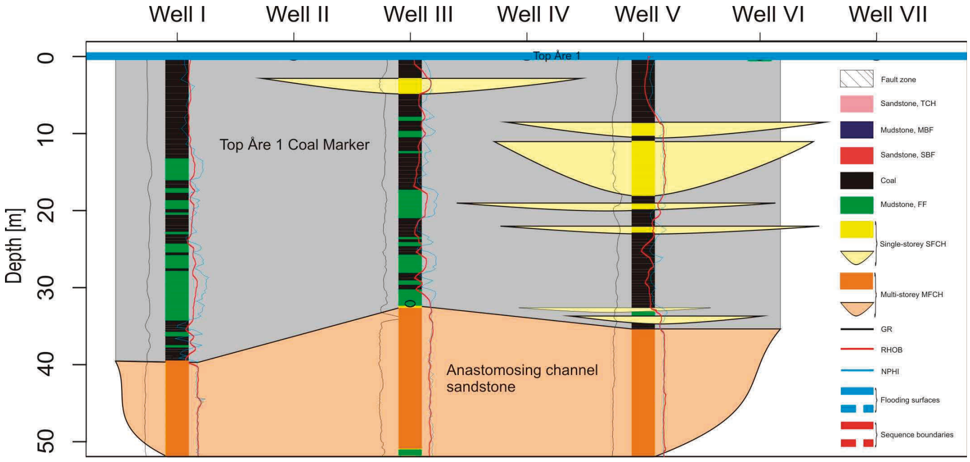


(d) Cross-section 4 showing 50m decompacted reservoir underlying the top Åre 2.2 incised valley fill (the Thrana et al. (2008) top Åre 2.2 surface). The valley fill displays large thickness variations across the studied area (total and partly faulted out in wells IV and V, respectively)). A correlatable coal is situated below this zone of increased abundance of channel sands and underlying this Top Åre 2.1 Coal, several channel sandstones are suggested correlatable (Fig. 8(e)).

Figure 8: continued



(e) Cross-section 5 showing 50m decompacted reservoir underlying the top Åre 2.1 coal. Three possible correlatable FCH sandstones and one correlated anastomosing FCH sandstone are suggested. In particular the uppermost channel sandstone (Intra Åre 2.1 channel) seems to have a lateral continuity extending all six wells penetrating this interval.



(f) Cross-section 6 comprising the Top Åre 1 Coal Marker. A correlation of MFCH deposits in wells I, III and V is suggested. The cross-section is interpreted as parallel to palaeoflow direction (south east) as these sandstones are suggested to represent anastomosing channel deposits indicating limited channel widths.

Figure 8: Reconstructed cross-sections of 50m decompacted intervals from Wells I-VII. Key sedimentary units are interpreted. See Fig. 8(f) for legend and Fig. 6 for location of wells.

dated correlation of the Åre 1 to Åre 3 is presented in Figs. 10 and 9

One coal zone has been mapped on seismic and correlated in all the wells penetrating this lower Åre interval, representing the top Åre 1 coal marker (Fig. 2). The zone ranges from a >15m relatively pure peat deposit overlying a >20m interbedded sequence of FF and peat in Well I, to a thick unit (several 10s of meters) of interbedded mudstones and peats, including a thin FCH sand deposit, in Well III (Fig. 8(f)). In Well V the sequence is dominated by ∼ 10m peats and thicker fluvial sandstones. By applying this flooding surface in our model, a lower channel feature appears as correlatable between wells.

The sandstones comprise up to ∼30m thick, vertical aggraded, fluvial channel sandstones underlain by a thick coal rich unit (Fig. 10). Svela (2001) interpreted these channel sandstone deposits as incised valley fill, suggesting a relative sea level fall prior to or during deposition. However, based on the presence of thick underlying peat deposits, a factor of compaction controlling sand deposition must have occurred and that autogenic rather than allogenic factors dominated during the deposition at this time. These peats, when compacted, created accommodation space for the channel sands to be deposited (i.e. Rajchl and Ulicný, 2005), i.e. autogenic controlled channel sand deposition promoted vertical accretion in an anastomosing channel environment.

From the well data used in this study, a change from the thick, multi-storey channel sandstones, to deposition dominated by single storey channels is observed going from Åre 1 to Åre 2.1. This is the opposite of what is observed on field scale where channel sands are thinner and less abundant in Åre 1 compared to Åre 2.1, with a NTG of ∼ 30% in Åre 1 compared to ∼ 40% in Åre 2.1. However, an increase in correlatable channel sandstones is, nevertheless, observed from the decompacted cross-section in Figs. 8(d) and 8(e) in Åre 2.1. This increase in correlatability of channel sandstones, and the fact that NTG increases from Åre 1 to Åre 2.1, may be related to a decreasing base level rise and subsequent fall. A base-level fall has been suggested for the overlying Åre 2.2 incised valley by Svela (2001). If a base level fall occurred at that time, then the underlying top Åre 2.1 sediments may represent late highstand deposition which would explain the presence of increased abundance of laterally extensive channel sandstones.

A zone rich in peat deposits occurs in the uppermost part of Åre 2.1, which is correlated in the studied wells. The zone is in a way similar, although thinner, compared to the coal zone occurring in Åre 1 (i.e. Fig. 8(d)). This could suggest that this zone represents a short period of increased base level rise and may therefore be interpreted as a local flooding surface. However, the zone is hard to correlate, especially in the bounding wells (well I and VII) and therefore not added as a flooding surface in Fig 2. Applying this surface as a backstripping surface reveals a possible correlation of four channel sandstone bodies (i.e. well Fig. 8(e)) of which the uppermost unit is correlated across the entire cross-section. These correlatable units are not part of the Thrana et al. (2009) reservoir zonation model for the Åre Fm. We suggest that these sands report, at least local, base level change and shows potential as possible reservoir flow units if they are truly lateral extensive.

In the uppermost part of the Åre 2, several significant channel features appear. Some of these channel sands represent laterally and vertically amalgamated river deposits, possibly braided (C. Thrana, 2008, pers.comm), corresponding to the Åre 2.2 reservoir zone of Leary et al. (2007) (i.e Fig. 8(d) and 8(c)). The unit is up to 15m thick in the studied wells and comprises individual channel sands on average 2-8m thick. This feature has been interpreted as an incised valley fill by Svela (2001) or a significant channel feature present across most of Heidrun Field area (Leary et al., 2007; Thrana et al., 2009) suggesting a base level fall during/prior to deposition. A sequence boundary was therefore interpreted at the channel base. However, as seen from correlation of decompacted reservoir sequences (i.e. 8(c) and 8(b)), this interval seems to comprise several separate channel features, in contrast to one significant incised valley fill or channel feature. Lateral and vertical amalgamation of channel fill does indeed occur within specific channel features and may represent more localized incision and subsequent filling. The increase in the abundance of channel deposits upwards in the Åre 2.1 and into Åre 2.2, together with the appearance of several correlatable channel deposit at the top of the unit suggest that the base level rise was decreasing and that these sediments therefore represents highstand or late highstand deposits.

As the valleys filled with sediments, the constraint on the river by the valley topography was suspended, enabling channel accretions onto the interfluves, consequently significantly decreasing the channel width to floodplain width ratio. The base-level increased, changing the controlling factors from predominantly allogenic to autogenic and, thus river style. The upper boundary of this unit is therefore interpreted as a flooding surface, marking a level of change in fluvial style in the sediments, from braided back to single story, meandering type deposits.

6.2. Correlation of Åre 3

The unit comprises sediments dominated by floodplain fines and single storey channel sands (some showing evidence of tidal influence) and bay fill deposits including both SBF and MBF. Marine influence, represented by SBF, MBF and TCH deposits, increase upwards. A tendency of more abundant and thicker fluvially derived sediments is observed in the central parts of the cross-section (Figs. 8(a) and 10), within zones Åre 3.2 to 3.3. Tidal influence increases upwards in the Åre 3 stratigraphy and towards the southeast, possibly indicating a retrogradational palaeocoastline in the southeast as earlier proposed.

A significant channel feature, up to ~20m thick, with a distinctive fining-upwards profile ("funnel shaped" signature of the abandonment phase on combined neutron porosity (NPHI)-density (RHOB) logs) capped with coal, is striking within this interval and is correlatable in all the studied wells. This channel thins towards the southeast and northwest. In areas where the main channel sandstone is thin (only a few m) as in Wells I, V, VI and VII, the channel termination phase is observed to comprise more abundant ~m scale sandstone units (crevasse channel) deposits. This could indicate that the palaeo channel developed along preferred courses, represented by the thicker channel sandstone units, such as in wells II, III and IV. The sand rich termination phase above represents an area close to these main channels, which are subjected to steady influx of crevasse sands during floods. This may also be suggested for the Top and Intra Åre 3.3 channel, although thinner as compared to the Åre 3.2 unit. In addition, the laterally correlatable coals representing Top Åre 3.2 and Intra Åre 3.3 appear thicker in the central parts of the cross-section which may suggest that the coals controlled the preferred course of the channels and subsequent channel sand deposition. The Åre 3.2 channel succession is always capped by coal in the studied wells which is interpreted to represent a local flooding surface.

Below this channel another coal interval appears and may possibly represent a local (not necessarily field-wide) flooding surface, probably originating from autogenic delta lobe switching (e.g. Emery and Myers, 1996). Using this surface as datum enables correlation of a third coal interval and two suggested correlatable channel sandstones (Fig. 8(b)). Although these correlations are uncertain, the stacking pattern reveals a reservoir architecture dominated by single storey channel deposits where some might be correlatable between wells. The upper boundary of Åre 3.2 is represented by up to a few m thick peat (now coal) deposits. This unit has been identified and correlated in central parts of the Heidrun Field (i.e. Fig. 8(a)) and is here interpreted as a local candidate flooding surface .

The central parts of the Åre 3.3 unit are sandier compared to the marginal parts, comprising relatively thin, possibly laterally extensive, single storey fluvial channel sands (i.e. Fig. 8(a) and 8(b)). A peat interval a few meters thick occurring in the middle part of the unit appears similar to the top Åre 3.2 coal and thinning towards the southeast. The lobate shape of this Åre 3.3 succession, as seen in cross-section, is somewhat distorted by a fault in well I (not seen on cross-section). Nevertheless, a depositional environment controlled by delta lobe switching is suggested as the main controlling factor during deposition, based on the geometries and stacking pattern of the facies associations, where compaction of peat to coal may have played an important part.

Compared to fluvially originated peat swamps, coals deposited in interdistributary bays are thought to have a greater lateral extent suggesting higher correlatability within such coals. These coals may have extended the total width of the bay, suggested by Kjærefjord (1999) to be 2-7 km wide in the Heidrun field, which is sufficient for good well-to-well correlatability with the current well spacing (<~1 km). A regionally correlatable, well defined bay fill succession defines the upper boundary of this unit and is interpreted as a candidate flooding surface by Leary et al. (2007). It has a distinct signature on wireline logs and is correlatable throughout the Heidrun field.

The Åre 3 reservoir zone shows sediments deposited in a transgressive environment as fluvial deposits below are gradually replaced by marine influenced bay fills and distributary channel sandstones.

The unit is relatively heterogeneous, dominated by thin beds of sand, silt and coal interpreted to be deposited in the transition zone between a fluvial and marine influenced delta plain environment, including fluvial channel sands, crevasses, lacustrine muds, paleosols and bay fill sediments.

A reservoir architecture interpretation of the Åre 1 to Åre 3 based on published and identified correlatable surfaces from this study is presented in Fig. 10.

7. Discussion

Due to the heterogeneous nature of the Åre 1-2.1 reservoir zones, correlation of channel sandstone bodies on wireline log data alone may be treacherous territory. Much effort has therefore been put in investigating methods to enhance inter-well interpretation on sub seismic scale in heterogeneous reservoirs (i.e. Stovas, 2007; Doveton, 1994). None of these methods, have, however, applied palaeoflat surfaces in a decompaction routine on wireline log scale.

As noted previously, backstripping, sensu sticto, is traditionally applied for basin reconstruction and therefore not directly applicable to reservoir scale reconstruction. Presented here is a reservoir reconstruction taking into account effects of differential compaction on intra-reservoir scale. Estimation of decompacted reservoir lithofacies classes using the backstripping approach on high resolution petrophysical data and interpreted flooding surfaces has shown to increase the correlatability of heterogeneous reservoirs by considering and removing the effect of differential compaction. This is in particular the case where highly compactable sediments, such as coals and muds, are present, such as in the lower Åre Fm in the Heidrun Field.

The presented model suggest several correlations of depositional units between known correlatable surfaces. No proof of actual connectivity exists, such as by pressure support indications. However, as the palaeo flow direction is fairly certain, indicating channel orientation towards the southeast, in addition to relatively closed spaced wells (<∼1km apart)(i.e. Fig. 6), correlations performed on decompacted reservoir architecture seems fairly valid, especially for the upper most part (<50m) of decompacted cross-sections. On the other hand, parts of individual meandering channels may flow perpendicular, or even opposite, of main palaeoflow directions which should be taken into consideration when doing correlation exercises.

Improvements regarding reservoir unit correlations are suggested within Åre 1, 2.1, 2.2 and 3 reservoir zones. Especially for the top Åre 2 (top 2.1 and 2.2) where a new interpretation of the channel sandstones is suggested. The intra Åre 2.1 channel sandstone (i.e. 8(d)) is suggested correlatable in all the studied wells. However, as the shape of the unit (in cross-section) seems to follow the base of the Åre 2.2 incised valley fill, one could argue that if the Åre 2.2 is truly an incised valley, less correlation between the shapes of the underlying 2.1 channel compared to the base of the valley should be expected. Also, based on the decompacted reservoir sections presented, several individual channel features replace the old single incised valley fill interpretation. Incision may still have occurred, however, on a smaller scale than previous works indicate. Both scenarios do, however, still conclude that base-level changes was the driving mechanism for this change in depositional style. For Åre 3, several additional interpreted horizons are identified, which enable a refined interpretation of the depositional environment for this reservoir zone, at least in the central parts of the Heidrun Field.

As discussed earlier, a relationship between channel sand deposition and compaction of peat-to-coal is suggested for some of the vertically aggraded channel sandstone successions. This is exemplified by the significant channel features in Åre 1, occurring in wells I, III and V, interpreted to represent anastomosing channel deposits. Anastomosing rivers comprise relatively narrow features with a low width-to-depth ratio (c.f. Nadon, 1994). With a well spacing of up to a kilometer apart, a correlation of the Åre 1 channel sandstone suggests that the cross-section is oriented along the palaeoflow direction, i.e. towards the southeast. This is supported by provenance studies of Early Jurassic rocks in the Heidrun Field, where Morton et al. (2009) found that the fluvial parts of the Åre Fm. have been sourced from a westerly source area. In addition, Thrana et al. (2009) also concluded with a southeastern palaeoflow direction based on lateral facies shifts within the Åre 1-2.1 zones.

As suggested from the decompacted sections in Figs. 8(a) and 8(b), an autogenic signature due to delta lobe switching is revealed within the Åre 3.3 reservoir zone. The lateral distribution and vertical stacking of facies associations within this zone suggests delta lobe switching was active in the study

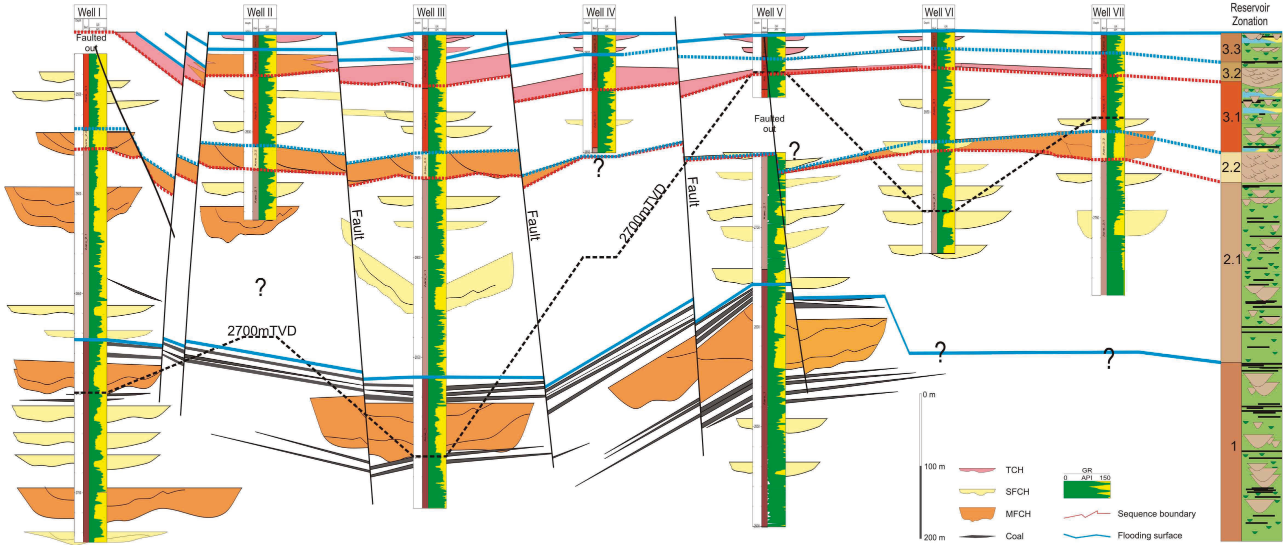


Figure 9: Present correlation of the Åre 1. 2 and 3 reservoir zones in the seven studied wells. Note no correlation of the Åre 1 channel feature is proposed in earlier works although interpreted as incised valley fill. Also note the Åre 2.2 unit which comprise only a single channel feature across the Heidrun Field.

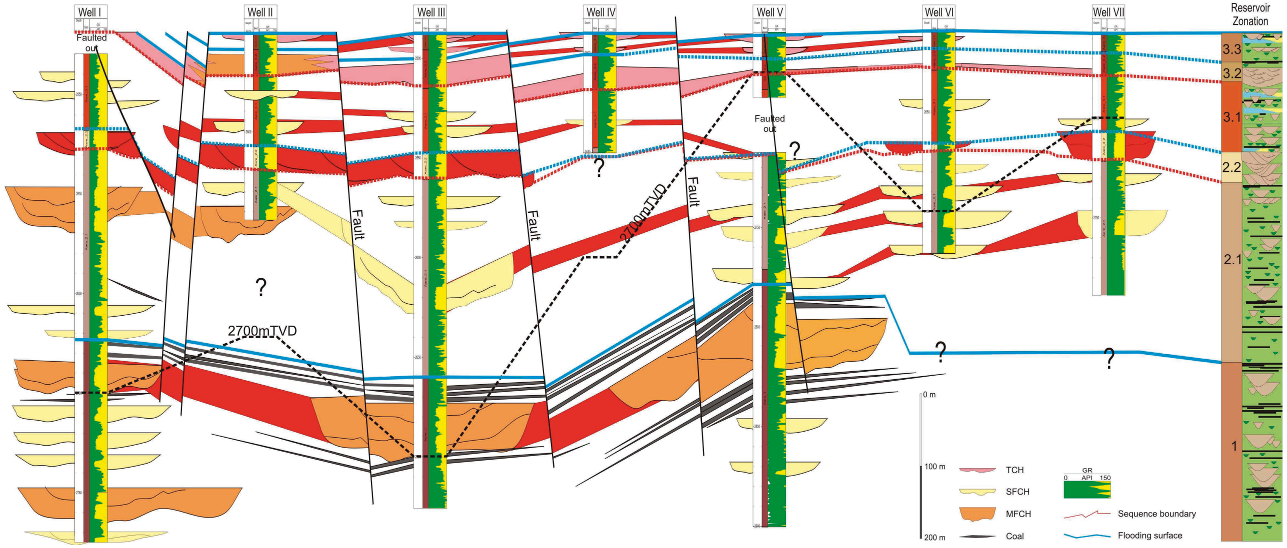


Figure 10: Updated correlation (red color) of the Åre 1. 2 and 3 reservoir zones in the seven studied wells based on correlation on decompacted reservoir sections. Published surfaces together with interpreted flooding surfaces, seen as correlatable coals, enable identification of correlatable channel sandstone units within top Åre 1, Top 2.1 and Åre 2.2, Intra Åre 3.3 and top Åre 3.3. Note the Åre 2.2 unit comprising several individual channel sandstone units. (See Figs. 8(f) to 8(b) for closer reference.)

area during deposition. The thickening of the reservoir units towards the center of the cross-sections and thinning towards the southeast seems to correlate well with the thickness of the top Åre 3.2 and intra Åre 3.3 coals. A relationship is therefore suggested between compaction of peat and deposition of sand. In addition, as the Åre 3.2 funnel-shaped channel also follow this trend of thickening towards the central parts of the cross-section, the weight of this sand may have created a focus point for subsidence in this area, evidently resulting in the peat distribution seen above.

The correlatable channel sandstones corresponding to intra and top Åre 3.3 may comprise the proximal part of individual prograding delta lobes, whereas the coals represents abandonment. As seen from the cross-sections a possible lateral shift towards the northwest of the main delta depocenter is inferred by the more westerly oriented top Åre 3.3 channel compared to the intra Åre 3.3 channel where the underlying top Åre 3.2 and intra Åre 3.3 coals controlled the preferred course of the channels and subsequent channel sand deposition.

The effect of differential compaction on correlatability is accounted for by correcting for the compactability of interpreted lithofacies classes by differential decompaction and by applying flooding surfaces as backstripping surfaces in a sequence stratigraphic backstripping exercise.

In addition to magnitude, timing of compaction is equally important, especially for coal rich fluvial deposits as the bulk of volume reduction in peat deposits occurs in the earliest phases of burial (first few meters) (Nadon, 1998). As observed in the Åre Fm. fluvial succession, several types of fluvial channel deposits occur. Single storey channel sands dominate, of which some are suggested correlatable between wells. Anastomosing channel sands are present in the lowermost unit and occur regularly above thick peat deposits (e.g. Fig. 8(f)). The presence of the underlying peat, in addition to the lower lateral extent of these units as compared to the upper Åre 2.2 sand, suggests that these sands are vertical accreted channel deposits where the compaction of peat created the accommodation for sand deposition. The unit Åre 2.2 sand, on the other hand, is regional, laterally correlatable over a 2km distance within the study area and varies in thickness from 3-34m, with a typical thickness of 10-15m. The unit is thinning towards the southeast and west with greatest thickness in the northwest. However, in some wells (i.e. Well V) the unit is missing due to normal faulting related to consecutive divergent tectonic activity in the study area (c.f. Fig. 6).

Due to tectonic activity, several faults have been interpreted in the studied wells, represented by missing sections in cross-section with length equal to the interpreted missing sediment thickness (compacted). The unit thicknesses in the reconstructed reservoir seem fairly uniform in un-faulted parts, increasing in thickness where faults are present. Keeping in mind that the cross-section represents partly decompacted sediments and that the thickening due to fault reconstruction would increase further during burial, leads us to imply an overestimation of the fault throws in the Åre Fm. This overestimation may be as much as 20m in the largest faults which is a significant amount, especially when vertical thicknesses of the reservoir sands in the fluvial part of the Åre Fm. usually are below this value. The basis for calculation of compactability and compaction rate for the lithofacies classes used in this study is porosity and rate of porosity change with depth. A basic requirement was therefore to discriminate between the different lithofacies classes. Due to long distance between source and receiver of some of the wireline logging tools, un-

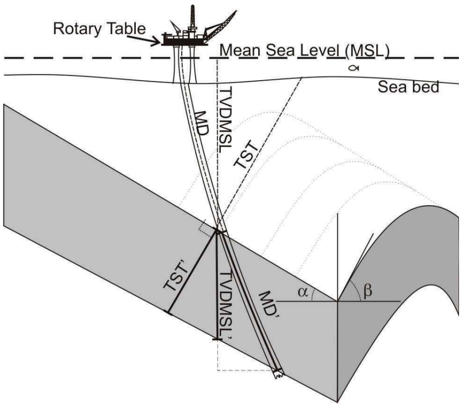


Figure 11: Sketched definitions of TST, TVDMSL and MD. TST is calculated based on TVD and the azimuth (α) and the dip angle (β). Thickness of the selected reservoir unit is MD', TVDMSL'or TST'. For vertical wells, TVDMSL'=TST=MD'. For wells with reservoir dip in the same direction as well dip: TST<TVDMSL', for opposite dips, TST>TVDMSL'. Note MD measured from rotary table, TVDMSL from mean sea level (MSL) and TST from sea bed.

precise petrophysical signature recording of specific geologic layers may occur. However, as the Heidrun Field is a mature hydrocarbon area, multiple relatively closed spaced wells, some of which are cored, are available. This creates the opportunity of reducing this bias effect by applying sedimentological log interpretations from core section in the lithofacies class interpretation process.

The lithofacies classes are derived from observations and interpretations of cores tied to specific wireline signatures. However, when core data is unavailable, methods such as principal component analysis (PCA) may be used by combining separate PCs derived from different lithological intervals to detect higher order heterogeneities that corresponds to small scale lithological variations within the lithofacies classes (c.f. Brandsegg et al., 2010).

Porosity variation vs depth is in the present study defined as an exponential decrease in porosity with depth (c.f. Eq. 3), where the degree of decrease is dependent on the facies association classification and the depositional (initial) porosity of the sediments. It has been widely argued that the exponential porosity-depth relationship does not fit shallower depth data particularly well (Falvey and Middleton, 1981; Falvey and Deighton, 1982). Falvey and Middleton (1981) proposed an alternative relationship by assuming incremental change in porosity is proportional to change in load. However, no explanatory reason is given for this improvement. However, the Sclater and Christie (1980) model has been successfully applied to calculate land subsidence rates due to early compaction in the coastal areas of the Netherlands (c.f. Kooi, 2000).

Exponential decrease in porosity vs depth may on the other hand be an oversimplification as errors are introduced due to e.g. overpressure (as discussed above) and diagenesis (cementation, dissolution), which may modify the pore space in the rock. These errors may be small for each effect; however the sum could be significant and influence the correlatability of the reservoir. It is therefore important to investigate the presence of diagenesis (e.g. Hammer et al., 2010) and overpressure before a backstripping routine is applied. Secondly, the determination of initial porosity is based on published values for different lithologies (c.f. Beard and Weyl, 1973). The initial porosity of the sand and silt of the Åre Fm. is not known, however, values are estimated based on comparison with published data and grain size, sorting, angularity and sand purity in the sandy deposits of the Åre Fm. Mudstones are on the other hand a larger source of error as these calculations are entirely dependent on published porosity-depth-curves. Third, coal compaction is determined by peat-to-coal ratios and published burial porosities. Coals may vary significantly from well to well and from interval to interval. This is exemplified in the text with coals varying from true "coal" to coaly units interbedded with sand and silt, which would reduce the compactability of the unit. However, as the calculations are based on direct indicators for peat-to-coal-compaction and the coals in the Åre Fm. are generally a mixture of coal, silt and sand, the presented values seems fairly valid.

In an optimal backstripping routine it is customary to use the true stratigraphic thickness (TST) to avoid errors due to inclined reservoir units caused by folding, faulting etc. (Fig. 11). The tilt on the stratal units from the studied interval in the Heidrun Field due to the tectonic history of this region (Blystad et al., 1995; Brekke et al., 2001; Bukovics et al., 1984; Bukovics and Ziegler, 1985; Dooley et al., 2003; Doré, 1991; Gjelberg et al., 1987; Schmidt, 1992; Swiecicki et al., 1998), should be accounted for and is traditionally included by using true stratigraphic thickness (TST) during backstripping. We are however using true vertical depth mean sea level (TVDMSL) thicknesses. The wells used in this study are near vertical wells and the difference between TST and TVDMSL is small (2% in average, reaching a maximum of 6% in Well IV). TVDMSL is also used because it is measured continuously throughout the well which is a neccessary criteria in a sample based model, as compared to TST thickness which is only measured for each reservoir zone. To investigate the intra zone architecture we are therefore compelled to use TVDMSL data. A third argument is that TST is a calculated thickness based on angle of dip and asimuth of the layers. Small errors in these values can lead to significant miscalculations of the TST thickness.

A major advantage in the presented model is the sample based decompaction routine. Any selected sample point (15cm interval) can be used as a potential datum (backstripping surface) and decompacted accordingly. This allows for a more interactive role for the user in the decompaction process. The petrophysical parameter values are retained from the original sample values making lithological interpretation between identified surfaces and in uncored wells possible at any desired level. New correlatable surfaces identified after decompaction can be used and implemented in the model and a new backstripping is modelled using the previous and the new surfaces as datums. This process is then repeated for any new surfaces identified to increase the correlation resolution after each iteration. In the present study each sample has been assigned, by observation and interpretation of core and wireline logs, to a specific lithofacies (1-9). This gives us the possibility to work with resolutions far beyond that of traditional backstripping. By using these available high resolution data in the backstripping process, we are able to reconstruct the reservoir architecture, as regards to decompacted facies distributions. This will potentially increase the productivity of such reservoirs by increasing the understanding of reservoir sand connectivity.

7.1. Recommendations

The technique described in this study can be applied to refine reservoir models, based on correlation of decompacted sediments, and implemented in a process-based modeling tool (e.g Nordahl et al., 2005). Simulation of permeability distribution and fluid flow by such modeling tools, and comparing the results to real production data (history matching) has the potential of optimizing production and increasing recoverable reserves by enhanced hydrocarbon flow prediction. It would also be beneficial to test this methodology on other fluviodeltaic deposits with less faults and other depositional environments in general, to test the robustness of our quantitative, sequential re-burial modelling tool. Furthermore, applying additional, and perhaps more refined, methods for reservoir subdivision, as exemplified by a study done by Morris et al. (2003) on interpreted sequence stratigraphy based on megaspore assemblages within the Åre Fm. in the Heidrun Field, shows potential and could have been added and tested in further studies.

