UPPER PALEOCENE ULTRAMAFIC IGNEOUS ROCKS OFFSHORE MID-NORWAY: RE-INTERPRETATION OF THE VESTBRONA FORMATION AS A SILL COMPLEX

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Original paper date of submission: 09.09.2016

Revised paper date of submission: 25.01.2017

ABSTRACT

Continental breakup between NW Europe and Greenland (~56 Ma) ago was associated with widespread magmatism. Silica undersaturated alkaline porphyritic igneous rocks of a similar age have previously been dredged near the mid-Norwegian coast. These igneous rocks of the Vestbrona Formation have previously been interpreted as either igneous plugs or volcanic flows. New 3D seismic data show that relatively small sill complexes are abundant in the same region. In total, 36 sills with a size of 0.1 to 9 km^2 have been mapped. In addition, ten seismic horizons were interpreted and tied to nearby wells to obtain a robust stratigraphic framework. The sills mainly intrude Cretaceous and Paleocene sequences, however, one sill is also identified in the pre-Cretaceous sequences. The sills locally form erosional remnants on the seabed due to massive uplifting and erosion of the continental margin. Vintage igneous and sedimentary dredge samples have been re-analyzed, including petrography, geochemistry (XRF, XRD), biostratigraphy, and Ar-Ar geochronology. The new Ar-Ar data suggest that the sills are 1-2 Ma older than breakup (ca. 57-58 Ma). Furthermore, the biostratigraphy and petrography of two sediment samples suggest that the samples were collected from near in-situ subcrops and not of an ice rafted origin. The sediment samples are of Danian age, and are strongly metamorphosed, most likely by contact metamorphism resulting from heating during sill emplacement. The newly identified sills have implications for the petroleum prospectivity of the study area including source rock maturation within thermal aureoles and the long term alteration of fluid migration pathways.

INTRODUCTION

Volcanic rifted margins, such as those within the North Atlantic Igneous Province (NAIP), are associated with voluminous igneous activity (e.g. Saunders et al., 1997; Menzies et al., 2002). The NAIP contains volcanic rocks emplaced during the Late Paleocene to Early Eocene, just prior to and at the onset of rifting between Greenland and Europe (Saunders et al., 1997; Hansen et al., 2008). These events are associated with extensive subaerial volcanism as well as the development of volcanic centers and sill complexes (e.g., Planke et al., 2000; Jerram & Bryan, 2015; Schofield et al., 2015). The Norwegian margin of the NAIP is a classic example of a volcanic rifted margin (Planke et al., 2000; Abdelmalak et al., 2016), where extensive sill complexes ≥80 000 km^2 in size, have been identified, intruding mainly into thick sedimentary basin successions such as the Vøring and Møre basins (Planke et al., 2005). These intrusions are commonly associated with hydrothermal vent complexes, which provide evidence for the thermal maturation of host sediments within the sill aureoles causing gas generation and release (Jamtveit et al., 2004; Svensen et al., 2004; Aarnes et al., 2012). Clearly the timing and location of sill complexes is important as they play a role in modifying the thermal history within a basin and directly effecting petroleum systems where present (e.g. Schofield et al., 2016; Senger et al., 2017).

Assessing the relative timing and impact of sills and other intrusions within sedimentary basins can be a challenge. The subsurface sills themselves are intersected relatively rarely by wells, and are even less commonly cored (e.g. Aarnes et al., 2015; Schofield et al., 2015), and often the expression of the sills in seismic needs to be constrained by the regional stratigraphic framework and any additionally available well control (e.g. Schmiedel et al., 2017). The Vestbrona Formation, which forms the focus of this contribution, is located across the central part of the Frøya High, close to the Norwegian coast and away from the main sill complexes on the margin (Figure 1). Within this study both direct sampling and high quality seismic data were used to assess the nature of the igneous rocks forming the Vestbrona Formation.

The Frøya High is defined at the level of the Late Jurassic-Early Cretaceous unconformity which is gently dipping towards the WNW (Blystad et al., 1995). Westward dipping Mesozoic and Paleogene sedimentary units, overlying high-grade metamorphic basement, form petroleum exploration targets offshore Kristiansund on the Mid-Norwegian margin (Figure 1). Several semi-circular bathymetric highs or seamounts are located in the study area, the Vestbrona Seamounts (Figure 2). Two of these seamounts were dredged, revealing exotic alkaline volcanic rocks with a K-Ar age of 55.7 ± 0.9 Ma (Bugge et al., 1980). The dredged rock samples were later named the Vestbrona Formation (Askvik & Rokoengen, 1985). The rocks are silica undersaturated alkaline porphyritic igneous rocks and were interpreted as igneous plugs (Prestvik et al., 1999).

The Vestbrona Formation dredge samples provide valuable information about both the nature of the igneous activity and the host rocks. Within this study we explore the link between these subcropping igneous rocks and their potential expression in the sub-surface. Recent 3D seismic data from the area provide deep seismic images which allows the full context and extent of these exotic igneous rocks to be assessed. This combination of seismic and dredged data allows the extent of the igneous rocks within the Vestbrona Formation to be determined, and an informed assessment of the petroleum implications of the igneous activity. Igneous rocks and emplacement processes may have an important impact on the petroleum prospectivity of volcanic basins (Aarnes et al., 2015; Jerram, 2015; Schofield et al., 2015; Senger et al., 2017). In specific to the NAIP, huge volumes of CH_4 have been demonstrated to have been generated in the thermal aureoles of sill intrusions (Svensen et al., 2004), results supported by well penetrations of sill intrusions on the Vøring Margin (Aarnes et al., 2015). Key questions exist in terms of the nature and distribution of igneous complexes and the relative dating and time span of the igneous activity in the basin (e.g. Trude et al., 2003; Aarnes et al., 2015), the effects of the igneous rocks on diagenesis, maturation and structure of the sedimentary sequences they intersect (Hansen & Cartwright, 2006; Hansen et al., 2008; Schmiedel et al., 2017), and the impact of igneous rocks and associated vent structures on fluid migration in the basin (e.g. Kennish et al., 1992; Svensen et al., 2004; Magee et al., 2016). The combination of 3D seismic data and direct sampling data offered by the Vestbrona Formation, provides the possibility to asses some of these questions along the Norwegian Margin.

The present study aims to provide documentation of the extent and nature of the Vestbrona Formation, using newly available geochemical, geochronological and 3D seismic data. Focus has been on the interpretation of the type and distribution of igneous rocks on seismic 3D data and a re-analysis of existing dredge samples and existing available data for the Vestbrona Formation. A new interpretation of the style of intrusions as well as new age constraints on the timing of the igneous events of the Vestbrona Formation is presented, and the petroleum implications of the new results are further discussed, including suggestions for future work.

DATA AND METHODS

1) Geological database

The main database for this project consists of vintage dredge samples and new 3D seismic reflection data. The dredge samples from the Vestbrona Seamounts have been the focus of several previous studies (e.g. Bugge et al., 1980; Prestvik et al., 1999; Torske &

Prestvik, 1991). These studies mainly focused on the geochemistry of the basic igneous rocks, and the context of the alkaline centers in relation to the geodynamic lithospheric framework of the area. One sample was dated using the K-Ar method (Bugge et al., 1980), whereas recovered sedimentary rocks have barely been described. Access was given by NTNU (Norges Teknisk Naturvitenskapelige Universitet) to the remaining samples from dredges B77-154/3 and B77-153/2 for new geochemical and geochronological analysis. This includes 17 thin sections, 9 powdered samples with various small volumes of material, two sedimentary samples (labelled as 154/3 Sed-1 and 154/3 Sed-2), five basic igneous rocks, and a small coarse-grained granitic sample (labelled xenolith).

Methodology

New analyses were undertaken for the two sediment samples to help constrain the age, type and diagenetic state of the rocks. Of particular interest was to check that the sediment samples were consistent with dredging of samples near in situ and not of ice rafted origin as previously suggested. Initial sedimentary petrology was carried out by binocular microscope on hand samples and two thin sections were prepared. The samples were blue dye stained to highlight connected porosity, where present, and imaged using a digital capturing system at PGP (Physics of Geological Processes), University of Oslo. XRD analysis was carried out to help determine the contents and possible clay types of the two sediment samples (analysis by J.M. Hugget at Petroclays, UK). A sub sample of each sediment sample was sent off for palynological analysis at APT, Kjeller. A standard palynology preparation procedure was followed.

