How Natural Remanent Magnetisation of basaltic units can dominate the Reduced to Pole Magnetic value; a case study from the Faroe Islands

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ABSTRACT: Early attempts to utilise magnetic data to understand the volcanic and sub-volcanic succession on the Faroese Continental Shelf have shown that conventional interpretation and modelling of magnetic data from this area leads to ambiguous results**.** Interpretation of the aeromagnetic data on the Faroese Continental Shelf shows that some previously identified basement highs coincide with reduced-to-pole magnetic highs, while others coincide with negative or mixed magnetic features. Similarly, igneous centres are characterised by different polarity magnetic anomalies. Palaeomagnetic analysis of the onshore volcanic succession has demonstrated that the thermoremanent magnetisation of the basaltic lavas is stronger than the induced magnetism, and that both reversely- and normally-magnetised units are present. We have tested this with 2½D profile modelling, using the palaeomagnetic information to correlate high amplitude magnetic anomalies with basalt-successions containing changes in magnetic polarity. This approach has enabled us to map the termination of the differently magnetised units offshore and thereby extend the mapping of the Faroe Island Basalt Group on the Faroese Platform and into adjacent areas.

KEY WORDS: Remanence, Magnetics, Seismic, Modelling

Introduction

The high impedance contrast when basalt is located at seabed has hampered seismic imaging of sub-lava geology on the Faroese Platform. In the basins surrounding the Faroese Platform the lavas are covered by a variable thickness of sediments, which lowers the individual impedance contrasts. This has resulted in better seismic imaging, but mapping pre-volcanic geology remains a challenge. This has led to an increased dependence on other methods, including the use of magnetic data.

Magnetic data are widely used for structural mapping and mineral exploration. Within the hydrocarbon exploration industry their ability to predict depth to the magnetic source, which in most cases coincides with depth to basement, is particularly valuable, and a variety of techniques have been developed for this purpose e.g. (Hinze et al., 2013 and references therein; Nabighian et al., 2005).

Early investigations e.g. Abrahamsen (1967), Saxov and Abrahamsen (1966), Schrøder (1971) and Tarling (1970) have shown that the Cenozoic lavas exposed in the Faroes area have both high induced (strong magnetic susceptibility) and high thermoremanent magnetization (acquired at the time of cooling), and that most of the lavas were emplaced in a reversed magnetic field.

There have been several attempts to understand the sub-lava geology on the Faroese Continental Shelf based on magnetic data. Morgan and Murphy (1998) used map interpretations and 2D Werner deconvolution in the Faroe Shetland Basin. A number of authors have performed 2-2½ D modelling. One area where different authors have attempted this is across the Wyville-Thomson Ridge (Figure 1) based on forward modelling of the measured potential field data. Results suggest that the ridge is either a deep inverted basin (Waddams and Cordingley, 1999) or a thick-skinned toe-thrust (Tate et al., 1999) with no sub volcanic sediments on the northeast side of the ridge and only limited thickness under the lavas on the ridge. Later potential field modelling, which was constrained by wide aperture seismic data modelling (Klingelhofer et al., 2005) indicated an underlying basement block with a sub volcanic sedimentary section at the location of the ridge and on either side. All three models were able to reproduce the measured gravity response and the first two models could also reproduce the magnetic response.

Efforts to model the sub-lava geology across the East Faroe High (Figure 1) trend resulted in different models, which demonstrated the non-uniqueness of potential field modelling when sufficient constraint on the input model is absent due to lack of sufficient quality seismic data. These models are not overlapping, but both cross the Annika Anomaly (AA), a magnetic feature to the SE of the Faroe Islands (AA on Figure 2). Sweetman (1997) suggests the Annika Anomaly is caused by a normally magnetised dyke within a major volcanic feeder system, while Smallwood *et al.* (2001) suggests that the anomaly is caused by termination of the normally polarised units within the Palaeocene Beinisvørð Formation lavas (Figure 3). The models are conceptually different but both could reproduce the measured magnetic and gravity responses.