8. Conclusion

A method for sequence stratigraphic backstripping in heterogeneous fluviodeltaic deposits is proposed which explicitly models stepwise deposition at intra-reservoir scale using lithofacies classes derived from wireline logs and core data.

Differential decompaction is calculated based on porosity change vs. burial depth for each identified lithofacies class and incorporated in the backstripping model. The presented model is sample based and measured values of petrophysical parameters are kept constant while relating the sample thickness change to changes in porosity with burial depth (decompaction). This enables interpretation and correlation of depositional units between known correlatable surfaces and different depositional scenarios can be evaluated. In particular, this can be valuable in reservoirs comprising highly compactable sediments, such as coals.

The effect of differential compaction on correlatability is accounted for by correcting for the compactability of interpreted lithofacies classes by differential decompaction and by applying flooding surfaces as backstripping surfaces in a sequential re-burial exercise.

This methodology was successfully tested on the fluviodeltaic Åre Fm. in the Heidrun Field. Several channel sandstones within the Åre Fm. are suggested as correlatable between wells. These correlations would be important for reservoir property modelling and drainage strategies, especially for the studied central area of the Heidrun Field. We also suggest a re-evaluation of the Åre 2.2 channelized reservoir unit as a channel dominated interval comprising several individual channel deposits, where of some are correlatable between wells, derived from decreasing base level rise.

Improving the reservoir sequence stratigraphic resolution strengthen the robustness of the reservoir geomodel and improved history matching. This methodology therefore has the potential as a decision making tool for hydrocarbon production optimalization. This would also benefit HC volume calculations of reservoir sections which are an important part of field economics.

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Appendix E

E Characteristic analysis -GIS and petroleum exploration risk

Sinding-Larsen, R.[1,2], Brandsegg, K.B.[1]

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Characteristic Analysis – GIS and Petroleum Exploration Risk

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1. Abstract

The GIS environment offers the exploration geologist a wide variety of options for integrating regionalized geodata. The full power of the methodology of Characteristic Analysis introduced in the eighties can now be exploited by means of GIS support. The characteristic analysis method uses cell based ternary coding to express both favorable and unfavorable conditions in addition to the situation where the controlling effect of an attribute is unknown or the occurrence is unevaluated within a cell. Favorability is computed by a weighted linear combination of ternary attributes using a special significance probability metric for selecting cells and variables. This paper will demonstrate the characteristic analysis metric and show how the derived favorabilities can be used to evaluate exploration risk on the Halten Terrace.

2. Introduction

Characteristic analysis (CA) is a multivariate technique that has been used successfully in identifying exploration targets for a wide variety of deposit types (McCammon et al, 1983, Brandsegg and Sinding-Larsen 2005). Since CA was proposed several new methods have been developed to improve prediction capabilities of the favorability function primarily based upon maximizing the correlation between the favorability function and target attributes or by using weight of evidence modeling approaches. However, none have fully exploited the original idea of CA using a target model based on the significance probability of the observed co-occurrence frequencies of ternary coded attributes within target model cells. The GIS version of the CA workflow presented includes options for the selection of regional cells suitable for characterizing different trapping models, the selection of variable that constitute the models and the choice of logical combinations of variables that best represent these models.

3. Data Transformation

In earlier applications, the data used in CA were transformed into binary form, 1 meaning favourable and 0 meaning unfavourable or unevaluated. In order that the two states represented by 0 could be distinguishable, the data were transformed into ternary form. 1 meaning favourable as before, -1 meaning unfavourable, and 0 meaning unevaluated. If data are missing, no assignment is made. The data for each variable are transformed into ternary form prior to CA of any area that has been divided into regional cells by use of ArcGIS. The manner in which this transformation is performed depends upon the nature of the exploration model and the nature of the data. From the original vector map, different fault trends were extracted into three separate vector maps. These vector maps were rasterized by a 1km by 1km pixel size.

4. Logical Combinations of Transformed Variables

In CA, the favourability f of a given cell is defined as a weighted linear combination of the ternary-transformed variables, that is

$$f = a_1x_1 + a_2x_2 + \ldots + a_nx_n \qquad (1)$$

where the a_i (i = 1, 2, …, n) represented the weights and the x_i (i = 1, 2, …, n) represented n transformed variables. However, an experienced explorationists commonly has prior knowledge of different logical combinations of variables using AND, OR and NOT combinations that are judged to be favourable (or unfavourable) with respect to particular models. Consequently, the $x_i s$ in (1) have been extended to include not only ternary-transformed variables but also logical combinations of ternary-transformed variables. The capacity to construct logical combinations of ternary-transformed variables enhances the result obtained by using CA as demonstrated in the current application and the regional results outlined by Brandsegg and Sinding-Larsen (2005).

5. Model Generalization

Most exploration models are based primarily on observations or measurements taken in and around known accumulations. It is presumed that similar observations or measurements in unknown areas are likely to reflect similar conditions and, therefore, are likely to be clues to favourable target areas. The degree of match between a set of observations or measurements in an unknown area and the observations or measurements that define a model forms the basis of "characteristic analysis". As noted, a model is generally defined by a selected set of ternary-transformed variables in areas of known interest e.g. where exploration wells have been drilled and trapping assumed to be adequate. The weights, a_i, in (1) are determined by solving the matrix equation

$$(X'X)\, a = \lambda a \qquad (2)$$

where λ is the largest eigenvalue of $(X'X)$. X is the $m \times n$ matrix of observations of n ternary-transformed variables (or combinations) for m selected cells that comprise the model. The $a_i s$ are the elements of the eigenvector a associated with λ and are scaled such that f in (1) lies between -1 and +1. The solution in (2) is equivalent to maximizing

$$\sum_{i=1}^{n} \frac{f' x_i}{f' f} \qquad (3)$$

The maximized value is a measure of the overall similarity of the expression in (1) to the values for the ternary-transformed variables in the model.

For a cell outside the model area, the favourability is determined using (1). Values of f close to 1 indicate high degrees of match with the model. Values of f close to -1 indicate a low degree of match with the model. Values of f close to zero indicate neither a high degree nor a low degree of match, and are judged to be neutral.

A problem that arises in model definition is cell selection. Most often, the cells selected are those that contain conditions of the type being considered. Because a trap usually has unique features, the data used to define a model are overly restrictive in the sense that data from other areas are unlikely to match them closely. Consequently, a model should be generalized by the inclusion of regional cells that do not contain wild-cat wells even if they are within a prospective zone. The following is a generalization procedure. Consider k cells that contain exploration targets. For n ternary-transformed variables, a model can be defined using (2). Suppose now that (1) is applied to other cells within a larger area and that l of these cells are determined to have the same or a greater degree of match with the existing model than the k cells have. A question that can be asked is whether this degree of match is due purely to chance or whether a significant relation exists between these cells and the cells that comprise the model. The question can be answered by considering the matches among the ternary-transformed variables for the $(k + l)$ cells. For each such variable, the value is 1, 0, or -1. Thus, for each variable for $(k + l)$ cells, there is an ordered array of $(k + l)$ 1's, 0's or -1's, for example, $\{1, 1, 0, -1, \ldots, 1\}$. For two variables expressed as vectors **u** and **v**, the number of nonzero matches m can be expressed as $m = u'v$. If the assumption is made that the observed sequences of values contained in **u** and **v** could have occurred in any order, it is possible to determine the probability that the observed number of matches is not a chance occurrence (the expression for this probability is given in McCammon et. al. 1983). If this probability is high, the two variables have highly similar patterns of occurrence (or non-occurrence). If the probability is low, the two variables have highly dissimilar patterns of occurrence (or non-occurrence). Consider now an $n \times n$ symmetric matrix P that contains these probabilities and that contains unity along the main diagonal. P can now be substituted for $X'X$ in (2), and a set of weights, a_is, can be calculated. The degree of match f is calculated for the $(k + l)$ cells, and those p cells having the highest values are selected as the cells of a generalized model. In this way, a model is defined that is not restricted in its application by the unique features of exploration targets.

6. The Halten Terrace

In this paper, an application of characteristic analysis to the pre-rift Halten Terrace play on the Mid-Norway continental shelf is presented, focusing on trap models and the choice of transformations applied to published fault data. The major reservoir is the Lower-Middle Jurassic shallow marine sands, which has two major source units, a gas/condensate-prone Upper Triassic-Lower Jurassic coal unit, and Upper Jurassic oil-prone black shale . Since 1997 the Lower and Middle Jurassic play of the Halten Terrace has seen a number of discoveries. The distribution of fields and discoveries is displayed in Fig.1. The regional fault data for the Halten Terrace were coded into 17 000 regional cells measuring 1km on a side. In this paper, only one sub area containing 4000 regional cells has been considered (Fig. 1). Of the original 3 fault variables initially coded for each cell, derivative variables were constructed using spatial transformation and evaluated in terms of relevance for the favourability of being a drilling target. For use in CA (Table 1) only 10 variables, 3 of them structural, 2 representing tectonic complexity, and 3 representing tectonic intensity as well as 2 logical combinations were finally selected.

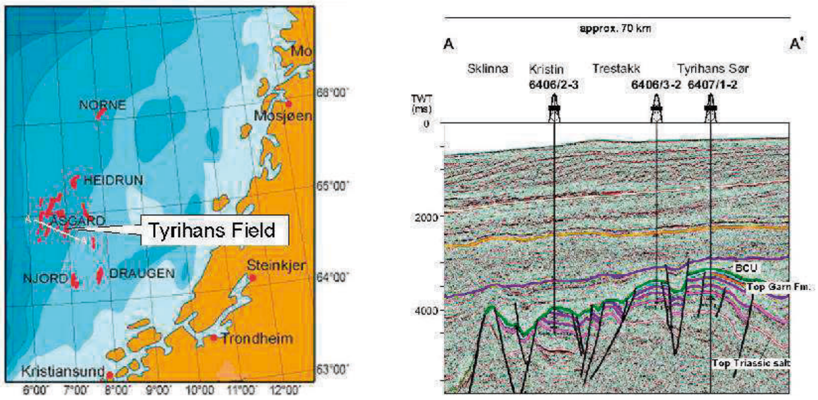

Fig. 1. A/B A presents the fields on the Halten Terrace and B is a seismic cross-section.

To a large extent, the success or failure of characteristic analysis of a given set of data rests upon the ability of the interpreter to determine what constitutes favourability for each variable. A more detailed description of the variables and how they were derived can be found in Brandsegg and Sinding-Larsen (2005).

Table 1 Ternary transformed variables related to the rotated fault block model used to describe exploration data in the Halten Terrace area. Norway

Structural NW-SE		Structural N-S		Structural NE-SW		Intensity count	
-1	0-2km	-1	at fault cells	-1	at fault cells	-1	>=2 faults
0	2-4km from fault	0	neighbour fault	0	neighbour fault cells	0	neighbour fault cells
+1	4-10km fault	+1	E of fault 1-4km	+1	SE of fault 1-4km	+1	<5km from fault
0	>10km fault	-1	W of fault 1-4km	-1	NW of fault 1-4km	0	>5km from fault
		0	> 4 km from fault	0	>4km from fault		
Intensity length		**Intensity ratio**		**Complexity count**		**Complexity length**	
-1	>1km fault dist.	-1	>500m fault ratio	-1	SD > 0.5	-1	SD>500
0	neighbour fault	0	neighbour fault	0	SD>0.3 and SD<0.5	0	SD>250 and SD<500
+1	<5km from fault	+1	< 5km from fault	+1	< 5km from fault	+1	<5km from fault
0	>5km from fault	0	> 5km from fault	0	5km from fault	0	>5km from fault

6.1. Rotated Fault Model

Many large and several small hydrocarbon accumulations have been found on the Halten Terrace, offshore mid-Norway. In this application favourable trapping conditions related to the regional fault pattern published by the NPD was used. In defining a trap model, it was necessary to consider how these accumulations occurs in relation to the regional fault pattern. The Smørbukk field e.g. is situated in an area dissected by a number of major, NNW-SSW basement-involved normal faults. The downthrown side to the West-Smørbukk Fault, contain the Smørbukk hydrocarbon field in its footwall (Richardson, N. J., Underhill, J. R. & Lewis, G. 2005). An initial trap-model was defined by considering only the cells that cover the Smørbukk deposit chosen 4km apart in order to capture lateral variability. They are shown in Fig. 2D. The Smørbukk accumulation covers an area of 30km by 5km. For the variables of interest, we calculated the characteristic weights for the 10 cells that comprised the initial model called S1. The weights are listed in Table 2. By use of these weights, the degree of match for each cell was calculated.

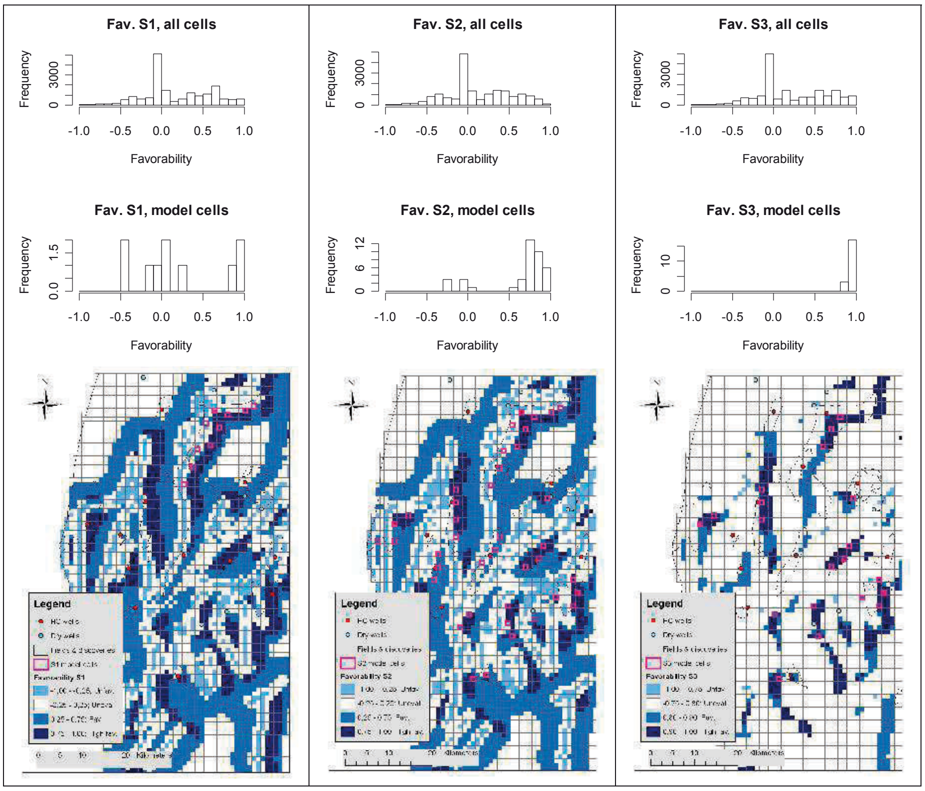

Fig. 2. A/B/C/D/E/F Histogram and maps of favorability for regional cells and model cells

Table 2 Characteristic weights of rotated fault block related variables

Variables	S1	S2	S3	Variables	S1	S2	S3
Structural NW-SE	0.383	0.298	0.324	Intensity ratio	0.396	0.340	0.358
Structural N-S	0.396	0.315	0.289	Complexity count	0.213	0.303	0.341
Structural NE-SW	0.144	0.293	0.235	Complexity length	0.308	0.334	0.358
Intensity count	0.308	0.335	0.358	Logical NS AND NE	0.111	0.266	0.000
Intensity length	0.396	0.340	0.358	Logical NS OR NE	0.340	0.330	0.358

The frequency distribution of the degree of match is given in Fig 2 A/B/C. For purposes of graphic display, the degrees of match were grouped into classes corresponding to the perceived modes in the frequency distribution. The degree of match is represented in Fig. 2D for 4 classes in which class 1 represents the mode for the lowest degree of match and class 4 represents the mode for the highest degree of match. The procedure is used throughout this paper to represent the degree of match in graphic form. As stated above, models based solely on cells that cover known drilling targets may not be optimal in that such models are overly restrictive in their application in other areas. Thus, we expanded the model S1 by including all cell in Fig. 2D in which the degree of match is highly favorable. The cells for which this is true inclusive of the 10 cells covering the Smørbukk field constitute what can be considered as a provisional generalized Smørbukk Trap model called S2.The problem now is that we may have overgeneralized the model by including cells in which the variables are unrelated. Cells with unrelated variables are detrimental and, therefore, should be eliminated. To identify unrelated variable cells, we calculated the characteristic weights based on the probability matrix as described above. These weights are given in Table 2. Using these weights the degree of match for each cell in the model (Fig. 2E) is calculated. The highest favorability class is associated with cells with adequate trap and formed the basis of a generalized model S3. The cells ultimately kept as model S3 are shown in Fig. 2F. To summarize, an initial model of 10 cells was expanded to a model of 40 cells and finally contracted to a model of 20 cells.

The generalized model can be interpreted as being representative of the trapping conditions associated with the Smørbukk type N-S trending rotated fault blocks and can be regarded as a model for exploration in areas in which similar tectonic settings exist.

7. Conclusion

Characteristic analysis has been used to characterize the Smørbukk trap model and to determine the degree of match between the central Halten Terrace area and this model. The model was based on fault derived variables and generalized to include data on surrounding structures. The generalized favorability map show favorable trapping conditions on the Trestakk field that did not show up on the initial Smørbukk model that is to specific to be of general use. Several areas of high favorability outside existing structures depicted by the generalized model need to be looked at closer especially to the north and north-east of the Smørbukk field. If used by experience interpreters, characteristic analysis is a valuable tool for (1) evaluating exploration risk, and (2) delineating favourable areas for use in hydrocarbon play assessment.

8. References

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Appendix F

Where should we explore in the Halten Terrace? -GIS and Characteristic analysis applied to a mature play in the Norwegian Sea

Brandsegg, K.B.[1,2], Sinding-Larsen, R.[1]

Extended abstract published and presented at IAMG'05 in Toronto, Canada
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Where Should We Explore in the Halten Terrace? -GIS and Characteristic Analysis Applied to a Mature Play in the Norwegian Sea

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1. Abstract

Characteristic analysis (CA) has been re-implemented in a GIS environment and used to calculate the favorability for rotated fault block traps in the Halten Terrace play from the Norwegian Sea. Vector maps available from the Norwegian Petroleum Directorate containing structural and play information from Upper and Lower Jurassic reservoirs form the basis for the input attributes. The ArcGIS system is used to calculate the favorabilities resulting from the CA method. The favorability based upon CA can be interpreted in terms of the geological information captured from the input attributes and evaluated against the objectives of the study. It is shown that adequate attribute preprocessing is vital for a good result and that image analysis and GIS are ideal tools to perform the tuning of ternary coding used as input. The favorabilities obtained show how the CA method can be used to express the favorability for rotated fault block traps.

2. Introduction

Characteristic analysis (CA) was introduced in the late 1960's and the potential of CA as an exploration tool for the oil industry have been demonstrated by Chaves (1993) using structural and lithostratigraphic variables in an area of known hydrocarbon discoveries. The joint presence of necessary conditions for trapping within any given area is one of the most important indicators for the presence of hydrocarbons. This paper presents an application of CA combining ternary patterns of fault features for mapping hydrocarbon trapping favorability on the Halten Terrace, offshore Norway. A geographical information system of geological and exploration well data downloaded from a public webpage (http://www.npd.no/factmaps) is used to examine empirically the spatial correlation between fault derived variables and drilled structures exemplified by wildcat wells.

3. Methodology

Characteristic analysis is a discrete multivariate procedure for combining and interpreting data. All geo-variables used are transformed into ternary form by assigning the value of 1 (favorable), -1 (unfavorable) and 0 (indeterminant/unevaluated) in each cell. The manner in which this transformation is performed depends upon the nature of the exploration model and the nature of the data. The technique requires a spatial discretization of maps into cells. The favorability of a given cell related to trapping potential is a weighted linear combination of the transformed variables. The weight of each variable is given by the principal eigenvector of the product matrix, where the product matrix is the matrix of the observed transformed variables for the cells that make up the model multiplied by its transpose. The weights based upon a probability for significant inter-variable correlation is used to select cells and variables to be used in the final calculation. The resultant favorability map is generated by scaled cell favorability values with values between -1 (unfavorable) and +1 (highly favorable). The background of the method can be found in Sinding-Larsen and Brandsegg (2005) and Chaves (1993).

4. Case Study

The Halten Terrace, a mature hydrocarbon area of about 17000 km^2, located in the Norwegian Sea was chosen to test the usefulness of quantitative methods in oil exploration. The Early to Middle Jurassic pre-rift sequence is the main target for exploration in the Halten Terrace play. The major reservoir is the Lower-Middle Jurassic shallow marine sands, which has two major source units, a gas/condensate-prone Upper Triassic-Lower Jurassic coal unit, and Upper Jurassic oil-prone shales. The dominant structural trends within the Halten Terrace are NE-SW, although the terrace additionally contains N-S trending normal faults which also bound the terrace to east and west. The area contains 84 drilled structures resulting in 39 hydrocarbon wells and 45 dry wells.

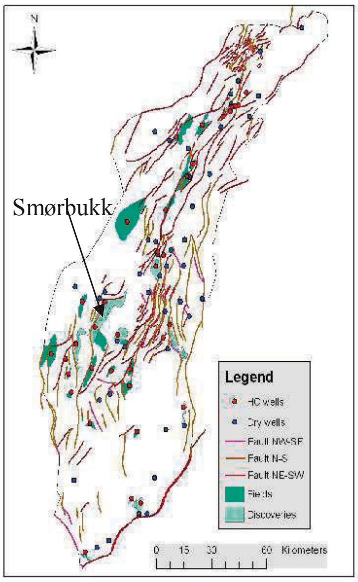

Fig. 1. Fault trends, discoveries and field in the Halten Terrace For locating fields please refer to (www.npd.no/factmaps).

In this study, the variables used are related to major faults in the Halten Terrace. The faults are divided into three subgroups based upon the following fault directions: NW-SE, N-S and NE-SW. The exploration data for the Halten Terrace was coded into 17 000 regional cells measuring 1km on a side. Of the original 3 fault variables initially coded for each cell, derivative variables were constructed using spatial transformation and evaluated in terms of relevance for the favorability of being a drilling target. This study focus on conditions favorable for trapping related to the regional fault pattern. In defining a trap model, it was necessary to consider how these accumulations occurs in relation to the regional fault pattern. The Smørbukk field e.g. is situated in an area dissected by a number of major, NNW-SSW basement-involved normal faults and can be chosen as a template for a trap model. 10 variables 3 structural, 3 tectonic intensity and 2 tectonic complexity, and as well as 2 logical combinations were finally selected to be used in the fault trap model. The transformation of selected variables (Table 1) are shown graphically in Figs. 2 and 3. The structural variables express the relation of 3 different fault trends and their influence distance. The Smørbukk field lies in the footwall up to 10km from the NW-SE fault. The zone less than 2km from the fault is judged unfavorable. The zone 4-10km is favorable and for both the 2-4km zone and the area exceeding 10km distance is set to unevaluated (Fig. 2A). The N-S trending faults have favorable conditions within a 1-4km zone east of the faults, while being unfavorable in a zone 1-4km to the west (Fig. 2B). The NE-SW trending faults have favorable conditions within a 1-4km zone southeast of faults, while the zone to the north-west is classified as unfavorable (Fig. 2C). Faulted cells are classified as unfavorable and their neighboring cells as unevaluated for all structural variables. Three intensity variables are defined; the intensity count variable indicates the number of faults within a specific cell (Fig. 2D), the intensity length variable shows the total length of faults within a specific cell (Fig. 3A) and the third variable is the computed length-count ratio. High intensity with 2 or more faults, large distance (>1km) and a large length-count ratio (>500m) within a cell indicate unfavorable conditions as the fault intensity put adequate trapping at risk. The complexity variable for a given parameter indicates variability within a 3x3 cells neighborhood measured by the standard deviation (SD). The complexity count variable show the number of faults within a cell related to neighboring cells (Fig. 3B). High (SD >0.5) indicate high contrast and assume unfavorable conditions while moderate values (SD 0.3-0.5) is indicated as unevaluated. High values for the complexity length variable (SD >500) indicate high contrast and are assumed unfavorable while moderate values (SD 250-500) are set as unevaluated. The neighboring cells of the unfavorable intensity variable cells are unevaluated and the cells within the 5km fault distance zone are favorable. Two logical operators are used (logical AND and OR) to define the relation between N-S and NE-SW fault influence zones (Figs 3C and 3D).

Table 1 Ternary transformation of variables

Structural NW-SE		Structural N-S	
-1	0-2km from fault	-1	at fault cells
0	2-4km from fault	0	neighbour fault cells
+	4-10km from fault	+	E of fault 1-4km
1	>10km from fault	1	W of fault 1-4km
0		-1	> 4 km from fault
		0	
Structural NE-SW		Intensity count	
-1	at fault cells	-1	>=2 faults
0	neighbour fault cells	0	neighbour fault cells
+	SE of fault 1-4km	+	<5km from fault
1	NW of fault 1-4km	1	>5km from fault
-1	>4km from fault	0	
0			
Intensity length		Intensity ratio	
-1	>1km fault distance	-1	>500m fault ratio
0	neighbour fault cells	0	neighbour fault cells
+	<5km from fault	+	< 5km from fault
1	>5km from fault	1	> 5km from fault
0		0	
Complexity count		Complexity length	
-1	SD > 0.5	-1	SD>500
0	SD>0.3 and SD<0.5	0	SD>250 and SD<500
+	< 5km from fault	+	<5km from fault
1	5km from fault	1	>5km from fault
0		0	

The initial trap-model was defined by considering only cells that covered the Smørbukk field. The characteristic weights were calculated by the use of the product matrix for the 10 cells that comprised the initial model called S1 (Table 2). A model based on cells that cover only the Smørbukk field may be too restrictive in their application in other areas. Therefore, the S1 model was expanded (S2) by including additional 30 high favorably classified cells. This model may be over-generalized by the inclusion of cells in which the variables are unrelated. To identify unrelated cells the characteristic weights for the variables of interest were calculated based on the probability matrix (Table 2). The 20 high favorable model cells in S2 were retained forming the basis of a generalized model, S3. The lowest weighted variable in S2, the logical NS AND NE, was removed from consideration, before the weights of S3 were calculated from the product matrix.

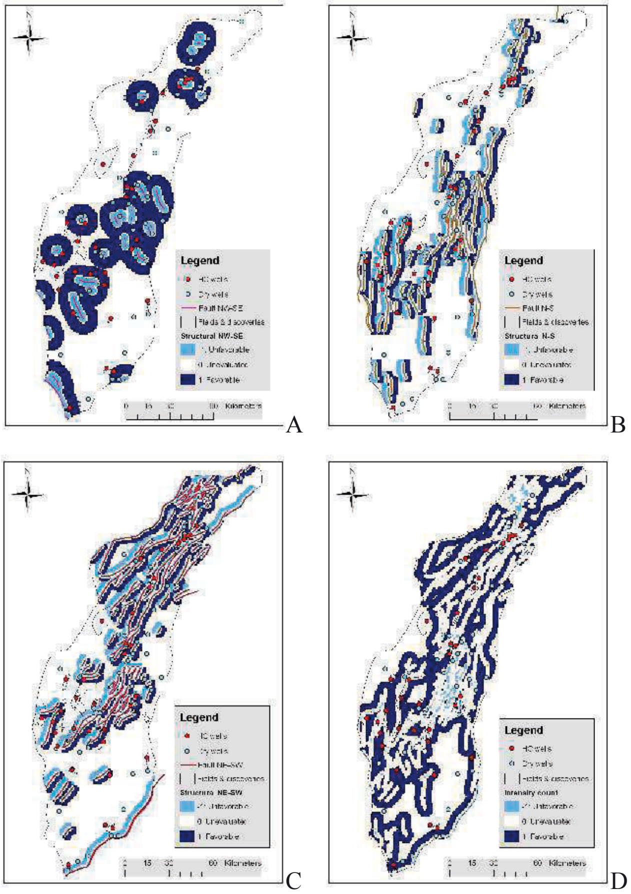

Fig. 2. Maps of ternary transformed variable suitable for the fault block model. (A) Structural NW-SE, (B) structural N-S, (C) structural NE-SW and (D) intensity of number of faults

The degree of match between the generalized trap model and each regional cell (Fig. 4) was then calculated based on the S3 weights. For details see Sinding-Larsen and Brandsegg (2005). The generalized model can be interpreted as being representative for the trapping conditions associated with the Smørbukk type rotated fault blocks and can be regarded as a model for exploration in areas in which similar tectonic settings exist. This study will be followed up with studies using more detailed fault data and other parameters relevant for prospect risking.