Original XRF analysis was reported for the Vestbrona samples by Prestvik et al. (1999). Some of the powders used in these original studies were re-analyzed in this study. New major and trace elements for three samples and standards were measured on an ARL

8420+ dual goniometer wavelength dispersive XRF spectrometer in the XRF Laboratory at the Department of Earth Sciences, Open University, Milton Keynes, United Kingdom. The original geochronological age of the Vestbrona Formation, 55.7 ± 0.9 m.y., was based on a K-Ar analysis. Such analysis can sometimes suffer from issues associated with excess argon which potentially gives unreliable ages. Additionally, the Ar-Ar dating technique has more recently superseded K-Ar analysis in volcanic rocks due to advances in the precision and accuracy of the analysis (e.g., Kelley, 2002). In the present study two samples were identified for analysis using the Ar-Ar technique, 153/2A and 154/3A. The analyses were carried out at NGU (Norges Geologiske Undersøkelse), Trondheim.

2) Geophysical database

The geophysical database used for this study consists of conventional 2D and 3D seismic, bathymetry, and well data. The total area of the 3D survey (SEN1101) is 1580 km^2. Four different versions of the 3D cube have been available for this study. The quality of the 3D data is generally good in the sedimentary sequences, down to Top Basement. Comparison of 2D and 3D data shows that the imaging of the main reflections and the total imaging depth is similar. Bathymetric maps were generated using the shared database of Olex (www.olex.no). The maximum water depth in the area is 300 m and the minimum is 130 m at the Vestbrona Seamounts. A recent MAREANO (Marine AREA database for Norwegian waters; www.mareano.no) cruise acquired multibeam bathymetric data across one of the dredging locations (B77-153/2) (Figure 2b). Well data were provided by Tullow Oil (formation tops and velocity-depth curve) and NPD (Norwegian Petroleum Directorate; www.npd.no). One wildcat well, 6306/6-1, is located within the study area. The main objective of this dry well was to test a potential hydrocarbon accumulation in Late Jurassic Rogn Formation sandstones. However, very good source rocks were encountered. The best source rock was observed in the upper section of Spekk Formation, containing marine anoxic, oil prone Type II kerogene. Lithostratigraphy in wells from the surrounding areas (6306/6-2, 6306/5-1, 6305/9-1) were further used to tie key seismic reflections in the study area.

Seismic interpretation

The seismic interpretation was done using the IHS Kingdom Suite software (www.seismicmicro.com). Ten key horizons, sill intrusions, and pipe-like piercement structures were interpreted on every 50th line (inline and crossline) of the 3D cube. Horizon interpretation focused on strong, continuous reflections that could be correlated over large areas. Horizon interpretations were not extended through areas with low interpretational confidence and reflection continuity. Some events, most notably Intra-1 and Intra-2, were picked as facies unit boundaries, e.g. between units of disrupted, high-amplitude reflections and low-amplitude, nearly transparent units. The key horizons were tied to one well within (6308/6-1), and several other wells around, the 3D area for stratigraphic control. The horizons were subsequently gridded using flexible and spline gridding functions, followed by grid to horizon and horizon snap. Different horizon and volume attributes were then calculated (e.g. horizon and RMS volume amplitudes).

Sill intrusions were interpreted and mapped based upon the reflection characteristics and methods described by Planke et al. (2005; 2015) (Figure 4). The sills were classified based on their stratigraphic levels, and their extents were drawn using the culture management tool.

GEOLOGICAL FRAMEWORK

Vestbrona Formation

The Vestbrona Formation (Askvik & Rokoengen, 1985) is a sequence of igneous rocks present offshore mid-Norway, near Kristiansund (Figure 2). They occur within Paleogene sedimentary sequences that overlie Precambrian basement gneiss. The Vestbrona Formation was first discovered in 1975 when a series of seamounts were identified approximately 60 km off the Norwegian coast with elevations up to 80 m above the sea floor (Bugge et al., 1975; 1976). Similar structural anomalies are also identified within the underlying sedimentary sequence which did not penetrate the sea surface. The seamounts were subsequently sampled in a dredge study by Bugge et al. (1980), and exotic alkaline porphyritic igneous rocks were recovered. These rocks are highly silica undersaturated and gave a K-Ar age of 55.7 ± 0.9 Ma (Bugge et al., 1980). Prestvik et al. (1999) performed a more detailed geochemical analysis of the dredged rock types and found a mix of olivine rich nephelinites and basanite rocks.

The alkaline rocks of the Vestbrona Formation are related to the igneous activity of the North Atlantic Igneous Province (NAIP) which accompanied continental break-up between Europe and Greenland during the late Paleocene to early Eocene (e.g. Saunders et al., 1997; Jerram & Widdowson, 2005; Nelson et al., 2015). Seismic reflection studies reveal that this break-up was associated with widespread sill complexes (Planke et al., 2005; Schofield et al., 2015). Igneous rocks associated with the NAIP are dominantly tholeiitic by volume with occurrences of alkaline affinity being much more volumetrically and spatially restricted. Occurrences of alkaline rocks from elsewhere in the NAIP include examples from East Greenland and the Hebrides, Scotland (e.g. Nielsen, 1987; Hole & Morrison, 1992; B.G.J. Upton Pers. Comm.).

The Vestbrona Formation is located along, but beyond, the southeastern trend of the Jan Mayen Fracture Zone (JMFZ). The igneous rocks are not located near to any other igneous centers on the mid-Norwegian margin and represent the most proximal Paleogene igneous deposits to the Norwegian coast. This observation, along with the location of alkali rocks on East Greenland beyond the north western trend of the JMFZ, led Torske & Prestvik (1991) to speculate that deep seated continental scale structures existed. These structures were interpreted to have facilitated the focusing and migration of the undersaturated alkali melts, prior to the onset of rift separation and seafloor spreading. The petrogenesis of alkaline magmas may be highly variable (e.g. Fitton & Upton, 1987). In the case of the Vestbrona Formation, melting is proposed to have occurred due to decompression enhanced volatile enrichment of the lithospheric mantle within these deep seated structures prior to melting in the Paleogene (Torske & Prestvik, 1991). Volatile addition has the effect of lowering the mantle solidus to promote melting, which would have been further enhanced by the elevated mantle temperatures associated with the NAIP (Torske & Prestvik, 1991; Hole & Millett, 2016). Based on isotopic arguments, however, Prestvik et al. (1999) proposed that although this model fitted the basanites, the nephelinites may have been produced by small degrees of partial melting of a plume derived asthenospheric mantle component.

Tectonostratigraphy

After extensional tectonic episodes during the Late Permian to Mid Jurassic time over the Norwegian Sea margin, a major regional tectonic phase started in the Late Jurassic and continued into the latest Ryazanian times with the rise of regional sea level and deposition of organic-rich shales like the oil prone Spekk Formation (e.g. Karlsen et al., 1995; Underhill, 1998; Brekke et al., 2001; Gabrielsen et al., 2001; Kyrkjebø et al., 2004; Müller et al., 2005; Smelror et al., 2007). The erosion of tectonic fault blocks appears as a regional unconformity, the Base Cretaceous Unconformity (BCU), which was buried during the Cretaceous by condensed carbonates and siliciclastic sediments as faulting continued and was followed by crustal subsidence and the formation of the deep-marine Møre and Vøring basins during the Cretaceous (Blystad et al., 1995; Brekke et al., 2001; Smelror et al., 2007).

