

On Regional Distribution and Characterization of The Klippfisk Formation Limestone

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Petroleum Geosciences Submission date: March 2016 Supervisor: Atle Mørk, IGB

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Abstract

This study documents and discusses the detailed sedimentology of the Berriasian to Early Barremian Klippfisk Formation on the western Barents Sea, at Bjarmeland Platform, northern part of the Bjørnøya Basin, northeastern part of the Nordkapp Basin, Nordland VII and Troms III areas of the Northern Norway.

The Klippfisk Formation is a condensed carbonate succession deposited on Barents Sea shelf. The formation mainly consists of limestone and marls, often glauconitic. Complete and fragmented shells of *Buchia* and *Inoceramus* are abundant in the Klippfisk formation. Rare echinoderms, brachiopods and belemnite are also present.

The depositional environment of the Klippfisk Formation has been studied through facies analysis of the core data. Twelve facies has been identified in the formation. At the Nord-land VII area, the calcareous siltstone interbedded with beds and nodules of limestone represent a deep shelf depositional environment that was deposited over a long time with low clastic sediments influx.

A shelf slope setting is interpreted at the Bjørnøya Basin, where platform is drowned and graded into slope of the shelf. The glauconitic sandstone is intermixed within the dolomitized limestone. The dolomite is followed by highly fossiliferous wackstone and packstone. The fossils identified are complete and fragmented bivalves of Buchia and Inoceramus, foraminifera and subordinate echinoderms.

The lowermost limestone of the Klippfisk Formation on the Bjarmeland Platform is mud supported that graded into micritic limestone and fossiliferous packstone. The micrite has algal origin and represent an oxic shallow marine shelf.

The regional trend of the Klippfisk Formation has a progradation from deep shelf to shallow marine environment across the Barents Sea shelf from the southeast to the northwest.

Acknowledgement

This thesis is part of a master's degree in petroleum geology at Department of Geology and Mineral Resource Engineering at NTNU. Professor II **Atle Mørk** has been the main supervisor.

I would like to extend my wholehearted thanks to my supervisor **Atle Mørk** for his exceptional guidance and unparalleled assistance at each stage of the project. He has been a source of moral support, motivation and encouragement for me. This thesis would not have been realized without his supervision irrespective of experimental work, results analysis or writing at all levels of the project.

I am also thankful to the Norwegian Petroleum Directorate (NPD), SINTEF Petroleum Research and NTNU for providing the core samples that are placed at Dora core store, Trondheim.

My deepest gratitude to my parent who have been my role models. Their continuous encouragement, endless love helped me to achieve in life, which I have achieved so far.

I do extend my sincere thanks to my friends Ata ul Rauf Salman, Hanif Khan and Subhan Abbasi who were always there to help me and cheer me during the dull phases of the project.

Finally, I must thank God for bestowing upon me his blessing and giving me the strength for making this attempt a fruitful one.

"I declare that this is an independent work according to the exam regulations of the Norwegian University of Science and Technology (NTNU)."

Signature

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Chapter 1

Introduction

1.1 Objective

This study focuses on the sedimentological development and regional variation of the Klippfisk Formation in the Barents Sea.

1.2 Background

Exploration activities from the past 35 years provide extensive information about the Mesozoic strata in the Barents Shelf. The present study will also include information on the depositional history of the mid-offshore Norway.

The present day sea floor of the Barents shelf was developed during and after the glaciation. The sediments of Cenozoic, Mesozoic and Upper Palaeozoic age rests on the hard basement of Caledonian age (Dypvik et al., 2004). The stratigraphic unit in the Cretaceous succession of Spitsbergen was defined by Parker (1967) and on Kong Karls Land by (Smith et al., 1976). Mørk et al., (1999) compile the latest Mesozoic lithostratigraphy of Svalbard and the Barents Sea.

The Adventdalen Group consist of Janusfjellet Subgroup in Spitsbergen (Mørk et al., 1999). In the Hammerfest Basin, the Adventdalen Group consists of the Fuglen Formation, Hekkingen Formation and Kolje Formation. During shallowing drilling in the Barents Sea and northernmost shelf of the Norwegian Sea, a unit of marl and limestone of Early Cretaceous age was discovered, which is named the Klippfisk Formation (Smelror et al., 1998) as shown in Fig 1.1.

Klippfisk is a Norwegian word used for the split, salted and dried cod. The Klippfisk Formation is mainly consisting of marls and limestones. The limestone is sometimes glauconitic and pyritic (Smelror et al., 1998). The depositional environment of the Klippfisk Formation is shallow marine and was formed during the transgression of the Tethyan Sea (Smelror et al., 1998). This formation is sandwiched between the Hekkingen Formation and the Kolje Formation. The Hekkingen Formation is dominated by the finely



Figure 1.1: The diagram shows the distribution of groups, subgroups and formations of the Adventdalen Group in the Barents Sea (Mørk et al., 1999).

laminated, organic-rich dark-grey claystone with no bioturbation (Smelror et al., 2001b). The Klippfisk Formation can be includes the Tordenskjoldberget Member on Kongsøya, on Kong Karls Land (Smelror et al., 1998 ;Smith et al., 1976). The Klippfisk Formation is strongly bioturbated and contain palynomorphs and nannoplankton of Valanginian and Hauterivian age (Smelror et al., 1998; Dypvik et al., 2004). The Klippfisk Formation is divided into two members: the Kutling Member located on the Western Barents Shelf and the Tordenskjoldberget Member on the Kong Karls Land (Smelror et al., 1998).

The Jurassic/Cretaceous boundary in the Barents Sea has an unconformity which is prograding within the Lower Cretaceous sediments. The unconformity is overlying on the black shales of Volgian age (Århus et al., 1990) as shown in Figure 1.2.

Bolides (meteorites and comets) occasionally fall down on earth and create craters. One such crater named Mjølnir Crater occurs on the Bjarmeland Platform. Normally craters can be divided into two types: the bowl-shaped simple craters and complex having central peaks and peak rings (Dypvik et al., 2004). Different steps are involved for the crater to impact on the sediments. The sediments are compressed and crushed and sometimes part of the sediments are ejected. The Mjølnir crater is a complex crater. The crater is located in the central Barents Sea on the Bjarmeland Platform at 73 48 N, 29 40 E. The diameter of this complex impact crater is 40 km. The crater is the result of meteorite impact (Smelror et al., 2001a). A thin slice of Hekkingen Formation and several meters of Klippfisk Formation is drilled on top of the crater material (Smelror et al. 1998) as shown in Figure 1.3.