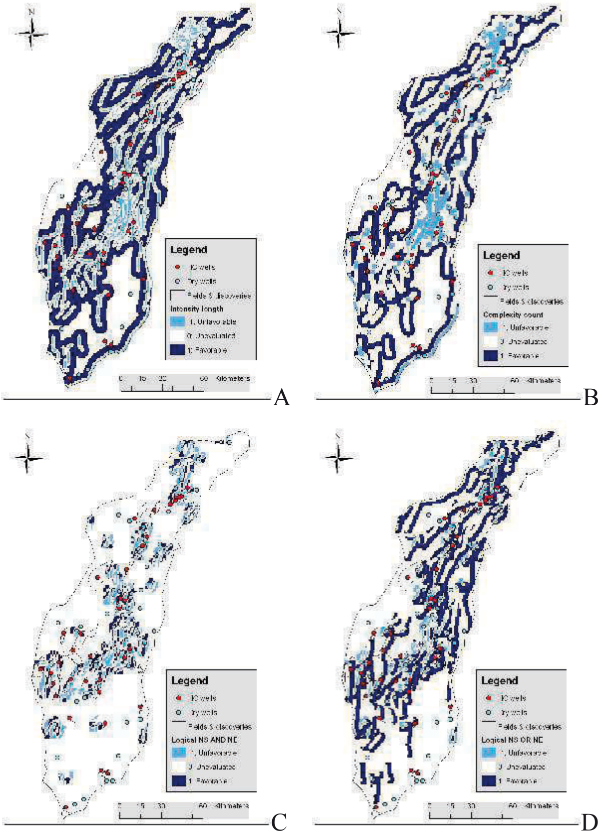

Fig. 3. Maps of ternary transformed variable suitable for the fault block trap model. (A) is fault length intensity, (B) complexity of number of faults, (C) logical AND and (D) logical OR.

Table 2 Characteristic weights of rotated fault block related variables

Variables	Fig.	S1	S2	S3
Structural NW-SE	2A	0.383	0.298	0.324
Structural N-S	2B	0.396	0.315	0.289
Structural NE-SW	2C	0.144	0.293	0.235
Intensity count	2D	0.308	0.335	0.358
Intensity length	3A	0.396	0.340	0.358
Intensity ratio	-	0.396	0.340	0.358
Complexity count	3B	0.213	0.303	0.341
Complexity length	-	0.308	0.334	0.358
Logical NS AND NE	3C	0.111	0.266	0.000
Logical NS OR NE	3D	0.340	0.330	0.358

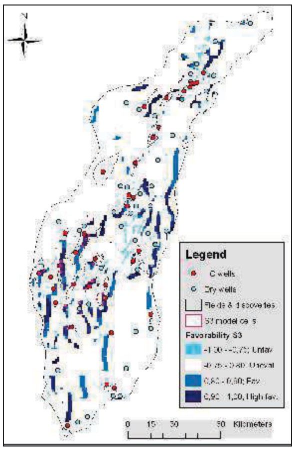

Fig. 4. Favorability map for generalized fault block model, S3

5. Conclusions

- A geographic information system is an excellent computing platform for building the database, map calculations, modeling operations and visualization of results that are required in the quantitative analysis related to hydrocarbon exploration.
- The approach using characteristic analysis for mapping trapping potential provides a simple statistical method for predicting potential drillable traps in plays where accumulations are known to be fault related.
- The generalized Smørbukk model favorable for rotated fault-block structures in the central Halten terrace area (Sinding-Larsen and Brandsegg, 2005) delineate interesting high favorability areas for trapping outside the primary application area.
- On the northern part of the Halten region several high-favorable zones occur north-east of the Lerke and Falk discoveries along regional NE faults. This very distinct zone pick up a signature similar to the Smørbukk rotated fault-block traps and should to be validated with detailed seismic to evaluate its significance.

6. References

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Appendix G

G Yet to find oil resources in Chad

Brandsegg, K.B.[1,2], Sinding-Larsen, Richard, [1]. In manuscript.

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Yet to find oil resources in Chad

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Abstract

Oil exploration in Chad started in the late 1950's and few reports on the total oil resources of the country are publicly available. A oil resource assessment has therefore been undertaken where both an analogue approach and the USGS World Petroleum Assessment workflow have been carried out. Firstly, this study outlines areas most likely to contain undiscovered oil resources and, secondly, quantification of these resources. Individual sedimentary basins containing dominantly oil have been assessed with total aggregated most likely oil resources of about 1400 mill bbl. Most of these resources are located in six areas, including the Doba-Bongor, Lake Chad and Erdis basins. Oil resource assessments provides not only inputs to petroleum explorers but can serve as a basis for policies related to oil exploration, production and taxation as well as an judge to what degree expected undiscovered oil resources can be a trigger for potential conflicts.

Key words: Prospective oil resources, Chad, resource assessment, hydrocarbon exploration

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1. Introduction

The Republic of Chad is located in Central Africa between 5-16°N and 13-24°E covers 1.284 million km^2 (Fig. 1). Chad is made up of two sedimentary domains, intra-cratonic basins in the northern and central parts and rift basins in the central and southern parts (Cratchley et al., 1984; Genik, 1993; Kusnir, 1997; Craig et al., 2009; Brownfield et al., 2010). The relief is generally low except around the Tibesti Massif, where altitudes range up to 3400m. Chad is the fifth largest country in Africa and is landlocked. This together with political instability has resulted in a patchy exploration effort since the start of oil exploration in the late 1950s (Klitzsch, 1994; Kusnir, 1997). Due to these challenges, the main oil exploration effort has been focussed around the capital, N'Djamena, along the western border towards Cameroon and in the southern part towards the Central African Republic border (Younous, 2008).

The development and use of hydrocarbon assessment methods (e.g. Otis and Schneidermann, 1997; Meneley et al., 2003) for national appraisals are an ongoing activity in most oil producing countries. Russia (Sandvik and Zakharov, 1996), China (Zhao et al., 2008), USA (Ahlbrandt and Klett, 2005) and Norway (NPD, 2007, 2009), assess their hydrocarbon resources regularly as part of their strategy to increase efficiency in hydrocarbon resource management. These assessments divide their resources into reserves and prospective / prognostic resources. Whereas the reserves can be divided into produced hydrocarbons and identified economic reserves, resources can be separated into prospective and hypothetical resources (Craig et al., 2001).

BP statistical Review of World Energy (BP, 2010) is one of the few publications that indicates a magnitude for the likely hydrocarbon reserves of Chad. The USGS world assessment is the most authoritative publicly available information on undiscovered resources and a recent assessment of the Cretaceous-Tertiary rifts of the Chad Basin province was published by USGS in 2010 (Brownfield et al., 2010).

Chad has, in addition to the areas with identified economic reserves (Lake Chad, Bongor and Doba basins, where oil currently is exported through a pipeline to the Atlantic Ocean (Table 1)), large

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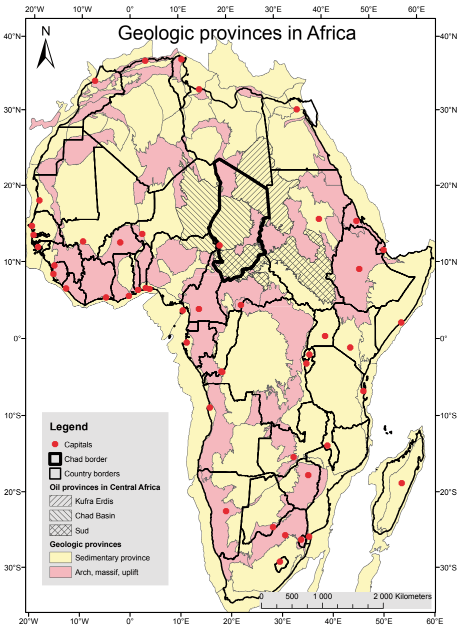

Figure 1: According to USGS (Charpentier et al., 2000), Chad can be divided into several structural provinces. The three sedimentary basin provinces within Chad are named Erdis Kufra in north, Chad Basin in central west and Sud in the south.

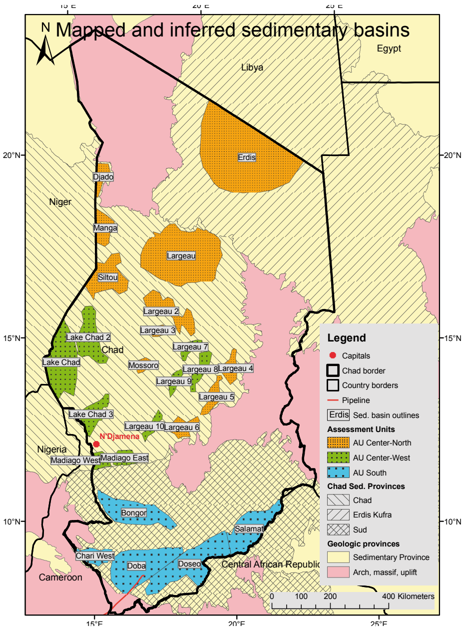

Figure 2: The mapped proven and inferred sedimentary basins within the available Chadian licensing blocks (Fig. 3) are interpreted from the Bouguer anomaly map (Fig. 4) of Louis (1969, 1970).

areas towards the N and SE where exploration drilling has not been performed due to remote access, harsh arid climate and remnants from armed conflicts (Azevedo, 1998; Kusnir, 1997; Younous, 2008)(Fig. 2). Oil exploration in the neighbouring countries; Nigeria (Olugbemiro et al., 1997; Obaje et al., 2006; Alalade and Tyson, 2010), Niger (Zanguina et al., 1998), Libya (Lüning et al., 1999; Guoping and Lei, 2007), Sudan (Mohamed et al., 2002), Central African Republic (United Reef Limited, 2004) and Cameroon (Njandjock et al., 2006; Nguimbous-Kouoh et al., 2010) has led to an increased interest beyond the Doba basin. Several studies have indicated that the unproven sedimentary basins in Chad can contain similar geological structures and hydrocarbon volumes as discovered in the proven plays of the neighbouring countries e.g. the Agadem/Lake Chad basins (Zanguina et al., 1998), the Murzuq/Djado basins (Davidson et al., 2000) in addition to the Kufra/Erdis basins that currently only contain unproven plays (Guoping and Lei, 2007; Craig et al., 2009).

The aim of the current study is to give an overview of the prospective oil resources of Chad by using publicly available data and identifying individual areas with a yet to find oil potential. This paper is organized as follows. Section 2 gives a brief overview of the geological framework of Chad. Section 3 deals with resource assessment methodology. Section 4 presents the hydrocarbon geology and past exploration efforts of three separate assessment units. Section 5 presents the estimated yet to find oil resources and their implications for future prospectivity and their role as potential triggers for conflicts.

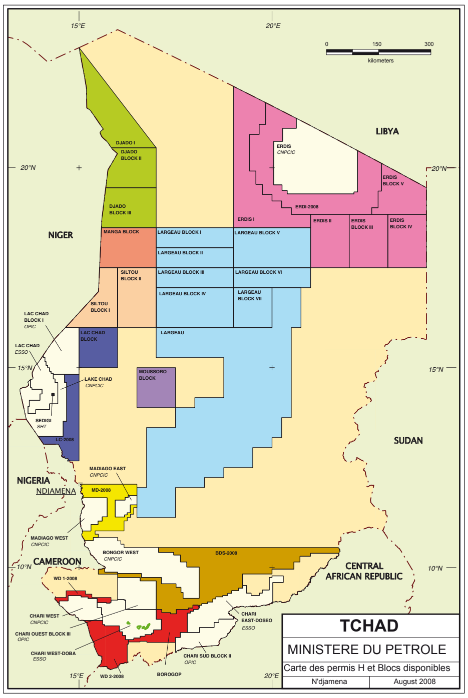

Figure 3: The map of Chad oil concessions from 2008 outlines both existing concessions and those concessions open for bidding (Younous, 2008). This map show that there is large areas available for further oil exploration. The colors represent regional groups of licenses.

2. Geological framework of Chad

During the last decade, several papers have been published that provide excellent syntheses on the African regional geological framework, such as the Phanerozoic development of the central and northern Africa reviewed by Guiraud et al. (2005), the synthesis of Africa's petroleum basins and systems (Purdy and MacGregor, 2003) and the evolution of the Neoproterozoic to Late Ordovician-Early Silurian petroleum systems in North Africa (Guoping and Lei, 2007; Craig et al., 2009). Interested readers can refer to these references for a detailed coverage of the general geological setting, tectonic evolution and stratigraphy. A brief overview compiled from Chad related published papers with a focus on hydrocarbon geology is given below.

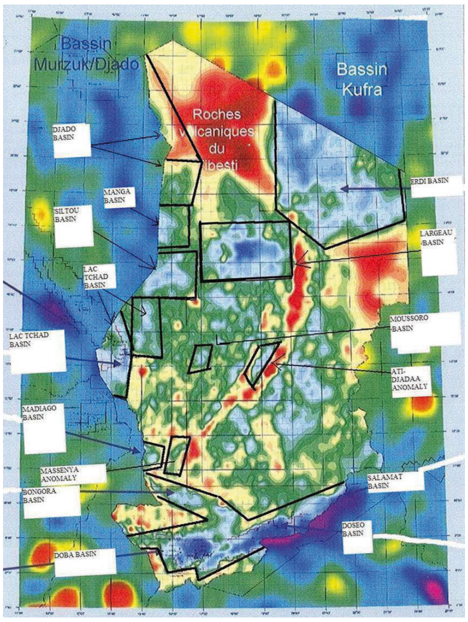

Figure 4: The Bouguer anomaly map of Chad (Louis, 1969, 1970) reflects the relative rock (mineral) density distribution below the Earth's surface, where red colours represent areas of the crust which contain high density rocks, whereas the blue colours show those areas which have rocks of a lower density (e.g. possible sedimentary basins). Interpretation of this map is in this study used to delineate potential sedimentary basins of Chad (Fig. 2).

Genik (1993) outlined that the structural framework of central Africa is composed of five phases, all of them are present in Chad:

1. Pan African crustal consolidation (750-550 Ma)
2. Palaeozoic-Jurassic platform development (550-130 Ma)
3. Early Cretaceous (130-98 Ma) to Late Cretaceous (98-75 Ma) rifting development
4. Maastrichtian-Palaeogene rift and subsidence (75-30 Ma)
5. Neogene-Recent subsidence and erosion (30-0 Ma)

Chad comprises three distinct sedimentary domains, the Palaeozoic-Jurassic intra-cratonic depression in the North and two rift systems in the S-SW related to Cretaceous-Tertiary rifting (Guiraud et al., 2005). Three major types of hydrocarbon source rocks can be found within these domains; Upper Paleozoic (Silurian) marine source rock (Guoping and Lei, 2007; Craig et al., 2009), Cretaceous lacustrine and marine shales (Genik, 1993; Alalade and Tyson, 2010) and Paleogene lacustrine shales (Genik, 1993; Alalade and Tyson, 2010). Several publications indicate that many of the large sedimentary basins in Chad can contain multiple types and amounts of hydrocarbons. This is explained by the presence of different types of both source rocks and reservoir rocks in combination with a favorable timing for the hydrocarbon generation (Genik, 1993; Lüning et al., 1999; Tawadros, 2001; Mohamed et al., 2002; Guoping and Lei, 2007; Craig et al., 2009).

Based upon these petroleum system elements, three composite assessment units (AU) were defined within Chad: (1) AU Center-North, including only Paleozoic source and reservoir rocks that are assumed to be present in both the Kufra Erdis and Chad Basin provinces; (2) AU Center-West, includes only Upper Cretaceous to Tertiary source and reservoir rocks that are assumed to be present only within the greater Chad Basin province; and (3) AU South, including only the Lower Cretaceous source and reservoir rocks of the Sud province. The mapped and inferred basins outlined in Fig. 2 can be categorized into three assessment units (AU):

1. AU Center-North: Erdis, Djado, Siltou, Manga and Largeau 1-6 basins
2. AU Center-West: Lake Chad, Madiago, Moussoro and Largeau 7-10 basins
3. AU South: Bongor, Chari West, Salamat, Doseo and Doba basins

3. Methodology and assessment procedures

Two separate assessments are performed, first basin analogue methodology and subsequently a basin play assessment methodology. Using a basin analogue is the simplest method for estimating the undiscovered petroleum potential of a basin. According to Meneley et al. (2003); Divi (2004), this method may have little reliability, as two basins rarely are geologically identical. However, as a first indication it may be beneficial to use this approach even to sedimentary basins like the Chadian with limited available geological information. By applying the reserve/resource density (reserves/km^2) from a geologic analogue that has been sufficiently explored with a fully realized resource potential to a target basin, an estimate of the resource potential of the target can be obtained.

The second methodology is similar to the methodology for conventional assessment carried out by the USGS for their World Petroleum Assessment 2000 (here named the USGS 2000 methodology). A total petroleum system (TPS) concept (Magoon and Dow, 1994; Magoon and Schmoker, 2000; Klett et al., 2005) was a cornerstone of the USGS approach and is used to delineate the three assessment units. The geologic elements of a TPS include hydrocarbon source rocks (source rock maturation and hydrocarbon generation and migration), reservoir rocks (quality and distribution), and traps for hydrocarbon accumulation.

The USGS 2000 methodology uses Monte Carlo simulations to combine the TPS parameters (Charpentier et al., 2000; Charpentier and Klett, 2005). The input parameters consists of information about the assessment unit, estimates of the number and size of undiscovered oil fields (Klett and Ahlbrandt, 2000). Oil is assumed to be the only viable exploration target (African Petroleum Producer's Association, 2008). The threshold value of the resource base for this assessment is set to 10 MMBO, thereby excluding small fields with no commercial interest. Risk is assessed separately for each individual basin, even if the undiscovered field sizes for each of the three assessment units have the same field size distribution for all basins within each assessment unit (AU) (Table 5). The chosen risking structure is based upon the assumption that the assessment units are reasonably homogeneous in terms of charge, rocks, and timing (Klett et al., 2000).

4. Hydrocarbon geology of the Chadian sedimentary basins

The sedimentary basins of Chad outlined below are inferred from the interpretation of the Bouguer anomaly map of Chad (Fig. 4), the 2008 Chad concession map (Fig. 3) and are inline with the definition of the individual petroleum system (TPS) within the three assessment units (Brownfield et al., 2010).

Even though exploration drilling have been performed within all these three AUs, proven economic oil accumulations related to effective source and reservoir rocks have only been identified within

Table 1: Oil reserves in Chad and their pool sizes based on USGS minerals yearbook (2000); EssoChad (2002, 2010); Chevron (2008); CNPC (2008, 2009); Geosint (2011); Liangqing (2008)).

Sed. basin name	Field name	Discovery name	Discovery closure area [km^2]	Reserves [MMBO]	Reserves/ closure area [MMBO/ km^2]	Nr. field basin area fields /1000km^2	Reserves/ basin area MMBO /1000km^2
Doba	Doba	Kome	50.8	588	11.6		
	Doba	Bolobo	13.5	135	10.0		
	Doba	Miandoum	22.7	227	11.3		
	Doba	Nya	1.3	11	8.4		
	Doba	Moundouli	15.0	69	4.6		
	Doba	Maikeri	3.2	22	6.9		
Sum Doba basin			106.5	1052	9.9	0.26	46.3
Lake Chad	Sédigui	Sédigui	5.0	15	2.0		
		Kanem/Kumia	2.0	4	3.0		
Sum Lake Chad basin			7.0	19	2.7	0.14	0.9
Bongor	Ronier	Ronier	30.0	243	8.1		
	Mimosa	Mimosa	10.6	86	8.1		
	Baobab	Baobab	5.6	44	8.1		
	Kubla	Kubla	9.4	76	8.1		
Sum Bongor basin			55.6	450	8.1	0.23	26.3
Total:			191.1	1583	8.3		

Cretaceous-Tertiary strata the S-SW Chadian sedimentary basins of Lake Chad, Doba, Bongor (USGS minerals yearbook, 2009).

Despite the fact that the Chadian government has opened for bidding from oil blocks that cover nearly all regions of Chad (Fig. 3), only technical discoveries (e.g. Doseo and Salamat basins) have been found outside the Lake Chad, Doba and Bongor basins (Table 1 and 4). The area of closure reserves, and areal yield from the discoveries in Doba, Lake Chad and Bongor basin are calculated from the proven reserves divided by the estimated closure area expressed as MMBO/km^2 and range from 2 to 11.6. Stratigraphically, all the major economic oil reserves in Chad is discovered in Cretaceous strata. Additionally, the Lake Chad basin has a thin oil zone discovered in Eocene sandstones (Genik, 1993). A summary of the major Chadian sedimentary basin characteristics and their assessment units (AU) are given in Tables 2 and 4.

4.1. Description of AU Center-North

The AU Center-North includes the mapped intra-catonic basins in the Kufra Erdis province, in addition to the inferred intra-cratonic basins further South along what has been hypothesized as a Transafrican Lineament that are not influenced by the Cretaceous-Tertiary rifting(Chratchley et al., 1984; Le Heron et al., 2009).

Hydrocarbon exploration and oil discoveries in AU Center-North

The first oil discovery onshore Algeria in 1953 and onshore Libya in 1956, resulted in a massive interest in oil exploration in northern Chad (Klitzsch, 1994). Exploration in the Erdis basin was initiated in the late 1950's by Petropar (the French Société de Participations Pétrolières) with geophysical studies East of the Hoggar Massif (USGS minerals yearbook, 1963). Through the 1962 mining and petroleum legislations, international actors were invited to perform exploration in Chad and rumours of an oil discovery in the northeastern Chad (Erdis basin) caused optimism (USGS minerals yearbook, 1963). The early 1960s publication of the Erdis and Djado basins raised the understanding of the regional geology related to oil exploration (Klitzsch, 1994). In 1965, after five exploration wells, Petropar concluded that there is only sand and water in the Erdis region of Chad

After the exploration wells drilled in the 1960's in the Erdis basin no exploration drilling has been performed within AU Center-North. Therefore, no production information is available as no oil resources are proven within the intra-cratonic basins of Chad. However, oil and gas resources are proven in the Murzuq basin in Libya, whereas the Kufra basin in Libya is still unproven (Guoping and Lei, 2007; Aziz and Ghnia, 2009).

Hydrocarbon geology of AU Center-North

According to the map of Chratchley et al. (1984), the tectonics and sedimentation of the Erdis and Largeau basins are assumed to be similar to the Kufra basin. These characteristics can also be applied to the mapped and inferred northwestern Chadian basins (Djado/Manga/Siltou) that are assumed to be prolongations of the intra-cratonic Murzuq basin in Libya and the Djado basin in Niger (Zanguina et al., 1998; Davidson et al., 2000).

As the published literature of the sedimentary basins of Northern Chad is almost absent, information about the basin development of the neighbouring countries, especially Niger (Zanguina et al., 1998) and Libya (Boote et al., 1998; Tawadros, 2001; Craig et al., 2009), are important. The largest of the AU Center-North basins, the Erdis basin (named Kufra in Libya and Moundou in Sudan), is part of a large intracratonic depression with a Palaeozoic succession (Craig et al., 2009). This basin developed first as an intra-cratonic sag during the late Hercynian phase of deformation and was subsequently buried unconformabily beneath poorly dated Jurassic and Cretaceous continental clastic deposits (Guoping and Lei, 2007). Later mid-Tertiary uplift followed by erosion of the surrounding highs has resulted in outcrops of the Palaeozoic strata around the basin margins (Boote et al., 1998; Craig et al., 2009; Le Heron et al., 2009).

Silurian marine shales form the most important source rock on the Sahara Platform of North Africa with total organic carbon (TOC) content between 2% and 17% (Boote et al., 1998). This source rock was predomininantly deposited in Libya, Algeria and Niger, however the source rock is assumed to extend into the northern part of Chad on both sides of the Tibesti Massif, in Erdis/Largeau and Djado/Manga/Siltou basins (Thomas, 1996; Boote et al., 1998; Lüning et al., 1999). The main source rock candidate is the Tanezzuft Fm. (Guoping and Lei, 2007; Craig et al., 2009). This source rock shale has not been adequately studied within the AU Center-North basins and the presence and potential remains unclear (Younous, 2008). However, the source rock has been tested sucessfully in the Murzuq Basin, where the Tanezzuft Fm. is assumed to be lateral extensive throughout the entire basin and acts both as source rock and cap rock (Davidson et al., 2000) and is estimated to have generated 8.3 to 19.4

Table 2: Known and inferred characteristics of the major sedimentary basins in Chad (Information assembled from Cratchley et al., 1984; Schull, 1988; Genik, 1993; Boote et al., 1998; Zanguina et al., 1998; Lüning et al., 1999; Tawadros, 2001; EssoChad, 2002; Purdy and MacGregor, 2003; Guiraud et al., 2005; Guoping and Lei, 2007; Craig et al., 2009; Brownfield et al., 2010).

Basin name	Assessment	Sub-system Unit	Size [km] (length/width)	Thickness [km] (Max/average)	Basin tectonics	Reservoir rock	Source rock	Trap	Hydrocarbon quality [API]
Erdis	AU Center-North	Intra-cratonic	450/300	-	Intra-cratonic	Ordov. sand	Silurian shale	-	-
Largeau		Intra-cratonic	280/230	-	Intra-cratonic	Ordov. sand	Silurian shale	-	-
Djado		Intra-cratonic	80/70	-	Intra-cratonic	Ordov. sand	Silurian shale	-	-
Manga		Intra-cratonic	110/50	-	Intra-cratonic	Ordov. sand	Silurian shale	-	-
Siltou		Intra-cratonic	120/100	-	Intra-cratonic	Ordov. sand	Silurian shale	-	-
Lake Chad	AU Center-West	WAS	575/200	13/5-6	Extension	Cret. shale	Cret. shale	Cretaceous	43-46
						Eocene sand	Cret. shale	Palaeogene shales	20-36
Madiago		WAS/CAS	60/45	-	Ext-Trans.	Cret. channels	Cret. shale	Cretaceous	-
East/West						L.Cret. fan	Cret. shale	Cretaceous	-
Bongor	AU South	WAS/CAS	300/75	7/4-6	Ext-Trans.	Cret. sand	Cret. shale	Rot. normal faults	-
Doba		CAS	300/150	7.5/4-5	Ext-Trans.	Cret. fluvial	Cret. shale	Anticline and shale	Avg. 34
						Cret. fluvial	E.Cret. lacustrine	Anticline and shale	15-25
Doseo		CAS	480/90	7/5-6	Trans-tension	Cret. fluvial	Cret. shale	Anticline and shale	24-39
Salamat		CAS	300/60	6/4-6	Trans-tension	Cret. fluvial	Cret. shale	Fault blocks	-

Table 4: Input parameters for the basin analogue approach assessing the sedimentary basin in Chad. The values in the Reserves/1000km^2 columns have the unit MMBO/1000km^2.

Case	AU C-North Fields	AU C-North Reserves	AU C-West Fields	AU C-West Reserves	AU South Fields	AU South Reserves
	pr. 1000km^2		pr. 1000km^2		pr. 1000km^2	
Min	0.05	5	0.05	5	0.05	5
Mean	0.15	10	0.15	20	0.20	50
Max	0.25	50	0.25	100	0.35	110

mmbbl/km^2 (Aziz et al., 2000). Subsidence curves from four wells in the Kufra Basin seems to indicate depths greater than 2km during the Phanerozoic and represent similar subsidence curves as in the Murzuq Basin (Gravråk, 2010). Several authors have postulated the presence of an Intra Cambrian source rock in the Kufra basin (Craig et al., 2009; Aziz and Ghnia, 2009) and this older source rock alternative could also be present in the AU Center-North basins. Given that depths similar to the Murzuk and Kufra basin depths are not found in the Erdis basin thereby indicating the likelihood for immature source rocks, lateral migration from Libya into immature areas of the Erdis Basin might be the only possibility (Boote et al., 1998; Lüning et al., 1999).

Within the Djado/Manga/Siltou basin, based on information from the Murzuq basin, the shoreface deposit sandstones of the Mamuniyat Fm. (Ordovician - Ashgill) can provide the primary reservoir unit, with the fluvial and shallow marine sandstones of the Hawaz Fm. (Ordovician - Llanv.) as a secondary target (Davidson et al., 2000). The most probable play in the Erdis and Largeau basins that may have identical plays as the Kufra basin could be an Ordovician-Silurian play characterized by a porous Ordovician sandstone reservoir rock.

Favorable factors for a prolific petroleum system in the Kufra sedimentary basin (and also other AU Center-North basins) are, according to Lüning et al. (1999), the lateral extent of source rock and a favourable burial depth history.

4.2. Description of AU Center-West

The AU Center-West is defined to include an Upper Cretaceous and Tertiary TPS that is characterized by lacustrine and marine source rocks, Cretaceous and Tertiary clastic reservoirs, shale seals and traps that are mostly structural (Brownfield et al., 2010).

Hydrocarbon exploration and oil discoveries of AU Center-West

The American company, CONOCO (Continental Oil Company), obtained in 1969 permits for exploration in southern Chad (USGS minerals yearbook, 1971). In 1972, CONOCO sold 50% of its concession to Shell and these companies stepped up their seismic campaign in the Lake Chad basin that resulted in Chad's first economic oil discovery (the Sédigui field) (USGS minerals yearbook, 1974). The establishment of the Conoco-Tchad consortium, owned by Shell (50%), Chevron (25%), Esso (12.5%) and the operator CONOCO (12.5%) aimed to construct a 350km long pipeline from Lake Chad to connect the Sédigui field with a refinery near N'Djamena that was never built. After several decades, the Sédigui field will now finally be developed and connected to a new refinery near N'Djamena that is estimated to be operative in 2012 (CNPC, 2009). The exploration effort conducted in this area has been low after the Sédigui discovery as there has been no economic feasible export option of the already proven oil reserves before a pipeline and a refinery was operational.

However, multiple companies have had concessions within the AU Center-West the last decades. Hunt International Petroleum Co. of the United States conducted oil exploration in central Chad in the 1980's without any reported success. Similar, the EssoChad consortium (Exxon (40%), Petronas (35%) and Chevron (25%)) increased their concessions in 2004 but later relinquish in 2008 (Chevron, 2008).