There are thus challenges regarding the use of magnetic data as a tool to predict sub-lava geology. Attempts to model the contribution from remanent magnetisations to the measured magnetic field have shown some promise when dealing with isolated anomalies e.g. (Clark, 2014; Foss and McKenzie, 2011; Pratt et al., 2014). Such an approach does, however, have limitations in an area like the Faroe Islands, where there are numerous phases of igneous activity occurring over a time period spanning several field reversals, with sources in close proximity or stacked on top of each other. The chosen alternative is to use measurements of the strength and direction of the remanent magnetisation. These measurements are correlated with onshore anomalies, where the igneous units are exposed and subsequently extrapolated into the offshore area, where 2½D modelling is used to test the interpretations. The 2½D models are constrained by high quality 2D seismic data.

1. Geological setting

The Faroese Continental Shelf is located on the European North Atlantic Margin (Figure 1) and has been influenced by regional events of both compressional (Boldreel and Andersen, 1993) and tensional (Lundin and Doré, 2005) nature. These events have resulted in the development of the present day structure of the area. The older dominant structural trends are identified as having a predominantly N/S trend (Doré et al., 1999), while the younger basins have a predominant NE/SW trend, possibly with slight anticlockwise rotation between the Cretaceous and Palaeocene trends (Dean et al., 1999). A number of NW/SE oriented lineaments (transfer zones) (Figure 1) have been recognised near the Shetland Platform (Rumph et al., 1993). These were thought to represent transcurrent crustal features, which have had continuing effect on the development of the area (Rumph et al., 1993). Ritchie et al (2011) proposed the term lineament for these features, which is the term used here. The NW/SE-NNW/SSE trend is most likely inherited from the Lewisian metamorphic basement (Ziska, 2012).

Continental breakup in the Early Eocene (Saunders et al., 1997) was preceded by regional uplift and erosion of exposed areas, which caused sediment influx into the Faroe Shetland Basin e.g. Smallwood (2005). The sediments were derived from the Shetland Platform, Greenland (Varming, 2009), and possibly from local basement highs (Ziska and Andersen, 2005).

Rifting and breakup during the Palaeogene was accompanied by the extrusion of large amounts of volcanic material in two phases separated by a period of volcanic quiescence, represented onshore by the sedimentary "A-horizon" (Rasmussen and Noe-Nygaard, 1969), later renamed as the Prestfjall Formation by Passey and Jolley (2009).

The first phase (Lopra and Beinisvørð Formations) was associated with an Early Palaeocene period of extension across a regional axis which was centred just west of the Faroese Platform (Lundin and Doré, 2005; Ziska and Varming, 2008). This exploited pre-existing SSE/NNW oriented structural features, most likely associated with the Lewisian-Ammasaliq orogenic belt (Ziska, 2012). The extrusion of lavas is mostly subaerial, although hyaloclastites directly beneath the subaerial lavas in the Lopra Well (Jolley and Bell, 2002) and in the 6104/21-1 well (Øregaard et al., 2007) show that these areas were submerged prior to volcanism. Refraction modelling across the 6104/21-1 well, shows these hyaloclastites to extend over large distances as a seismic low velocity zone (Raum et al., 2005).

There is a disagreement within the literature regarding when the extrusion of the Faroe Island Basalt Group started. Radiometric dating by e.g. Waagstein et al (2002) extrapolated the results of radiometric (K-Ar) dating to predict an age of 58.8 +/- 0.5 Ma at at depth of 3100 m below the top of the Beinisvørð Formation in the Lopra-1 well. Later Ar-Ar analyses led Storey et al. (Storey et al., 2007) to propose an age of 60.1+/-0.6 Ma for the deeper section drilled by this well. Jolley (2009) proposed, on the basis of biostratigraphical evidence, that widespread volcanism commenced in Flett Formation times, which means later than 56.6 Ma. The presence of extrusive lavas within the early Vaila Formation well 6005/15-1 on the Faroese Continental Shelf (Árting and Riishuus, 2017) proves that volcanism started more than 60 Ma years ago, which supports the published radiometric ages for volcanism rather than the biostratigraphical interpretation (Figure 3).