Figure 1.2: Location of the Klippfisk Formation in the boreholes 7430/10-U-01, 7231/01-U-01, 7425/09-U-01 and 7320/03-U-01 (Smelror et al., 1998).



Figure 1.3: Mjølnir crater in the southwestern Barents Sea, also the location of two drilled wells are shown (Dypvik et al. 2004).

1.3 Goals

The main goals of study the Klippfisk Formation are: The transition from the condensed carbonates to the overlying claystones. The regional distribution of the Klippfisk Formation throughout the Barents Shelf, and northernmost part of the Norwegian Sea. The characteristics of the Klippfisk Formation.

Chapter 2

2 Geological Framework

The Lower Jurassic to Early Cretaceous rocks in the Barents Sea consists of Fuglen Formation, Hekkingen Formation, Knurr Formation, Klippfisk Formation and Kolje Formation (Smelror et al. 1998). The lower contact of the Klippfisk Formation is with the Hekkingen Formation while the upper contact is with the Kolje Formation (Smelror et al. 1998).

2.1 Hekkingen Formation: (Late Oxfordian-Berriasian)

The Hekkingen Formation was penetrated in the wells 7018/05-U-01 and 7018/05-U-02 in Troms III. The total thickness of the Hekkingen Formation in this area is 260 m. There is a stratigraphic overlap of 51 m in the two cores (Smelror et al. 2001). The upper 210 m of the Hekkingen Formation is named as the Krill Member while the lower 50 m is the Alge Member (Smelror et al. 2001). The proposed age for the Hekkingen Formation is late Oxfordian-Berriasian on the basis of the fossils found at different level of the formation (Smelror et al. 2001). The sediments in these two cores are thinned, finely laminated, non-bioturbated, organic rich dark grey to black shale and claystone (Smelror et al. 2001).

The uppermost part of the Hekkingen Formation in the core 7329/03-U-01 was penetrated in the Mjølnir crater. The lithology of the core is black to medium grey, organic rich shales. The shales are thin laminated (74.05 - 57.20 m) (Dypvik et al. 2004). 16 m of the Hekkingen Formation in the crater is dark shale. The common fossils in this formation are bivalves (Buchia) and a few ammonites were identified (Smelror et al. 2001). Another borehole 7430/10-U-01 was drilled 30 km NNE of the rim of the Mjølnir crater. The ejecta from the Mjølnir crater are deposited in the form of separate beds in the Hekkingen Formation and named as the Sindre Bed and occur within the Hekkingen Formation (Dypvik et al. 2004). The Hekkingen Formation in the core consists of finely laminated, dark grey, organic-rich shale (Dypvik et al. 2004).

In the Nordland VII area, two wells 6814/04-U-01 and 6814/04-U-02 were drilled. The Hekkingen Formation is divided into three parts in the Nordland area i.e. the Alge Member, the Krill Member and RauÅte Member (Smelror et al. 2001). The Alge Member comprise 20 m in the core 6814/04-U-01 and 50 m in the 7018/05-U-01 of the Troms



Figure 2.1: The Sindre Bed in the Hekkingen Formation in the well 7430/10-U-01 (from Dypvik et al. 2004)

III. It is organic-rich, fine laminated pyritic, non- bioturbated dark to very dark grey silty claystone. The common fossils are ammonites, belemnites and benthic bivalves (Smelror et al. 2001). The upper 210 m of the Hekkingen Formation in the well 7018/05-U-01 and 120 m of the well 6814/04-U-01 is referred as the Krill Member (Smelror et al. 2001). The Krill Member is differentiated from the Alge Member on the basis of lower gamma readings and lower fossils content. The lower part of the Krill Member has low fossil contents while the fossils content is high at the upper 50 m with ammonites and benthic bivalves (Smelror et al. 2001). Carbonate-cemented beds with siderite, ankerite and less common dolomite are identified in both members but more abundant in the Krill Member (Smelror et al. 2001).

The two wells 7320/3-U-1 and 7425/9-U-1 were drilled on the Bjarmeland Platform by the drilling ship Bucentaur, by the Norwegian Continental Shelf and Petroleum Technology Research Institutes (IKUs) Barents Sea Mapping Program in 1985 (Århus et al. 1990). The lithology of the Hekkingen Formation in the core 7320/3-U-1 is grey clayey and sandy siltstone with wood fragments. There are some fine sand and silt lamination (Århus et al. 1990). Glauconite is abundant at the top of the formation (0.2-05 m). The well 7425/9-U-1 has no record of the Hekkingen Formation (Århus et al. 1990).

2.2 Klippfisk Formation: (Early Berriasian-Early Valanginian)

The Klippfisk Formation was penetrated in the core 7430/10-U-1 and 7321/01-U-01 of the Bjarmeland Platform and Nordkapp Basin respectively. In the Bjarmeland Platform the core length is 8.9 m while, and 4.5 m in the Nordkapp Basin (Smelror et al. 1998). The formation is composed of limestone and marls. The carbonates are intermixing between wackstone and packstone and are often glauconitic and pyritic. The presence of pyrite and glauconite indicated oxygen rich environment. The colour of the Klippfisk Formation is usually greenish to white or light green (Smelror et al. 1998). The Klippfisk Formation is highly bioturbated. The depositional environment of the Klippfisk Formation is probably representing transgressive, shallow marine deposits. These deposits cover the platform areas and local structural highs on the Barents Shelf (Smelror et al. 1988). The common fossils are Inoceramus prisms and other bivalve fragments and high bioturbation. Other commonly found fossils are foraminifera, echinoderms and bryozoans. The bivalve fossils are mainly thin-walled except the Inoceramus which is thick walled and shows a shallow marine shelf environment of deposition (Smelror et al. 1998).

The well 7329/3-U-01 was drilled in the Mjølnir crater in late august 1988. The Klippfisk Formation thickness in the crater is 7.1 m and the lithology consists of heavily bioturbated, light greenish-grey, argillaceous carbonates. The carbonates are mainly marls (Dypvik et al. 2004). The lithology of the Klippfisk Formation is same as in the well 7430/10-U-01 in the Bjarmeland Platform (Smelror et al. 1988).