In Lake Chad, three fields of total 150 MMBO have been discovered (Table 1). In the Agadem basin (E Niger) six oil discoveries and one gas discovery have proven approximately 400 MMBOE (TG World Energy Corporation, 2008). The sediment thickness of the Lake Chad basins are not as thick as in the Agadem basin, however, the discovery of the Sédigui field proves a potential for further discoveries in the Lake Chad basin as well as other of the AU Center-West basins.

Hydrocarbon geology of AU Center-West

The AU Center-West and AU South were developed from the similar Cretaceous rift system, termed the West and Central African rift system (WCAS) which is subdivided into two coeval parts, the West African Rift Subsystem (WAS) and Central African Rift Subsystem (CAS) (Genik, 1993). The origin of the WCAS is attributed to the

Table 3: Resource assessment summary of the sedimentary basin in Chad using the basin analogue approach. The ultimate number of fields and resources are calculated from the values in Table 4 for each mapped and inferred sedimentary basin areas defined in Fig. 2. Maps of the mean number of fields and mean resources are shown in Fig. 5 and resources Fig. 6, respectivily.

ID	Mapped area [km^2]	Name	Assessment Unit	Status	Fields			Resources [MMBOE]		
					Min	Mean	Max	Min	Mean	Max
1	67994	Erdis	AU Center-North	Drilled	3	10	17	136	680	3400
2	3502	Djado		Undrilled	0	1	1	7	35	175
3	5914	Manga		Undrilled	0	1	1	12	59	296
4	12667	Siltou		Undrilled	1	2	3	25	127	633
5	1584	Mossoro		Undrilled	0	0	1	3	16	79
6	43942	Largeau		Undrilled	2	7	11	88	439	2197
7	11007	Largeau 2		Undrilled	1	2	3	22	110	550
8	1860	Largeau 3		Undrilled	0	0	1	4	19	93
9	3735	Largeau 4		Undrilled	0	1	1	7	37	187
10	4049	Largeau 5		Undrilled	0	1	1	8	40	202
11	4354	Largeau 6	AU Center-West	Undrilled	0	1	1	9	44	218
12	2725	Largeau 7		Undrilled	0	0	1	5	27	272
13	4682	Largeau 8		Undrilled	0	1	1	9	47	468
14	2212	Largeau 9		Undrilled	0	0	1	4	22	221
15	2415	Largeau 10		Undrilled	0	0	1	5	24	224
16	20821	Lake Chad		Economic discovery	1	3	4	42	208	2082
17	11490	Lake Chad 2		Undrilled	1	2	2	23	115	1149
18	6997	Lake Chad 3		Undrilled	0	1	1	14	70	700
19	3206	Madiago West		Undrilled	0	0	1	6	32	321
20	3807	Madiago East		Undrilled	0	1	1	8	38	381
21	17098	Bongor	AU South	Economic discovery	1	3	6	85	855	1881
22	5178	Chari West		Undrilled	0	1	2	26	259	570
23	22698	Doba		Economic discovery	1	5	8	113	1135	2497
24	23676	Doseo		Technical discovery	1	5	8	118	1184	2604
25	15209	Salamat		Technical discovery	1	3	5	76	760	1673
Total resources in the Chadian basins					13	51	79	855	6382	23090

breakup of Gondwana and the start of separation between Africa and South America (Guiraud et al., 2005). The Early Cretaceous rifting (phase 3) induced major fractures representing reactivated Pan African crustal discontinuities of phase 1 (Genik, 1993). The WAS was developed through a transtensional opening accompanied by the extensional subsidence of the Niger and West Chad basins (Genik, 1993). During phase 3 in the Late Cretaceous, a late rift to sag stage was accompanied by a marine transgression (Genik, 1993). During the Late Cretaceous rifting (phase 4) thick fluvial and lacustrine sediments were deposited. In phase 5, no tectonic rifting activity have been active in the WCAS rift system (Genik, 1993). However, there has been an uplift associated with tectonic and (or) magmatic activity during the Pliocene in the Tibesti Massif (NW Chad), the Darfur region (E Chad) and along the Cameroon Line (SW Chad) (Guiraud et al., 2005; Swezey, 2009) that can have affect the petroleum systems of Chad.

Within AU Center-West, three source rocks are identified; Early Cretaceous lacustrine, Late Cretaceous marine and Paleogene lacustrine (Genik, 1993). In the Lake Chad basin, oil of $20° - 36°$ API has been discovered in Eocene lacustrine sandstone reservoirs which are sourced from Late Cretaceous shallow marine and Eocene lacustrine shales (Genik, 1993). In the Agadem basin (Niger), the elongation of Lake Chad basin, oil ($30° - 45°$ API) and gas have been discovered in fault blocks and faulted anticlines in marine tidal Late Cretaceous reservoir sands, which are sourced and sealed by coeval marine to estuarine shales (Zanguina et al., 1998).

4.3. Description of AU South

The AU South area is defined as the Lower Cretaceous TPS, consisting of lacustrine source rocks and Early and Late Cretaceous reservoir rocks located in the hydrocarbon province named Sud by the USGS and extending into southern Sudan.

Hydrocarbon exploration and oil discoveries in AU South

The first exploration within the AU South area was carried out by CONOCO and Shell with seismic campaigns in the Doba, Doseo and Salamat basins that led to a oil discovery in the Doba basin in 1989 (USGS minerals yearbook, 1998). Further exploration drilling of the Doba basin in the 1990's increased the total estimated reserves up to one billion barrels (USGS minerals yearbook, 1998). The appraisal drilling of this first campaign discoveries

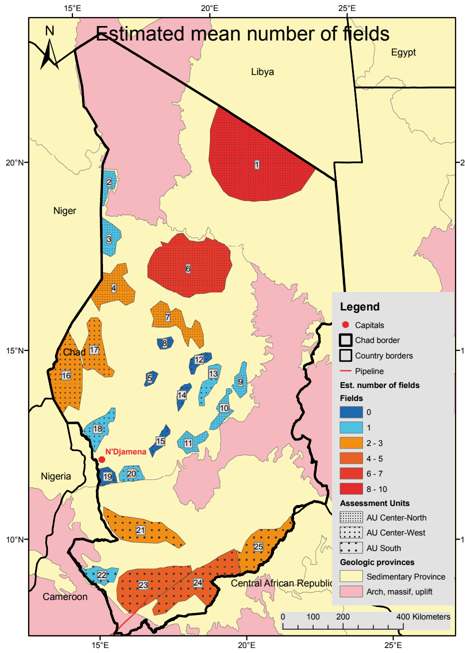

Figure 5: Estimated ultimate number of oil fields in Chad using the reference (mean) scenario of the analogue methodology. Full details are given in Table 3.

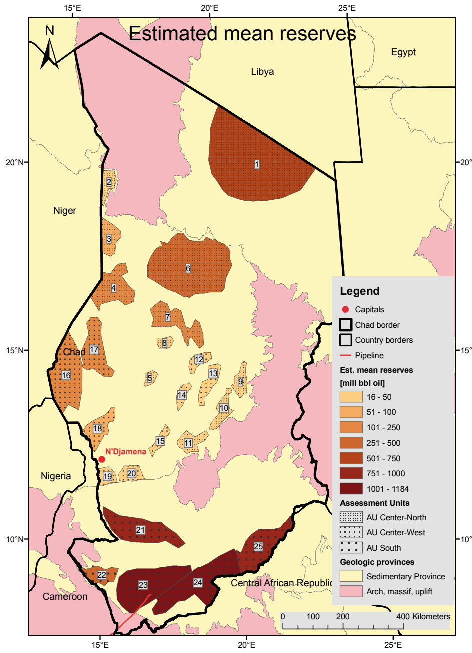

Figure 6: Estimated ultimate oil resources [bill bbl oil] in Chad using the reference (mean) scenario of the analogue methodology. Full details are given in Table 3.

(now named the Doba field) was finished in 1994 and proved sufficient volumes to build a transportation pipeline for export to the international market (USGS minerals yearbook, 1995). The consortium withdrawal of Shell and Elf prior to the development of the Doba field resulted in a three company consortium reconstruction, EssoChad; Exxon (40%), Petronas (35%) and Chevron (25%) that had assistance from the World Bank (EssoChad, 2010). After a construction period of only three years, oil production commenced in late 2003 (EssoChad, 2010). The consortium increased their concessions in 2004 including new exploration areas covering the Chari Ouest (Doba), Chari East (Doseo). In 2005, the Consortium began work on the Nya-Moundouli expansion project, which was developing two new oil fields in the vicinity of the original three fields of Komé, Miandoum, and Bolobo (EssoChad, 2010).

In 2004, the Chadian government awarded oil exploration permits to Canadas Energem Petroleum Corporation. These permits were for the Chari-Ouest basin, located near the Doba basin. In 2006, OPIC of Taiwan (a CPC - Chinese Petroleum Corporation subsidiary) signed for exploration rights to blocks Chari I, II and III in the Doba basins.

The Bongor basin concession was in 1999 signed to Trinity Gas and Carlton Energy of the United States as well as Nigerian Oriental Energy Resources (Djimrabaye, 2005). This concession was in 2002 given to EnCana, that focused on exploration primarily in the Bongor basin (Petzet, 2007). In 2007, EnCana sold its Chadian assets (Permit H) to the China National Petroleum Company (CNPC) after having drilled 11 wells in the Bongor basin during the last five years but were unable to prove economic quantities of hydrocarbons (Petzet, 2007). In the following year, the CNPC discovered sev-

Table 6: Assessment results of the total undiscovered oil resources of Chad using USGS 2000 methodology (Table 5). Sedimentary basins with area less than 3000 km^2 (ID: 5, 8, 12, 14, 15) are not displayed as their sediment volumes are interpreted to be insufficient for an active TPS. These sedimentary basins are displayed without any oil resources in Figs. 7-11.

ID	Basin area [km^2]	Basin area name	Probability		Undiscovered oil [MMBO]												Mean unrisked/ 1000km^2	Mean GArisk/ 1000km^2
			Geo	Geo& access	unrisked				Geologic risk				Geologic+access					
					P90	P50	P10	Mean	P90	P50	P10	Mean	P90	P50	P10	Mean		
1	67994	Erdis	0.43	0.30	120	328	601	334	52	165	303	169	36	116	212	118	4.9	1.7
2	3502	Djado	0.34	0.24	22	63	165	84	7	21	55	21	5	15	39	20	24.0	5.7
3	5914	Manga	0.29	0.23	22	64	166	85	6	18	48	24	5	15	28	20	14.4	3.4
4	12667	Siltou	0.25	0.23	36	94	219	117	9	24	55	29	8	21	49	27	9.2	2.1
6	43942	Largeau	0.24	0.19	112	242	461	243	27	58	111	66	22	47	89	53	5.5	1.2
7	11007	Largeau 2	0.25	0.20	36	91	215	114	8	19	45	24	6	15	36	19	10.4	1.7
9	3735	Largeau 4	0.15	0.12	22	63	165	84	5	15	40	20	4	12	32	16	22.7	4.3
10	4049	Largeau 5	0.15	0.11	22	63	165	84	5	15	40	20	3	11	29	15	21.0	3.8
11	4354	Largeau 6	0.15	0.12	22	63	165	84	5	15	40	20	4	12	32	16	19.5	3.7
13	4682	Largeau 8	0.25	0.17	21	61	149	77	5	21	36	19	5	21	36	19	16.7	4.1
16	20821	Lake Chad	1.00	1.00	70	169	316	185	70	169	316	185	70	169	316	185	8.9	8.9
17	11490	Lake Chad 2	0.81	0.81	36	89	191	105	29	72	155	85	29	72	155	85	9.1	7.4
18	6997	Lake Chad 3	0.58	0.58	22	61	146	77	12	35	84	44	12	35	84	44	11.0	6.3
19	3206	Madiago West	0.51	0.41	22	61	146	77	12	31	75	40	12	31	75	40	24.1	12.5
20	3807	Madiago East	0.51	0.41	22	61	146	77	12	31	75	40	12	31	75	40	20.3	10.5
21	17098	Bongor	1.00	1.00	68	166	324	184	68	166	324	184	68	166	324	184	10.8	10.8
22	5178	Chari West	0.73	0.73	25	72	164	87	19	52	119	63	19	52	119	63	16.7	12.1
23	22698	Doba	1.00	1.00	25	71	165	87	25	71	165	87	25	71	165	87	3.8	3.8
24	23676	Doseo	1.00	1.00	66	163	308	178	66	163	308	178	66	163	308	178	7.5	7.5
25	15209	Salamat	1.00	1.00	41	102	212	118	41	102	212	118	41	102	212	118	7.8	7.8
	Total undiscovered resources							2481				1436				1347		

Table 5: Input parameters for the USGS 2000 methodology assessing the undiscovered oil resources in Chad. Sedimentary basins with a area less than 3000 km^2 (ID: 5, 8, 12, 14, 15) are not displayed as their sediment volumes are interpreted to be insufficient for an active TPS. MMBO, million barrels of oil. Minimum field size assessed is the undiscovered field size minimum (10 MMBO). The probability indicates the likelihood of at least one equal to or greater than the MFS.

ID	Basin area [km^2]	Basin area name	Assignment Unit	Status	Probability				Undiscovered Fields					
					Fluids	Rocks	Timing	Access	Number			Size [MMBO]		
									min	med	max	min	med	max
1	67994	Erdis	AU Center-North	Drilled	0.8	0.9	0.6	0.7	3	9	18	10	30	600
2	3502	Djado		Undrilled	0.7	0.8	0.6	0.7	1	2	4			
3	5914	Manga		Undrilled	0.6	0.8	0.6	0.8	1	2	4			
4	12667	Siltou		Undrilled	0.6	0.7	0.6	0.9	1	3	5			
6	43942	Largeau		Undrilled	0.5	0.8	0.6	0.8	2	7	11			
7	11007	Largeau 2		Undrilled	0.5	0.7	0.6	0.8	1	3	5			
9	3735	Largeau 4		Undrilled	0.5	0.6	0.5	0.8	1	2	4			
10	4049	Largeau 5		Undrilled	0.5	0.6	0.5	0.7	1	2	4			
11	4354	Largeau 6		Undrilled	0.5	0.6	0.5	0.8	1	2	4			
13	4682	Largeau 8	AU Center-West	Undrilled	0.7	0.7	0.5	0.7	1	2	4	10	30	400
16	20821	Lake Chad		Economic discovery	1.0	1.0	1.0	1.0	1	5	9			
17	11490	Lake Chad 2		Undrilled	0.9	0.9	0.9	1.0	1	3	5			
18	6997	Lake Chad 3		Undrilled	0.8	0.9	0.8	1.0	1	2	4			
19	3206	Madiago West		Undrilled	0.8	0.8	0.7	1.0	1	2	4			
20	3807	Madiago East		Undrilled	0.8	0.8	0.7	1.0	1	2	4			
21	17098	Bongor	AU South	Economic discovery	1.0	1.0	1.0	1.0	1	4	8	10	35	400
22	5178	Chari West		Undrilled	0.9	0.9	0.9	1.0	1	2	4			
23	22698	Doba		Economic discovery	1.0	1.0	1.0	1.0	1	2	4			
24	23676	Doseo		Technical discovery	1.0	1.0	1.0	1.0	1	4	8			
25	15209	Salamat		Technical discovery	1.0	1.0	1.0	1.0	1	2	5			

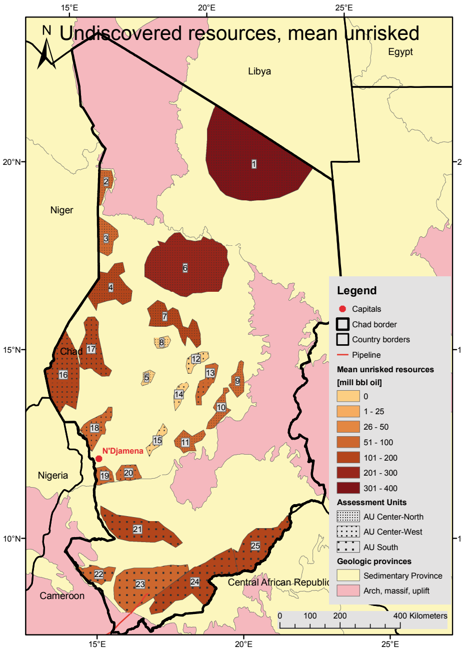

Figure 7: Estimated mean unrisked undiscovered oil resources in Chad using the USGS 2000 methodology.

eral large economic oil discoveries in Bongor basin (CNPC, 2008, 2009).

The present economic quantities of oil in AU South (Table 1) have been discovered within the Bongor (450 MMBO reserves from 1850 MMBO oil in place) (CNPC, 2008, 2009) and Doba basins (1052 MMBO) (Chevron, 2008; EssoChad, 2010). Within the last year, the addition Chadian oil reserves are solely derived from the Bongor basin, including the discoveries of Mimosa, Kubla, Baobab and Ronier fields (CNPC, 2008, 2009).

The result of the ExxonMobil consortium exploration in the surrounding structures of the Doba field has only resulted in the 2007 Timbre minor discovery. This discovery was tied to existing infrastructure and production started in 2009 (Johnston and Rogers, 2008; EssoChad, 2010).

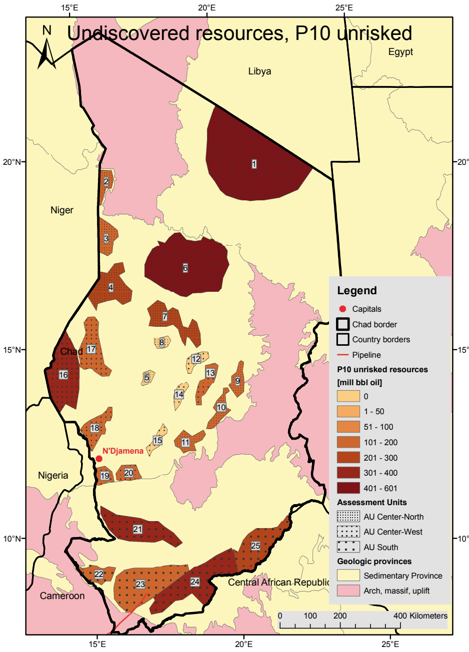

Figure 8: Estimated P10 unrisked undiscovered oil resources in Chad using the USGS 2000 methodology.

Hydrocarbon geology of AU South

Whereas the WAS was developed through a trans-tensional opening accompanied by the subsidence of the Chad Basin province, the CAS in southern Chad (Sud province) was developed by an obliquely opening and subsidence, where only continental sediments were deposited (Genik, 1993). The phase 3 and 4 rifting in Late Cretaceous is not identified in the southern Chad basins (Genik, 1993).

The major source rock in AU South is the Early Cretaceous lacustrine shales (Genik, 1993). Source rock kerogen type analysis within the sedimentary basins in Chad have been identified as a mixture of type I and III kerogens leading to waxy oils with low sulfur content (Schull, 1988; Carroll and Bohacs, 2001). Source rock analysis has also been published from the Muglad basin, SW Sudan. The Muglad basin comprises, as was the case for Doba/Doseo basins, two Early Cretaceous source rocks with an

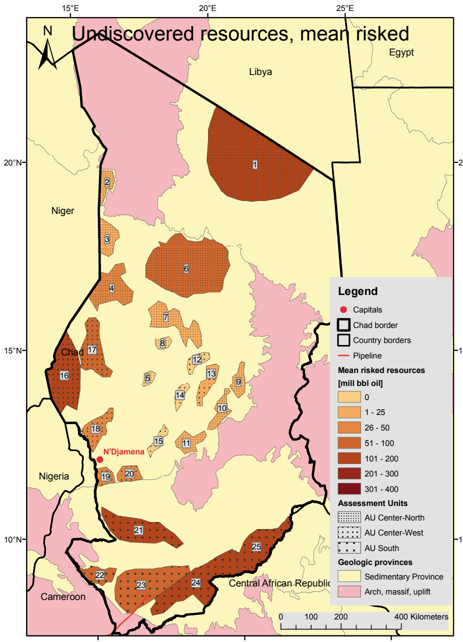

Figure 9: Estimated mean risked undiscovered oil resources in Chad using the USGS 2000 methodology

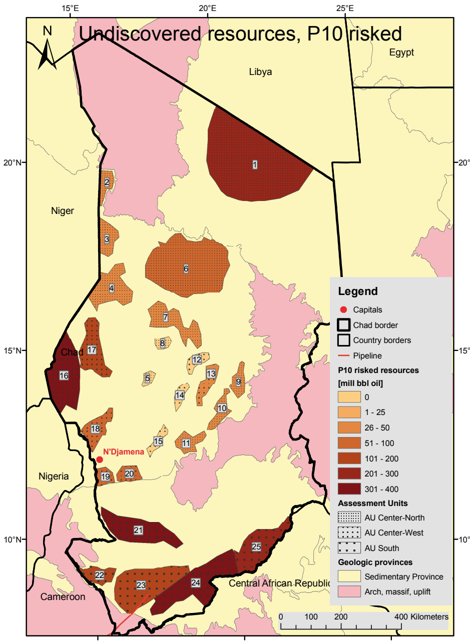

Figure 10: Estimated P10 risked undiscovered oil resources in Chad using the USGS 2000 methodology.

oil-prone Type I kerogen and a gas-prone Type III kerogen (Mustafa and Tyson, 2002). This is different to the wells in the Bongor basin that contain predominantly lighter oil (CNPC, 2008). This is due to the fact that Bongor basin has a marginal influence by WAS that includes a Upper Cretaceous marine shale (Genik, 1993).

5. Oil assessment results of Chad

Basin analogue methodology results

The three assessment units have different maximum fields sizes and reserve yields (Table 4), where the AU South is assumed to be more prolific than both the AU Center-West and AU Center-North. In the high case scenario, reserves and field densities like the Bongor basin are assumed, whereas for the reference case Doba basin reserves and field densities are applied. The intra-cratonic basins of AU Center-North are assumed to have a lower field density and reserve density than the rift basins to the South.

The results (Table 3 and Figs. 5 and 6) show that the total number of estimated fields and the total ultimate reserves are a function of the extent of the inferred/mapped sedimentary basin areas. The largest number of postulated fields are within the Erdis and Largeau basins and in the rift basins in S-SE (Doseo and Salamat) that to date only have technical discoveries (Fig. 5). This is supported by the many leads identified by the independent petroleum potential analysis of the Central African part of the Doseo and Salamat basins (United Reef Limited, 2004). The total resources map (Fig. 6) shows that the Erdis, Largeau and Doseo basins have the most undiscovered mean resources.

The USGS 2000 methodology results

The results of the USGS 2000 methodology are based upon sedimentary basin specific input parameters (Table 5). The results of using Monte Carlo simulations of 50000 runs in the excel-based program Emc2 (Klett et al., 2000) are outlined in tabular form (Table 6) as well as on maps (Figs. 7- 11). Compared to the basin analogue method, this approach is more dependent on incorporating quantified geologic understanding that portrays the specificities of the individual sedimentary basins.

The assessment units have been aggregated with full dependency within each unite due to a common dependency on a within source. The assessed risked most likely (mode) undiscovered volumes (Table 7 and Fig. 12) for the intra-cratonic AU (AU Center-North) is 240 MMBO. Most of the undiscovered resources are expected to be in the Erdis and Largeau basins, with a modest potential in the Siltou basin as it is only partly within Chad. The assessed risked most likely undiscovered volumes in AU Center-West are 310 MMBO. Most of the remaining undiscovered resources are likely to be in the Lake Chad area and the Madiago basins. This estimate compares well with the estimated 2315 MMBO mean risked undiscovered resources of the USGS assessment for the greater Chad Basin province, that includes Algeria, Cameroon, Chad, Niger and Nigeria, with only approximately 20% of the area within Chad (approximately 463 MMBO (Brownfield et al., 2010)). For the AU South the assessed risked most likely undiscovered volumes are 780 MMBO. Most of the undiscovered resources are expected to be in the Bongor and Doseo basins. In Chad, the total estimate of mode risked undiscovered resources are 1420 MMBO. This mode is used to report ultimate resources due to its lack of sensitivity fir a higly uncertain upside potential.

Future directions for oil exploration in Chad

The estimated mode risked undiscovered resources are about half of the ultimate mean resources of 42639 MMBO (Table 7). Although Chad is generally underexplored in both the intra-cratonic and the rift development related basins, they are estimated to contain significant yet to find oil that can potentially lead to field developments and to sustain Chad's oil export volumes. Most of the undiscovered resources are expected to be in the intra-cratonic Paleozoic strata (Erdis and Largeau basins), in the Upper Cretaceous-Tertiary strata (Lake Chad, Madiago basins) and the Lower Cretaceous strata (Bongor and Doseo basins).

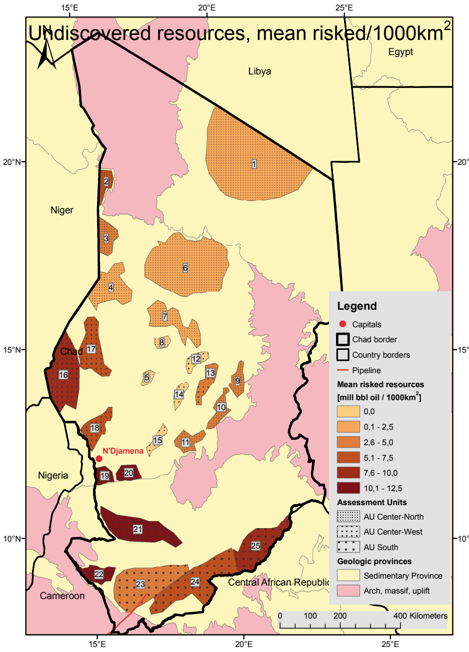

Figure 11: Estimated mean risked undiscovered oil resources pr 1000km^2 in Chad using the USGS 2000 methodology.

The fully-operated Doba pipeline in southern Chad, the development of the 350 MMBO Niger discoveries near Chad's western border (Petzet, 2007), the development of central Libya discoveries (Lüning et al., 1999) and the Sudan pipelines assembled about 500km from the border of eastern Chad (Mohamed et al., 2002), can represent options for tieback from future discoveries. The exploration results in the Kufra basin will have strong influence on the exploration in the Erdis and Largeau basins. Similarly, the exploration of the undrilled sedimentary basins in north-eastern Chad (Djado, Manga and Siltou basins) will be influenced by the exploration effort in the Djado basin in Niger and the exploration of the southern part of the already proven prolific Murzuk basin (Aziz and Ghnia, 2009). Based on this, the future exploration areas in Chad can be divided accord-

Table 7: Chad ultimate technically recoverable oil are compiled from proven reserves (Table 1), cumulative oil production (EssoChad, 2010) and the oil assessment results using the USGS 2000 methodology (Table 6). MMBO, million barrels of oil. Results shown are fully risked estimates. P90 represents a 90 percent chance of at least the amount tabulated; other fractiles are defined similarly. The individual basin results are aggregated under the assumption of full interdependency due to the regional uncertainty about the presence and the adequacy of a mature source rock. AU, assessment unit.

Assessment Unit (AU)	Field Type	Cumulative production	Identified reserves	Original reserves	Total undiscovered Resources Oil (MMBO)					Ultimate resources (mode)
					P90	P50	P10	Mean	Mode	
AU Center-North	Oil	-	-	-	103	285	552	304	240	240
AU Center-West	Oil	-	19	19	139	368	739	413	310	329
AU South	Oil	354	1210	1564	270	699	1002	630	780	2344
Total		354	1229	1583	877	1376	1900	1347	1420	2639

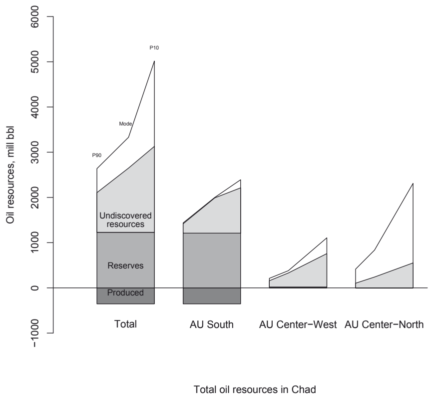

Figure 12: Chad ultimate oil resources. Graphical display of Tab. 7. The upper non-shded area of the resource column indicates the magnitude of undiscovered resources given removal of the geological and access risk.

ing to future potential into two categories: High to medium and low prospective areas. The former areas, such as Doseo, Madiago East, Madiago West and Lake Chad basins, are areas where the petroleum system is well constrained. Low prospective areas, such the Largeau basins in AU Central-North, represents high risk, but could contain large quantities of oil if the petroleum system in Erdis proves to be adequate.

In 2000, the Chadian government revised its Petroleum Code and the revision allowed for production sharing agreements (PSAs) between foreign companies and the Chadian government. This opened for Chad's first national oil company, the Soci*é*t*é* des Hydrocarbures du Tchad (SHT). With this, Chad indicated a desire to control 60 % of the country's oil sector (Younous, 2008). This national oil company has also shares in the new refinery that is beeing built. The increased governmental control of the petroleum sector and sudden changes in oil policy such as tax increases (Frank and Guesnet, 2009) and potential domestic and international armed conflicts (Brandsegg, 2011) can significantly influence the result of future oil exploration in Chad.

The resource assessment results provide in Table 7 could shed light on the potential relation between greed as a motive for conflicts when the area distribution of anticipated future wealth favors rivalry within and between different groups (Brandsegg, 2011).