During Maastrichtian to the Early Paleocene, a prominent phase of uplift occurred and thick delta like wedges prograded from platforms into the basin and, downlapping on the Base Tertiary Unconformity (BTU), deposited at the intra-basinal slopes during the Danian (Egga Member) (e.g. Vergara et al., 2001; Lien, 2005; Martinsen, 2008; Nøttvedt & Johannessen, 2008). Crustal extension during the Late Paleocene culminated with continental separation in the Early Eocene and the initial opening of the Norwegian-Greenland Sea. Renewed regional uplift of the marginal areas of the developing Norwegian-Greenland Sea accompanied break-up (Lundin & Doré, 1997; Doré et al., 1999; Brekke et al., 2001; Smelror et al., 2007). Large scale thermal uplift associated with the proto-Icelandic thermal anomaly is also proposed during the Late Paleocene to Early Eocene (Saunders et al., 2007), with some researchers arguing for multiple short lived pulses of uplift (Hartley et al., 2011). During continental rupture, extensive eruptive and intrusive igneous activity affected the developing rifted margins with sub-areal lavas, hyaloclastite deltas, extensive sill complexes and high velocity lower crustal intrusions being emplaced (Planke et al., 2000; Gernigon et al., 2006). The extensive volcanism associated with the volcanic rifted margins is generally associated with higher than ambient mantle temperatures associated with the proto-Icelandic thermal anomaly (e.g. Hole & Millett, 2016), however lower temperature hypothesis also exist (Foulger & Anderson, 2005). The distribution and magnitude of igneous rocks is also related to the distribution of lithospheric thickness variations which vary markedly along the conjugate margins due to asymmetric rifting and inherited structure (e.g. Howell et al., 2014; Hole & Millett, 2016).

The basins along the eastern margin of the Norwegian Sea experienced compressional tectonics in the Middle Eocene/Early Oligocene and another in Middle Miocene (Lundin & Doré, 2002). During Late Miocene-Early Pliocene, the Molo Formation developed as a result of mid-Miocene compression and uplift in mainland Norway (Brekke et al., 2001; Eidvin et al., 2007). The Late Neogene was tectonically a very active period with the Norwegian mainland affected by km-scale uplift, extensive erosion and development of prograding clinoforms (Naust Formation) along the shelf offshore mid-Norway as a result of several glaciations in Plio-Pleistocene time (Rise et al., 2005; Smelror et al., 2007; Hafeez, 2011; Faleide et al., 2012).

Petroleum plays

The most prominent petroleum play in the area belongs to the Middle and Upper Jurassic Viking Group (Melke, Rogn and Spekk formations). The play is known to contain good quality reservoirs elsewhere, which are currently being produced in the Draugen field northeast of the study area (http://www.npd.no/en/Topics/Geology/Geological-plays/Norwegian-Sea/Upper-Jurassic/). The Paleocene play containing the Danian sandstones of the Egga Member is also present in the area. The main reservoir of the Ormen Lange field to the west of the study area is sandstones of Paleocene age in the Egga Member (http://www.npd.no/en/Topics/Geology/Geological-plays/Norwegian-Sea/Paleocene/). The Egga Member is eroded by repeated glaciations along the mid-Norwegian shelf and pinching with the Upper Regional Unconformity (URU). Speculative plays in the region include weathered basement rocks of the Frøya High and Triassic or Paleozoic plays in the Frøya Basin.

SEISMIC INTERPRETATION RESULTS

Horizons and sequences

Ten key horizons plus sills and piercement structures were interpreted on the 3D data. Seven of the horizons were tied to the well 6306/6-1 in the study area (Figure 3); other regional horizons are shown in Figure 4a. Furthermore, seismostratigraphic units are interpreted on the basis of amplitude and continuity of reflections, nature of the bounding surfaces, geometry and extension. The main mapped horizons are described below.

Seabed is picked as a high amplitude (peak), continuous reflection. It is poorly imaged in the southeastern part due to shallow water depth. The seabed is picked by auto tracking with good confidence and continuity. A total of 21 seamounts were mapped, and named the Vestbrona Seamounts. The seabed grid (depth) shows glacially eroded troughs and seamounts (Figure 2). The amplitude and RMS (Root Mean Square) amplitude maps reveal marks of glacial activity (plough marks, ridges developed by ice grinding). The ridges are present in the southwestern part of the study area and are cross cut by the NE-SW oriented glacial furrows and plough marks. Glacially eroded troughs and plough marks describe the direction of ice streams moving NE-SW and EES-WWN. Amplitude maps reveal the movement of three ice streams which adjoin in a bigger trough in the west of the study area. Small circular depressions like pockmarks are abundant in the northeastern part of the study area. However, high-resolution data are required for the confirmation of pockmarks in this area.

Upper Regional Unconformity (URU) is marked by toplap truncations of older strata with the horizontally overlying glacial sediments (Figure 4). The seismic amplitude of URU is variable in nature. The reflection is extensively present in the whole study area except in the southeastern part where it merges with the seabed. URU is a composite unconformity developed by the erosion of multiple glacial advances (~30) during Plio-Pleistocene time on the continental shelf (Faleide et al., 2012; Hafeez, 2011). A huge amount of sediments are eroded by the glacial activity from mainland Norway and deposited on the continental shelf in the form of westward dipping clinoforms (Naust Formation) (Figure 4). Depressions are present at the level of URU developed by the glacial erosion of Plio-Pleistocene age (Faleide et al., 2012; Hafeez, 2011). The Molo Formation, consisting of sandstone and high angle clinoforms, stands as a resistive ridge at the URU level (Figure 4).

Regional Downlap Surface (RDS) is mapped by the downlaping clinoforms of the Naust Formation (Figure 4). Naust Formation consists of a Plio-Pleistocene succession of westward prograding clinoforms gently dipping and downlapping to the RDS, dated back to about 2.8 Ma (Faleide et al., 2012; Hafeez, 2011).

Intra-1 (I1) is interpreted on the basis of seismic facies. It is the top of a sequence of high-amplitude, discontinuous and faulted reflections (Figure 4). Intra-1 corresponds to the upper part of the piercement structures (level of subcropping) at the base of the Molo Formation. Intra-1 represents the top of a polygonally faulted, high amplitude unit overlying a band of transparent facies. The reflection is identified in the western part of the study area, and subcrops at URU. Regional well tie lines suggest a Top Tare (Lower Eocene) age.

Intra-2 (I2) is interpreted on the basis of similar criteria as Intra-1. It is located at the top of a unit of polygonally faulted, high-amplitude segmented reflection band separated by a transparent seismic facies unit from Top Egga (Figure 4). The reflection is interpreted in the west-central part of the survey. It is absent in the western part of the study area, where it merges into transparent facies. It disappears to the east prior to termination at the URU. It is not possible to tie the reflection to nearby wells, but it is tentatively assigned an intra (top) Tang (uppermost Paleocene) age. The Paleogene strata (Tare and Tang formation) are highly faulted due to dewatering of sediments (Berndt et al., 2003).

Top Egga (TE) is a high amplitude and continuous reflection marking the boundary between the Egga sandstone and the overlying transparent facies of the Tang Formation (Figure 4). The horizon can be picked with high confidence in the central part of the study area where it downlaps to the Base Tertiary Unconformity (BTU). In the southern part it may reappear as a mappable thin band of deep marine facies. At certain places the continuity is disturbed by the presence of sills. The internal stratification pattern is downlaping on the BTU. The thickness of the Egga Member increases up dip and thins down dip, finally disappeared in northwestern part of the study area. Exploration wells along the Norwegian margin shows that the Danian is the most sandstone prone interval of the Paleocene.

Base Tertiary Unconformity (BTU) is a continuous and high amplitude reflection marking the boundary between the Upper Cretaceous shales and the Egga Member (Figure 4). The westward prograding clinoforms are downlapping to BTU and defines the surface as a maximum flooding surface. BTU is extensive in the study area except in southeast where lower Tertiary sediments have been eroded and Cretaceous sediments subcrop at the seabed or at URU.

Top Lange (TL) can also be traced with high confidence as a high amplitude and continuous reflection which downlaps on the Top Basement towards west (Figure 4). A package of Cretaceous strata bounded by the Top Lange and BCU is thinning towards west and eventually pinch out at the BCU or Top Basement.

Base Cretaceous Unconformity (BCU) is variable in nature (amplitude) but can be easily picked as an erosional surface on the seismic except in the areas where seismic imaging is poor due to sill intrusions. BCU merges with Top Basement on the western flank of the Frøya High.

Top Basement comprises the deepest mapped reflection and forms a continuous high amplitude reflector in the seismic data (Figure 4). It is mappable over most of the study area except where occluded by overlying volcanic intrusions and piercement structures.