The opening of the North Atlantic in the early Eocene was accompanied by a new phase of volcanism. This volcanic period was initially dominated by compound lava flows (Malinstindur Formation), (Rasmussen and Noe-Nygaard, 1969) (Waagstein, 1988). The tabular flows of the latter part of the second phase (Enni Formation) were subsequently extruded (Rasmussen and Noe-Nygaard, 1969). Younger volcanic units are found onshore Greenland (Larsen et al., 1999), but these have so far not been sampled on the Faroese Continental Shelf.

The period after volcanism was characterised by post rift subsidence in the Faroe Shetland and Faroe Bank Channel Basins. These periods of subsidence were punctuated by several phases of compression (Ritchie et al., 2003).

2. Database

An aeromagnetic dataset (Figure 2) was acquired over the Faroese area by World Geoscience (now CGG) in 1995. The aeromagnetic survey was acquired along flight lines with spacings of 1.5 km in the east and 3 km in the west, oriented WSW-ENE; orthogonal tie lines had spacings of 4.5 km in the east and 9 km in the west. In the offshore area the sensor elevation was 80 m above sea level, with a nominal terrain clearance of 80 m over the islands (although in practice the ground clearance was often greater because of the severity of the terrain and safety considerations).

These acquisition parameters suggest that there is likely to be a degree of aliasing in the data: (Reid, 1980) recommended that, in order to avoid misleading interpolated results, the sample spacing should not exceed a distance equivalent to twice the mean height of the sensor above the magnetic sources (and that more severe constraints apply if the data are to be suitable for detailed applications such as calculation of gradients and modelling, the latter requires a 1:1 relationship between distance to magnetic source and flightline spacing (Reid, 1980)). In the Faroe Platform area, where the top of the basalt typically lies between 100 m and 500 m beneath the sensor elevation, application of this rule of thumb suggests an ideal sampling interval of 200 m to 1000 m (or less). Aliasing is therefore likely to occur between the lines when interpolating the data to produce images.

After tie line levelling a minimum curvature algorithm was used to interpolate the flightline data onto a regular grid with a node spacing of 500 m. Although use of this combination of acquisition and gridding parameters plainly violates the previously-described criterion, it attempts to strike a balance between honouring the along-line sampling (about 10 m) and an acceptable degree of interline aliasing of anomalies. Although aliasing is seen to be at an acceptable level over most of the image (Figure 2), it becomes especially apparent where the top of the basalt is close to the sea bed. In such areas it is often possible to identify the continuity of features when their strike of features is orthogonal to the survey lines, but such identification becomes more difficult when features strike obliquely to widely spaced flight lines and aliasing makes a number of alternative correlations possible.

The seismic data used, were acquired by Western Geophysical (now WesternGeco) in 1994 and 1995, and were reprocessed in 2011 by TGS (Figs 6 and 9). The survey was shot with a 6 km streamer and an airgun array size between 4500 in^3 and 6000 in^3. The primary purpose of the seismic survey was to attempt to image beneath the basalts seismically, so optimising acquisition and processing for the first few hundred milliseconds within the basalt on the platform areas were not prioritised. This is reflected in the poor S/N ratio in the upper part of the section on the Faroese Platform (e.g. Figure 4)

3. Magnetic properties of the Faroese basalts

Geophysical and petrophysical data acquired in the Faroese area in the 1960s and 1970s revealed the contrasting nature and sources of magnetic and gravity anomalies in that area (Saxov and Abrahamsen, 1966). The primary focus in the years that followed was on the acquisition of palaeomagnetic data on the Faroese lavas (Abrahamsen et al., 1984; Riisager et al., 2002b; Schoenharting and Abrahamsen, 1984). These data demonstrated that most of the lavas were emplaced in a reversed magnetic field (Figure 3). Two sections towards the top of the Beinisvørð Formation (first phase of volcanism) were however emplaced in a normal magnetic field. These two sections have been well resolved by multiple palaeomagnetic determinations (Riisager et al., 2002a;

Tarling, 1970; Waagstein, 1988) and shown to have a significant effect on the magnetic field variations measured by marine and airborne surveys (Schrøder, 1971; Ziska and Morgan, 2005).