In the Bjarmaland Platform and Barents Sea, two wells 7425/9-U-1 and /7320/3-U-1 were drilled respectively (Århus et al. 1990). The core length of the Klippfisk Formation is 3.3 m in the core 7320/3-U-1 which consists of dolomite, marl and limestone. The carbonates are intermixture of wackstone and packstone (Århus et al. 1990). The fossils found are Buchia, Inoceramus, Foraminifera and fragments of echinoderms. The lower part of the Klippfisk Formation is glauconitic and pyritic (Århus et al. 1990). The 14.5 m long core of 7425/9-U-1 is divided into 4 main parts. The two carbonates parts are marked in the well 7425/9-U-1 at 64.5-63.8 m and 58.8-53.5 m. the lower 0.7 m is greyish green marl (wackstone) with abundant of fossils Buchia and Inoceramus. While the 5.3 m consists of greyish green marly limestone (Århus et al. 1990). The Buchia is dominant in the lower part whereas the Inoceramus are abundant in the upper part (Århus et al. 1990) The age equivalent of Klippfisk Formation in the Hammerfest Basin is the Knurr Formation. The lithology of the Knurr Formation is dark grey to greyish brown claystone with interbedded of limestone and dolomite (Worsley et al. 1988).

2.2.1 Kutling Member

The name of the Kutling Member was assigned after the Norwegian name of a saltwater fish of the suborder Gobioidea. The Kutling Member represent the whole Klippfisk Formation in the Barents Sea, with the lithologies described above (Smelror et al. 1988).

2.2.2 Tordenskjoldberget Member

The Tordenskjoldberget Member named after a mountain on the southeastern Kongsøya, Kong Karls land (Smith et al., 1976). The lithology of the member is calcareous, white

and light yellow, loosely cemented, coarse to medium sandstone. The sandstone consists entirely of the prismatic bivalves Inoceramus fragments. The Tordenskjoldberget Member also have belemnite and complete bivalve shells of Buchia (Smelror et al. 1998).

2.2.3 Kolje Formation

The Kolje Formation is recovered of a 30 m long core in the well 7018/05-U-01 of the Troms III. The lithology of the Kolje Formation is dark laminated claystone with thin beds of carbonates in the upper and lower parts of the Formation (Smelror et al. 2001). Based on palynomorphs and foraminifera study, the age of Kolje Formation is suggested middle Berremian to early Albian (Smelror et al. 2001). The Kolje Formation is not found on the Mjølnir crater, where the Klippfisk Formation is overlying by the Quaternary sediments (Dypvik et al. 2004).

In the Nordland VII, the 33 m Kolje Formation overlies on the Klippfisk Formation in the well 6814/04-U-02. Kolje Formation in the Nordland VII is dark-grey claystone. The age is Hauterivian-? early Barremian. The base has a sharp contact with the Klippfisk Formation (Smelror et al. 2001). The formation consists of dark-grey mudstone with thin beds of carbonates. The carbonate thin beds are siderite and ankerite (Smelror et al. 2001). Bioturbation is observer locally. The presence of dinoflagellates, absence of microfossils and sparse bioturbation indicate a restricted marine depositional environment (Smelror et al. 2001).

The 29.95 m thick sequence of dark grey silty claystone to clayey sandy siltstone drilled in the well 7320/3-U-01 in Barents Sea. In the lower part horizontally thin lamination of clay and slit present (Århus et al. 1990). Macrofossils are not found except some Inoceramus fragments and minor bioturbation. Siderite is also present as early diagenetic mineral (Århus et al. 1990).

In the Bjarmeland Platform, the well 7425/9-U-1 is drilled through the Kolje Formation (3.8 m). The transition is abrupt from carbonates to grey silty claystone. There is a 3 cm thick bed of coarse grain sandstone containing glauconite in the core. Thin lamination in claystone occur locally but is disturbed by the burrows (Århus et al. 1990). Siderite in yellow brown concretions are found at different level of the core. The Kolje Formation has fair to good organic matter content.

Chapter 3

Results and Interpretation

In this chapter the results obtained from the core samples are presented. The logs will be presented, together with interpretation. The various parts of the results will be discussed and compared.

Since the study is about the characteristics and regional distribution of the Klippfisk Formation, the focus will be the deposition of the Klippfisk Formation and to understand the regional depositional environment of the Klippfisk Formation.

3.1 Facies

A total of 20 facies have been identified in the Hekkingen Formation, Klippfisk Formation and Kolje Formation. Based on the logs, a description of facies and facies association were made.

Table 3.1 shows the wells studied during this thesis along with the location and drilling date. The thickness of the three formations are represented by two different numbers in meter. The upper number shows the total core recovered during drilling while the lower numbers are the core studied during this thesis.

3.1.1 Facies A1, Dark organic shale/claystone, laminated

This facies was found in all the seven cores studied (Figure 3.1). The facies is mainly consists of dark grey organic claystone. The claystone is thinly laminated with fossil bivalves, see Fig 3.1 B. The thickness of the facies varies from 260 m to 2.5 m.

At Bjørnøya Basin, the claystone has thin lamination of sand and silt, see Fig. 3.1 A. The lowermost 2.8 m of the core 7329/3-U-1 is black to medium grey laminated shale (60-57.20m). The fossils Buchia is abundant throughout the facie and are thin walled. Minor amount of white crushed ammonites shell are also found at the upper part of the facies with pyrite concretions. The upper part of the shales is medium grey and is highly bioturbated.

Well no.	Location	Hekkingen Formation	Klippfisk Formation	Kolje Formation	Drilled year
6814/04-U-02	Nordland Area	120m 2+ m	26 m	33 m 2+ m	1991
7018/05-U-01	Troms III	260 m 1.1+ m	1.35 m	30 m 2.5+m	1992
7320/3-U-1	Bjørnøya Basin	2.9 m 1+ m	4 m	29.95 m 2.95+ m	1985
7425/9-U-1	Bjermaland Platform	5 m	5 m	3.78 m 1+ m	1985
7329/3-U-1	Mjølnir crater	16.85 m 2.8+ m	8 m	Not present	1998
7430/10-U-1	Bjermaland Platform	22.4 m 2.2+ m	10 m	1.66 m	1998
7231/1-U-1	Nordkapp Basin	2.5 m 1.6+ m	5 m	22.46 m 2.9+ m	1986

Table 3.1: Location of the studied wells. Thickness of the units and drilling year



Figure 3.1: Core photos. A) Facies A1 at core 7320/03-U-01, dark organic claystone with thin beds of sand and silt, from 35.60 m. B). Facies A1 at core 7018/05-U-01, grey laminated claystone, from 50.45 m.



Figure 3.2: Core photos of facies A1 with log interval from core 7329/3-U-1. A) Dark grey claystone, laminated and thin shelled bivalves at 59.10 m. B) Highly bioturbated light grey claystone at 58.5 m.