6. Conclusions

The present oil resource assessment of Chad indicates that Chad has a significant undiscovered oil potential. Three separate assessment units have been modeled to properly assess Chad's total oil potential. Based upon two sets of oil resource assessments, the USGS 2000 methodology gives a more credible indication of the remaining potential for oil than the basin analogue methodology. This is due to the uncertainty in the upscaling from discovery/field to basin scale and the application of these values to other sedimentary basins that can be considered as representative. The most prolific basins are the Palaeozoic in the Erdis and Largeau basins, the Cretaceous in the rifted grabens in the Bongor and Doseo basins and the Cretaceous-Tertiary in the West Chad rifts (Lake Chad and Madiago basins). Chad's current declining oil production will be supplemented by the soon completed development of the Bongor and Lake Chad discoveries. It is to be hoped that the national oil company (SHT) will manage to promote increased exploration efforts in the more remote regions of Chad will be essential for discovering the yet to find oil and sustain production. Chad is estimated to have mode risked undiscovered resources of 1420 MMBO. This is about half of the ultimate recoverable resources (2639 MMBO). The calculated undiscovered resources give a quantitative indication of a significant potential within the Chadian sedimentary basins, but will require considerable effort and dedication to establish their existence.

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Appendix H

Non-renewable resources and domestic conflicts within a Chadian resource management framework

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Non-renewable resources and conflicts within a Chadian resource management framework

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Abstract

The relation between proven and prospective non-renewable natural resources and the governance of such resources is not fully understood. This present study outlines the exploration, development and exploitation history of non-renewable natural resources in Chad and how this has co-existed with violent conflicts. Further, the magnitude of prospective non-renewable resources has been outlined and discussed in relation to their impact on the future governance challenges in Chad. Chad, a large, land-locked country in central Africa, has since its independence in 1960, seen the discovery of multiple types of non-renewable natural resources in terms of uranium, gold, diamonds and hydrocarbons. The country is infested with a wide-spread poverty, poor education system, a negligible industrial sector and political turbulence that includes several coup attempts and fatal civil wars. Following increased exploration efforts after the 1960 independence from France, several areas are indicated to hold mineral enrichments, but without any appearance of world class mineral deposits.

Based on a review of the literature (scientific articles, press releases, company reports and reports from both international and non-governmental organizations) the co-existence between non-renewable resource exploration/production and violent conflicts has been identified. Further, has two separate mineral and oil potential resource maps have been created to outline spatially the prospective non-renewable resources of Chad. These maps have been studied in relation to the governance of Chad and the results show that future income from hydrocarbon resources are most like to be exploited from southwestern Chad, along the western border, to northeastern Chad, whereas the mineral resources are most likely to be exploited in southwest, in east and in northwestern Chad. These prospective resources are by large in distal parts of the country that are more distant from the capital than the present hydrocarbon production. This differs from the near future income, which will to come from hydrocarbon development around the capital. This study concludes that Chad will most likely have a co-existence of natural-resource exploration/exploitation and conflicts in the future.

Key words: Prospective natural resources, Chad, conflict

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1. Introduction

The Republic of Chad is located in Central Africa between 5-16°N and 13-24°E covers 1.284 million km^2 (Fig. 1). The relief is generally low except around the Tibesti Massif, where altitudes range up to 3400m. The diverse landlocked country with an area of 1 284 000km^2 (fifth largest in Africa), stretching 1700km from north to south and 1000km west to east, bounded in the north by Libya, in the east by Sudan, in the west by Niger, Nigeria and Cameroon, and in the south by the Central African Republic (Fig. 2). Chad has three distinct major geographical zones: (1) The desert zone in north with an annual rainfall of 50mm cover about half of the national territory, (2) The Sahelian zone account for around 40% of the national territory with a rainfall of 300 - 600mm, and (3) The Sudanian zones in the south covering roughly 10% and has a annual rainfall of 900mm (World Bank, 2000).

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In manuscript 1st March 2011

The borders have locked together around 130 ethnic groups, where the Sara group in the south (mainly a sedentary agricultural population), represent only a small proportion of the total population compared to the dominant groups of (desert nomad) Arabs in the north (Posner, 2004). However, during the French colonial time, the Sara ethic group, was used both as soldiers for the French army and for industrial labor force, particularly Chad's main export commodity, the cotton industry. The most civilized Muslims Arabs of northern Chad was used in the capital's central governments civil service (Azevedo, 1998).

The geographical constrains together with political instability has resulted in a patchy exploration effort since the start of mineral and hydrocarbon exploration in the late 1950s (Klitzsch, 1994; Kusnir, 1997). No economic quantities of mineral resources have been discovered, however several prospective areas are in an exploration phase (USGS minerals yearbook, 2009). The oil discovery of the large Doba field with reserves upto 1000 million barrels of oil (MMBO) in the late 1980's was assumed to be the blessing of Chad that potentially could make Chad economic self sufficient (May and Massey, 2000). In 1999, by the aid of the World Bank, an export pipeline was initiated for transporting oil from Chad to a seaport in Cameroon (EssoChad, 2002).

The aim of the World Bank supported oil for poverty project was innovative, not for its size, remoteness or complexity, but as it was the first time environmental management and institutional capacity-building was linked to hydrocarbon development (World Bank, 2000). However, in the beginning of 2009, Pegg (2009) concluded that Chad is the last victim of the "resource curse" as the World Bank driven oil-for-poverty project in Chad had failed, categorizing Chad along with Angola, Equatorial Guinea, Nigeria and Sudan, where the oil abundance has fostered increased greed, corruption, patronage and rent-seeking behavior rather than generating an efficient and competence state (Frank and Guesnet, 2009).

Chad is today one of the ten poorest countries of the world, ranking 170 of 179 countries in the United Nation's 2008 Human Development Index (Frank and Guesnet, 2009). With a per capita income of under \$250 a year, and 55% of the population living under the poverty line, Chad also struggles with low social indicators: more than half of the population over the age of 15 is illiterate and electricity is accessible to only 1% of the population (OECD, 2008). The Human Poverty Index (HPI), focuses on the proportion of people below a threshold level, living a long and healthy life, having access to education, and a decent standard of living, the value is 56.2% for Chad, ranks 133rd among 135 developing countries for which the index has been calculated (OECD, 2008).

The exploration and exploitation of nonrenewable natural resources have attracted several researchers and policy makers to try to find the causal mechanisms that such resource wealths have on, among others, civil conflicts (e.g Collier, 2000) and democracy (e.g. Ross, 2001). Whereas some argue that resource wealth can finance rebellions (e.g. Collier and Hoeffler, 2004) or making separatism financially attractive in resource-rich regions (Le Billon, 2005), others argue that resource wealth lowers the state capacity (Fearon and Laitin, 2005; Humphreys, 2005).

Di John (2010) states that the extent to which mineral and fuel abundance generate developmental outcomes depends largely on the nature of the state and politics as well as the structure of ownership in the export sector, all of which are neglected in much of the research-curse literature today.

The purpose of this current paper is to explore the history of the exploration efforts under the Chadian resource management and intra-state and international conflicts. I have focussed on three main areas: Firstly, I assessed the main sources of nonrenewable natural resource information, press releases and reports form exploration companies, information provided by UN and governmental agencies and the activities of non-governmental organizations. Secondly, I reviewed available nonrenewable resources in Chad and had during the 2008 CIOME conference (in N'Djamena, Chad) personal interviews with Division Manager of Ministre du Petrole, representatives from multinational oil companies as well as NGO's present in Chad. Thirdly, I have examined how the relation between conflicts and resources has been outlined in the literature.

In chapter 2 gives a overview of the minerals and hydrocarbon exploration evolution and its relation to the political history of Chad. Section 3 presents the status of the known and prospective hydrocarbon and mineral deposits of Chad. Section 4 presents how Chad has managed its nonrenewable resources under domestic conflict since independence.

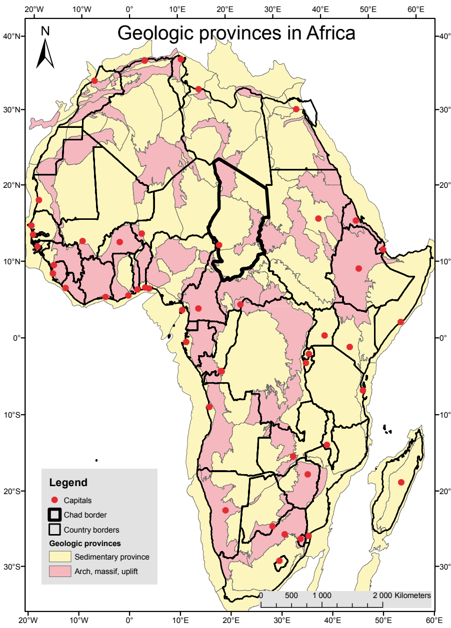

Figure 1: Structural provinces in African (according to USGS Charpentier et al., 2000) and the location of Chad.

2. Minerals and hydrocarbon exploration evolution and its relation to the political history of Chad

This section briefly outlines the exploration history of the non-renewable natural resources in Chad (Fig. 3) paralleled with political changes. Historically, Chad's mineral and energy industry has, until the oil export stated in 2003, not played a significant part in the national economy (USGS minerals yearbook, 2009). Prior to oil export, soda ash and salt has been the only mineral commodities produced, primarily for domestic consumption (Kusnir, 1997). Prior to becoming an oil exporter, the Chadian economy was heavily reliant on the cotton sector, and agriculture generated 40% of GDP and provided a livelihood for 85% of the population (USGS minerals yearbook, 2004). The national economy followed the cotton price fluctuations and year with drought result in predominantly relying on foreign aid.

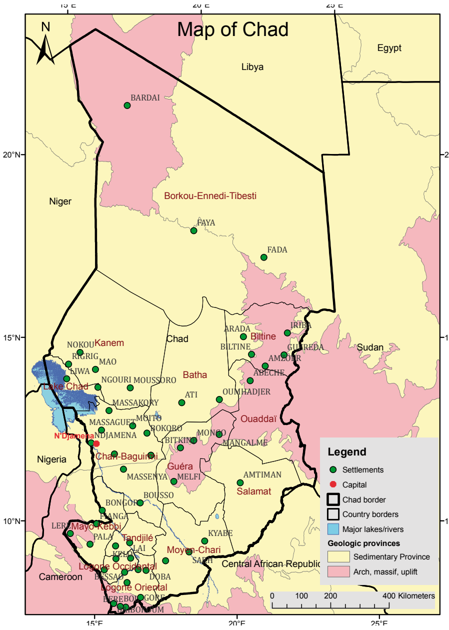

Figure 2: Administration boundaries and major settlements in Chad.

2.1. Pre-independence

Before colonialisation, non-centralist societies in the south co-existed with Islamic kingdoms in the Sahelian zone. The French-British convention of 1899 drew up the borders in West and East, and Chad became a French colony in 1920. The northern border was defined after a French-Italian agreement in 1936 (Azevedo, 1998). The first exploration for natural resources in Chad, performed in the Tibesti massif in northern Chad, was conducted by Desio in 1935-36 investigated the land in proximity to the Italian colony of Libya with the purpose to obtain topographic maps (Klitzsch, 1994).

During the colonial times, France became aware of the hardship to administer Chad with its huge size, rough topography, geographical disparities, scarce resources and poverty (Azevedo, 1998). The French taxation approach, following the colonial trend of how to best govern Chad in such way that it would benefit France, focused on southern Chad, with its savannas and rainforests, leaving the northern parts neglected due to its poverty and lack

Table 1: Guerrilla, fractional and national armies in Chad, 1969-1995 (Azevedo, 1998).

Year	Military Units	Numbers	Leaders
1969-1978	French troops	1500-2500	Cortadellas, Forest
1974	FAT (Forces Armèes Tchadiennes	4000	Tchadian Officer
1979-1980	GUNT (Government of National Union	4000-5000	Gukuni
	FACP (Forces Armées Populaires	4000-5000	Acyl
	FAT	4000	Kamougue
	CDR (Comité Démocratique de Révolution)	3000	Acyl
	Isl. legion	7000-90000	Qaddafi
	FAO	1000	Acyl
	FAN (Forces Armées du Nord	4000-6000	Habre
1983	OAC'S IAF	3800	Ajiga
	FANT (Forces Armèes Nationales Tchadiennes)	10000	Habra
1985	Codos	3000-5000	Djogo et al
1986	French Op. Manta	3500	French Generals
1987	FANT (Forces Armèes Nationales Tchadiennes)	28000	Habre
1993	ANT (Armèes Nationales Tchadiennes)	40000	Deby
1995	ANT (Armèes Nationales Tchadiennes)	25000	Deby

of significant natural resources (Azevedo, 1998). Azevedo (1998) conclude that the pre-independent Chad was so chaotic and violent at the end of the colonial time as the colonial system by nature was prone to abuse due the unequal power and the marginal supervision of the territories from Chad's capital.

Parallel to the independence of Chad, exploration for economic natural resources within the region was carried out (Klitzsch, 1994). The systematic exploration in Chad started in the beginning of the 1950s as an extension of the exploration of the French occupied Fezzan province (SW Libya) and the primary target was mineral resources as the vast quantities of oil in the African interior were unknown at that time. The discovery of oil onshore Algeria in 1953 followed by the first oil discovery onshore Libya in 1956, peaked by the first Libyan economic discovery in 1959, resulted in a massive interest in oil exploration in northern Chad (Klitzsch, 1994).

2.2. The Nineteen Sixties

The independence of Chad, led by a colonial-imposed solution, aimed to form a national unity preventing divisions along religious and ethnic lines (Azevedo, 1998). The first president of Chad, Tombalbaye, from the Sara ethic group, was first representing Moyen-Chari county in the Territorial Assembly and later forming the provisional government in Chad prior to the independence in 1960 (Azevedo, 1998). At first, Tombalbaye was attempting to unite all parties by forcing them to collaborate with his own party. This tactic failed, and in 1962, he banned all political parties except his own(Azevedo, 1998). The following was the start of series of arrests from prominent cabinet ministers to regular Christians and Muslims activists. The increased tension following the introduction of a single-party state led to massive deadly conflicts by the opposition with following counter-attacks by government forces (Azevedo, 1998).

Through the 1962 mining and petroleum legislations, Chad invited international actors to perform exploration and rumors of a substantial oil find in the northeastern Chad caused optimism (USGS minerals yearbook, 1963). In 1962, Petrodar, a company led by a subdivision of the French ELF company, explored for oil in Erdis basin in northeastern Chad (Borkou-Ennedi-Tibesti county, BET). After five exploration wells, this exploration concluded in 1965 that there is only sand and water in this region (USGS minerals yearbook, 1965). This disappointed President Tombalbaye, who saw the potential of future oil revenue disappearing and he canceled the 152 000 km^2 Pertrodar concession (Djimrabaye, 2005). Angry with the French exploration effort, Tombalbaye, forced the French troops out of BET (Azevedo, 1998) and sought to United States and Italy for exploration participation. Following this he announced an intensive 5-year plan for mineral exploration including hydrocarbons in the Erdis basin, geologic mapping near Abeche and mineralized veins and Uranium in the Tibesti (USGS minerals yearbook, 1965). Now without any French support, the United Nations Special Fund Aid stepped up and financed the mineral exploration resulting in the discovery of columbite, tin and tungsten in the Tibesti Mountains and a limestone deposit in Maya-Kebbi and diamonds along the Lobaye river in Logone Occidental county, however all deposits were too small, widely scattered and of too low quality for large-scale exploitation

(USGS minerals yearbook, 1967).

In 1966, the establishment of the National Liberation Front (FROLINAT) by northern politicians and nationalists, whose objective was to overthrow the Sara led regime in N'Djamena by force, led to a further escalation of the revolt that proliferated further south into other regions, such as Chari-Bagirmi and Wadai regions (Azevedo, 1998). In 1968, a legislation was adopted by the government of Chad, encouraging mineral development in favor of foreign investments including generous tax and custom benefits (USGS minerals yearbook, 1968). The map of the mineral deposits within Chad (Chaussier, 1968; Kusnir, 1997) that described and located the principal mineral deposits led to an increased tension within the government of Chad as this map indicated prospective national revenues (Azevedo, 1998). Before further drilling for oil in the Erdis basin, it was important for the government to secure a Chad-Libyan agreement for a possible pipeline through the most obvious oil transportation route through the Libyan desert (Djimrabaye, 2005). In 1968, and the signature of bilateral friendship and technical agreements resulted in an large northern rural revolt, including an increased opposition within the government (Azevedo, 1998). President Tombalbaye had to reconnect to France and ask President Charles de Gaulle to honor the French-Chadian military pact (Azevedo, 1998). The French intervention in 1969 helped to keep the rebels at distance. During the first half of 1970s, President Tombalbaye survived several coup attempts as he was facing even more opposition than he was able to prevent (Azevedo, 1998).

In late 1969, the government of Chad granted a 5-year permit for hydrocarbon exploration to Continental Oil Co. (CONOCO) covering a 600 000km^2 area of the Lake Chad Syncline and Chari Depression in the central and southern Chad (USGS minerals yearbook, 1969). During the fist years CONOCO performed only magnetometric and photogeologic surveys over their concessions (USGS minerals yearbook, 1971), followed by drilling 28 exploration wells with 11 discoveries between 1969 and 1986 (Djimrabaye, 2005). This was the first oil exploration within the southern areas. In parallel, the government was encouraging minerals exploration surveys that resulted in the discovery of uneconomic salt deposit in the BET area and gold veins near Abeche and copper near Lere (USGS minerals yearbook, 1969).

2.3. The Nineteen Seventies

The Erdis basin permit was in September 1970 reassigned to the French company Ste. Indèpendante de Recherches et d'Exploitation Pètrolières (SIREP). The mentioned map of Chaussier (1968) specified 14 locations potentially containing uranium deposit in the Tibesti region and these resources were one of the reasons why Libya, in 1972, occupied the Aouzou strip of Northern Chad (Huliaras, 2001). The military intervention in Chad was undoubtedly Libya's most significant external involvement, as Chad was the center piece of Colonel Qaddafi's Libya intention for a large Muslim central African cooperation. Libya spent important financial resources with an intense anti-imperialism in supporting Coup d'Etats and radical governments all over sub-Saharan Africa to give support to this ambition (Huliaras, 2001).

In 1972, CONOCO sold 50% of its concession to Chad Shell Exploration and Development Corp. CONOCO and Shell stepped up their seismic campaign in Mondou, Doba and Sarh; south of Bousso; Kanem northeast of Lake Chad. Both oil exploration and mineral activities in the south were hampered by local unrest (USGS minerals yearbook, 1973). The UNPD (United Nations Development Programme) 10 000 km^2 geologic survey program of the Mayo-Kibbi region trained the Chad Geologic Survey staff as part of a institutional capacity-building effort that resulted in evidence for the presence of gold, nickel, uranium and complex sulfide ores (USGS minerals yearbook, 1976). This exploration surveys for gold, copper and lead occurrences were continued in Mayo-Kebbi and Ouaddai regions. The gold deposit was classified as poor in contrast to some interesting nickel and uranium anomalies thought to present promising targets for future exploration (USGS minerals yearbook, 1979).

The first economic oil discovery in Lake Chad region was hit in September 1974 (USGS minerals yearbook, 1974). This opened for full exploration in the Lake Chad and Doba areas. Despite that the military took control over the Government in April 1975, there was no change in the Government's position towards mining and petroleum ventures (USGS minerals yearbook, 1975). The subsequent year, 1975, oil was discovered near the town Doba (USGS minerals yearbook, 1976).

The assassination of President Tombalbaye during the successful coup d'etat 1975, where the opposition, led by Malloum, a Sara ethnic, blamed the president for dividing the country, putting the tribes one against the other, and for humiliating the military (Azevedo, 1998). From 1975 to 1982 Chad was under military rule including a civil war. The French was expelled from Chad in 1975 after the new head of state, Malloum, discovered that the French government had directly negotiated with the northern rebel groups in the 1974 capture of a French German group (Azevedo, 1998). This misstep paved the road to N'Djamena for the northern rebels and the French army returning to Chad in 1978 could not prevent the break out of the Chadian Civil war where the southern Chad population lost their influence (Azevedo, 1998). The war was significantly international, where Libya was fighting a war against Chad backed by France (Huliaras, 2001).

Despite the civil war, Conoco-Tchad, owned by Shell (50%), Chevron (25%), Esso (12.5%) and the operator CONOCO (12.5%), planned to construct a 350km long pipeline from Lake Chad connection the S*é*digui field with a purposed new refinery near N'Djamena with scheduled completion by late 1979 (USGS minerals yearbook, 1977). The company Standard oil bought Chevron's share and became operator of the Doba oil concession. The escalation and spreading of the civil war delayed the planned refinary as well as Chad's hope of becoming an oil producer as most foreign personnel fled Chad (USGS minerals yearbook, 1980).

2.4. The Nineteen Eighties

The cease of the civil war in November 1981 resulted in the withdrawal of Libyan forces from nearby N'Djamena (Azevedo, 1998). The government outlined then a 5-year plan which included both hydrocarbon exploration and evaluation of uranium resources (USGS minerals yearbook, 1981). New riots in 1983 from the Libya-backed northern rebels were defeated with the help of French troops (Azevedo, 1998). The Conoco-Tchad oil exploration in southern Chad concluded in 1987 that the expenses of producing oil for domestic use, coupled with the cost of constructing a refinery, made the refinery building program financially unfeasible in the near future USGS minerals yearbook (1988). The ending of the Libya-Chad conflict over the Aozou strip in northern Chad terminated in 1988 with the final withdrawal of the Libyan troops in 1994 after the International Court in Haag ruling that Aozou strip belongs to Chad (Azevedo, 1998). In 1988, Hunt International Petroleum Co. (US) signed an agreement with the government to conduct oil exploration in central Chad (Lake Chad area) (USGS minerals yearbook, 1989). Chad's Direction de Gèologiques et Minières (DRGM) funded by the United Nations Development Program (UNDP) had during the 1980's identified tin, tungsten, and uranium mineralization in the Tibesti massif in the northwestern part of the country (USGS minerals yearbook, 1996).

2.5. The Nineteen Nineties

In the late 1980s civil unrest escalated as President Habrè could not control the ethnic tension amongst government troops serving in the south as well as disaffection in the capital (Azevedo, 1998). Beyond military superiority and clever negotiation, Habrè relied on the twin support of the United States and, in particular, France (May and Massey, 2000). These assumptions did not materialize and following the successful coup d'etat led by Dèby, a Zaghawa ethnic from eastern Chad (May and Massey, 2000). The new government indicated a more democratic rule and strengthened their systematic prospection for mineral and energy resources by encourage investors to carry out research and exploit known mineral resources that would diversify the energy sector (Frank and Guesnet, 2009). The new mining code (law No. 011/PR/1995 of 1995) and petroleum code (Law No. 001/pr/99 of 1999) led to an increase in exploration for both mineral and petroleum (Frank and Guesnet, 2009).

In the beginning of the 1990s, the mining prospection focused on economic re-evaluating the gold seams in Mayo-Kebbi region and the mining potential in Quaddai, Guera and Kanem regions (USGS minerals yearbook, 1991). The Dèby regime process of democratization was played out against a backdrop of constant civil conflict (May and Massey, 2000). Through 1991 and 1992 the government faced several coup attempts and these were answered with reprisals that extended beyond rebel fighters (May and Massey, 2000). The appraisal drilling of the discoveries constituting the Doba field was finished in 1994 and proved enough volumes to make a transportation pipeline for oil export to the international market feasible (USGS minerals yearbook, 1995). In 1996, Chad and Cameroon agreed to a bilateral treaty that provided for the construction and operation of the pipeline and other oil transportation facilities. During this appraisal drilling and later, the Dèby regime was in more or less constant struggle and negotiations with the southern rebels which terminated at Moundou in 1997, where the most dangerous armed rebels were liquidated (May and Massey, 2000).

2.6. After the Millennium

In 2003, the first significant oil exploitation started after three year development of the World Bank supported a 1070km long pipeline, including pumping stations and production facilities to transport oil from the Doba field in southern Chad, to the port of Kirbi, Cameroon (EssoChad, 2010).

In 2005, the Consortium began work on the Nya-Moundouli expansion project, which was developing two new oil fields in the vicinity of the original three discoveries of the Doba field (EssoChad, 2010). In 2007, EnCana sold its Chadian assets, permit H, to China National Petroleum Company (CNPC), after drilled 11 wells in the Bongor basin within the last 5 years (EnCana, 2007). The entrance of the CNPC provided new possibility for the Dèby Itno regime. Following the potential development of Sèdigui field, near Lake Chad, and the hydrocarbon discoveries in Bongor basin, including an oil refinery (that is be operational in 2012) designed to meet more than Chad's domestic consumption (CNPC, 2009).

The mineral industry of Chad is for the time beeing fully overshadowed by the petroleum exploration leading to minimal focus on mineral exploration (USGS minerals yearbook, 2006).

In the beginning of 2004, president Dèby Itno resisted political instability after the amendment of the constitution that abolished the limitation of the number of re-elections (Frank and Guesnet, 2009). The President announced in 2005 a desire to renegotiate the oil revenue management plan with a raise in the non-priority sector from 13.5% to 30% and inclusion of new priority sectors such as justice, security and territorial administration (Frank and Guesnet, 2009). The abolition in late 2005 by the Chadian parliament of the future generation funds displeased the World Bank and resulted in a freeze of its accounts to Chad (Pegg, 2009).

In Spring 2006, a unsuccessful Coup d'etat was performed by rebel groups supported by Sudan as a result of the rebel growth in eastern Chad, relating to the Darfur crisis in Sudan (Frank and Guesnet, 2009). The following month President Dèby Itno, who threatened to expel 200000 Darfur refugees from Chadian Territory, came to an agreement after talking with France and the US that he would receive 10% more of the oil revenue by lowering the poverty reduction percentile (Pegg, 2009). The next step of was to create a national oil company (SHT), whose aim was to have an ownership of 60% in the oil industry (Acyl, 2008). The welcoming of the Chinese investments in the oil industry changed the Chadian commitments to France and US (Pegg, 2009). After getting a larger share of the oil revenue income, President Dèby Itno, accused Petronas and Chevron for failing to pay taxes and threatened to expel them from the country, but came to an agreement were Petronas and Chevron had to pay Chad $289 million (Pegg, 2009). At the end of 2007, after the Dèby Itno regime had first replaced the commitment of the 5 percent fund of royalties paid to the oil-producing region by his own hand-picked government appointees and secondly, dissolved the national coordination for the oil project, the World Bank realized that their position in the pipeline project was not sustainable (Pegg, 2009). The World bank ended the involvement after conveying its concerns to Chad about the 2006 Memorandum of Understanding the breach of Chad answered by respondly fully paying all outstanding World Bank loans (Pegg, 2009).

The eastern multi-ethnic rebels that also include the same ethnic group as Dèby Itno, have attacked the capital twice, 2006 and 2008, where the Dèby Itno regime defeated the opposition with minor help from France (Pegg, 2009).

3. Known and prospective mineral and hydrocarbon deposits of Chad

The exploration history in Chad in the last 50 years has resulted in the identification of large amount of mineral (Table 2 and Fig. 3) and hydrocarbon deposits (Table 3 and Fig. 4). Despite the fact that most of the proven mineralizations have been evaluated, several of the them need to be reevaluated due to new permit owners, new analytical methods, change in world demand / commodity price (Griffiths, 1978; Moutaye, 2008). All publicly available known mineral deposits in Chad are summarized in Table 2. These deposits are clustered in three regions of Chad located in specific areas (geologically defined as arches, massifs and uplifted areas) that are more prone for mineral deposits than those defined as sedimentary basins (Fig. 3).

Numerous types of minerals are proven within favorable provinces (Fig. 3), known as mining districts, within the Mayo-Kebbi (gold, uranium),

Table 2: Known mineral exploration discoveries in Chad

ID	Name	Latitude	Longitude	Commodity	Rock type	Region
1	Ribao	9.783	14.317	uranium	Syenite	Mayo-Kebbi
2	Zalbi	9.783	14.317	uranium	Syenite	Mayo-Kebbi
3	Massonebare	9.783	14.317	uranium	Syenite	Mayo-Kebbi
4	Bouboa	9.783	14.317	uranium	Syenite	Mayo-Kebbi
5	Bakou	13.183	22.100	uranium	Syenite	Ouaddai
6	Tibesti	22.200	17.450	uranium	Syenite	BET
7	Fada Itou	17.1847	21.590	uranium	Syenite	BET
8	Fada Itou	17.1847	21.590	uranium	Syenite	BET
9	Yedri Tenere	22.200	17.450	uranium	Syenite	BET
10	Yedri Tenere	22.200	17.450	uranium	Syenite	BET
11	Yedri Tenere	22.200	17.450	uranium	Syenite	BET
12	Sodje Mbaye	9.400	14.933	uranium	Syenite	Mayo-Kebbi
13	Abeche	13.817	20.817	Diamond	Alluvial	Ouaddai
14	Biltine	14.533	20.917	Diamond	Alluvial	Biltine
15	Am Zoer	14.217	21.383	Diamond	Alluvial	Biltine
16	Adre	13.467	22.200	Diamond	Alluvial	Ouaddai
17	Melfi-Bitkine	11.060	17.930	Diamond	Alluvial	Guera
18	Baibokoum	7.750	15.683	Diamond	Alluvial	Mayo-Kebbi
19	Teubara	9.654	14.230	Gold	Proterozoic greenstone	Mayo-Kebbi
20	Gambok	9.366	14.900	Gold	Proterozoic greenstone	Mayo-Kebbi
21	Massond	9.366	14.900	Gold	Proterozoic greenstone	Mayo-Kebbi
22	Mbibou	9.366	14.900	Gold	Proterozoic greenstone	Mayo-Kebbi
23	Mourbame	9.600	14.150	Gold	Proterozoic greenstone	Mayo-Kebbi
24	Mayo N'Dala	9.667	14.500	Gold	Alluvial	Mayo-Kebbi
25	Goz Beia	12.217	21.416	Gold	granite/quartzite contact	Ouaddai
26	Am Ouchar	12.000	21.850	Gold	granite/quartzite contact	Ouaddai
27	Echbara	12.700	21.333	Gold	granite/quartzite contact	Ouaddai
28	Ade	12.667	21.900	Gold	granite/quartzite contact	Ouaddai
29	Ardelik	12.4167	21.383	Gold	granite/quartzite contact	Ouaddai
30	Aozou strip	21.837	17.427	Gold	Alluvial	BET
31	Haidjen Hadid	13.450	21.667	Iron ore	Precambrian ferrious quartzites	Ouaddai
32	Gourgoudji	13.300	21.700	Iron ore	Precambrian ferrious quartzites	Ouaddai
33	Koukou Angarama	12.017	21.683	Iron ore	Hematite schist	Ouaddai
34	Tile Nougar	12.583	19.233	Iron ore	oolitic fm	Guera

Ouiddai (Gold, Diamond) and Tibesti (gold, uranium, tin, tungsten, wolframiite) provinces, having the highest concentrations (Kusnir, 1997; Soo-Young and Se-Jung, 2001; Brinkley Mining, 2008; Mining Weekly, 2009; Signet Mining, 2009; USGS minerals yearbook, 2009). In addition, are several alluvial deposited minerals (gold, diamonds and bauxite) identified scattered over a large area mainly restricted the southern half of Chad (Fig. 3). This includes the bauxite deposit at Koro de Lai with an estimated 7 million metric tons grading 57% Al_2O_3. . Madagzang prospect near Lere is in a final stage of production feasibility (Mining Weekly, 2009; Signet Mining, 2009), with a postulated production of 1000 t/yr, which is about 2% of the total world uranium production (World Nuclear Association, 2008; IAEA, 2009).