The magnetisation of rocks (M) induced by the Earth's magnetic field (H) is directly proportional to the susceptibility (γ) as shown in the equation $M = \gamma H$. The magnetic susceptibility of the Faroese basalt has been investigated by a number of authors (Table 1). Most of the published values are from the older Beinisvørð Formation (Figure 3). The susceptibility in the Beinisvørð Formation varies between 16×10^{-3} and 39×10^{-3} SI (Abrahamsen, 2006; Abrahamsen et al., 1984; Schoenharting and Abrahamsen, 1984), which is comparable to an average of 70×10^{-3} SI for basalt quoted by Telford *et al.* (1990). Measured susceptibility is generally lower in the Malinstindur and Enni Formations, with values between 1×10^{-3} and 30×10^{-3} SI (Abrahamsen et al., 1984; Abrahamsen and Waagstein, 2006). Average values for metamorphic basement is according to Telford (1990) between 0.7 and 6×10^{-3} SI. (Powell, 1970) documented values of 50×10^{-3} SI for zones within the Lewisian crystalline basement. Wide aperture seismic data show high velocities at 5 km depth on the Faroese Platform, which is interpreted to represent basement (Raum et al., 2005; Richardson et al., 1999). Anomalies generated at such depth will typically have much lower amplitude than those generated by the near-surface highly magnetic basalts.

The total measured magnetic response over igneous lithologies can be strongly influenced by magnetic remanence, which is the magnetisation exhibited by a rock unit in the absence of an external field. The orientation of the remanence vector is a function of the location of the sampling site and the polarity of the Earth's field at the time the magnetisation was acquired (during cooling below the Curie temperature for magnetite following Cenozoic extrusion, in the case of the Faroese lavas), and the influence of any subsequent structural deformation. The strength of the remanent magnetisation in the Malinstindur Formation can be estimated from data from the Vestmanna-1 well, where values for the entire drilled section lie between 0.8 and 27 A/m. Measurements on bottomhole cores and sidewall cores in the Lopra-1 well have yielded values between 1.5 and 14 A/m in the Beinisvørð Formation.

The relative contribution of remanent magnetisation to the total magnetisation of a body can be presented as the Königsberger ratio (Q-ratio) which is the ratio of remanent to induced magnetisation in the local magnetic field (Nielsen, 1977). When the direction of the induced and remanent magnetisions are near antipolar, which is the case within the investigated stratigraphy in this paper, then the remanent magnetisation will dominate the total magnetic field when the Q-ratio is higher >1 (Morris et al., 2007). The Beinisvørð Formation basalts have a Q-ratio between 0.9 and 15 in six cores taken in the Lopra-1/1A well (Table 1), which penetrates the older parts of the formation and below 3 in parts of the youngest section of the same formation in the Vestmanna-1 well. Nineteen sidewall cores from Lopra-1/1A yielded Q-values between 0.032 and 9.224 excluding one suspected erroneous value of 77.4 (Abrahamsen, 2006). The average Q-ratio for the sidewall cores was 1.85. The Q-ratio for the Malinstindur Formation is primarily sampled in the Vestmanna-1 well: Abrahamsen et al. (1984) suggests generally lower values in most of the underlying Beinisvørð Formation (< 3), compared to the overall mean of 13.3 for the entire well. No data points for the youngest basalt formation (Enni Formation) are known.