Interpretation

The Hekkingen Formation in core 7018/05-U-1 core is referred as the Krill Member (Smelror et al. 2001). The suggested age of the facies is latest Volgian-earliest Ryazanian (Smelror et al. 2001).

In the late Oxfordian, regional transgression took place which triggered the deposition of the upper Jurassic dark shale in the western Barents Sea and Svalbard (Smelror et al. 2001). The Alge Member of the Hekkingen Formation is organic rich with ammonite fossil found at the base of the Alge Formation. The Alge Formation deposition can be explained with the help of the stratified basin model (Tyson et al. 1979). In a restricted environment, the low density bottom water is isolated form the surface oxygenated waters. The circulation of oxygen to the bottom water is dependent on the vertical circulation. The lack of oxygen in the bottom area becomes a favourable to accumulate the organic matter. In this sense, the depositional environment for the Alge Member was deep shelf anoxic environment.

During transgression of the western Barents Sea shelf in the late Oxfordian- late Kimmeridgian, the Alge Member was deposited which is followed by a lower organic rich shale of the Krill Member. The shales are deposited in a highstand and regressive deposits which can be identified from lack of bioturbation and low organic content (Smelror et al. 2001). The shales of Krill Member are deposited in a dysoxic to oxic environment.



3.1.2 Facies A2, Laminated grey claystone

Figure 3.3: Facies A2 in different cores. A) Light grey claystone in core 7018/05-U-01. B) Grey laminated claystone in 7231/01-U-01 at 59.50 m. C) Organic rich claystone with pyrite at 29.10 m in 7320/03-U-01.

Observation

This massive thin laminated, grey claystone and shales facies is observed in five wells studied in this thesis, but the facies is not present in the cores drilled at the Mjølnir crater and Bjarmeland Platform, see Table 3.1. The colour of the facies vary in some core. The facies colour is fluctuating between black to dark grey, see Fig. 3.3. Diagenetic minerals glauconite and pyrite are found in the facies in the Nordland area, see Fig. 3.3 C. The facies is mostly less bioturbated and very few fossils are identified throughout the section. The rare fossils found in the facies are fragmented shells of bivalve Buchia and Inoceramus, foraminifera and wood fragments. The facies is assigned as Kolje Formation (Smelror et al. 1998; Århus et al. 1990; Smelror et al. 2001)

Interpretation

The suspended sediments are setting down which form this laminated claystone in transgressive environment. The colour fluctuating of the claystone is probably depending upon the presence of organic content in the unit. The fossils content and amount of bioturbation suggested that the claystone was deposited in open marine deep shelf with sufficient amount of oxygen.

3.1.3 Facies A3, Calcite cemented highly bioturbated claystone



Figure 3.4: Core photo. Facies A3, calcite cemented claystone, highly bioturbated and glauconitized at 49.10 m.

Observation

The calcite cemented, grey green, highly bioturbated facies A3 can be observed only in the shallow core 7018/05-U-01 of the Troms III area. According to Smelror et al. (2001), the facies suggested to belong to the Klippfisk Formation the Late Oxfordian-Berriasian, see Fig 3.4. The claystone is cemented with fine grained calcite. Pyrite is found at the lower part of the facies. The thickness of the facies is 1.25 m and it is highly fossiliferous with Chondrites and thick-walled Inoceramus.

Interpretation

The facies is a condensed claystone unit and highly bioturbated. The occurrence of the fine grained cement in the claystone could be interpret by the transgression, shallow marine deposits. The presence of bivalve Inoceramus and chondrites indicate that the depositional environment was starved oxic shelf.

3.1.4 Facies A4, Greenish mudstone



Figure 3.5: Facies A4 from the cores. A) Mudstone. Base of the Klippfisk Formation in 7231/1-U-1. B) Mudstone. Top of the Klippfisk Formation in 7231/1-U-1. C) Glauconitic mudstone in core 7430/10-U-01.

Observation

This fine grained and mud supported facies is observed in the Nordkapp Basin and Bjarmaland Platform, see Appendix 5 &6. The colour of the mudstone is grey to green. Glauconite is found in the facies with thin walled fragmented bivalves. The facies belongs to the Klippfisk Formation (Smelror et al. 1998).

Interpretation

The mudstone shows the transgressive depositional environment and display the transition from deep shelf environment to a high stand shelf environment. The green colour of the mudstone is maybe due to the presence of glauconite in the mudstone, see Fig. 3.5 C. In the core 7231/1-U-1, the mudstone was observed in the top and bottom of the Klippfisk Formation. The bottom shows the transition from deep marine environment to relative shallow marine environment, see Fig.3.5 A. On the other hand, the top of the Klippfisk Formation, the environment of deposition is changing form shallow marine to deep open marine by the addition of clayey sediments and packstone, see Fig. 3.5 B.

3.1.5 Facies A5, Red shales/claystone



Figure 3.6: Core photos of the facies 7425/9-U-1. A) Highly bioturbated red shale, thin shelled bivalves at. 58.30 m. B) Intermixed beds of red shale and greenish marl at 57.90 m.

Observation

These reddish brown shales are only observed in the core 7425/9-U-1 on the Bjarmeland Platform. The thickness of the shale is 5 m and sharply overlain by facies C3. The shales are high fossiliferous. The fossils found are crushed thin walled bivalve Buchia and In-oceramus with sub-ordinate foraminifera, belemnite and wood fragment, see Fig. 3.6. The top of the shales has intermixed beds of facies C3., see Appendix 3. The age suggested by Århus et al. (1990) for this facies is from Early Boreal-Berriasian to intermediate Boreal Berriasian-Valanginian.

Interpretation

The detrital claystone was deposited in a deep marine environment with abundance of iron mineral. After the regression, claystone is exposed to surface conditions. The reddish brown colour of the claystone is due to oxidation of clay mineral and haematite ore. The red beds are of marine environment due to the presence of marine fossils complete and fragments of bivalves Buchia and Inoceramus with echinoderms, belemnite and wood fragments (Wagreich & Krenmayr 2005).

3.1.6 Facies B1, Sandy siltstone



Figure 3.7: Facies in core 6814/04-U-02. Facies B1, sandy siltstone, from 51.20 m.

Observation

This greenish sandy siltstone facies was observe in the Nordland Area in the core 6814/04-U-02. The thickness of the facies is 0.4 m. Glauconite is found in the facies. The facies is burrowed with Zoophycos. It shows the gradual transition from calcareous siltstone to sandstone, see Fig. 3.7.

Interpretation

A coarse texture is start to appear above the fine grained sediments. These are the prograding deposits which follow the fined grained. The sandy siltstone shows a relative shallow marine environment of deposition on the shelf with low energy.