Sill complexes

Numerous sill complexes at various stratigraphic levels are interpreted based on their characteristic reflection shapes and high amplitudes (Figure 4; Planke et al. 2005; 2015). Sills are generally characterized by continuous, very high-amplitude reflections that exhibit both concordant and discordant relationships with sedimentary reflections. Other criteria are also applied to differentiate sills from other high amplitude events such as lavas, sandstones, carbonates, injectites, or gas layers. To interpret a seismic reflection as a sill, we have used the following main characteristics:

- High amplitude (peak)
- Transgression (locally cross-cutting sedimentary strata)
- Saucer shaped
- Abrupt terminations

Layer parallel, planar transgressive, and compound geometries are also identified (Figure 4; Planke et al., 2005). The sills have typically circular or irregular geometries on time slices. Sill complexes appear as high amplitude semi-circular complexes on maximum amplitude maps generated for different stratigraphic intervals.

Sills are widely distributed in the eastern part of the study area having variable sizes (0.1-9 km^2) and stratigraphic depths (Figure 4g). In total 36 sills have been interpreted and mapped to determine the stratigraphic level and extent of the intrusions. The largest sill complex of 9 km^2 lies within Cretaceous sediments in the southeastern part of study area. This sill complex is compound in nature, and creates a problem for seismic imaging of the deeper sequences. Another sill complex, with an areal extent of 6 km^2, occurs in the Egga Member. Many smaller sill complexes are present in the Paleogene and Cretaceous sediments with a size range of 0.1-0.5 km^2.

The sills are present at different stratigraphic levels, but are most widely distributed in Cretaceous sequences and within the Danian sandstones of the Egga Member (Figures 4 and 9). Some shallow sills are also present at the Intra-2 level (Upper Paleocene), however, few (and uncertain) sills are present in the sequence between Intra-1 and Intra-2 (Figure 4c). No sills are identified stratigraphically above Intra-1. Sills are not common in pre-Cretaceous sequences, and only one sill complex is identified below BCU (Figure 4f). Doming of overburden sediments ('forced folds') related to sill intrusions is also observed (Figure 4d).

A total of 45 piercement structures are identified in the study area. The uppermost part of these structures is typically a high amplitude, mounded reflection (Figure 5a). The exceptions are a few flat-topped examples at the URU or Seabed levels. Seismic imaging below the top of the structures is poor, and no deeper reflections can be mapped with confidence. Upward-bending reflections are common in the pipe structures, but these are possibly migration artifacts. The detailed description and interpretation of these structures is not the focus of this paper.

GEOLOGICAL RESULTS

Igneous samples

The igneous dredge samples (Figure 5b) contain a variety of textures, typically glomeroporphyritic (clusters of large crystals in a fine grained matrix). Examples of these olivine rich textures are given in Figure 6. The olivine and feldspars were found to be remarkably fresh (e.g. Figure 6b), providing the potential for confident geochemical and geochronological analysis.

Original XRF analysis was reported for the Vestbrona samples by Prestvik et al. (1999). Some of the powders used in these original studies were supplied in the sample set received for the present study, and these were used for new analysis. The original rocks were classified as melilite nephelinite (Type 1), olivine nephelinite (Type 2), and basanite (Prestvik et al., 1999). In the present study three new XRF analysis were carried out to confirm existing data with the latest standards, providing a re-assessment of the rock type classification. The following samples were chosen to represent the three previously reported igneous rock types; 153/2A melilite nephelinite (Type 1), 153-2B – olivine nephelinite (Type 2), and 154/3B – basanite.

The summary results for the new analysis are shown in Figure 6c. The rocks plot with elevated alkali signatures, but are not far from picrite-picrobasalt compositions. Olivine rich compositions are often found at the onset and early stages of flood volcanism (e.g. Jerram et al., 1999; Jerram & Widdowson, 2005; Hole et al., 2015), however, are less commonly highly alkaline. Examples of such elevated alkali compositions can be found in other rift settings such as the African rift valley (e.g. Baker et al., 1972), and are characterized by relatively low volume melts, with the timings of these occurrences being variable (Fitton & Upton, 1987). A high bulk density of up to c. 3 kg/m^3 is calculated for the samples using the MAGMA (http://www.lanl.gov/orgs/ees/geodynamics/Wohletz/KWare/Index.htm) petrological modelling program, a consequence of the high MgO olivine rich nature of the rocks. PRIMELT (Herzberg & Asimow, 2008) primary magma calculations do not produce viable solutions for the Vestbrona samples and are in any case not applicable where the presence of hydrous melting is likely and, therefore, an accurate estimate of the mantle potential temperature during melting is not possible (e.g. Hole & Millett, 2016). However, the high MgO wt. % of the rocks, coupled with the presence of high forsterite olivines (e.g. Fo% c. 78-90; Prestvik et al., 1999) and a well-developed HREE garnet signature (Prestvik et al., 1999), demonstrates the possibility that the magmas were generated at higher than ambient mantle temperatures. The porphyritic nature of the samples and a lack of fresh groundmass glass restricts the potential for accurate emplacement temperature estimates based e.g. on olivine-liquid equilibrium (Roeder & Emslie, 1970; Keiding et al., 2011), however, assuming the high Fo olivines are not inherited, for which there is no clear evidence (e.g. kinking), emplacement temperatures could have been up to c. 1200°C.

Samples 153-2A and 154-3A were chosen for geochronological age dating with Ar/Ar analysis. The rationale for the dating was that the original age analysis of the Vestbrona Formation was done using K-Ar techniques reported by Bugge et al. (1980) (original sample analyzed: 154/3). As such, the estimate of the timing of igneous activity can potentially be questioned, as old K-Ar techniques can yield anomalous ages, and with only one sample age, the data is limited and needs to be checked.

A whole rock analysis of sample 153-2A (Figure 6d), yields four concordant steps and gives a weighted mean plateau of 56.6 ± 0.55 Ma (analytical error). The inverse isochron analysis yields similar results, 57.2 ± 0.61 Ma (analytical error). This can be considered a robust age as the two techniques overlap. The spectrum analysis of 154-3A whole rock yields concordant overlapping apparent ages from step 2-4, which gives a weighted mean plateau age of 59.2 ± 0.57 Ma (analytical error). The same steps yield an inverse isochron age of 61.1 ± 2.93 Ma (note significant error). This age data is less reliable, but again suggests an older age than the published 55.7 Ma K-Ar age. The rocks are therefore provisionally considered to be emplaced around 57 Ma during the early phase of magmatism in the basin, and closer to early magmatic pulses of the NAIP (Saunders et al., 1997).

Sedimentary samples

The dredged sediment samples (Figures 5b and 7) consist of a light buff-brown sample and a black crudely bedded and indurated sample. The buff brown sample 154/3 Sed-1 is a fine-grained mudstone, with a bleached and mottled appearance. The oxides are patchy and have a spotted appearance. The close up inspection reveals isolated vugs (and clustered distribution of oxides). The sample is relatively soft and appears like a marl. Thin section analysis (Figure 7) clearly reveals the distribution of patchy clustered oxides, within a very fine-grained matrix. Secondary calcite can be observed in patches and the isolated vugs are particularly clear from cross-polarized light. The vugs must be isolated in 3D as they have not been impregnated successfully with blue resin applied to the sample during the thin-section preparation. The re-distribution of oxides and calcite precipitation can occur at the hot contacts with igneous bodies (e.g. Jerram & Stollhofen, 2002). The development of the vugs could be related to dissolution/precipitation reactions.

Sample 154/3 Sed-2 is a fine-grained mudstone/ shale, with occasional larger grains and fragments. There is some crude bedding visible in the small hand specimen, but very little else can be seen in hand view. Thin section analysis reveals lithic and quartz fragments in a very fine black matrix. Again, the sample has not taken any blue dye staining during thin section preparation, suggesting that any porosity present is very limited in terms of connectivity.

XRD results are given in Figure 7d. More clay was extracted from the 154/3 Sed-1 sample, as from an equal volume of 154/3 Sed-2. This indicates that the phyllosilicates in the Sed-2 sample are micas and chlorite, rather than clay minerals, i.e. Sed-2 has been baked and metamorphically altered. The identification of abundant feldspar can make identification of other minerals difficult in XRD; in this instance the identification of microcline makes it difficult to be certain whether ankerite and siderite are truly present in the sandstone. The illite-smectite may be derived from alteration of ferromagnesian minerals, either from within the sediments, or reworked from weathered igneous rock. As the grain-size is so fine in these two samples, further study of these samples with SEM and EDAX would be required, so a complete identification of clay/mica phases can be realized.