Diatomite, dolomite, granite, kaolin, limestone, and marble deposits were also reported (USGS minerals yearbook, 1995). Still, no world class mineral deposits are discovered in Chad and according to (Moutaye, 2008), this is assumed to be related to the low exploration effort carried out in Chad. Even though Orris and Grauch (2002); USGS minerals yearbook (2009) state that there are currently no discoveries of rare earth element (REE) minerals within Chad, Africa Mining (2000) outlines the post-tectonic granitic rocks of Tibesti to host niobium, tantalum and beryllium, and Columbotantalite in alluvial deposits in Tibesti.

Chad has identified economic hydrocarbon reserves in three sedimentary basin; Lake Chad, Bongor and Doba basins (Table 3). In Lake Chad, three fields of total 19 MMBO have been discovered. The present economic quantities of oil in the southern part of Chad have been discovered during the last years within the Bongor (450 MMBO) including the discoveries of Mimosa, Kubla, Baobab and Ronier fields and Doba basins (1052 MMBO).

3.1. Prospective minerals

The exploration for minerals in Chad has a long history ranging from the tungsten and uranium identifications in the Tibesti region at the end of the colonial era to the present gold and uranium evaluation for development in the Mayo-Kebbi region (Fig. 3). Predominantly, this mineral exploration has been sparse and patchy with several discoveries without any world class deposit (Kusnir, 1997; Frank and Guesnet, 2009).

Table 3: Oil reserves in Chad and their pool sizes based on USGS minerals yearbook (2000); EssoChad (2002, 2010); Chevron (2008); CNPC (2008, 2009); Geosint (2011); Liangqing (2008)).

Sed. basin name	Field name	Discovery name	Discovery closure area [km^2]	Reserves [MMBO]	Reserves/ closure area [MMBO/ km^2]	Nr. field basin area fields /1000km^2	Reserves/ basin area MMBO /1000km^2
Doba	Doba	Kome	50.8	588	11.6		
	Doba	Bolobo	13.5	135	10.0		
	Doba	Miandoum	22.7	227	11.3		
	Doba	Nya	1.3	11	8.4		
	Doba	Moundouli	15.0	69	4.6		
	Doba	Maikeri	3.2	22	6.9		
	Sum Doba basin		106.5	1052	9.9	0.26	46.3
Lake Chad	Sédigui	Sédigui	5.0	15	2.0		
		Kanem/Kumia	2.0	4	3.0		
Sum Lake Chad basin			7.0	19	2.7	0.14	0.9
Bongor	Ronier	Ronier	30.0	243	8.1		
	Mimosa	Mimosa	10.6	86	8.1		
	Baobab	Baobab	5.6	44	8.1		
	Kubla	Kubla	9.4	76	8.1		
	Sum Bongor basin		55.6	450	8.1	0.23	26.3
	Total:		191.1	1583	8.3		

Table 4: Assessment results of the total undiscovered oil resources of Chad using USGS 2000 methodology (Brandsegg, 2011). Sedimentary basins with area less than 3000 km^2 (ID: 5 (Mousso), 8 (Largeau 3), 12 (Largeau 7), 14 (Largeau 9), 15 (Largeau 10)) are not displayed as their sediment volumes are interpreted to be insufficient for an active TPS. These sedimentary basins are displayed without any oil resources in Fig. 4.

ID	Basin area [km^2]	Basin area name	Undiscovered oil [MMBO]			
			Geologic+access			
			P90	P50	P10	Mean
1	67994	Erdis	36	116	212	118
2	3502	Djado	5	15	39	20
3	5914	Manga	5	15	28	20
4	12667	Siltou	8	21	49	27
6	43942	Largeau	22	47	89	53
7	11007	Largeau 2	6	15	36	19
9	3735	Largeau 4	4	12	32	16
10	4049	Largeau 5	3	11	29	15
11	4354	Largeau 6	4	12	32	16
13	4682	Largeau 8	5	21	36	19
16	20821	Lake Chad	70	169	316	185
17	11490	Lake Chad 2	29	72	155	85
18	6997	Lake Chad 3	12	35	84	44
19	3206	Madiago West	12	31	75	40
20	3807	Madiago East	12	31	75	40
21	17098	Bongor	68	166	324	184
22	5178	Chari West	19	52	119	63
23	22698	Doba	25	71	165	87
24	23676	Doseo	66	163	308	178
25	15209	Salamat	41	102	212	118
Total undiscovered resources						1347

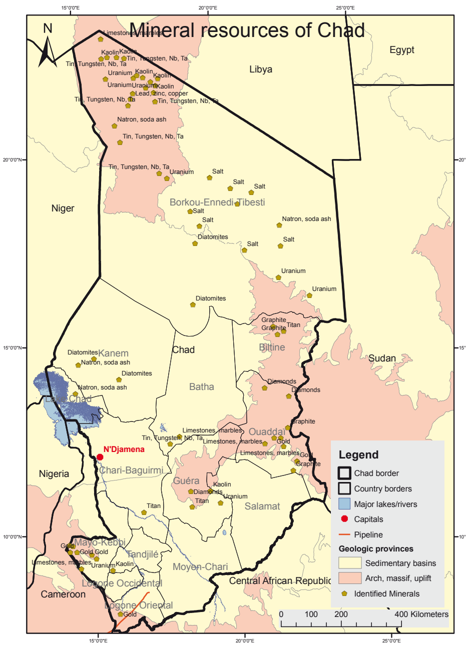

Figure 3: The Mineral discoveries outlined in Table 2 are shown geographically including province boundaries, and major settlements.

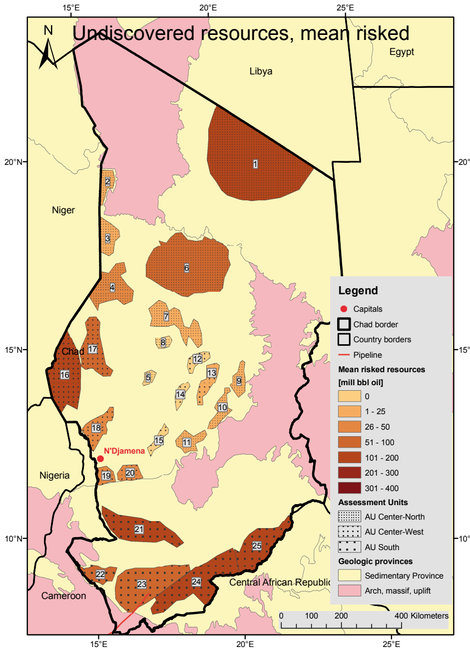

Figure 4: Geologic and access risked P50 undiscovered hydrocarbon resources [MMBO] of Chad using the USGS 2000 methodology. Names of the specific sedimentary basins (labelled 1-25) are given in Table 4

The latest assessment by USGS, named Quantitative Global Mineral-Resource Assessments, that aimed to delineate areas of the world that are geologically permissive for the occurrence of undiscovered selected non-fuel mineral resources, together with estimates of the quantity and quality of those resources (Taylor et al., 2009). This study concluded that there are high potential to discover numerous prospects for significant undiscovered non-fuel mineral resources in Africa. For Chad's case, the assessment outlined no major prospective mineral resources. However, Taylor et al. (2009)'s study bring to a close that the less that is known about an area, the more likely that mineral/ore deposits are left undiscovered. The remoteness of mining districts, together with overlying deposits of sand obscure much detail and have therefor curtailed exploration activity in Chad (Moutaye, 2008).

The non-fuel mineral operations of Africa and Middle East were digitally published by USGS, following the 2004 USGS Minerals Yearbook, and presented information about the mineral facilities including their location, ownership or operating company, operating status, and capacity (Orris and Grauch, 2002; Eros and Candelario-Quintana, 2006). Related to Chad, this map outlined only the artisanal Mayo Dala gold placer with an annual production of 150 kg per year. The subsequent work that delineated areas in Africa that are geologically permissive for the occurrence of selected undiscovered non-fuel mineral resources together with estimates of the quantity and quality of these resources, presented new knowledge of the African abundance, distribution, and general geologic setting of non-fuel mineral commodities (Taylor et al., 2009).

As the energy resources of the world holds a more strategic economic significance, USGS are excluding both existing and prospective uranium resources (the three exceptions are Rössing mine in Namibia and Akouta and Arlit mines in Niger) and prospective hydrocarbon resources. The uranium mines and prospects in Chad need to be identified/estimated by other sources (Bamba and Petry, 2010). However, Goodell (1992) pointed out that Tibesti massif could become a major source of uranium in the future. The exploration effort in Tibesti is currently inactive therefore in a short term perspective the uranium resources in the Mandagzang prospect (near Lere) are assumed to be developed first (Bamba and Petry, 2010).

Alluvial mineral deposits, known as placer deposits, are accumulation of valuable minerals formed by deposition of dense mineral phases in a trap site and are remembrance of weathered rocks which have been transported by water and accumulated a deposit concentration (Craig et al., 2001). The host rock of the alluvial diamond in Biltine, Guera and Ouaddai counties are not yet discovered, and is assumed to be within Chad (USGS minerals yearbook, 2006). Alluvial diamonds are mined on the Central African Republic side of the border and alluvial gold are discovered in conjugation of the Precambrian greenstone rocks in Mayo-Kebbi and Ouaddai (Kusnir, 1997). Generally, such placer deposits are located within sedimentary basins near crystalline provinces where the potential host rock is present (Craig et al., 2001). Based on this information a prospective mineral resource map is compiled (Fig. 3) indicating that no significant future mineral deposits are assumed near N'Djamena.

Due to the large number of mineral types already identified and that Chad is a large country with multiple mining provinces, it is not feasible to estimate the number of mineral occurrences or their volumetric or monetary value. However, the mining districts are assumed to be located in igneous or metamorphic rock provinces (arches, massifs) or in alluvial deposits near these provinces. Based on this, the main locations for discovering new mineral deposits that has a high potential to become economic are (Fig. 3):

- Tibesti massif (Uranium, Tin, Tungsten, copper sulfides, silver, zinc, wolframe, REE)
- Mayo-Kebbi area (Uranium, gold)
- Ouaddai area (Iron ore, gold, diamond)
- Guera area (Gold, diamond)

3.2. Prospective hydrocarbon resources

As outlined in the yet to find hydrocarbon assessment of Chad (Brandsegg, 2011) using USGS World assessment methodology (Klett et al., 2000), there are sedimentary basins in Chad that could contain undiscovered hydrocarbon resources (Table 4 and Fig. 4). The estimated mean risked undiscovered resources (1350 mill bbl oil) are about one-third of the ultimate mean resources of 4300 mill bbl oil. Although Chad is generally underexplored in both the intra-cratonic and the rift development related basins, they are estimated to contain significant yet to find oil that can potentially lead to field developments and to sustain Chad's oil export volumes. Most of the undiscovered resources are expected to be in the intra-cratonic Paleozoic strata (Erdis and Largeau basins), in the Upper Cretaceous-Tertiary strata (Lake Chad, Madiago basins) and the Lower Cretaceous strata (Bongor and Doseo basins).

The fully-operated Doba pipeline in southern Chad, the development of the 350 MMBO Niger discoveries near Chad's western border (Petzet, 2007), the development of central Libya discoveries (Lüning et al., 1999) and the Sudan pipelines assembled about 500km from the border of eastern Chad (Mohamed et al., 2002), can represent options for tieback from future discoveries. The exploration results in the Kufra basin will have strong influence on the exploration in the Erdis and Largeau basins. Similarly, the exploration of the undrilled sedimentary basins in north-eastern Chad (Djado, Manga and Siltou basins) will be influenced by the exploration effort in the Djado basin in Niger and the exploration of the southern part of the already proven prolific Murzuk basin (Aziz and Ghnia, 2009). Based on this, the future exploration areas in Chad can be divided according to future potential into two categories: High to medium and low prospective areas. The former areas, such as Doseo, Madiago East, Madiago West and Lake Chad basins, are areas where the petroleum system is well constrained. Low prospective areas, such the Largeau basins in AU Central-North, represents high risk, but could contain large quantities of oil if the petroleum system in Erdis proves to be adequate.

The exploitation of hydrocarbon resources is the priority of energy policy in Chad (Younous, 2008) and can be summarized as (Fig. 4):

- Erdis in the north: Undrilled since 1960. High potential.

- Lake Chad in the west: Moderate reserves, moderate potential.
- Largeau in the Center: Undrilled, highly speculative.
- Madiago in south-west; Undrilled, moderate reserves with further moderate potential.
- Bongor and Doba and in the South: large reserves, where Bongor has most remaining potential.
- Doseo and Salamat in South East: Minor potential.

4. Prospective non-renewable natural resources and its co-existence to future conflicts in Chad

The general assumption in the literature is that there is a correlation between exploration and exploitation of non-renewable resources and violent conflicts, however the causal mechanisms for this correlation is highly debated (Collier, 2000; Ross, 2004; Buhaug, 2007). This is evident in quantitative research (large-N studies) where global or regional data are tested for identifying significant causal mechanisms that is observed on country level scale. (Buhaug, 2007) argues that both large-N studies and case studies must be applied for the purpose to fully understand the causal mechanisms of natural resources and conflicts. According to (Collier et al., 2009), quantitative analysis based on global scale data has its own severe limitations imposed by data constrains and so should be seen as complimenting qualitative in-country research rather than supplanting it.

Humphreys (2005) supports this view and attempts to look behind the observed correlations and suggests ways to introduce finer division of the data that can help to chose between plausible underlying causal mechanisms. This paper tries to compile conflict evidence and ultimate resource values to help complement some weaknesses in the current information base regarding the potential conflict-natural resource links in Chad.

Several researchers and policy makers has tried to identify the causal mechanisms that resource wealths have on, among others, civil conflicts (e.g Collier, 2000) and democracy (e.g. Ross, 2001). Whereas some argue that resource wealth can finance rebellions (e.g. Collier and Hoeffler, 2004) or making separatism financially attractive in resource-rich regions (Le Billon, 2005), others argue that resource wealth lowers the state capacity (Fearon and Laitin, 2005; Humphreys, 2005).

(Humphreys, 2005) outlined several mechanisms that can explain the relation between natural resource and civil war and these are exemplified below with examples from Chad.

The **greedy rebels mechanism** can be divided into three parts: (1) Domestic groups may engage in quasi-criminal activity to benefit from resources independent from the state. (2) Natural resources increase the ”prize” values to gain state control (Fearon and Laitin, 2005). This is evident when Dèby Itno performed a successfully coup d'etat using only 2000 soldiers (Eriksson and Hagstrømer, 2005). (3) Natural resources are concentrated in a particular region of the country (Ron, 2005). In the 1990s in southern Chad, the citizens were fighting to obtain a share of the money that would later be generated from the Doba oil fields (May and Massey, 2000). The appraisal drilling of the discoveries constituting the Doba field was finished in 1994 and proved enough volumes to make a transportation pipeline for oil export to the international market feasible (USGS minerals yearbook, 1995). In 1996, Chad and Cameroon agreed to a bilateral treaty that provided for the construction and operation of the pipeline and other oil transportation facilities. During this appraisal drilling and later, the Dèby regime was in more or less constant struggle and negotiations with the southern rebels which terminated at Moundou in 1997, where the most dangerous armed rebels were liquidated (May and Massey, 2000). By this, President Dèby Itno obtained full control over both the Doba production unit and eliminated a potential greedy rebel conflict.

The **grievance mechanism** is related to inequality, political rights, ethnic polarization and religious fractionalization (Collier and Hoeffler, 2004). The process of extraction may produce grievances, for example, through forced migration and natural resource wealth may be seen as more unjustly distributed than other wealth. This is evident in Chad as the local citizens near the Doba oil fields have received land compensation when the field was constructed as well as the local leaders receive annual compensation (such as infrastructure, clean water, schools) directly from the company operating the field (EssoChad, 2010).

Similar, the grievance mechanism was develop-

Table 5: Chad ultimate technically recoverable oil are compiled from proven reserves (Table 3), cumulative oil production (EssoChad, 2010) and the oil assessment results using the USGS 2000 methodology (Table 4). MMBO, million barrels of oil. Results shown are fully risked estimates. P90 represents a 90 percent chance of at least the amount tabulated; other fractiles are defined similarly. AU, assessment unit.

Assessment Unit (AU)	Field Type	Cumulative production	Identified reserves	Original reserves	Total undiscovered Resources Oil (MMBO)					Ultimate resources (mode)
					P90	P50	P10	Mean	Mode	
AU Center-North	Oil	-	-	-	103	285	552	304	240	240
AU Center-West	Oil	-	19	19	139	368	739	413	310	329
AU South	Oil	354	1210	1564	270	699	1002	630	780	2344
Total		354	1229	1583	877	1376	1900	1347	1420	2639

ing after the independence of Chad the government abuses in 1968 led to beginning of the northern rebellions fight against N'Djamena. The Chadian Independence, led by a colonial-imposed solution, aimed to form a national unity preventing divisions along religious and ethic lines (Azevedo, 1998). The first president of Chad, Tombalbaye, from the Sara ethic group, was first representing Moyen-Chari in the Territorial Assembly and later forming the provisional government in Chad prior to the independence in 1960 (Azevedo, 1998). At first, Tombalbaye was attempting to unite all parties by forcing them to collaborate with his own party. This tactic failed, and in 1962, he banned all political parties except his own and was performing abuses to the northern citizens (Azevedo, 1998). In 1966, the establishment of the National Liberation Front (FROLINAT) by northern politicians and nationalists, whose objective was to overthrow the Sara led regime in N'Djamena by force, led to a further escalation of the revolt that proliferated further south into other regions, such as Chari-Bagirmi and Wadai regions (Azevedo, 1998). In 1968, a legislation was adopted by the government of Chad, encouraging mineral development in favor of foreign investments including generous tax and custom benefits (USGS minerals yearbook, 1968). The map of the mineral deposits within Chad (Chaussier, 1968; Kusnir, 1997) that described and located the principal mineral deposits led to an increased tension within the government of Chad as this map indicated prospective national revenues (Azevedo, 1998).

The **feasibility mechanism** argue that natural resources could provide a way to finance rebellions that have been started for other reasons, thereby increasing the prospects of success (Collier et al., 2009). Either is this through control of exploitation of natural resources during war time, or through the sales of prospective resource revenues, named booty futures (Ross, 2004). In Chad, the booty futures argument has been identified since Chad's independence. The map of uranium deposits of the Tibesti (Chaussier, 1968; Kusnir, 1997) was one of the arguments for Libya to control the Aozou strip in 1970's (Huliaras, 2001) (The main aim was to include Chad as the center piece of Colonel Qaddafi's Libya intention for a large Muslim central African cooperation). It is also indicated that the successful coup d'etat of President Dèby Itno in 1990 was supported by France as French troops were passive during the revolt and did not intervene with the rebels (Eriksson and Hagstrømer, 2005). This resulted in that ELF (a French company) received a stake in the southern Doba oil field after this coup d'etat (Humphreys, 2005).

The **weak state mechanism** argues that state structures may be weaker in natural-resource dependent economies (Collier and Hoeffler, 2005; Sobek, 2010). There are two prominent variants of the argument focusing on the strength of state-society linkages; (1) As the general citizens of Chad is untaxed by the government, it has less power over them. This include that these citizens have less information about the government activities. (2) The increase of state capacity in Chad was one of the arguments World Bank used to initiate the Doba pipeline (World Bank, 2000) that intended, among others, to increase the payment to the counties of Chad and make the oil revenue transparent so that the citizens and the world community could see how the oil revenue was spent. This World Bank initiative was, after the oil was started to be produced, in 2006 terminated by President Dèby Itno, corresponds with the second argument of the weak state mechanism arguing that governments relying on natural resources rather than taxation have weakened incentives to create strong bureaucratic institutions. This is also argued by Fearon (2005) that oil states are more likely to have weak structures as they have less need for intrusive bureaucracies to raise revenue. Based on this argument, President Dèby Itno has no interest to increase the bureaucracies as long as he has revenues from e.g. oil. This corresponds also with rentier state concept in Basedau and Lay (2009) indicating that governments use abundant resources to buy off opposition or suppress armed rebellion, thereby contributing to political stability and preventing armed conflict. as well as the last rebellion attacks in N'Djamena, the 2008 attempt, where the rebel forces tried to oust Chad's President Dèby Itno for the purpose to gain state control (Ngarmbassa, 2008).

These examples have identified several mechanisms related to natural resource-conflict that is evident in Chad. Based on this history is clearly a co-existence between prospective natural resources and conflicts in Chad. This allows for using the known and prospective mineral and hydrocarbon resources in Chad as a basis for indicating how the future of Chad will develop.

As Chad has only produced 25% of its identified reserves (300 mill bbl of oil out of about 1200 (Table 5)) and that the Bongor and Lake Chad areas are not yet started to produce, Chad is likely to recieve similar or higher annual oil revenues in the future given a steady oil price. The assessment results indicate ultimate recoverable oil resources in Chad in the order of 2639 mill bbl oil. Following the greed motive of Fearon (2005), this opens for more coup d etat, as the "prize" to win is higher than the previous successful and unsuccessful attempts.

As earlier stated, there are geographically variations of where the prospective non-renewable resources in Chad are located in terms of type and quality. New regions that can contain producible quantities of oil (Fig. 4 and Table 5) represent windfall economic opportunities. The most likely areas are the Erdis basin, as well as the Bongor and Lake Chad area. The Erdis basin lies within an area with marginalized control from the government with historically a low level for local unrest.

In parallel to the prospective oil resources, the other prospective non-renewable resources (e.g. gold, diamonds, uranium) is geographically located in other regions of Chad than where the current oil production is. Similar as oil revenue is important for the current Chadian government, the government will apply effort to obtain revenue from new oil discoveries and/or potentially other non-renewable resources (e.g. gold, diamonds, uranium). Such new discoveries can in the future both destabilize and strengthen the Dèby Itno regime as the current oil production facilities are under strong governmental protection, it is likely that new locations of extractive resources need to have identical control of the government. The location of the prospective mineral resources, e.g. mineral district of Tibesti in northern Chad and the district in the east can both increase the possibility for conflicts.

Di John (2010) concludes that the extent to which mineral and fuel abundance generate outcomes that benefit development depends largely on the nature of the state and politics as well as the structure of ownership in the export sector, all of which are neglected in much of the research-curse literature today.

5. Conclusions

The conflict literature do not agree on the exact extent and role that the natural resources abundance play in relation to armed conflict. In Chad, international and national companies are seeking to increase their reserves by exploring for commercial quantities of both minerals and hydrocarbons. Simultaneously, there is an endemic tension between rebel groups and the central government throughout the modern history of Chad. The last rebel tension started after the 2005 government election where the majority of the opposition parties withdrew from the election indicating that the election was fixed by the sitting President Dèby Itno.

Despite the many severe conflicts in Chad since its independence, co-existence between exploration (and later production) and violence has been observed. On the one side is the extractive industry seeking to increase their reserve base and production volume, and on the other side, the government is dependent on the revenue derived from these activities and both those in power and those that take power will benefit from an undisruptive revenue stream.

As the quantitative (large-N) analysis has limitations imposed by data constraints and that finding the causal natural resource-conflict mechanisms for the study of civil wars is not simple and need explanations with finer grain, such as public policy responses that require stories about who is doing what and why. This study has first outlined the results from exploration for non-renewable resources, including the development and extraction of these resources, in conjugation with variations in Chad's domestic and foreign policy that has affected Chad. Secondly, this study has through resource assessments identified within which regions it is most likely to find, develop and exploit future non-renewable resources. Thirdly, this study has outlined potential implications these resources would have on the governance of Chad.

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Appendix I

The environment and non-state conflicts in Sub-Saharan Africa

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The Environment and Non-State Conflicts in Sub-Saharan Africa.[1]

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Abstract

Pressure on renewable resources is frequently referred to as an important driver of armed conflict. Case studies have suggested that the role of resource scarcity is more prominent in small-scale conflicts than in international conflicts or large-scale civil wars, and that conflicts are due more to changes in access to resources than to the absolute level of resources available. Large-N studies have been less supportive of the scarcity-conflict hypothesis, yet they have tested the relationship only with data on civil or international conflict. In this paper we test the relationship between resource scarcity and internal armed conflict on smaller-scale internal conflicts with no direct state involvement, so-called non-state conflicts, for Sub-Saharan Africa in the period 2002-2005. To measure resource scarcity we use geo-referenced data for rainfall, population growth, and level of development. Our main finding is that population density and the mean level of precipitation increases the risk of conflict bivariately, but neither remains significant when we control for the number of neighbouring areas with conflict. In our multivariate models we find no direct relationship, however dryer regions with high variations in rainfall are running a higher risk of conflict than others, but this relationship is not robust. We cannot confirm that changes, rather in levels, in pressure on renewable resources are more related to conflict. Regions worse off in material terms are found not to be affected harder by scarcities than other regions. We can tentatively conclude that the risk of non-state conflicts is only marginally affected by a decreasing access to renewable resources. For future research it should be looked at how and if non-state conflicts relate to the escalation of civil wars. If there is found a link, prevention of conflict could be made less costly if we know how to prevent them at an early stage.

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Introduction

> *What we're seeing across Africa now is that the herders who are on the southern edge of the Sahel are being forced southward into the agricultural areas ... In Nigeria, it's a conflict between Muslim herders and Christian farmers. In Darfur, in Sudan, it's between Arabs and blacks….. And all across Africa that conflict is playing out.*
>
> Lester Brown, head of the Earth Policy Institute, cited in Large (2006).

Over the last 15-20 years, the assumption that scarcity of renewable resources increases the risk of violent conflict has been widely influential in academic and policy circles. In alarming terms a report to the Pentagon by Schwartz & Randall (2003) warns that resource scarcity as a consequence of abrupt climate change can lead to a world with Hobbesian struggles of all against all. Scarce water has been argued to be the issue around which a next large war might evolve (see for instance Klare 2001), and quite a few prominent diplomats and politicians claim that the two largest genocides during the last fifteen years, Darfur and Rwanda, are to a large extent driven by resource scarcity. While the growth rate of the global population has tapered off, it remains quite high in quite a few less developing countries. In addition to more frequent extreme weather as a consequence of the predicted climate changes this has argued to be a strain on renewable resource access to such an extent that it might bring violence (see for instance Kahl 2006).

To date, all large-n studies that have investigated the scarcity-conflict nexus have focused on either inter-state or civil armed conflicts. However, case studies point to an inverse relationship between the importance of scarce resources and the scale of conflict: the smaller the scale of the strife, the more important resource scarcity tends to be. In line with this we choose to focus on lower level intrastate conflicts between groups out of which the government of the state is not an active part – so-called inter-communal or non-state conflicts (Eck 2005: 4). Furthermore, the theoretical literature suggests (i) that stress on renewable resources is threatening to peace in less developed countries only (see for instance Barnett & Adger 2007); and (ii) that negative changes to people's access to resources, rather than absolute resource levels, are most salient in bringing about conflict (as found in Miguel et al. 2004; Hendrix & Glaser 2007).

We test these contentions using geo-referenced measures of rainfall, deviations in rainfall, population growth and density, on data on the incidence of non-state conflicts in Sub-

Saharan Africa for the period 2002-2005. To our knowledge this is the first large-n study of non-state conflicts and it is also the first conflict study that uses disaggregated data on development for the whole of Sub-Saharan Africa. Our main finding is that resource scarcity is only very weakly related to internal armed conflict, and the only finding that holds somewhat in our multivariate models is that regions that both have lower levels of rainfall and a high deviation in rainfall are running a higher risk of experiencing armed conflict.

The paper has four parts. The first section discusses theoretical issues in the debate on population and environment as we derive three propositions for testing.[4] The method used and important methodological caveats are noted in part two, while part three is devoted to an empirical analysis of the hypotheses. The last part summarizes our findings followed by a discussion of results in relation to existing conflict theory.