The polarity of the remanent magnetisation is reversed throughout the second volcanic phase (Abrahamsen et al., 1984; Riisager et al., 2002a). In the Beinisvørð Formation most of the basalt is reversely magnetised but two sections in the upper part are normally magnetised (Figure 3). The uppermost normally polarised section is 400 +/-130 m thick, while the lowermost section is 180 +/-20 m thick. The intervening reversely polarised section is 510 +/-30 m thick (Waagstein, 1988). These thicknesses are measured on the island of Suðuroy. The Vestmanna-1 (Figure 1) well was terminated within the uppermost normally magnetised unit in the Beinisvørð Formation (Abrahamsen et al., 1984). The lateral extent and potential thickness variations of these magnetic units beyond Suðuroy is not known at present.

Five cores were taken from the Beinisvørð Formation below the normally polarised zones in the Lopra-1 well (Figure 1). Palaeomagnetic analysis of these cores showed that two of them are normally magnetised, two are reversely magnetised, while the last exhibits a mixed polarity (Schoenharting and Abrahamsen, 1984) (Figure 3). Based on the stability of the magnetisation Schoenharting and Abrahamsen (1984), concluded that the entire drilled section was originally reversely magnetised, and the normal/mixed polarities are a result of secondary magnetisation caused by low temperature oxidation.

4. Description of the main aeromagnetic anomalies

The reduced to pole aeromagnetic data from the Faroe area are shown in Figure 2. There are a number of high amplitude anomalies occurring within the survey area, both positive (red) and negative (blue). Some of the larger known basement features are plotted with the data as black outlines. The Faroe Platform, Munkagrunnur Ridge, Fugloy Ridge, Wyville-Thomson Ridge and the Faroe Bank are characterised by a higher frequency content compared to other areas due to the shorter distance between the sensor and the magnetic source, i.e. the basalt surface.

The Faroe Platform, Munkagrunnur Ridge and Fugloy High are areas where depth to the top of the volcanic sequence, which in effect is the magnetic basement (Morgan and Murphy, 1998), is fairly constant. This area is characterised by a variable magnetic response. There are areas which are predominantly positive, while others are predominantly negative delineating trends and features which are discussed below.

4.1. Faroese Platform

Little is known about the deeper structure on the Faroese Platform, which precludes direct correlation of magnetic anomalies with deeper structures. The platform, where the basalt is at seabed, is predominantly characterised by a positive magnetic response (Figure 2). There is, however a distinct anomaly on the north-western part of the platform. It is shaped as two concentric half-circles, the outer crossing the island of Mykines and the western tip of Vágoy (Figure 2). The anomaly, which has a diameter of 50 km, represents variations in excess of 1000 nT. This anomaly will be referred to as the Mykines Anomaly (MA). An elongated but otherwise similar anomaly is seen on the northern part of the Munkagrunnur Ridge, here referred to as the Suðuroy Anomaly (SA), with the island of Suðuroy located towards the northeast part of the anomaly. This anomaly is about 100 km long and 40 km wide and also represents variations in excess of 1000 nT.

The southernmost part of the Munkagrunnur Ridge has a varied response, with predominantly higher magnetic field values between the Annika Anomaly (Figure 2) and the Faroe Bank Channel Knoll.

4.2. Features outside the Faroese Platform

The mapped basement features within the Faroe Shetland Basin east of the Munkagrunnur Ridge (Figure 2) exhibit mixed magnetic responses: the Heri High, East Faroe High south and Tróndur High are associated with predominantly negative magnetic field values, while the Mid-Faroe High and East Faroe High central and north are associated with magnetic highs. The Sjúrður High has an intermediate magnetic response.

The most pronounced structures west of the Munkagrunnur Ridge are the Faroe Bank and the Wyville-Thomson Ridge. Only the easternmost part of the Faroe Bank is covered by the magnetic data. This area shows a strong magnetic low (<-500 nT) partially surrounding a high (>500 nT) closer towards the centre of the structural Faroe Bank feature. The central section of the Wyville-Thomson Ridge is associated with a strong magnetic low (<-500 nT), although a small positive feature occurs in the section where the basalt thickens northwestward from its thinnest point (Ziska and Varming, 2008).