The sample '154/3 Sed-1' did not yield organic materials, and nothing can be said about its origin from palynological examination. The sample '154/3 Sed-2' however, provided some vital new information with regard to its palynological analysis (Figure 7c). The black homogenous shale yielded a relatively rich organic residue. All the organics are greyish black (metamorphosed) and fragmented indicating exposure to elevated temperatures, a preservational state that is often seen in the proximity of intrusive rocks. This can be seen quite clearly with metamorphosed fragments of wood (e.g. Figure 7c).

The sample is of marine origin as evidenced by the numerous fragments of dinoflagellate cysts, and it can be dated to the earlier parts of the Late Paleocene (~61 Ma) on the presence of common *Palaeoperidinium pyrophorum* and common *Areoligera spp* (Figure 7c). This assemblage is known from a rather narrow zone around 61 million years.

The pollen genus *Trudopollis* is also represented, which has its main distribution in the Maastrichtian, but is also well known from the Paleocene.

DISCUSSION

Igneous rocks and processes in the Frøya High area have been studied using new 3D seismic reflection data and a re-analysis of vintage dredged samples. Detailed mapping of ten seismic horizons, which were tied to nearby wells, were used to obtain a local stratigraphic framework. Within this context we can consider the emplacement and type of igneous bodies, the evolution of the Vestbrona Formation and its petroleum implications.

Subcropping sill

The seismic data reveal the presence of an extensive sill complex in a 500 km^2 region in the eastern part of the study area. In total, 36 sills have been mapped. The sills are dominantly present in Cretaceous and Paleocene sequences. However, one sill is also mapped in pre-Cretaceous strata. No well-defined sills are found above the Intra-2 (late Paleocene?) level. The sills are fairly small, with a maximum aerial size of ca. 9 km^2, and scattered compared with the sill complexes found in the Vøring and Møre basins (e.g., Planke et al., 2005). It is difficult to determine the thickness of the sills based on the seismic data, but they are likely quite thin (estimated as 25-40 m thick). Sills below this thickness range are below vertical resolution of common seismic surveys and potentially will not be imaged (Planke et al., 2015; Schofield et al., 2015). The sill complexes are layer parallel, saucer shaped, planar transgressive and compound in geometries. No feeder dikes are identified. Characteristic domes or ‘forced folds’ are observed above many of the saucer-shaped sill complexes (Hansen & Cartwright, 2006; Jackson et al., 2013).

Igneous rocks of the Vestbrona Formation have been sampled by dredges (Bugge et al., 1980). These rocks were interpreted to represent igneous plugs (Bugge et al., 1980) but have also been speculated to be lava flows based on a recent MAREANO ROV survey (Thorsnes et al., 2012).

We interpret the sampled igneous rocks to be erosional remnants of sill intrusions. Figure 8a shows a seismic profile across one of the sampled seamounts. The seamount is located in an area with subcropping Egga Member rocks. Sill intrusions are common in the Egga Member, and several shallow sills are identified within this sequence a few kilometer down-dip (Figure 8a). Igneous rocks are erosionally resistant, and sill-capped mounts are common in volcanic basins such as so-called 'kopi' (table top) mountains in the Karoo Basin, South Africa (Figure 8b). We suggest that these kopi mountains are terrestrial analogues to the sampled seamounts in the Frøya High region.

The erosional sill model is supported by palynological analyses of the dredged sedimentary rocks. The palynological age of one sediment samples is 61 Ma, i.e., uppermost Danian. The Egga Member is of Danian to Early Selandian age (Vergara et al., 2001), supporting the interpretation that the analyzed sediment samples are near in-situ. Evidences from the sediment samples suggest that they may have been thermally metamorphosed, and we suggest that this was caused in-situ by heat from the igneous intrusions of the Vestbrona Formation.

An implication of the erosional sill model is that the disturbed seismic below the seamount is an imaging problem. The high impedance and rough topography of the sill will cause strong scattering of the seismic energy and poor, or no, imaging of the deeper structures. A continuity of the deeper sequences can possibly be determined by special seismic acquisition and processing (e.g. undershooting of the seamount).

The Ar-Ar dating suggests a pre-breakup age of ca. 57 Ma of the igneous rocks. This is older than the previously published K-Ar age of 55.7 ± 0.9 described by Bugge et al. (1980). Igneous activity of Late Paleocene age is known from the entire NAIP and indirect dating of some of the sill complexes in the Møre Basin (Planke et al., 2005).

Both the new and published geochemistry and petrography of the Vestbrona Formation show that they are exotic alkaline porphyritic igneous rocks. These silica undersaturated rocks are often found in association with large igneous provinces.

Evolutionary model

Figure 9 shows a schematic evolutionary model of the Vestbrona Formation and associated piercement structures. Two types of vertical pipe-like regions of disturbed strata are imaged; one is a geological piercement structure likely related to fluid escape, whereas the other is due to seismic imaging problems below erosional igneous remnants at the seabed.

(1) The initial stage is infilling of a sedimentary basin throughout Cretaceous and Paleocene times (Figure 9a).

(2) The second stage is low-volume intrusive magmatism of high-temperature melts forming sill complexes in a 500 km^2 large area prior to breakup (~57 Ma). The seismic interpretation suggests that the piercement structures likely formed during the same time period (Figure 9b).

(3) The third stage is slow sedimentation until mid-Miocene times. The piercement structures may have been reused for fluid seepage (Figure 9c).

(4) The final stage is uplift and tilting of the margin, and glacial erosion and deposition of glacial sediments. Sill complexes are more resistant to erosion and will form seamounts on the seabed where intruded Cretaceous and Paleocene sediments sub-crop at the seabed (Figure 9d).

Petroleum implication

Sill intrusions can have wide ranging implications for petroleum systems and are becoming increasingly investigated for their effects on petroleum systems worldwide, (Schutter, 2003; Delpino & Bermúdez, 2009; Senger et al., 2017). In specific they may cause heating of host rock sediments in the metamorphic aureole and can cause the generation of large volumes of hydrocarbons where sills are intruded into organic rich sediments (Svensen et al., 2004; Rodriguez Monreal et al., 2009; Aarnes et al., 2015). Sills and associated dykes may also create barriers and baffles to fluid flow, potentially significantly altering the migration pathways (Filho et al., 2008; Rateau et al., 2013). Sills may also create a range of trapping features including directly associated features where the intrusion morphology creates the trap (e.g. Schutter, 2003; Senger et al., 2017) and traps where for example host sediments are 'jacked-up' by sill inflation, often termed forced folds, which can create four-way closures in the overburden above sills (Hansen & Cartwright, 2006; Jackson et al., 2013). Finally, intrusions are also known to form reservoirs in a number of regions globally such as Argentina (Witte et al., 2012) and Thailand (Schutter, 2003), where hydrocarbons are produced from fracture and cavity networks within the intrusions.

The Vestbrona Formation magmatism may have had a similar effect on the prospectivity of the Frøya High. However, the effect of the igneous activity is mainly restricted to the Cretaceous and Paleocene sequences, as few sills are identified in the pre-Cretaceous units (only one identified; but there might be more). One uncertainty is whether the sills are also present within the Jurassic source rocks in the study area. Sills are commonly observed to preferentially intrude organic rich units within field examples (e.g. Eide et al., 2016; Schofield et al., 2015). However, we have identified only one sill in the Jurassic, and even if there are more present, thin, layer-parallel sills would be difficult to identify. For instance, it has been demonstrated that sills <40 m in thickness are commonly below the vertical resolution limit of seismic data within the Faroe-Shetland Basin, (Schofield et al., 2015). Given the generally small size of the sill complex and a lack of clear evidence for large scale fluid migration features directly associated with them, it is likely that the effects of the intrusions were relatively localized. Whether deeper intrusions or sub-seismic interconnected sheet intrusions have caused source rock compartmentalization or contributed to a ‘shadow-zone’ for hydrocarbon migration above the intrusion networks (e.g. Rateau et al., 2013), remains unconstrained from the current dataset.

CONCLUSIONS

Within this study we present a detailed multi-disciplinary investigation focusing on the Vestbrona Formation in the Frøya High region, offshore mid-Norway. The results of our study can be summarized as:

1. The igneous rocks of the Vestbronna Formation comprise a sill complex dominantly intruded into Cretaceous and Paleocene sediments.
2. Previously sampled seamounts are demonstrated to form the erosional remnants of an extensive sill complex that extends down into the sub-surface. The sill complex was tectonically tilted and then exhumed by erosion, resulting in the formation of the Vestbronna Seamounts.