3.1.7 Facies B2, Silty claystone



Figure 3.8: Core Photo. Facies B2 silty claystone, greyish green, bioturbated with wood fragments at 65.80 m.

Observation

The greyish green silty claystone facies occurs only at the Nordland area in the core 6814/04-U-02., see Fig. 3.8. The thickness of the facies is 0.6 m. Zoophycos and wood fragments were identified in the facies. The silty claystone shows a gradual transition to facies B3, greenish calcareous siltstone at the top, see Appendix 7.

Interpretation

The claystone is coarsening upward with inclusion of more silt grains. The change of fine grain sediment to relative coarse grain sediments indicates that the silty claystone was deposited in a transitional environment, where the environment of deposition is changing from deep restricted towards the relative shallow due to transgression.



3.1.8 Facies B3, Greenish calcareous siltstone

Figure 3.9: Facies B3 in the core 6814/04-U-02. The arrow indicates the Zoophycos burrow in the facies at 53.70 m.

Observation

This massive dark-grey to greenish calcareous siltstone facies occurs in the core 6814/04-U-02 in the Nordland Area. The thickness of the facies 30 m with nodules and beds of carbonates (limestone). At 51-52.10 m, the siltstone is changed to coarse grained greenish sandstone. The facies belongs to the Klippfisk Formation. The whole unit is burrowed by Zoophycos with coquina beds, with fragments of Inoceramus, see Fig. 3.9. The sedimentological log with interpretation is given in Appendix 7.

Interpretation

The condensed calcareous siltstone was probably deposited in a low wave energy on the shelf slope. The presence of Zoophycos indicated that the deposition took place in a well oxygenated starve shelf environment. The calcareous mud in the siltstone indicate that the sedimentation rate was slow and the fractured nodules (fractured filled with fine silt) of the limestone mark that the deposition continued for a long time and absence of micritisation in the limestone beds suggests that the deposition occur below the photic zone. The Klippfisk Formation development can be correlated with the Leira Member of the Nybrua Formation at Andøya (Smelror et al. 1998).

3.1.9 Facies B4, Greenish sandstone



Figure 3.10: Core photo. Facies B4, greenish sandstone from the core 6814/04-U-02, from 51.30 m

Observation

The medium to coarse grained greenish sandstone facies occurs in core 6814/04-U-02 of the Nordland area. The thickness of the facies in the core is 1.0 m. The facies is highly fossiliferous. The fossils observed are Zoophycos and thin walled bivalves, see Fig. 3.10.

Interpretation

The greenish sandstone overlies on the glauconitic sands in the Nordland area and shows that the deposition occurs in a shallow marine transgressive environment. The sedimentation rate was high and rapid.

3.1.10 Facies B5, Glauconitic greenish sandstone



Figure 3.11: Core photo. Facies B5, coarse grained glauconitic sandstone from core 7320/03-U-01. The glauconite is in the form of faecal pallets, from 33.20 m.

Observation

The coarse grained, greenish glauconite rich sandstone occurs at the Nordland area and Bjarmeland Platform in core 6814/04-U-02 and 7320/3-U-1 respectively. The thickness of the facies in the Bjarmeland Platform is 0.7 m and at Nordland area the facies comprises 0.3 m, see Fig. 3.11.

Interpretation

Glauconite sand is the diagenesis of non-expandable (illite) and expandable (montmorillonite) clay minerals (Triplehorn 1965). The diagenetic mineral glauconite are in the form of faecal pellets in the two cores and shows the hardground. The glauconite shows that sedimentation rate was slow and hardground shows unconformity.



3.1.11 Facies C1, Marly limestone with bioclasts

Figure 3.12: Core photo with log interval of the core 7329/03-U-1. Facies C1, marly limestone with bioclasts.

Observation

The mixed marly limestone with bioclasts facies can be observed in the core 7329/03-U-1 on the Bjarmeland Platform. It occurs at the top of the shallow core. The thickness of the facies is 0.5 m and it is highly bioturbated, see Fig. 3.12. The bivalve Inoceramus are found within some pyrite concretion. The top of the facies is directly overlain by Quaternary sediments.

Interpretation

As discussed earlier the core 7329/3-U-1 is drilled on the faulted rim of the Mjølnir crater. The mixture of the fine grained sediments in the marly limestone are the pelagic sediments. The sedimentary basin in which the sediments were deposited is at shallow depth. Traces of reworked sediments is observed in the facies. The extensive postimpact deformation of the impact affected rock volume which triggered the deposition of postimpact sediments (Tsikalas et al. 1998).



3.1.12 Facies C2, Greenish marly limestone



Observation

This greenish, heavily bioturbated marly limestone facies is observed in the core drilled in the core 7329/03-U-01 and 7430/10-U-01. The thickness of the facies varies from a few cm to massive unit of several meters, see Appendix 4 & 6. The facies is highly fossiliferous. The fossils identified are complete and fragments of bivalve Inoceramus, belemnite and ammonite, see Fig. 3.13. The facies is pyritic abundant and few calcite veins were identified in the facies.

Interpretation

The well 7329/03-U-01 was drilled at the edge of the up-dipping edge of the Mjølnir crater central high in late august 1998 by the drillship M/S Bucentaur. Also the 7430/10-U-01 was drilled 30 km from the Mjølnir crater on the Bjarmeland Platform. During an

impact crater at sea, there are three stages involve in cratering: compression/penetration, excavation and modification. The penetration phase is the asymmetrical and high energy stage; excavation is the intermediate-energy phase in which the high energy ejecta moves away from the crater impact while low-energy crater ejecta falls near the crater rim and finally the modification phase which are symmetric and it determine the final size of the crater (Shuvalov & Dypvik 2004). (Dypvik et al. 2004b). The Mjølnir crater is an oblique impact event and is a large complex impact structure (Tsikalas 2005). The marly limestone deposited in a high stand environment where the water is well oxygenated and well packed with fossils.

A 10 cm 10 cm

3.1.13 Facies C3, Limestone (wackstone-packstone)

Figure 3.14: Core photos. Facies C3, limestone. A) Grey packstone, thick shelled bivalve in the core 7425/9-U-1, from 54.35 m. B) Coquina bed in core 7320/03-U-01, from 33.35 m. C) light reddish wackstone, thin shelled bivalves in the core 7320/03-U-01, from 30.12 m.