One of the most pronounced anomalies on the aeromagnetic map is the Annika Anomaly (AA in Figure 2), which does not seem to be correlated with known deeper structure. It is 200 km long and 20 km wide. The south-western part of the anomaly has a high positive amplitude (500 nT), with magnetic lows on either side (-200 nT towards the SE and 0 nT towards the NW), while the amplitude is lower (200 nT) at the north-eastern end of the anomaly. NE of the Westray Lineament (Figure 2), the anomaly changes to a broad positive feature, with a stepwise transition to a magnetic low on the south-eastern side (200 nT through 0 nT to -300 nT). Towards the SW, there are indications of a continuation of the anomaly as a band of intermittent magnetic highs across the Munkagrunnur Ridge and the Faroe Bank Channel Knoll.

4.3. Igneous Centres

Four igneous centres have been identified within the survey area (Figure 1 and 3). These are Frænir igneous centre, Faroe Bank Channel Knoll, Regin Smiður and Drekaeyga. The magnetic response of the igneous centres is mixed, with Regin Smiður having a 20x15 km elliptical positive anomaly (>500 nT) with a relative minimum (200 nT) in the centre. The dominant magnetic response over the Faroe Bank Channel Knoll is positive (>500 nT), while negative lobes occur over the eastern and western parts (-100 nT and 0 nT respectively). Drekaeyga (15x10 km) is associated with a sharply defined magnetic high (500 nT), while the magnetic data do not show a specific anomaly associated with the Frænir igneous centre which is identified on the basis of its strong gravity expression. Seismic data do not give any indication of the structure, except to indicate that the source lies beneath relatively undisturbed strata of the second volcanic phase (Malinstindur and Enni formations).

5. Interpretation/modelling

The varying magnetic response across mapped basement features shows that a conventional approach with reduced-to-pole magnetic highs indicating basement highs, is not straightforward in a basaltic environment such as the Faroese Continental Shelf. There are, however, several observed distinct magnetic anomalies, which can be correlated to what is known about the magnetic properties of the basalt onshore Faroe Islands.

5.1. Onshore–offshore correlation

The first documented onshore magnetic survey on the Faroe Islands was commented upon by Saxov (1971), who saw that there was a distinct change in the measured magnetic response in the areas where the Beinisvørð Formation outcrops, compared to areas where the Malinstindur Formation outcrops. This led Saxov (1971) to suggest that it is possible to map the transition from the Beinisvørð Formation to the Malinstindur Formation using magnetic data. Schrøder (1971) tested this hypothesis by creating a conceptual 2D model based on what was known about the magnetic properties at the time, i.e. before the magnetic properties of the lower part of the Beinisvørð Formation was known. He created a model, which reproduced the overall shape of measured anomalies west of the island of Suðuroy.

5.2. Geology on the Faroese Platform

The working hypothesis is that the Mykines Anomaly is caused by the succession of normal and reversely magnetised sections being truncated at seabed. Seismic data across this anomaly (Figure 4) show intravolcanic units with apparent dip decreasing towards the northeastern end of the line. Truncations of intravolcanic units coincide with the anomaly, supporting such an interpretation. The semi-circular shape of this anomaly indicates a circular structure. This is supported by measured inclination of geological strata onshore Faroe Islands (Rasmussen and Noe-Nygaard, 1969). These measurements show that the general dip is away from the anomaly (Figure 132 in (Rasmussen and Noe-Nygaard, 1969)), with the steepest dips (up to 20 degrees) closest to the anomaly.