3. Seismic imaging problems below the erosional remnants of the high-velocity igneous rocks create vertical zones of disturbed reflections, obscuring identification of underlying reflectors.
4. New XRF and Ar-Ar dating on dredge samples from the Vestbrona Seamounts reveal that the sills are of pre-breakup age (~ 57 Ma; ca. 1-2 Ma older than breakup) and were formed from small volume alkalic melts.
5. New biostratigraphy and XRD analysis of sediment dredge samples from the Vestbrona Seamounts suggest that these samples are c. 61 million years old, were sampled near in-situ and have been exposed to elevated temperatures, inferred to relate to the emplacement of the Vestbrona Formation sills. The age of the sediments is therefore, consistent with the igneous rock ages being less than 61 Ma.
6. The identified sill complex have affected the petroleum system within the study area dominantly by source rock maturation within the thermal aureoles of the intrusions and by altering of the potential migration pathways within the area.

Suggestions for future work include basin modelling studies focused on the impact of the mapped sill complexes on the temperature history and fluid migration history of the basin, with particular focus on sills intruding Mesozoic rocks. The erosional sill remnant model could also be further constrained by seismic undershooting experiments or seismic re-processing.

ACKNOWLEDGEMENTS

We are very grateful for data access and publishing permission from Tullow Oil. Furthermore, access to the dredge samples by NTNU (T. Prestvik and M.B. Mørk) are also greatly appreciated. The detailed biostratigraphy was done by H. Selnes (APT), being an important contribution to the project. Discussions and data from Spring Energy throughout the project period are also greatly appreciated. We further acknowledge the support from the Research Council of Norway through its Centers of Excellence funding scheme, project 22372, and from the MIMES project. We are also thankful to J.M. Hugget for his contribution to analyze clay samples.

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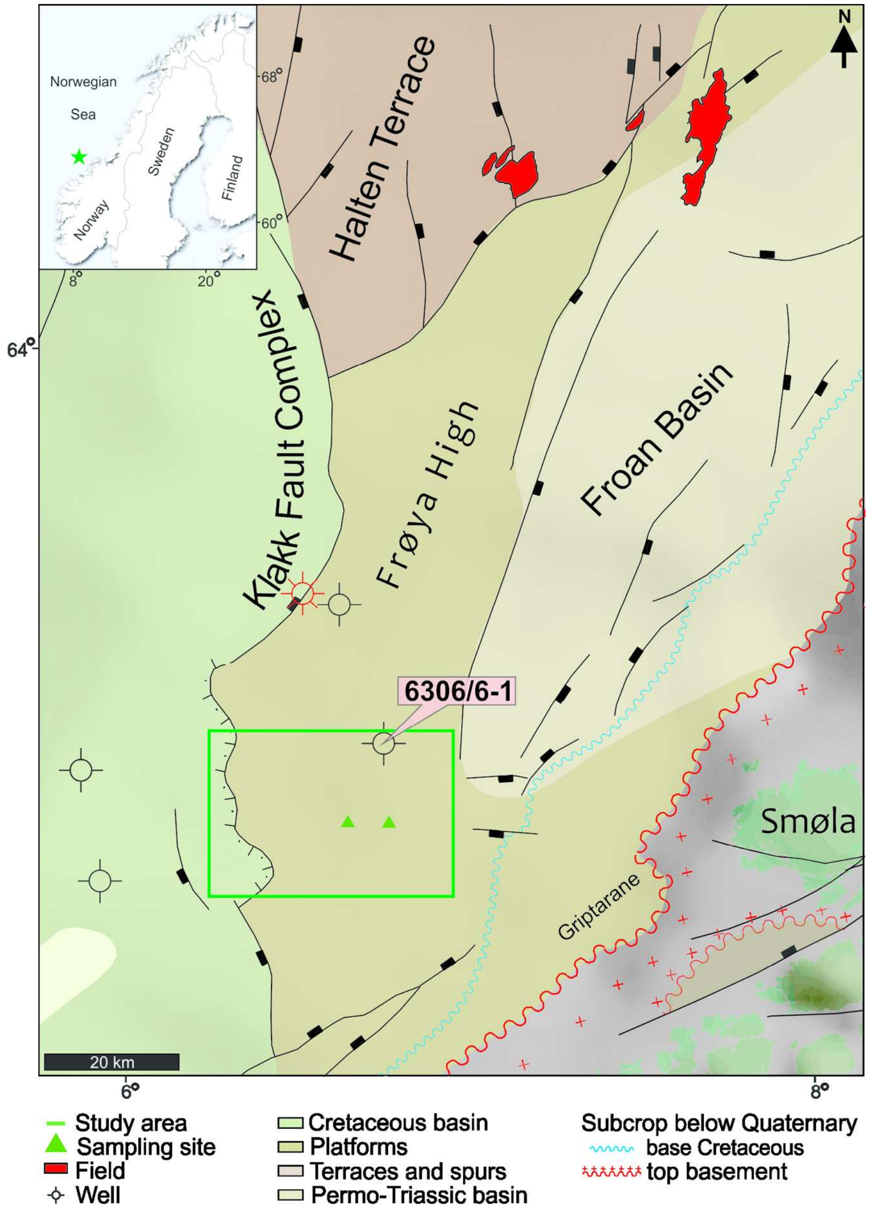
Figure 9. Schematic evolutionary model of the Vestbrona Formation in the Frøya High region.



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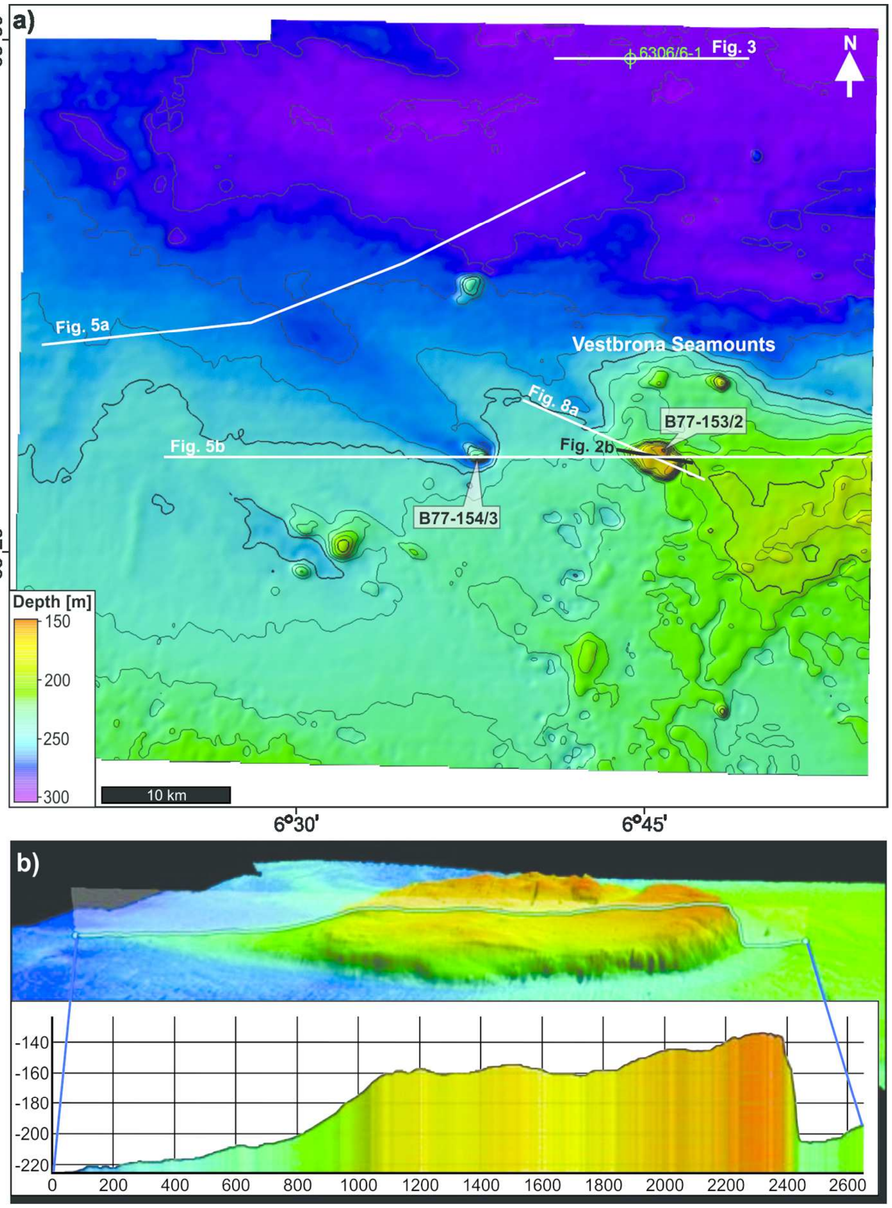