Observation

The limestone facies occurs at the Bjarmeland Platform, Nordkapp Basin and Bjørnøya Basin. The limestone facies consists of intermingling wackstone and packstone intervals. Few cm beds of this facies were also observed at the Nordland area in core 7320/1-U-1 at the Bjørnøya Basin, the thickness of facies 1.10 m, see Appendix 2. The facies is highly fossiliferous with fossils Bivalve Buchia and Inoceramus. The coquina beds were identified in the facies with few pyrite concretions. The colour of the facies is reddish grey to dark grey, see Fig. 3.14. At the Nordkapp Basin, the thickness of the facies is 3.5 m. the colour of the facies is light greenish to light grey. The facies in Nordkapp Basin is highly

fossiliferous. The lower greenish wackstone is abundant with thin walled bivalves while the upper part packstone has thick walled bivalves, see Appendix 5.

At the Bjarmeland Platform, the facies is identified in core 7430/10-U-01 and 7425/9-U-1. The facies are mixed with interbedded marly limestone. The fossils identified are both complete and fragments of bivalves Buchia and Inoceramus, echinoderms and belemnite. Pyrite is identified throughout the facies, see Appendix 3 & 6.

Interpretation

The intermixing intervals of wackstone and packstone shows that the limestone were deposited in agitated environment, where the sea level changes with rapid intervals of time. The presence of thin shelled bivalve in the wackstone shows the deposition in a relative calm conditions. On the contrary the packstone has thick walled bivalves which is an indication for a high energy deposits.

3.1.14 Facies C4, Nodular limestone



Figure 3.15: Core photo. Facies C5, yellow colour conglomeritic limestone from the core 7018/5-U-1. From 48.60 m.
Observation

This facies was only observed in the core 7018/5-U-1 in the Nordland Area. The colour of the facies is light yellow and fossiliferous. The thickness of the facie in the core is 10 cm. The limestone nodules are cemented by fine grained claystone and exhibit conglomeratic structure. The fossils found are thick shelled bivalve Inoceramus, see Fig. 3.15. For the sedimentological log description, see Appendix 1.

Interpretation

This facies can be interpreted as the nodular limestone are formed by the sub-solution of the sediments. The sub-solution occurs after the deposition. The nodular limestone is then mounted together by fine grained calcite to exhibit a conglomeratic structure.

3.1.15 Facies C6, Cemented limestone (micrite)





Observation

This fine grained facies occurs only in core 7329/3-U-1 drilled at the Mjølnir crater. The colour of the facies is light brown. The thickness of facies ranges from 10 cm to 2 m. The

facies is intermixed with marly limestone, see Appendix 4. The facies in highly bioturbated. The fossils identified are Inoceramus, see Fig. 3.16. Few odd pyrite concretions were also identified in the facies.

Interpretation

This carbonates deposited by the chemical precipitation of one or another chemical mineral in sedimentary environments. The micrite which is fine grained aragonitic in nature, produce due to abrasion of the large carbonate fossils. The micrite cement may also be formed due to the quick death and burial of the sponges and algae in an anoxic condition with no fresh water inclusion. The lime mud is precipitated in the pore space between carbonate crystals. The cementation of the limestone took place in relative shallow marine environment (Hanken et al. 2010).

3.1.16 Facies D1, Dolostone





Observation

This light reddish, high fossiliferous dolostone facies was only observe in the core 7320/3-U-1 in the Bjørnøya basin. The thickness of the dolostone in the core is 2.3 m. The base of the facies is mixed with the glauconitic sandstone facies B5, see Appendix 2. The top of the facies has a sharp contact with the facies C3. Bivalves Buchia and Inoceramus are abundant and scattered throughout the facies as well as foraminifera and fragmented echinoderms, see Fig. 3.17. Coquina beds are identified at different depth, see Appendix 2. According to (Århus et al. 1990), the facies belongs to the Klippfisk Formation.

Interpretation

The dolostone are formed as a result of the diagenesis of limestone. The condensed limestone deposition can be related to an inner shelf margin, close to the slope. The dolostone is followed by facies C3, limestone. The dolostone and limestone are separated by a glauconite rich matrix, hardgrounds. The hardground is the indication of reworked deposition and the decline of deposition. They often mark unconformities (Decarlis & Lualdi 2008).

3.1.17 Facies D2, Dolostone with chert (nodules)



Figure 3.18: Core photo. Facies D2, dolostone with chert of the core 7018/5-U-1, from 46.58 m.

Observation

This dolostone facies is found in the Kolje Formation at 46.20 m and 46.60 m in the core 7018/5-U-1 of the Nordland Area. The dolostone is nodular and reddish in colour, see Fig. 3.18 D. The angular cavities of the dolostone facie are filled with the quartz cementation.

Interpretation

The dolostone facies D2 in Kolje Formation are septarian nodules. A septarian nodule can be describe as tensile angular cavities which are filled with the calcite precipitation. The angular cracks are formed in response to the burial stress on the nodules. The septarian nodules are the secondary diagenetic mineral (Astin 1986).

The septarian nodule in the Kolje Formation are formed as a result the overpressure on the claystone during the transgression in Barents Sea. The higher overburden pressure on the claystone results in the faster compaction of the sediments. Also the fluid pressure increased with the burial depth. The red colour of the nodule is due to oxidation and it is siderite concretion. The continuous deposition of the claystone creates an overburden pressure on nodule. The vertical orientation of the cracks indicates that the maximum principle stress was being vertical with lack of horizontal orientation. The combine effect of fluid pressure, low horizontal pressure and burial depth gives instantaneous fracture of a rock. These angular fractured are filled with fine grained calcite.

3.1.18 Facies E1, Fractured nodules of carbonates



Figure 3.19: Core photo. Facies E1, carbonate nodules from the core 6814/04-U-2, fractured filled with fine silt. From 53.50 m.

Observation

This facies was found in the core 6814/04-U-02 in the Nordland Area. The nodules are found within the calcareous siltstone facies B3 and scattered throughout the facies B3, abundant in the upper part of facies. The nodules are light greenish colour. These nodules are fractured which is then cemented with fine silt. The carbonate nodules are coated with fine grained silt, see Fig. 3.19. No bioturbation has been observed in this facies. Rare pyritic concretion can be found within the facies.

Interpretation

This facies represent the extreme overburden pressure on the carbonate soft nodules. The calcareous silt shows that the sedimentation rate was very slow and the sediments have high bioclasts ratio. The soft carbonate nodules are buried in the calcareous siltstone.