Theory and Previous Research

This section is structured as follows: first we review the debate between those who argue that there are indeed scarcities and that these have consequences for the conflict risk versus those who argue that resource scarcity as a problem is negligible. Secondly, we take resource scarcity as a 'given' and look at what kind of conflicts it is argued to cause. Lastly we distil three causal hypotheses from the literature for testing the relation between scarcity and conflict.

Population, Environment, and Conflict

Until the mid-1990s, arguments connecting scarce renewable resources to armed conflict were popular but vague. Since the late 1990s, however, the empirical knowledge and theoretical sophistication in this field have increased considerably. Still, the relative importance for armed conflict of renewable resource scarcity and depletion remains hotly debated. According to Gleditsch (1998) the argument that scarcities and resource depletion increases the risk of violent conflict is a result of the attempt to merge two prominent debates within international relations, namely the debates on environment and security. This attempt has not been uncontested (for a much-noted example see Lomborg 2001).

In the literature, scarcity of a natural resource tends to be conceptualised in terms of the absolute amount of, demand for, and distribution of the resource in question. Yet in this paper we wish to test the effect of environmental and demographic factors on the incidence of

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[4] For a more detailed discussion of the environment-conflict nexus see Gleditsch (2001a,b, 2003), and Gleditsch & Theisen (forthcoming).

inter-group conflicts. In order to do so the traditional scarcity concept cannot be used, since it incorporates both environmental and demographic issues, as well as distributional aspects (cf. Fairhead 2001: 217; Hartmann 2001: 44).[5] Given these analytical problems, our operational definition of 'scarcity of a renewable resource' is 'a low access to a renewable resource of which decreased absolute input and/or increased demand leads to absolute scarcity'. This definition sheds light on whether a conflict is driven by absolute physical scarcity and/or depletion of a resource, or by distributional issues highlighted by studies using the conventional scarcity concept, including so-called 'neo-Malthusian' studies.

With his 'human needs' approach, Malthus raised the concern about how a growing population can maintain food production at a sufficient level, given the system's ecological limits. Neo-Malthusians are less deterministic than their predecessor with regards to these prospects, but they do in general view the future with pessimism in light of the fact that the world population is still projected to grow.[6] Building on the original components of the Malthusian model, population and food production, neo-Malthusians have argued that challenges stemming from a deteriorating environment, human inability to solve problems around the consumption of collective goods, and more recently, distributional aspects, add to the burden of meeting basic human needs. The relatively moderate neo-Malthusians writing on conflict generally argue that (i) parts of the world is not producing enough food; (ii) the situation is likely to get worse; and (iii) people under stress are less able to handle stress. This last point has especially been fronted by Homer-Dixon (1999), who hypothesizes that an 'ingenuity gap' will develop between those (richer) societies that manage to cope with the increasing scarcities versus those (poorer) societies that will not, and in consequence will suffer even more than they do today.

In-depth case studies on the consequences of population pressure in developing countries have lent support both to the pessimistic neo-Malthusian view and to the more positive Cornucopian standpoint. André & Platteu's (1998) study of population pressure, land scarcity and distribution in a community in north-eastern Rwanda for the period 1988 to 1995, found that a decreasing land per person ratio in conjunction with rising inequalities and low

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[5] Thomas Homer-Dixon distinguishes between three different components of physical scarcity (1991; 1994; 1999; Homer-Dixon and Blitt 1998). Its first component is *supply-induced scarcity*, meaning the absolute supply of a renewable resource, i.e. the absolute 'input' of a resource (Homer-Dixon 1999: 49ff). The second kind of scarcity, *demand-induced scarcity*, is dependent on the size of the population and consumption per capita (ibid: 52). The third kind of scarcity, *structural scarcity,* is skewness in the distribution of resources within a given society, which causes scarcity for some parts of a population (ibid). All three factors together are labelled *environmental scarcity*. For a slightly modified version see Kahl (2006: 29f).

[6] For a more thorough discussion of the different strands of thought within the environmental debate see Dryzek (1997), for a discussion of the debate on armed conflict and the environment see Gleditsch (2001a).

off-farm employment opportunities, increase tensions considerably, including violence. They therefore question the general findings of Boserup (1965) who argues that population pressure is a prerequisite for modernization as it brings economies of scale. On the other hand, a case-study of the Machakos District in Kenya (Tiffen et al., 1994) finds that from the 1930s to the late 1980s the population of the area quintupled, the number of livestock doubled, the output per hectare increased tenfold, and the share of area cultivated grew from 15% to between 50% to 80%, despite this being a semi-arid area in a developing country. They accredit the reversal of the soil erosion to the fact that farming was made profitable, stimulating private investment and innovation in soil conservation and agricultural production for the locals by the locals, i.e. solid support for Boserup's (1965) thesis. Following Boserup, so-called Cornucopians deny that there are widespread problems with scarce resources resulting in food scarcity, and that human ingenuity will overcome scarcities through more efficient pricing, market liberalization, substitution, and more efficient resource use (Lomborg 2001). Thus, population pressure in agricultural societies will lead to the development of more efficient crop-methods as well as diversification of the rural economy. In total this is argued to result in more food for all and in general a higher level of development.

Concerning population growth and its consequences, Cornucopians and moderate neo-Malthusians (e.g. Cincotta et al. 2003) agree that if there is a problem with scarcity due to high rates of population growth, it is likely to be temporary as the first demographic transition has reached literally the entire world, while the second, third, and fourth (and the possible fifth) stage is taking place with increasing levels of development nearly without exception. Given this backdrop on the effect of population pressure directly and indirectly (via its impact on the natural environment in developing countries) on scarcity, we now turn to treating scarcity as a given factor, and provide an outline of how this has been linked to armed conflict.

A common topic in the scarcity literature is African drylands, allegedly undergoing desertification due to anthropogenic activity. Overgrazing by the herds of nomads and deforestation due to firewood consumption are argued to lead to soil degradation as well as the spread of deserts, which again is linked to armed conflict (cf. Bächler 1999: 63; Kahl 2006: 234). Recent research of dryland areas has weakened these arguments, by indicating that human activity has very little impact on where the Sahara begins, as variations in rainfall is seen as the main determinant of how far the desert stretches (Benjaminsen 2002: 35). Nevertheless powerful institutions such as the UN, summoning for increased awareness of desertification in 2006, emphasize direct anthropogenic causes of desertification (www.un.org). Thus the debate whether there is a process of desertification going on and what its causes are is not settled.

Even though deviation in rainfall is likely to be affected by human induced climate change, this debate is beyond the scope of this paper (see Reuveny 2007). Hendrix & Glaser's model of projected rainfall for Africa (2007: 20) finds that overall precipitation is expected to increase in the next fifty years, but the variability is not likely to be greater than it has been for the current period. Sudden negative shifts in rainfall or other renewable resources is one facet of the neo-Malthusian argument that remains unanswered by Cornucopians, as Boserup (1965) and Simon (1989) are concerned with incremental changes rather than sudden shifts, it could therefore be expected that shocks rather than slower changes are more salient in bringing about acute scarcity.

If There Is Scarcity, Who Will Fight?

While most neo-Malthusians and Cornucopians do not say much about violence; some neo-Malthusians, argue that scarcity can produce violent conflict. Eco-scarcity scholars, as they also are labelled, argue that conflicts are first and foremost likely to take place within poor countries and take the form of insurgencies or intra-group conflicts over scarce renewable resources such as farmland and water (Bächler 1999; Kahl 2006).

Taking into account resource mobilization theory, Goldstone (2001) points to several weaknesses in most neo-Malthusian works. The apprehension of environmental change as dramatic and all-encompassing overlooks the role that elite leadership, alliances, and state weakness play in order to translate discontent into civil conflict. Goldstone argues that environmental degradation mostly takes a form that *strengthens* elites, the state and/or the relationship between them, thus decreasing the likelihood that opposition against the degradation is strong. Without political struggles that set elites in opposition to the state or each other, large-scale violence is unlikely to occur (ibid: 93). Agreeing with Goldstone's argument Suhrke (1997: 261), Kahl (1998; 2002; 2006), and Klare (2001: 208) points to that the degradation of the resource base can deprive people of their natural habitat, but their effective conflict potential vis-à-vis the state is minimal. Insurgencies are therefore likely to be unsuccessful; a fact that frequently results in resignation, not rebellion, by those hit the hardest.

The fact that fighting a government army requires a considerable amount of organization and resources should make us expect that conflicts between non-state actors, called non-state conflicts, are to a greater extent affected by environmental scarcities than conflicts between a given group and the government of a state. If the conflict is over the *scarcity* of resources, the aggrieved could be expected to be relatively weaker than compared to a situation in which natural resource scarcity is not a motivation for violent collective action.

Since non-state conflicts represent a breach of the state monopoly of force, their occurrence requires that the state somehow allows them to take place and/or that it is unable to prevent them from occurring. Kahl (2006: 83) argues that relative deprivation theory ignores the play of politics by state elites, since it is solely a bottom-up approach. He generally criticizes the hypothesis that scarcity of renewable resources leads to conflict only when they generate relative deprivation and/or a weak state. These viewpoints neglect the potentially active role of the state in facilitating conflict. Kahl proposes a type of scarcity conflict in which government elites capitalize on demographically and environmentally induced scarcities (1998: 83f). Scarcity can lead to a crumbling of regime legitimacy, which in turn leads elites more or less actively igniting inter-ethnic conflict without *direct* state involvement.[7] He argues that this can divert attention from unpopular state policies, make those groups that the state implicitly support even more dependent on it, and (if conducted successfully) provide an ample opportunity at crushing political opponents (ibid: 88).

Suliman (1999a) commenting on the Environment and Conflicts Project (ENCOP) case studies in the Sahelian belt and the Horn of Africa, contends that a decreased person-to-resource ratio, plus the denial of access to land, has led neglected farmers to migrate or ignite armed inter-group conflict in rural areas among other places in Senegal, Mali, Niger, Sudan, Ethiopia, Somalia, and Eritrea. Population growth and the degradation of renewable resources have produced a situation in which the former abundance of non-cultivated land, providing ‘safe havens’ in times of scarcity, is disappearing (ibid: 34). Growing scarcity has weakened the historically cooperative climate between groups, which has led to an upsurge of conflict between neighbouring groups in which one inhabits a more fertile eco-zone than the other, dubbed the ‘desert versus the oasis syndrome’ (Suliman 1999b: 187). The easy access of arms has led these conflicts to go from mere demonstrations of power to claiming quite a few casualties (Suliman 1999a: 39). Suliman concludes that in Africa today, conflicts over renewable resources are mostly local, but the frequency and intensity of these is increasing,

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[7] This is also called privatized state violence and can be defined as ‘coercion orchestrated by the state against real or perceived opponents but carried out by non-state actors, such as vigilantes, paramilitaries, and militias, who are directly or indirectly supported by the government’ (Roessler 2005: 209). Privatized violence requires that the state financially, or by other means, supports or refuses to quell repressive activities by non-state actors for political gain (ibid).

even though they can relatively easily be prevented through a more diversified rural economy (ibid: 41f).

There exists no large-n study on non-state conflicts to date. This is mainly due to the lack of data on such conflict; however the new UCDP data on non-state conflicts (UCDP 2006) makes it possible to analyze this kind of conflicts. Meier, Bond & Bond's (2007) article on the Karamoja cluster in the Horn of Africa is the one that comes closest to date. They find a substantial lag between the driest periods and the periods with least forage. The latter are the most conflict prone, due to the importance of livestock in a nomadic culture. Scarcity of water and forage do not lead to an increased *frequency* of conflict behaviour, but the most *severe* incidents with most persons killed take place in times of scarcity (ibid: 22). Bocchi et al. (2006: 195) find that several parts of Kenya are affected by decreasing access to water and pastures. Although they have no strict indicator of conflict, they report that in the worst-affected regions, there have been deadly clashes between groups over scarce resources. Raleigh & Urdal (2007) and Hendrix & Glaser (2007) find mixed evidence for a link between renewable resource scarcity and armed conflict, but that is for civil conflicts.

If There Is Scarcity, Why Will There Be Violence?

The most profound causal arguments for linkages between scarcity and conflict have been put forward by Homer-Dixon (1991; 1994; 1999; Homer-Dixon & Blitt 1998). He argues that rural-to-rural migration, motivated by scarcity in the place of departure, leads to further ecological and economic decline at the place of arrival. This is because the newcomers do not have sufficient local knowledge to treat the ecosystems properly, leading to overexploitation and irremediable damage. This process is labelled *environmental marginalization* and is argued to have caused deprivation conflicts in Chiapas (Mexico)[8] and the Philippines (Homer-Dixon 1999: 78f). López (1999: 31) describes a similar situation of environmental marginalization in the Brazilian Amazon forest, where the scarcity-related process has fuelled conflicts over land, although rarely violent ones with large death tolls. A related effect of migration suggested by Homer-Dixon is ethnic clashes, as large population movements caused by environmental stress can induce antagonism between groups, or lead to a spiral of

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[8] Bobrow-Strain (2001: 157ff) argues that the actual scarcity in Chiapas, which Homer-Dixon & Blitt (1998) refers to, is not due to environmental factors or matters of land distribution, but rather politically charged forces that push producers towards less effective and less labour demanding production, in turn causing unemployment. He also points out that the population density of Chiapas, although increasing quite rapidly, has not yet reached the average levels found in many of Mexico's other highly rural states. The trend in land distribution is also contrary to the eco-scarcity argument, as small peasants achieved a progressively higher share of the land in the province during the fifty years prior to the rebellion. The liberalization of trade and the abolishment of state financial support for farmers created a crisis for small peasants and ranchers *alike*.

insecurity as the demographic balance between groups shift (Homer-Dixon 1999: 145; 1994: 7).[9] Thus, environmental degradation in conjunction with population movement increases the risk of armed conflict through relative deprivation. Since there are no good data available on internal migration, this mechanism cannot be tested directly. However, it could be argued that, since scarcity is both the cause and effect of the migration, the scarcity in the receiving area should be a good proxy.

The assumptions of the eco-violence literature do not follow relative deprivation theory exclusively.[10] Two other possible, and quite complementary factors, can be distilled from the neo-Malthusian conflict literature. The first of these is the lower rebel recruitment cost that arises as a result of decreasing agricultural output due to environmental and demographic processes. Grossman's (1991) equilibrium model of insurrections in a peasant society maintains that less employment opportunities in the formal sector makes the opportunity cost of partaking in criminal activities more attractive, holding the capacity of the state to suppress crime constant. If there is a general lack of other income-earning opportunities, the willingness to join an armed conflict will be higher. Moreover, fewer employment opportunities make it cheaper to finance combatants compared to a situation in which there are sufficient jobs. In such situations, an increased number of people is likely to turn from peaceful productive activities to violent or criminal activities, since the relative rates of return for the former compared to the latter has decreased (Collier & Hoeffler 2002; Miguel et al. 2004). Thus, a loss of livelihood from scarcity of resources such as fresh water and productive land is argued to be of a growing importance in countries in which the modern economic sector cannot absorb the residual population. Ohlsson (2003: 5) argues that large cohorts of young men deprived of their livelihoods constitute the major share of rebels in third world militias. As 'angry young men' are more easily recruited to illegal activities, scarcity of renewable resources in less developed countries with high unemployment increase the risk of conflict.

The contention that state capacity is weakened through environmental and demographic processes is also relevant in the study of inter-group conflict. Even though not explicitly arguing from such a perspective, Homer-Dixon claims that state repressive capacity

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[9] According to Suhrke (1997: 257), this statement is based on one single case, namely the communal conflicts between Assamese (India) and migrants from Bangladesh. Nevertheless, Homer-Dixon claims that it is enough to reject the null hypothesis of no relationship between eco-migration and conflict.

[10] Applying relative deprivation theory to environmental decline might be problematic, as one man's degradation might be another man's upgrading (Benjaminsen 2002: 34). Furthermore, Goldstone (2001) argues that if the population at the place experiences the environmental change as beneficial to themselves (for instance cutting of trees to clear farmland), the process is not seen as degradation by them, thus making conflict over this highly unlikely. As in all conflict literature linked to relative deprivation perceptions are crucial (cf. Rule 1988: 212).

is affected by environmental scarcity, since it might cause both state legitimacy and revenue streams to decrease (1991, 1999: 145). The analysis of Homer-Dixon found that societies already having problems with adaptation – i.e. those that are on 'the wrong side' of the ingenuity gap – are likely to be affected by scarcity of renewable resources as well; as a result of one or a combination of the following factors: market failure, social friction and the emergence of narrow coalitions, lack of available capital, cognitive limits to ingenuity, growing costs of research, the non-linear pace of scientific discoveries, and the vulnerability of research to social unrest (Homer-Dixon 1999: 112ff). All in all increasing population pressure as well as the degradation of renewable resources is thought to increase the risk of armed conflict in developing countries as shown in Figure 4 below.

Thus three different theoretical angles have led eco-scarcity thinkers argue that scarcity of renewable resources increase the risk of armed conflict indirectly, but (possibly excluding Bächler 1999) most also concede that increased environmental and demographic stress, all other things being equal, increases the risk of conflict in developing countries. This leads to the following testable proposition:

Proposition 1: A lower absolute amount/level of renewable resources available in a country increase the risk of internal conflict incidence.

Mirroring Davies' j-curve (1962), Gurr's (1985) analysis can be seen as the link between relative deprivation theory and related arguments in the neo-Malthusian literature. Gurr argues that serious scarcities of resources are likely to generate internal armed conflict, as economic growth and political institutions are only to some extent able to mitigate scarcities, especially to negative trends. If an abrupt change takes place, adaptation is hard (ibid: 59). In poor societies where many people already live on the margin of subsistence, the effect of increasing scarcities can be increasing inequalities leading to factional conflict over government (ibid:71). Gurr contends that scarcity of renewable resources will produce a change of state into an *enduring* condition of scarcity, in which the political issue becomes how to distribute privation in a negative-sum game. Græger (1996) and Ohlsson (2003) concur, stating that it is not 'as much the *state* of poverty, as the rapid falling *into poverty* due to scarcity that matters (Ohlsson 2003: 6). Thus, it could be expected that:

Proposition 2: Negative *changes* in people's access to renewable resources increase heighten the risk of internal conflict incidence more than absolute amount/level of renewable resources available in a country.

In developing countries, areas located in the geographic periphery that have little economic significance are frequently marginalized. Such peripheral areas have to a larger extent been left to local rule, often implying that there is no powerful third party to mitigate if friction occurs (Suliman 1999a). Bächler (1999) argue that more or less deliberate state discrimination towards peripheral areas in conjunction with renewable resource scarcity has led to inter-group conflicts in several developing countries. Increasing scarcities will lead to a limited local ability to cope with problems, as rural peripheries are more dependent on renewable resources. Increasing scarcities can therefore lead to further social segmentation and dysfunctional institutions, weakening the buffers against violent solutions (ibid: 133). Markakis (1998: 3) concurs stating that: "areas whose natural endowment is poor and depleted, and where little or no compensation has taken place, are also areas where conflict has flourished". Following this train of thought it can be argued that:

Proposition 3: Marginalized areas within one country experiencing pressure on renewable resources are more prone to armed/violent conflict than better of areas.

Data and Method

What Physical Factors Matter?

The dependent variable in this study is the incidence of armed non-state conflicts within quadratic100x100km grid cells. Since we have only four years of information on our dependent variable using an incidence design is the only defensible option. We are using development, population density and growth, and precipitation variables to try to explain where non-state conflicts break out on a sub-national level. This reduces the problem of ecological fallacies drastically, as we are using a sub-national approach much more fit to test whether the theorized local fact is an empirical local fact (Buhaug & Rød 2006). For the sake of comparability we use 100x100km grids as our unit of analysis, just as Buhaug & Rød (2006).[11]

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[11] We choose not to use smaller grids for one reason. Since we are interested in using population density as a proxy for pressure on land in agricultural societies, we need to include non-urban areas in most of our grids in order to claim that we are still measuring land pressure. The fact that most violent events recorded were reported

In this study, a non-state conflict is defined as “the use of armed force between two organized groups, neither of which is the government of a state, which results in at least 25 battle-related deaths” (Eck 2005: 4). We run a cross-sectional analysis for the time-period 2002-05 for Sub-Saharan Africa. The conflict data are taken from the Uppsala Human Security Project (Kreutz 2006), covering non-state conflicts for the 2002-05 period. We code each non-state conflict location by the conflict midpoint from each conflict event on a standard approach where all events are weighted equally. We use a circular radius similar to the longest event distance from the conflict centre point rounded upwards to the closest 50km, consequently the most distant event is within the conflict zone and not located exactly on the rim.[12] Each conflict zone within a country is set to not exceed neighbouring country borders and the variable contains therefore no spill-over effects. First and second order spill-over variables are generated separately by recording the number of conflict cells within the surrounding 8 cells for the first-order spill-over variable, and the 24 cells for the second spill-over variable.

The reasoning behind the so-called ‘ingenuity gap’ and related arguments among eco-scarcity thinkers, leads us to restrict our sample to the least developed, and therefore most relevant part of the world, namely Sub-Saharan Africa. In addition and connected to this, the region is the most dependent on agricultural production as well as in the median African country only 1 percent of the cropland is irrigated (Miguel et al. 2004: 726). Homer-Dixon (1991; 1994; 1999), Ohlsson (1999), Kahl (2006), and Bächler (1999) argue that factors such as soil degradation, with its extreme desertification, freshwater scarcity, and deforestation are likely causes of armed domestic conflict. As shown above there is scant evidence for claiming that there is actually a major desertification going on. There are some data on soil degradation, mainly the GLASOD (Global Assessment of Soil Degradation) study by Oldeman et al. (1990), but this has been severely criticized. The data consists of 250 expert assessments of soil degradation in their area of expertise. The lack of “cross-expert” comparability and the potential role of incentives which could bias the reported degradation

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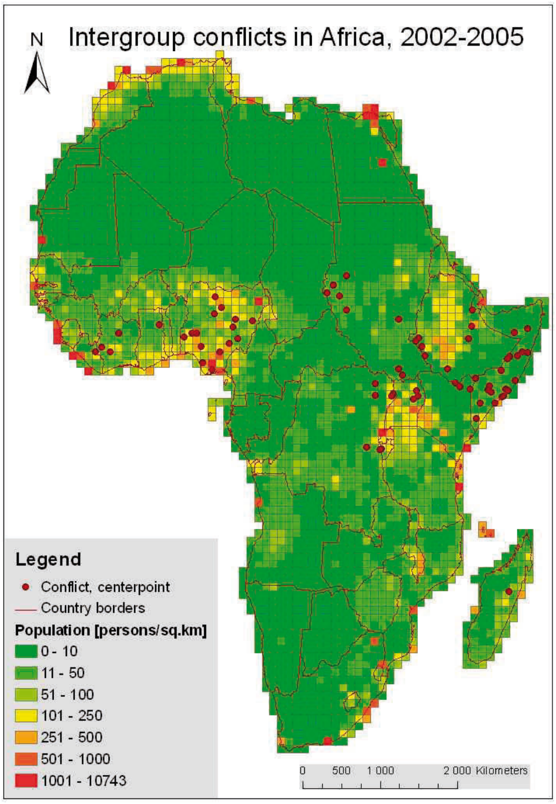
to be taking place in villages and towns, could bias the results towards a positive finding, had we chosen a smaller level of resolution.

[12] There are several methods used for calculating conflict influence zones. Raleigh & Urdal (2005) used a circular 300km radii influence zone from each conflict event, while Buhaug & Rød (2005) used the method expressed in the Upsala/PRIO ACD project where the circular influence zone was related to conflict intensity. We will use the approach chosen by Buhaug & Rød (2005) here. B&R: “In this study we use a refined version of the conflict location data, where we relax the crude assumption of circular conflict zones and rather use polygon generated through GIS. These polygons can take on any shape and are thus better suited to represent the actual conflict zones.” Therefore Buhaug & Rød (2005) used the method expressed in the Upsala/PRIO ACD project where circular influence zone were omitted using polygons related to conflict intensity which represent the actual conflict zones better.

make it hard to validate the data (Benjaminsen 2002: 35). The GLASOD measure has been criticized for overestimating the extent of soil degradation in Africa, as it only concerns the degradation of farmed land (Niemeijer & Mazzucato 2002). Thus, even though processes of degradation and desertification are allegedly important, the lack of valid measures prevents us from testing these claims. If the assumption that the ebb and flow of deserts mainly follow precipitation patterns holds, our measure of rainfall should capture the main ‘desert-effect’. In addition, if the core neo-Malthusian argument about a negative effect of population pressure on food production through deteriorating the soil holds, the effect of population pressure should proxy for this, and therefore an alleged increase in the risk of conflict.

The population data are downloaded from Center for International Earth Science Information Network (CIESIN 2006a) of the Earth Institute at Columbia University, which has gathered the Gridded Population of the World, version 3 (GPWv3). It renders the human populations in a common geo-referenced framework at a resolution of 2.5 arc minutes (about 5km at equator). Three types of population estimates are available in GPWv3; (i) population counts adjusted to match UN totals, (ii) population densities unadjusted, persons per square km, and (iii) population densities adjusted to match UN totals, persons per square km. The population estimates are available for each five years covering from 1990 to 2005, in addition to future population estimate predictions for 2010 and 2015. In this study population estimates from 1990 to 2005 are applied. The measure of population density is simply the GPWv3 value for category 3 above log transformed. Population change is measured as the percentage change from 1995 to 2000 of this density estimate. Both these measures are derived from the mean calculated population density within each 100x100 km grid cell.

Fig 1. Population density and conflicts 2002-05 .



Precipitation data were downloaded from the Climate Prediction Center, US National Weather Service (CPC 2006). Annual precipitation data in the time interval 1995 to 2000 were acquired by the algorithm RFE1.0 (Rainfall Estimates 1.0) followed by RFE2.0 from 2001 to 2005. We use three precipitation variables:[13] (i) the average precipitation for the period 2001-05; (ii) the percentage change in precipitation for the period 2001-05 as compared to 1997-2000; (iii) the standard deviation of rainfall within the 2001-05 period. The measure for mean precipitation has been log-transformed, and the measures for average precipitation and percentage growth in precipitation have been reversed so that higher values reflect more resource scarcity.

Our measure of development, infant mortality rate, is produced by the Columbia University Center for International Earth Science Information Network (CIESIN). The Global

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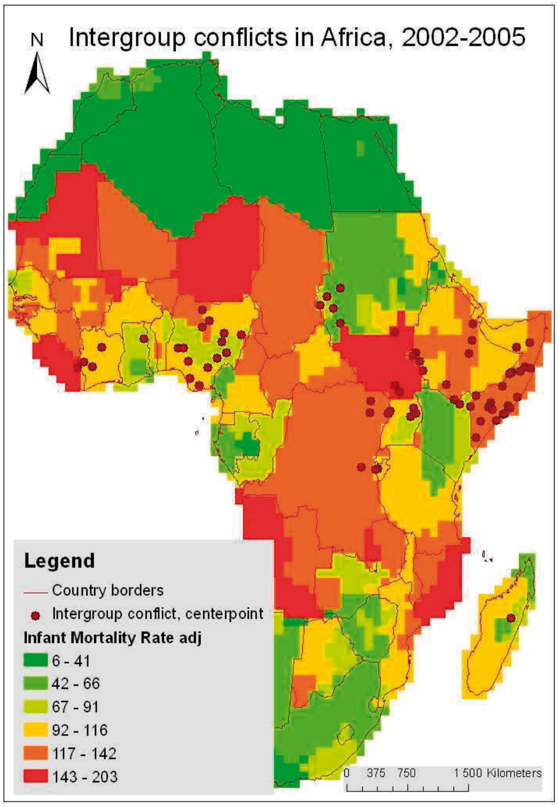
[13] We included the year 2001 in order to account for potential time lags in soil humidity.

Subnational Infant Mortality Rates, hereafter IMR, consists of estimates of infant mortality rates for the year 2000 (CIESIN, 2006b). The IMR is defined as the number of children who die before their first birthday for every 1,000 live births. The variable has a 2.5-minute resolution and cover the entire Africa. The dataset have classified the Southern Sudan as a missing data region. South Sudan has been dominated by both internal wars and non-state conflicts in the last decades, which could have made the estimation of IMR difficult. A study by the New Sudan Centre for Statistics and Evaluation in association with UNICEF has done a major contribution to quantify the best estimates of social indicators for Southern Sudan (UNICEF, 2005) and the IMR in the region is set to be 150 deaths for every 1,000 live births.[14]

Map 2. Infant mortality rate and conflicts 2002-05.



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[14] This also demonstrates the potential endogeneity in this kind of data.

To capture the effect of marginalization we applied the mean of IMR (adjusted to UNICEF's measures) for each grid cell and subtracted the UNICEF national mean. Thus the measure of marginalization is not an absolute measure, but a measure relative to national standards as it says something about the relative prioritizing of the state government in terms of providing basic infrastructure.[15] This measure might therefore catch each and/or all of the following aspects: (i) state-led conflict resolution institutions/capacity to quell large scale violence; (ii) ability/willingness to develop the region; (iii) ability to provide help if a crisis (for instance a drought) occurs; and (iv) threshold for joining criminal/violent activity in the marginalized region relatively to more developed regions where people have more to lose.

In order to see whether state capacity affects the risk of conflict, we included one variable measuring the distance to the national capital for the centerpoint of each 100x100km cell. This is based on the assumption that the control capacity of a state is strongest in its capital and diminishes as the problem is removed farther from the capital (cf. Herbst 2000), thus the probability of incidence of non-state conflict should increase with distance to capital. To control for potential spatial spill-over effects we introduced two variables. The first captures the number of first order neighbouring pixel cells with conflict. The other captured the number of second order neighbouring pixel cells with conflict.