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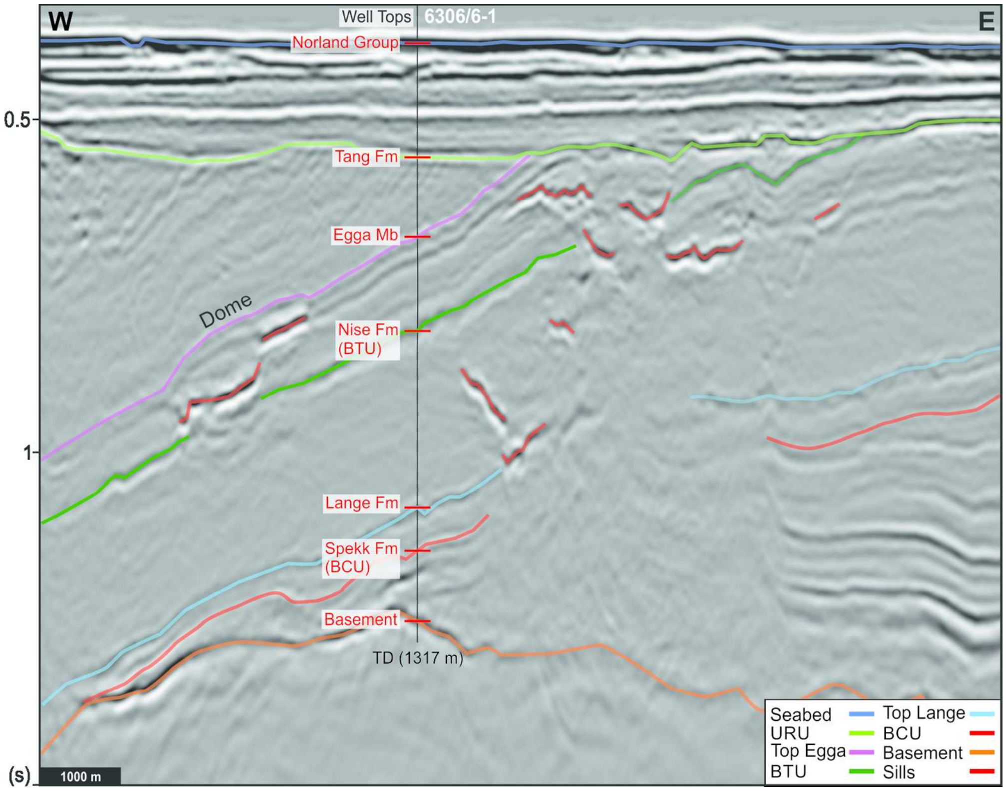

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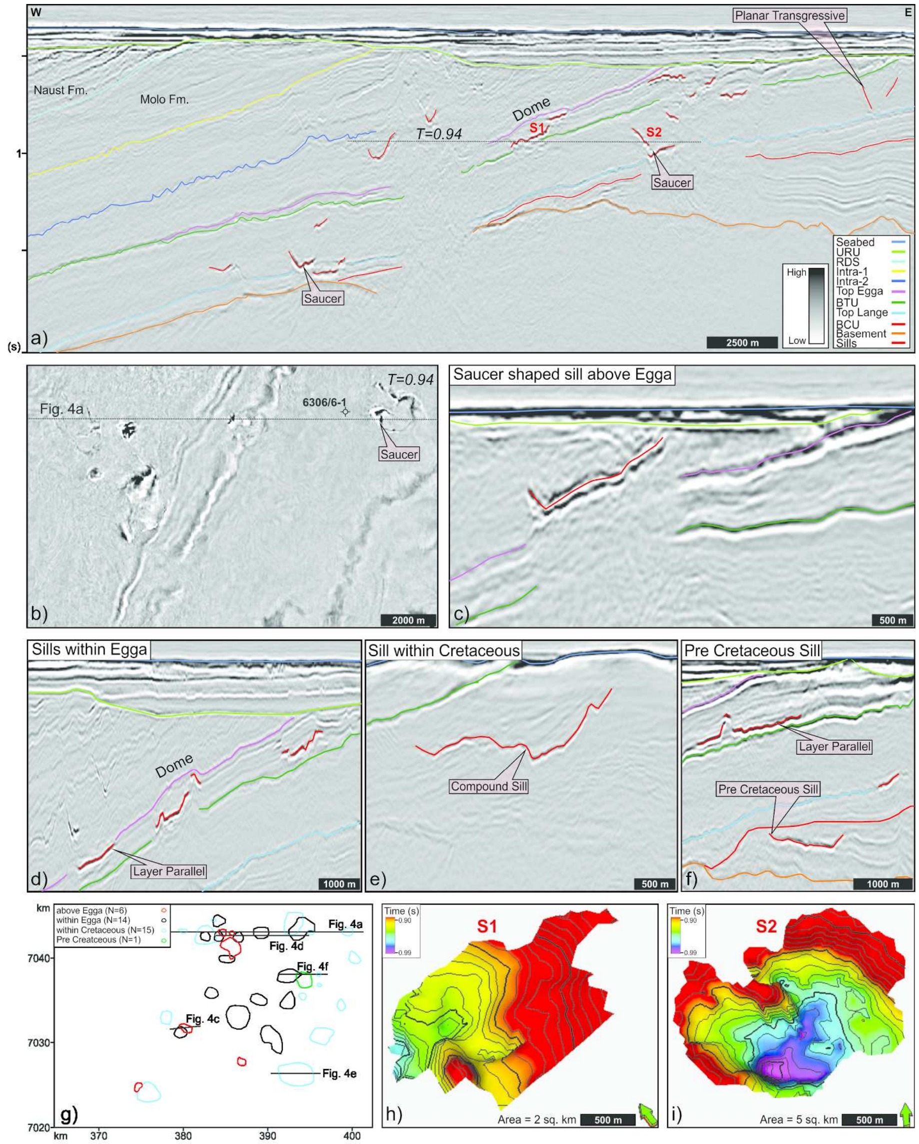

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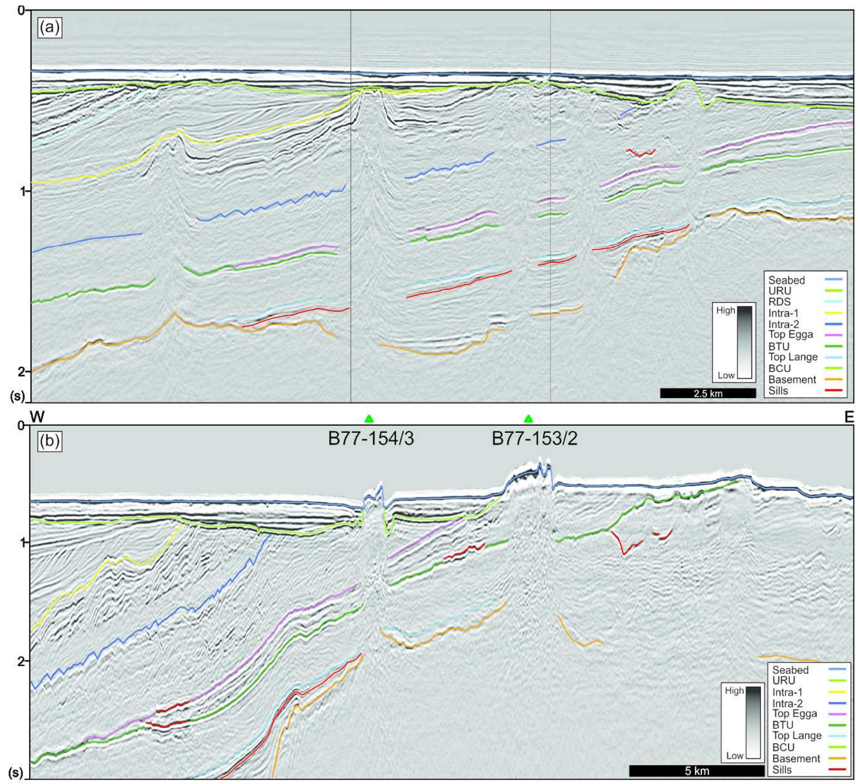