The upper part of the Beinisvørð Formation outcrops on the westernmost part of Vágoy and Mykines (Figure 1 and 3). Based on the dominant nature of the remanent magnetisation relative to the induced magnetisation (above), it is to be expected that the Mykines Anomaly can be correlated with the outcrop of palaeomagnetic polarity changes in the upper part of the Beinisvørð Formation. Figure 5a shows the outcrop of the upper part of the Beinisvørð Formation, which has been extended offshore based on the published dip of the top of the Beinisvørð Formation (Passey, 2009). The correlation of outcrop of the Beinisvørð Formation with magnetic "stripes" reflecting changes in palaeomagnetic polarity (Figure 5b) , supports the hypothesis that the truncation of differently magnetised units is the primary cause of the Mykines Anomaly, and the detail of this correlation (total field magnetic highs over the subcrops of the top boundaries of the normally magnetised zones) is supported by the modelling discussed below.

The Mykines Anomaly crosses the proposed Skopunarfjørður Fault at right angles (Figure 5a,b) without any evidence of a 4.2-6.2 km horizontal displacement as proposed by Passey (2009).

The upper part of the Beinisvørð Formation outcrops onshore Suðuroy and is associated with a strong magnetic anomaly. This anomaly continues offshore towards the northwest and southeast of the island where it forms the north-eastern part of the Suðuroy Anomaly. Figure 6 shows that the volcanic units dip away from the crest of Munkagrunnur Ridge on both sides, and that a significant portion of the lava sequence is truncated at the crest. The strong positive anomaly can be seen to coincide with where the top of the Beinisvørð Formation (red line on Figure 6) is truncated at the seabed.

To further test the hypothesis, 2½D modelling (Figure 7) was performed along the seismic profile in Figure 6. The observed magnetic properties of the Faroe Island Basalt Group are described in section 3 above. In this modelling we adopt a simplified model of magnetic properties that is guided by the observations: normally-magnetised lavas have been assigned an NRM orientation of inclination 61°, declination 8° and reversely magnetised lavas an orientation of inclination -61°, declination 188°. Rotation of the magnetisation direction across the fold can provide information regarding the age of folding relative to the age of the acquisition of the remanent magnetisation (Graham, 1949). The small structural dips along the profile and the orientation being east-west i.e. roughly perpendicular to the magnetic dip vector means that structural deformation is unlikely to have a significant effect on the orientation of the remanent magnetisation. Both normally-and reversely-magnetised basalts were given an NRM magnitude of 3 $A.m^{-1}$ and a susceptibility of 0.025 SI units. Rocks belonging to the Lopra Formation were assigned zero NRM magnitude and susceptibility.

A model southeast of Suðuroy (Figure 7) is oriented SW-NE, coincident with the central part of the seismic line on Figure 6. The model shows how the positive magnetic anomalies at each end of the profile can be modelled by dipping normally-magnetised intervals (shown in dark grey) within reversely-magnetised lavas (shown in light grey). Relating this model to the map shown in Figure 2 suggests that the annular magnetic anomaly extending through Suðuroy and to its south arises from a truncated dome structure.

5.3. Feature outside the Faroese Platform

The most pronounced magnetic anomaly in the area southeast of the Faroe Islands is the Annika Anomaly (above). A NW/SE oriented model that crosses the Annika Anomaly is seen in Figure 8. In the vicinity of that anomaly, regional seismic interpretation constrains the base of the volcanic sequence at around 8 km, with the lower section of the sequence assumed to be represented by hyaloclastites, volcaniclastics and volcanogenic sedimentary rocks, and hence to be weakly magnetised. The presence of such units was seen in the deeper part the Lopra-1, 6104/21-2 (Brugdan II) and 6005/13-1A (William) wells (Árting and Riishuus, 2017). The extent of these units is partly constrained by wide aperture data (e.g. (Raum et al., 2005; Richardson et al., 1999), where the volcaniclastic units are seen as a low velocity layer beneath overlying high velocity basalt. Seismic interpretation of the base of the volcanic sequence constrains the magnetic model by ruling out an intrusive body at shallower depth. A magnetic source at depth greater than 8 km requires extreme, and probably unrealistic, properties in order to generate an anomaly of the observed magnitude and spatial wavelength. The preferred interpretation explains the Annika anomaly by the dipping truncation, at a depth of about 3.5 km, of a thick normally-magnetised interval within reversely magnetised lavas; although no such abrupt truncation is directly observed on seismic data, a change in seismic character is seen to coincide with this magnetic feature.