The raster data used are defined by the earth's latitude and longitudes measured in decimal degrees in a geo-referenced coordinate system. The area of each raster pixel will therefore differentiate from regions around equator where the pixel area is largest, to regions different to equator with less area per degree. Using geo-referenced coordinate system is therefore not optimal when statistics applied to varying pixel closure areas. The solution is to use a projected coordinate system, here World Eckert VI. The strength of a standard block with fixed closure area is that is independent to latitude.

The resolution problem when transforming from polygon data to pixel data, such as international borders, is adjusted so that each pixel only can be assigned to one country. The method used is if a pixel intersects several countries, then the country position that is at the centre of the unit is given the pixel. Transforming and applying raster data with values recorded at 5 and 10 km units to lower resolution, such as 100km unit squares involves choosing an aggregation type. We applied the mean value for all of our grid covariates.

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[15] Horizontal inequalities are explicitly *not* linked to relative deprivation in this study as we do not study rebellion against the state. If we were to test whether a dissatisfied group attacks its better of neighbours, a dyadic approach requiring (i) the georeferencing of where ethnic groups are located and (ii) the coding of inequalities in material welfare between these. This is an interesting venue, but here the focal point is state neglect of peripheries.

Minority and majority values within each cell were tested and found to be unsuitable in this study, as using one of these as basis for aggregation will e.g. give the result that the population in a small town is not taken into consideration when using majority due to the low population density in the surrounding areas.

Control Variables at the Nation-Level

Since there are no previous large-n studies of non-state conflicts, our choice of control variables are to a considerable extent borrowed from studies of civil conflict. To control for all of these is not our purpose here, since it would lead to models that were inclusive yet over-complex, possibly blurring the effects of our variables of interest (cf. Ray 2005). One of the most consistent finding within this literature is the positive impact of population size on risk. This interpretation signifies that large populations gives, all other things equal, more potential insurgents (Buhaug & Gates 2002; Fearon & Laitin 2003), or in our case, combatant parties. This measures the size of a country in square kilometres and is taken from the Correlates of War homepage (Correlates of War 2006). Due to its skewness the variable has been log-transformed.

Another frequent finding in the civil war literature is that less developed countries have a higher risk of conflict.[16] The reason for this is disputed. Scholars with a 'Hobbesian' bent argue that a higher level of income in the population means more to tax and therefore also a richer state, with a more efficient military increasing the opportunity cost of rebellion (de Soysa 2002a; Fearon & Laitin 2003). Others argue that the costs of recruiting rebel soldiers are lower in low income countries, because potential rebels have less to lose from joining an insurgency (Collier & Hoeffler 1998; 2004; Collier 2001). Scholars emphasizing the motivational aspect of civil violence claim that development might reduce conflict along a society's fault lines (Hegre et al. 2001; Esty et al. 1998). Our focus will be mainly on the state-capacity using this measure, measured by the national average infant mortality rate (UNICEF 2006). Relative recruitment cost as well as the degree of marginalization is taken care of by the disaggregated IMR-measure (see above).

Several studies have found a curve-linear relationship between the level of democracy and civil conflict (Hegre et al. 2001 among others). Even though no previous quantitative research exists on non-state conflicts, we will argue that the expected relationship is relatively similar

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[16] This is a very robust finding as both infant mortality rate (Esty et al. 1995; 1998; Urdal 2004; 2005) and GDP per capita (Collier 2001; Collier & Hoeffler 1998; 2004; de Soysa 2002a,b; Ellingsen 2000; Fearon & Laitin 2003; Hauge & Ellingsen 1998; Hegre et al. 2001, and others) are found to affect the risk of civil conflict.

here. First, stark autocracies do not need any camouflaged proxy to crush opposition, and are often strong enough to deter such movements from arising anyway (cf. Roessler 2005). The regimes that mostly need such an indirect way of crushing opposition (through internal proxies) should be semi-democracies. These are also the weakest regimes least able to prevent large scale fighting from occurring (Fearon & Laitin 2003). In fully democratized states, it should be expected that to resort to arms will not be a likely way of addressing problems. However, Tambiah (1996) argues that in democracies where the party structure has become divided among ethnic lines, communal violence is a natural part of democracy. In order to control for political factors we include a continuous measure of democracy taken from the Polity IV dataset (Marshall & Jaggers 2002).[17] This variable varies from -10 to 10 where the lower values indicate a less democratic government, and is the "Polity2" variable in the Polity IV dataset. To capture a potential curve-linear effect we added a square term of the original variable. Both the continuous and its squared term have been lagged one year to reduce the problem of reverse causality, and thereafter each country's average score for the period 2002-05 was calculated.

Political instability is often found to increase the risk of civil conflict regardless of the level of political democracy (Ellingsen 2000; Fearon & Laitin 2003; Hauge & Ellingsen 1998; Hegre et al. 2001). Therefore, we included a variable denoting the time since last regime change, coded as such if the state had experienced a change of 3 or more points on the combined Polity2 score during the last three years. We operationalized this as a decay-function capturing the risk of regime change given information on the time the state experienced either a regime or independence (cf. Hegre et al. 2001), following the formula 2^(years since regime change/X). We tested different half-life values (X) and found out that a 1-year half-life estimator gave the lowest LogLikelihood value. The values have been averaged for the period 2002-05. We use an identical approach to capture the effect of civil conflict in the country as we code the proximity in years since the country last experienced civil conflict. The values are averaged for the period 2002-05 using a half life estimator of 1.

Ethnicity is frequently argued to be of great importance in internal conflicts. Although identities are far from confined to ethnicity, most of the literature concerning civil conflict

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[17] One critique of the Polity IV measure is that it does not record the level of participation, leading South Africa under apartheid to score 10 (most democratic). An alternative measure, the Polyarchy index developed by Vanhanen (2000), includes a measure of actual participation, but lacks some other important components. Other alternatives are Freedom House's scale of democracy (www.freedomhouse.org), and Przeworski et al.'s (2000) measure. For the sake of comparability, we have chosen the Polity IV measure. Another problem in using the Polity IV data for analyzing conflict is that ongoing widespread political violence or inter-group conflict may result in the score on democracy to drop automatically (Gleditsch et al. 2007: 14).

focuses on the Third World in which this kind of identity is argued to be more salient than others e.g. classes, political parties etc. (Tambiah 1996: 21; Horowitz 2000). When it comes to internal conflicts that are not rebellions, theory is much sparser. Although it is clearly relevant, we will not deal with this aspect in this paper, as our focus is on pressure on renewable resources.

We have centred all variables to reduce potential collinearity problems, as well as to facilitate interpretation. We use robust standard errors and cluster on country, in order to reduce the potential impact of within-state dependence between units.

Results

Given the relatively unsystematic support for neo-Malthusian claims in large-n studies of civil armed conflicts, it could be expected that if there is something of substance to this strand of thought the results should be more supportive for non-state conflicts than for civil or inter-state conflicts. Model 1 shown in Table 1 reports the result of a bivariate cross-sectional analysis of non-state conflicts using binary logistic regression. The dependent variable is non-state conflict incidence for at least one of the years 2002–05 in the grid cell. All time-varying explananda (democracy, stability, national infant mortality rate, population size, population growth, average rainfall, change in rainfall, deviations in rainfall) are averaged for the four year period.

Table 1, models 1-5 reveals some interesting results.[18] First, the level of democracy seems to be negatively, but not significantly related to conflict (even bivariately). The effect however is very close to significance at the 10 percent level (0.101) in Model 2. We also tested whether democracy has a curvilinear relationship to conflict incidence. This was not the case. Regime instability seems to be related to this kind of conflict as it does to civil conflicts, but the effect is not very robust as it is significant only when the grid level covariates in Model 5 are introduced. IMR at the country-level on the other hand, is insignificant and in the opposite direction of what we expected even bivariately. We also see that national population size increases the risk of conflict, just as expected both bivariately and in the multivariate models. Proximity to civil conflict (in years) is not affecting the risk of conflict. Regarding the disaggregated measures (models 1, and 3-5), the lack of significant results warrants attention. First of all, lack of development at the point is not related to conflict (Model 3), even if we drop the marginalization measure. In line with our expectations the bivariate regression on relative poverty compared to the national mean shows that marginalized regions are running a

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[18] Bivariate regressions are given in the appendix.

higher risk of conflict, but when we control for other relevant factors in Model 5 the results are no longer significant. Thus neither absolute nor relative poverty seems to increase the risk of conflict. The only robust local predictor of conflict in models 1-5 is the number of neighbouring cells with conflict which significantly and substantially increases the risk of conflict with a huge impact on the marginal risk of conflict.

The variables proxying for pressure on renewable resources are only to a limited extent in line with our expectations. In the bivariate analyses as shown in Model 1, only population density increases the risk of conflict significantly, while the reversed measure of level of precipitation reveals that the dryer a cell is the safer it is. When we introduce controls for conflict in neighbouring cells, all the grid-level covariates except for the conflict in neighbouring cell control turn insignificant. This is also the case for the multivariate analyses shown in models 2-5. Thus proposition 1, 2 and 3 gets little support.

Since considerable parts of Sub-Saharan Africa can be considered uninhabitable due to desert-like conditions, it could be argued that units that are fully covered by desert should be excluded from the analysis as they are "politically irrelevant". We tested this combining the ESRI ArcAtlas map of desert vegetation with our conflict-zone map. We found that several cells with conflict are in desert cells, thus these units should not be exempt from analyses of inter-group conflict. [19]

As outlined in proposition 3, marginalized areas with increasing scarcities were expected to be more prone to experience non-state conflicts Table 2 and 3 reveals that this is not supported by our analysis. The only interaction that proved significant was the one between population growth and marginalization which is significant at the 10 percent level only and has a negative impact on conflict risk. An analysis of the marginal effects of the interaction term reveals that marginalization increases the propensity for conflict in this model, while population growth is relatively unimportant. Multiplicative terms between absolute local poverty and conflict did neither result in any significant findings. We also tested the interaction of the different measures of resource pressure with each other, without finding much support for the scarcity-conflict scenario, with the possible exception of dry regions with a high standard deviation in rainfall which seem to run a substantially higher risk than other areas. The marginal effect of this multiplicative term increases the probability of conflict from 0.005 when both are at the 10th percentile to 0.097 when both are at the 90th percentile. This result, however, is not robust to dropping the grid-cells of Somalia and/or

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[19] This is the same conclusion as Buhaug & Rød (2006) reach in their analysis of civil conflict. We find that all of the conflicts in Sudan's western region Darfur are partly or wholly taking place in the desert.

Senegal from the analysis. The main conclusion from the empirical analysis is that the only environmental factor indicating an increase in the risk of conflict is high variability in rainfall in dry areas.

Discussion

This analysis has lent little support to the claims of eco-scarcity scholars. The models yield no more support to the contention that scarcity breeds conflict when it is measured as negative changes rather than levels, as none of the effects are significant when controls included. The only significant effect of environmental factors was the interaction term between level and variability of precipitation, indicating that droughts and floods in dryer regions increase the risk of conflict. When it comes to proposition 3 it receives no support, implying either that our measure of marginalization does not perform very well, or that marginalized regions are not worse off when it comes to handling renewable resource scarcity. It is doubtful that the results for the terms capturing scarcity would be more revealing had the sample been global, as Homer-Dixon a.o. argues, scarcities in developed countries are not relevant. Of course, our sample covers only Sub-Saharan Africa, thus leaving out a large portion of the developing world, but this part of the World is the least developed and should therefore be the one in which societies are theoretically least able to cope with resource shortages. We therefore trade testing the theory on the universe of cases with the relative homogeneity and theoretical relevance of Sub-Saharan Africa.

The complexity of eco-scarcity conflict models, especially the model of Homer-Dixon, makes it hard to test these claims, whether by using comparative case studies or statistical methods.[20] The number of feedback loops and contingent arguments has indeed left Homer-Dixon and associates, in some cases, doubting their own conclusions. In the case of South Africa, Homer-Dixon & Blitt (1998: 136) acknowledge that they could not know whether violence would have erupted in a situation where there was not a decreasing access to renewable resources. Thus, the failure of testing the case with a counterfactual strategy showed the limitation of most of the neo-Malthusian models: if there was no degradation, would there have been less violence? Thus, some of the most prominent neo-Malthusian conflict models are not able to single out the environmental and demographical element from general relative deprivation models of conflict to such an extent that the impact of the 'ecoviolence' component is very unclear. The fact that they have not looked at cases in which

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[20] A method that does allow for more complex models and is especially suited for theoretical arguments involving many interactive functions is Qualitative Comparative Analysis as outlined by Ragin (1987).

there is violence but no degradation, makes them unable to test whether it is the scarcities that lead to conflict, or if conflict would most likely have occurred anyway due to an overlooked factor. Furthermore, the selection on the dependent variable might have made eco-scarcity scholars overemphasize the importance of scarce resources in the cases they study. Roessler (2005) suggests a related framework for the same case as Kahl (1998) studies, namely inter-tribal warfare in Kenya in the early 1990s, but adds the violence in Rwanda prior to the genocide in 1994, another favourite case among neo-Malthusians and eco-scarcity scholars (see Bächler 1999; Diamond 2005; Ohlsson 1999). However, for Roessler, it is external donors' pressure for democratization in conjunction with internal demands for regime inclusiveness that drives the state to privatize violence, as the cost of conventional repression are to high due to (i) the omnipresent opposition and (ii) the international donor's scrutiny of the democratic transition (Roessler 2005: 211). He claims that this tactic is successful only in cases where ethnic divides are sufficiently militarized. More importantly, he does not mention renewable resource scarcity with a single word in his conflict model. This might suggest that the scarcity component in Kahl's state exploitation hypothesis is not a *necessary* condition for state led violence for Kenya, neither for the Rwandan genocide and civil war.

We argue that the focus of this paper has special merit to the eco-scarcity line of thinking, since it is frequently argued that the larger the role of scarcities, the smaller the conflicts is (Homer-Dixon 1999; Bächler 1999; Suliman 1999a; Thomasson 2006). Hence, these conflicts are less likely than full-scale civil wars to be caused by factors that are common to the country as a whole. Testing the impact of scarce resources on civil and non-state conflicts respectively is beyond the scope of this paper. The fact that we do not find robust support for inter-group conflicts being caused by resource scarcity in our analyses, might imply that other venues such as genocides and violence not directly related to organized conflicts should be investigated.

An important caveat for our results concerns the homogeneity of the subject matter sub-types of non-state conflicts. Since the dataset on these conflicts contains all conflicts not involving official forces, the degree of similarity between the different conflicts is one thing that should be kept in mind. However distinguishing for example between what is a conflict between militias and what is a conflict between tribes could be quite futile as most armed conflicts of a substantial magnitude follow ethnic boundaries. Another limitation of the data we have used relates to the temporal category. Four years is not a complete time series when it comes to conflict studies. In order to be more certain about what way the causal arrow runs, a longer time-span should be investigated. Furthermore, both the non-findings on level of democracy and development is most likely because our sample is Sub-Saharan Africa, a region in which most of the countries are less developed and there less variation in the level of democracy than in the world at large. These results might very well have been different had we analyzed the World.[21]

Perhaps the major challenge for analyzing the role of scarcity in renewable resources in non-state conflicts is to get to know how other factors also affect the risk. The lack of a more general theory on non-state conflicts made us use some of the ‘standard’ determinants of civil conflict. It turned out that a few of them fared well, while others most notably the local level variables turned out to have little effect. Further theoretical and empirical investigations of other determinants correlating with non-state conflicts need therefore to be undertaken in order to bring forward more robust results.

Conclusion: Bad Theory Leads to Bad Policy?

“Fierce competition for fresh water may well become a source of conflict and wars in the future.”
Kofi Annan, UN Secretary-General, March 2001 cited in AAG (2001).

Although there are only a few scholars that argue in favour of a strong direct link between renewable resource scarcity and conflict, the most pronounced being Kaplan (1994), their arguments carry a disproportionate weight in policy circles relative to their more moderate counterparts, for instance Goldstone 2001; Kahl 2006. Why is this so? Our best guess is that the former give an interpretation of the world that is much easier to grasp than an explanatory model with eight mediating factors between the physical scarcity and the violent outcome as for instance Homer-Dixon’s model (1999: 82). The implications of having to choose between an overtly simplified model and a very complex and vague one when trying to form effective policies are harmful, we will contend. If we take for granted that scarcity does lead to violent conflict, time constraints and the need for justifying policy in an understandable manner will most likely in the face of blurred models lead to one out of two outcomes. If country A is considering intervening in country B in which there is a conflict with an allegedly substantial component of scarcity, the most likely result is inaction. The reason for this is that policymakers do not want to risk implementing policies based on a model that is too complex to be flexible, nor if they are convinced that there is indeed a direct relationship as e.g. population growth is hard to prevent, implying a relationship with a scent of determinism

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[21] An analysis using states as the units of analysis for the entire world revealed a negative and significant relationship between GDP per capita and the incidence of non-state conflicts.

between scarcity and conflict. Allow us to draw a parallel to the latter scenario. During the Balkan wars, the first Clinton administration was heavily influenced by the writings of Robert D. Kaplan, especially his book *Balkan Ghosts*. In this he argued that the cause of the conflict was ancient hatred between ethnic groups (1993: xxi), a fact that would remain the same with or without external intervention. The result was inaction by the world's only superpower. Facing the choice between a simple, albeit direct and therefore slightly deterministic relationship, and a more complex model, policymakers are likely to choose the more easily comprehensible model and take action and act as if there is a direct relationship. Yet as we have seen, few of the most prominent neo-Malthusians agree with this simple model.

The results of this analysis have lent limited support to the eco-scarcity argument, implying that the arguments that pressures on renewable resources is a security threat do not gain support. One very important caveat has to be noted. This is, to our knowledge, the first cross-national study of non-state conflicts, so further empirical and theoretical studies is needed to get better modelling of the conflict dynamics and contextual effects. Looking at the statement from Lester Brown in the introduction a close look at herder-farmer conflicts alone might seem like the most promising way to go. It will also make more theoretical sense to test onset of non-state conflicts rather than incidence, as scarcities are not regarded as a positive factor in catalyzing conflict. This requires time series for a longer period than what has hitherto been available. Another point on the 'data wish list' would be information on even lower intensity conflicts with perhaps as few as five casualties, as it is the low-intensity conflicts that are argued to b the ones in which the resource scarcity element is most influential. Such a dataset is, however, a far cry from what we are able to collect at present.

For policy, perhaps the most important task to embark on is to figure out how and if non-state conflicts relate to the escalation of civil wars and hostilities in general. If they are found to be somewhat different to civil conflicts, but also a part of the escalation to these, prevention of conflict could be made less costly if we know how to prevent them at an early stage. That is why the search should go on.

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Appendix

`Bivariate results`

Table 1. Results

	(1)	(2)	(3)	(4)	(5)
National level					
Democracy	-0.082	-0.113			-0.020
	(0.94)	(1.64)			(0.44)
Population	1.075	1.108			0.324
	(3.16)***	(2.59)***			(2.10)**
Stability	0.723	0.453			1.095
	(1.02)	(0.74)			(2.80)***
Proximity to civil conflict	-0.000	0.000			0.000
	(0.48)	(0.28)			(1.42)
IMR	-0.011	-0.010			
	(0.93)	(1.04)			
Grid level					
IMR	-0.001		-0.008		
	(0.12)		(0.54)		
Marginaliz	0.021		0.026		0.012
	(1.76)*		(1.55)		(0.97)
Population	0.372		0.194		0.136
	(2.99)***		(1.25)		(1.31)
Pop Δ	0.005		0.005		-0.004
	(0.85)		(1.03)		(0.30)
Preci.(avg.)	-0.003		-0.159		0.328
	(0.43)		(0.53)		(1.61)
Preci. Δ	-0.003		0.001		0.001

	(0.43)		(0.10)		(0.34)
Prec.dev.	0.004		0.001		0.002
	(1.31)		(0.26)		(0.65)
Dist. Capit.	0.000			-0.000	
	(0.27)			(0.01)	
1.o.spillo	1.768			2.407	2.320
	(10.76)***			(8.41)***	(8.57)***
2.o.spillo	0.698			-0.511	-0.473
	(9.46)***			(4.01)***	(3.87)***
Constant		-2.045	-1.501	-4.080	-4.503
		(3.77)***	(4.28)***	(11.47)***	(9.00)***
Log Likelihood		-950.478	-1040.444	-115.941	-111.686
Observations		2418	2110	2418	2110

Robust z statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
Note: All variables are centred. The measures of average precipitation and change in precipitation are reversed to ease interpretation.
Note 2: IMR (national mean) was dropped due to collinearity. The coefficient was not significant when included and the disaggregated measures of development were excluded. Exactly the same was the case for the disaggregated development measure. Dropping the squared democracy term does not result in substantial changes.

Table 2. Interactive effects

	(1)	(2)	(3)	(4)
Stability (nat'l)	0.405	0.424	0.307	0.359
	(1.28)	(1.35)	(0.94)	(1.11)
Marginaliz (grid)	0.011	0.009	0.012	0.014
	(1.09)	(0.75)	(1.16)	(1.58)
Population (grid)	0.145	0.160		
	(1.46)	(1.52)		
marg_pop (grid)		0.005		
		(0.72)		
Pop Δ (grid)			-0.004	-0.012
			(0.33)	(0.81)
marg_ Pop Δ (grid)				-0.001
				(1.65)*
1.o.spillo (grid)	2.383	2.388	2.368	2.375
	(8.34)***	(8.26)***	(8.33)***	(8.33)***
2.o.spillo (grid)	-0.507	-0.505	-0.513	-0.507
	(3.93)***	(3.82)***	(4.06)***	(3.90)***
Constant	-4.143	-4.165	-3.954	-3.967
	(12.49)***	(12.36)***	(10.81)***	(10.83)***
Log Likelihood	-114.684	-114.489	-114.668	-114.023
Observations	2418	2418	2110	2110

Robust z statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
Note: All variables are centred. The measures precipitation and change in precipitation are reversed to ease interpretation.

Table 3. Interactive effects (cont.)

	(1)	(2)	(3)	(4)	(5)	(6)
Stability (nat'l)	0.263	0.264	0.309	0.368	0.368	0.336
	(0.65)	(0.67)	(0.90)	(1.05)	(1.31)	(1.29)
Marginaliz (grid)	0.010	0.008	0.010	0.011	0.012	0.011
	(0.96)	(0.65)	(0.88)	(1.09)	(1.19)	(1.16)
Preci.(avg.) (grid)	-0.090	-0.150				
	(0.58)	(0.88)				
marg_preci (grid)		-0.009				
		(0.91)				
Preci. Δ (grid)			-0.002	-0.002		
			(0.64)	(0.78)		
marg_ Pre. Δ (grid)				-0.000		
				(0.82)		
Prec.dev. (grid)					0.002	0.003
					(0.91)	(2.10)
marg_precdev (grid)						0.000
						(1.59)
1.o.spillo (grid)	2.400	2.411	2.403	2.406	2.394	2.424
	(8.32)***	(8.29)***	(8.28)***	(8.33)***	(8.44)***	(8.49)
2.o.spillo (grid)	-0.517	-0.526	-0.515	-0.520	-0.514	-0.518
	(3.92)***	(3.94)***	(3.93)***	(3.98)***	(3.88)***	(3.91)
Constant	-4.054	-4.076	-4.039	-4.069	-4.066	-4.098
	(11.20)***	(11.08)***	(10.93)***	(10.64)***	(11.70)***	(11.77 *
Log Likelihood	-115.168	-114.965	-115.166	-114.881	-114.501	-113.5
Observations	2418	2418	2418	2418	2418	2418

Robust z statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
Note: All variables are centred. The measures precipitation and change in precipitation are reversed to ease interpretation.

Table 4 Interaction effects

	(5)	(6)
Stability	.480 (1.78)*	.634 (2.09)**
Grid level IMR	-.008 (-1.25)	-.008 (-1.26)
Preci.(avg.)	-.011 (-0.08)	.542 (2.25)**
Prec.dev.	.002 (0.58)	.011 (2.74)***
Prec.*dev.		.007 (1.91)*
1.o.spillo	2.408 (7.74)***	2.437 (8.66)***
2.o.spillo	-.509 (-4.22)***	-.510 (-4.16)***
Constant	-4.156 (-10.57)***	-3.824 (-10.84)***
Log Likelihood	-114.658	-112.724
Observations	2418	2418

Robust z statistics in parentheses
* significant at 10%; ** significant at 5%; *** significant at 1%
Note: All variables are centred.

Table 6. Cross tabulation of results of interactive tests

Interacted with	Marginalization	Local IMR)	Density	Pop Δ	Average rainfall	Rainfall Δ	Distance to border	Distance to capital
Density	No	No					No	No
Pop Δ	No (0.098), opposite	No	No				No	No
Average rainfall	No	No	No	No(0.071), opposite			No	No
Rainfall Δ	No	No	No	No	No		No	No
Deviation in rainfall	No	No	No	No	Yes (0.056), as expected	No	No	No
Local IMR							No	No(0.035) opposite

Figure XX. A simplified version of the neo-Malthusian conflict model.

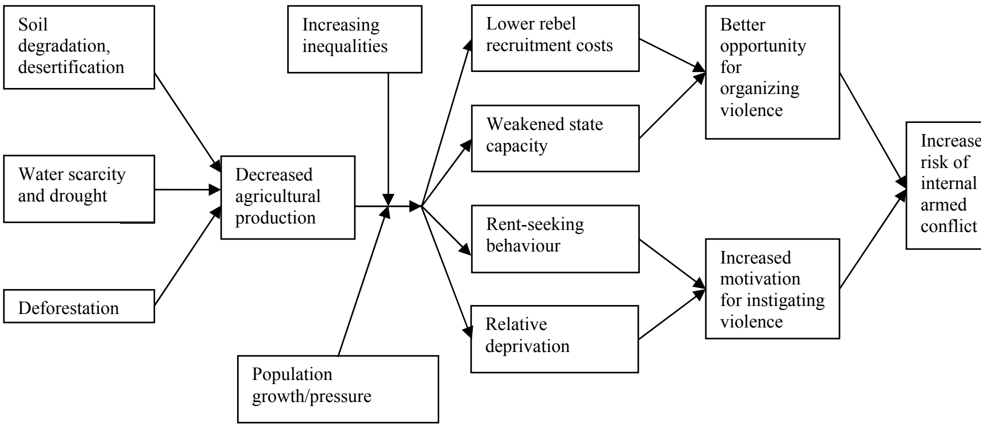

Table XX:states with conflict grid zones*

	150km. Conflict zones			300km. Conflict zones			Individual conflict zone sizes		
State	Value	Frequency	Percent	Value	Frequency	Percent	Value	Frequency	Percent
Burundi	1	3	100	1	3	100	0	1	33.33333
							1	2	66.66667
							Total	3	100
Cote d'Ivoire	0	16	43.24324	0	1	2.702703	0	10	27.02703
	1	21	56.75676	1	36	97.2973	1	27	72.97297
	Total	37	100	Total	37	100	Total	37	100
Ethiopia	0	57	50.44248	0	22	19.46903	0	48	42.47788
	1	56	49.55752	1	91	80.53097	1	65	57.52212
	Total	113	100	Total	113	100	Total	113	100
Ghana	0	26	92.85714	0	11	39.28571	0	26	92.85714
	1	2	7.142857	1	17	60.71429	1	2	7.142857
	Total	28	100	Total	28	100	Total	28	100
Kenya	0	42	67.74194	0	31	50	0	53	85.48387
	1	20	32.25806	1	31	50	1	9	14.51613
	Total	62	100	Total	62	100	Total	62	100
Madagascar	0	73	82.95455	0	56	63.63636	0	11	12.5
	1	15	17.04545	1	32	36.36364	1	77	87.5
	Total	88	100	Total	88	100	Total	88	100
Nigeria	0	20	20.83333	0	3	3.125	0	13	13.54167
	1	76	79.16667	1	93	96.875	1	83	86.45833
	Total	96	100	Total	96	100	Total	96	100
Sudan	0	185	72.26563	0	133	51.95313	0	89	34.76563
	1	71	27.73438	1	123	48.04688	1	167	65.23438
	Total	256	100	Total	256	100	Total	256	100
Somalia	0	20	24.09639	0	6	7.228916	0	20	24.09639
	1	63	75.90361	1	77	92.77108	1	63	75.90361
	Total	83	100	Total	83	100	Total	83	100
Uganda	0	9	37.5	0	2	8.333333	0	13	54.16667
	1	15	62.5	1	22	91.66667	1	11	45.83333

	Total	24	100	Total	24	100	Total	24	100
D.R.C	0	202	85.95745	0	166	70.6383	0	159	67.65957
	1	33	14.04255	1	69	29.3617	1	76	32.34043
	Total	235	100	Total	235	100	Total	235	100

* 1 indicates that there is conflict within the grid, 0 indicates no conflict.
Note: it is the individual conflict zone sizes which have been applied here.

Countries included in the sample are: Angola, Burundi, Benin, Burkina Faso, Botswana, Central African Republic, Cote d'Ivoire, Cameroon, Congo, Rep., Djibouti, Eritrea, Ethiopia, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Kenya, Liberia, Lesotho, Madagascar, Malawi, Mali, Mozambique, Mauritania, Namibia, Niger, Nigeria, Rwanda, Sudan, Senegal, Sierra Leone, Somalia, Swaziland, Chad, Togo, Tanzania, Uganda, South Africa, Congo, Dem. Rep., Zambia, Zimbabwe.