3.2 Facies associations

These 19 facies have been grouped into three main facies association see, Table 3.2: (i) Deep restricted shelf (ii) High energy shelf and (iii) Open marine shelf. These associations are explained in this study. The Deep restricted and High energy shelf associations are appeared in all the seven wells. While the open marine shelf association is absent in Mjølnir crater and Barents Sea, see Table 3.1

Colour	Name	Facies association	Included facies
	FA1	Deep restricted shelf	A1, A4,B1,A5,
	FA2	High energy shelf	A3, ,B3,B4,B5,C1,C2,C3,C4,C5,C6, D1,E1
	FA3	Open shelf	A2, B2, D2

Table 3.2: Facies Associations

Chapter 4

Discussion

In this section, the three facies association among the seven wells have been discussed and correlated. The facies associations are based on the environment of deposition, see Fig. 3.19. There are variations in facies distribution within the facies association (FA1, FA2 and FA3).

Facies A1 is distributed in all the wells studied in this thesis. Facies A consists of dark grey claystone of the Hekkingen Formation. At the Bjørnøya Basin the claystone has thin beds of sand and silt and is organic rich and unconformably overlied by FA2. At the top of 7320/3-U-1, facies A1 is changing from claystone to sandy claystone. The claystone is siltier and cemented with calcite and have low organic content at Troms III. The core 7425/9-U-1 at the Bjarmeland Platform has 5 m massive unit of oxidized red shale with thin shelled bivalves.

FA2 (Klippfisk Formation) occurs at all studied sections, see Table 1. It is mainly comprising marly limestone and condensed carbonate unit. Often highly bioturbated cemented claystone (Facies A3) are followed by conglomeratic nodular limestone (Facies C5). At Troms III area, FA2 is sharply overlain by FA3. At the Nordkapp Basin, the FA2 includes calcareous siltstone (Facies B2) with limestone nodules and beds (Facies E1 & C3). At the Bjørnøya Basin the FA2 includes facies D1 and C3 with coquina beds. FA3 deposits overlied unconformably FA2. At the Bjarmaland Platform, variation observed in FA2 are facies C1 (cemented limestone with bioclasts), Facies C2 (greenish marly limestone), Facies C3 (wackstone and packstone) and C6 (cemented limestone).

Succession dominated by laminated claystone FA3 (Kolje Formation) is found in all seven wells studied in this thesis except in 7329/3-U-1 at the Mjølnir crater which is overlain by Quaternary deposits. The Kolje Formation is thinning from south to north shows the shifting of sedimentation from deep shell to relative shallow marine environment. The claystone has different colour due to organic content. At the Nordland area the claystone is mixed with silt (Facies B2), and there are few vertical fracture filled with fine grained silt (Facies E1).



Figure 4.1: Correlation panel of measured core sections with interpreted facies association. Locations of well site are in Table 1. Note that the section from Nordland VII has a vertical scale of 1:50. The other log sections has 1:20 scale. Legend in the Appendix.

In the Early Mid Kimmeridgian, fault movements in the western Barents Sea changed the tectonic settings. The faults movements formed different new tectonic elements. The Loppa Ridge is formed due to basin subsidence in the Hammerfest Basin and Bjørnøya Basin. The faulted hinge zone bounded the Hammerfest Basin and separate the Bjørnøya Basin in the eastern shallow province (Rønnevik et al. 1982). The regional transgression that took place in the late Oxfordian triggered the deposition of the fine grained organic rich claystone in the southwestern Barents Sea (Hekkingen Formation) and Svalbard (Agardhfjellet Formation; Mørk et al. 1999). The claystone is deposited in a deep marine environment with anoxic bottom condition (Worsely et al. 1988).

The regional flooding in the western Barents Sea Shelf reached its maximum (Alge Member of Hekkingen Formation) which is followed by claystone of Krill Member. The Krill Member was deposited in a high stand regressive environment with dysoxic to oxic conditions. The Hekkingen Formation deposited at Bjørnøya Basin has thin sand and silt lamination that shows that the claystone was deposited on the slope of the shelf. Thin lamination of coarse sand and silt is also an indication of deposition at the shelf slope. The Krill Member at the Nordland area and Troms III area has low organic content that can be seen at Bjørnøya Basin and Bjarmeland Platform (Århus et al.1990; Worsley et al. 1998). In the western Barents Sea, Alge Member of the Hekkingen Formation is more organic rich than the overlying Krill Member (Leith et al. 1992).

On the Barents Sea shelf at the Nordland area, black shale deposition continuous during the Volgian-Berriasian. The sea level decreased at the mid Volgian that is reflected in the form of silt in the claystone of Hekkingen Formation. The thickness of the Klippfisk Formation is thicker than in Troms III area and anywhere in the seven wells studied during this thesis; see Fig.4.2. The Klippfisk Formation at the Nordland VII correlates with the Leira Member of the Nybrua Formation at Andøya (Dalland 1975). The FA1 is gradually changes to FA2 in the Nordland area. The calcareous siltstone in the 6814/04-U-2 can be associated with slow sedimentation and appearance of diagenetic mineral glauconite indicates that the sedimentation take place during a very long time. The calcareous siltstone is borrowed by Zoophycos. One possible argument of the limestone beds and nodules in the Nordland area is that during transgression the calcareous sediments were soft and un-condensed. At the time of deposition, fault movement was also active. The calcareous sediments were initially deposited at a horst then laterally graded into deeper sedimentary basinal zones in the graben. Slow sedimentation and high bioclasts input in the Nordland area results in the dissolution of the calcareous material that was deposited in the form of calcareous siltstone. As there is no evidence of micritisation in the limestone bed, it may mean that deposition occurs below the photic zone (Smelror et al. 2001). The fractured nodules of limestone in the Nordland area is also an indication of the deep burial of softer sediments, followed by dissolution and then the fractured filled by fine grain material.

In the late Valanginian, transgression at the Troms III area initiated the deposition of condensed clay unit of the Klippfisk Formation (Smelror et al. 2001). The thickness of the claystone is 1.25 m. The transgression resulted in deposition of claystone. The claystone of the Klippfisk Formation is calcite cemented which is followed by nodular limestone conglomerates of Hauterivian age. The deposition of the nodular limestone can be the reason of the regional tectonic activities in the Barents Sea that slow down the sedimentation rate in Valanginian to Hauterivian age (Smelror et al. 2001).



Figure 4.2: Depositional pattern of the Klippfisk Formation at the Barents Sea shelf. Lines showing the well location at sea shelf.