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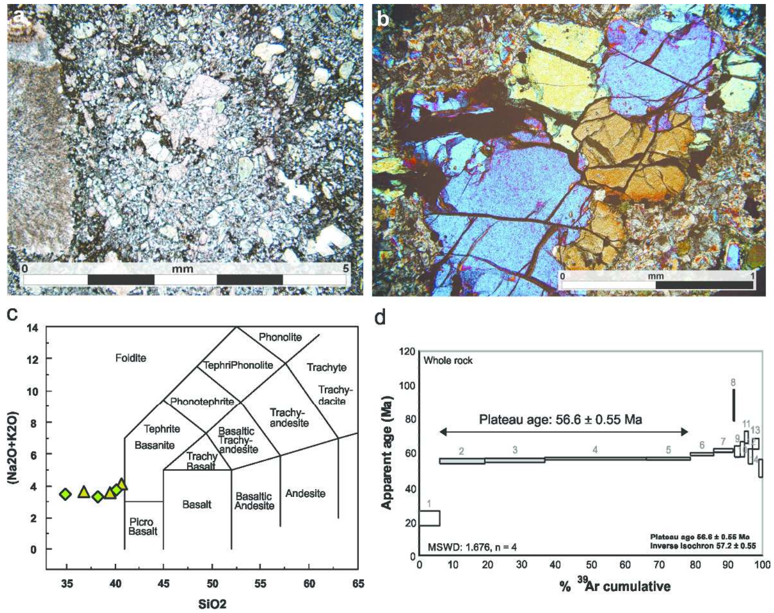

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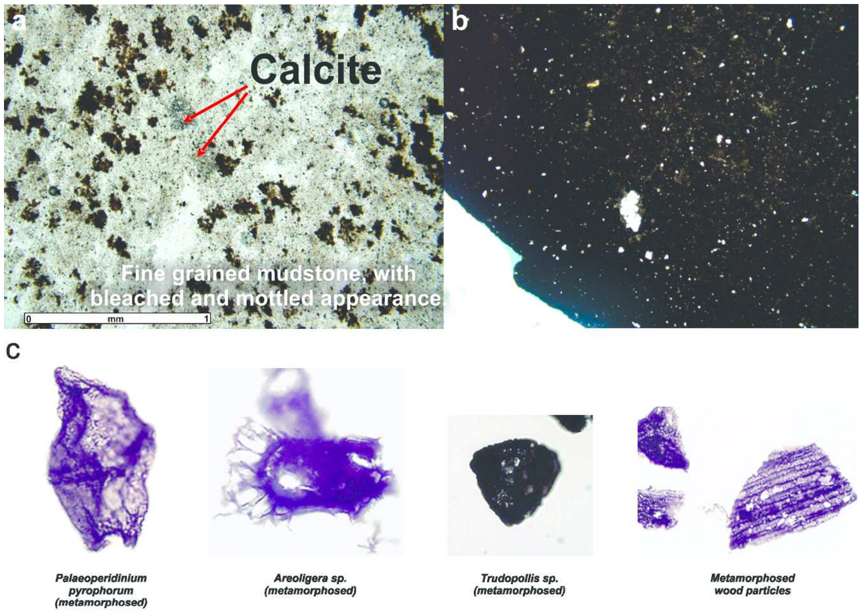

d

Sample	illite & mica	illite-smectite	chlorite	quartz	microcline	plagioclase	ankerite	siderite
154/3 Sed1	31%	3%	6%	30%	25%	0%	3%	3%
154/3 sed2	42%	0%	24%	29%	2%	1%	0%	1%

sample	illite	illite-smectite 90% illite	illite-smectite (55% illite)	chlorite
154/3 Sed1	46%	4%	49%	1%
154/3 Sed2	59%	7%	19%	16%

Figure 7

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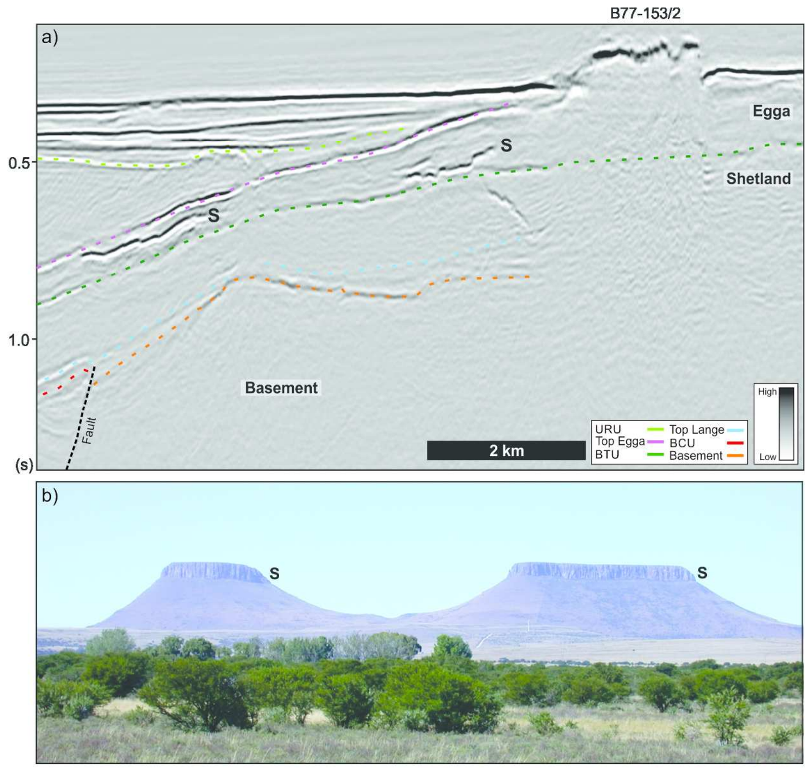

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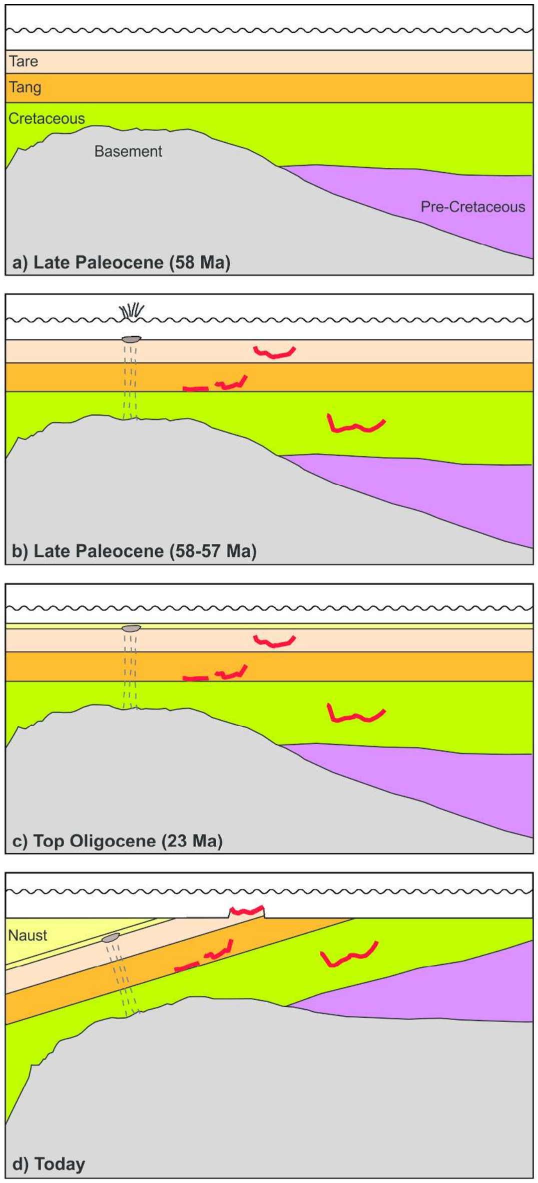

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