In Early Cretaceous, the North Atlantic Rift system affected the Southwestern Barents Sea. The Barents Sea receives three main tectonic phases. The first phase is the Berriasian-Valanginian which triggered the uplifting of the Bjørnøya Basin (Heinicke 2012). The uplifting exposed the rocks to atmospheric agencies and cause the erosion which formed an unconformity. The glauconitic sand in the core is found in the form of faecal pallets with thin lamination of dolomite. The regional transgression in the late Valanginian cause the deposition of condensed carbonate unit in the Bjørnøya Basin (Århus et al. 1990). The dolomite that occurs at the Bjørnøya Basin are preferentially formed by replacing micrite in the original carbonates. Dolomicrite formed in an initial phase of dolomitization. Later transformation of this dolomicrite produced crystals of dolomite. These crystals are either created as a result of replacement of initially produced calcite cement or by growth in the void spaces (Varol & Magaritz 1992). The dolomitization and the glauconite can be associated by local sea level fluctuation i.e. minor regression and transgression periods which cause the formation of dolomite. The dolomitization followed by intermingling fossiliferous wackstone and packstone with coquina beds also indicate that deposition occurs at relative slope area of shelf.

The Klippfisk Formation at the Bjarmeland Platform has as previously mentioned, been interpreted to represent a high stand shallow marine deposits. The Late Jurassic-Early Cretaceous deposits at the Bjarmeland Platform indicates the regional sea level rise during the Volgian-Hauterivian. The sea level rise also shows a climate shift from warm humid environment in Volgian to arid cold climate in the early Hauterivian (Mutterlose et al. 2003). The facies A1 (dark claystone) are sharply overlied by facies A4 (greenish mudstone). The lowermost mudstone of the Klippfisk Formation marks the transgression of the sea which favours the deposition of carbonate. On the other hand, the supply of fine grained terrigenous sediments of continental origin was also high and became mixed with carbonate. The high bioturbation degree in the mudstone took place during the transgression and there is a rich foraminiferal assemblage. The thin shelled bivalves suggest the shifting of low oxygenated bottom water to fully oxygenated. The upper part in facies

association FA2 at the Bjarmeland Platform are the transgressive system tracts deposits at the carbonates platform. The system tracts represent very slow rate of accumulation. The accumulation rate is characterized by micrite rich sequences and early submarine cementation at the platform (Sarg 1988). The Klippfisk Formation at the Bjarmeland Platform commonly consists of parasequences of shoaling from subtidal mudstone and wackstone to fossiliferous packstones. Bioturbation is found at the platform; see Fig. 25. Flora and fauna are abundant and include brachiopods, sponges, echinoderms, foraminifera and algae. The environment of deposition of Klippfisk Formation at the Bjarmeland Platform represent shallow marine shelf.

In late Barremian, a shift of sediments took place at the Barents Sea shelf, from condensed carbonates to dark grey shale which continuous until Aptian. The sedimentation rate shifted from very slow to rapid. The contact between FA2 and FA3 is very sharp which shows an unconformity. Hardgrounds at the top of the Klippfisk Formation in the Nordland area marks the unconformity. In the Troms III area the same sharp contact can be seen between the Klippfisk Formation and Kolje Formation. At the Nordland VII area, septarian nodules are found in the Kolje Formation that was formed due to high overburden pressure and faster compaction. No bioturbation was observed in the Kolje Formation at the Nordland VII and Troms III areas but it is highly bioturbated at the Bjørnøya Basin. Smelror et al. (2001) mentioned the deposition of Kolje Formation in a transgressive system tract. The dinoflagellates presence shows that the Kolje Formation was deposited in a marine environment. The absence of macrofossils in the formation indicates a restricted environment with low water circulation. At the Mjølnir crater, the Klippfisk Formation are directly overlain by Quaternary sediments in the central part of the Bjarmaland Platform (Dypvik et al. 2004). The thin lamination in the Kolje Formation at the Bjarmeland Platform show homogeneous sedimentation in an open marine environment.

Chapter 5

Conclusion

- The Klippfisk Formation is a condensed carbonate unit deposited on platform areas on the western Barents Sea, at Bjarmeland Platform, northern part of the Bjørnøya Basin and northeastern part of the Nordkapp Basin areas. The Klippfisk Formation are also cored at the Troms III and Nordland VII areas.
- The age of the Klippfisk Formation ranges from Berriasian to Early Barremian with several major and minor stratigraphic gaps. Twelve different facies were identified during studying of the core samples.
- The Klippfisk Formation is sharply overlying the dark shale of the Hekkingen Formation. The diagenetic mineral glauconite is found at the base and marks an unconformity. The upper contact of the Klippfisk Formation is mark by the transition from carbonates to overlying dark grey claystone of the Kolje Formation or younger strata at the Mjølnir crater. Hardgrounds and glauconite is found at the upper part of the Klippfisk Formation which indicate an unconformity.
- At the Nordland VII area, the condensed massive Klippfisk Formation consists of calcareous siltstone with alternative beds and nodules of limestone. The formation is burrowed with Zoophycos. The nodules are fractured and the fractures are filled with fine grained silt. Soft carbonate sediments were deposited at the horst in Nordland VII area. Faulting was active during the deposition of sediments. High calcareous mud is present in the sediments which can be explained by low clastic sediments input. The absence of micritisation in limestone beds represents a deep shelf environment (below photic zone) of the age Valanginian-Hauterivian.
- At the Bjørnøya Basin the Klippfisk Formation contain dolomite with intermixed layers of glauconitic sandstone. The dolomite grade into highly fossiliferous wackstone and packstone. The dolomite is formed due to the replacement of micrite cement in the carbonates which is followed by limestone (wackstone and packstone) upward in the succession. The upper succession of the Klippfisk Formation at the

Bjørnøya Basin are platform sediments. The platform is finally drowned and thus grading into shelf slope environment.

• On the Bjarmeland Platform, the Klippfisk Formation consists of marly limestone, bioturbated mudstone, and micritic limestone. The micrite is partly formed due to the abrasion of algae. The abundance of bivalves, foraminifera, sponges and algae shows that the environment of deposition was a well oxygenated shallow marine environment.

Chapter 6

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Figure 7.1: Sedimentalogical Log of the core 7018/05-U-1



Figure 7.2: Sedimentalogical Log of the core 7320/3-U-1



Figure 7.3: Sedimentalogical Log of the core 7425/9-U-1



Figure 7.4: Sedimentalogical Log of the core 7329/03-U-01



Figure 7.5: Sedimentalogical Log of the core 7231/1-U-1



Figure 7.6: Sedimentalogical Log of the core 7430/10-U-01



Figure 7.7: Sedimentalogical Log of the core 6814/04-U-2