Magnetotelluric data show that high resistivity units, interpreted to be basalt, increase in thickness from less than one kilometre to more than four kilometres (Orange et al., 2002) at the location of the Annika Anomaly. This supports the abrupt termination of the normally magnetised units. No fault of sufficient magnitude to explain the horizontal transition from normally to reversely magnetised basalt has been interpreted. The Brugdan II well did, however drill through a series of sills from the base of the Enni-/Malinstindur Formation to TD. Within the hyaloclastites a total of 200 m of sills were encountered, constituting about 10% of the total section, while from top Lamba to TD, the well penetrated a total of 500 m of sills, constituting about ¾ of the total section (Statoil, 2015). The reversely magnetised section below the base of the Enni-/Malinstindur Formations thus most likely represents intrusive basaltic units.

The sudden change in the appearance of the Annika Anomaly northeast of the Westray Lineament (Figure 2), indicates thickness variations of the different basaltic units (primarily the normally magnetised units) across the lineament. This suggests that the lineament has affected the emplacement and/or weathering/erosion of the basaltic section. Other lineaments (dashed lines on Figure 2) do not have a visible effect on the magnetic field across the Annika Anomaly.

5.4. Igneous centres

The magnetic anomalies associated with the Faroese volcanic centres also highlight the issues with strong remanent magnetism in volcanic units, because the four mapped igneous centres, which all are associated with positive gravity anomalies, are characterised by different magnetic responses. The high magnetic field values associated with Regin Smiður (Figure 1, 3 and 9a) and Drekaeyga (Figure 1 and 3) are most likely caused by a normally magnetised central plug. The change from a positive to negative magnetic response across the Faroe Bank Channel Knoll (Figure 1, 3 and 9b) could indicate units with different polarities of remanent magnetisation being part of this igneous centre. It is not possible with the available data to determine the relative age of these units. Regin Smiður and Faroe Bank Channel Knoll are both large volcanoes (Figure 9), where the shield of extruded lavas forms an inward thickening volcanic section (Ziska and Varming, 2008). Frænir igneous centre (Figure 1 and 3) is most likely reversely magnetised, and probably older than the other igneous centres (Ziska, 2012). Performing profile modelling across the igneous centres is beyond the scope of this paper, where the primary focus is to attempt to understand the and consequently understand the magnetic signatures of the main lava sequence. Producing 2½D models across the igneous centres is however a task, which would be interesting to address in the future.

6. Conclusions

- The strong remanent magnetisation of the volcanic rocks of the Faroese area has to be taken into account when modelling the sources of the magnetic responses observed across them. This requires the incorporation of both normal and reverse magnetic polarity elements.
- The thickness of the extrusive subaerial basalt changes from one kilometre to almost four kilometres across the southern part of the Annika Anomaly, while the total thickness of the volcanic section, including weathered and eroded basaltic material only changes slightly. The termination of normally magnetised lava units is interpreted to be the primary cause of the Annika Anomaly.
- The Westray Lineament appears to be the only lineament which has affected the emplacement, weathering and/or erosion of the normally magnetised units along the Annika Anomaly.
- The Frænir igneous centre, which predates the second phase of volcanism (Malinstindur and Enni formations), was probably active in a period with a reverse magnetic field, while Drekaeyga, Regin Smiður and Faroe Bank Channel Knoll seem to have been primarily active during periods with a normal magnetic field.
- Magnetic data do not support a large horizontal displacement on the Skopunarfjørður Fault.
- A high-resolution magnetic survey of the Faroes region would enable greatly improved magnetic mapping by better resolution of anomalies due to thickness variations in units with contrasting magnetic properties, and by improved identification of faulting affecting those units.

Figure Legends

Figure 1: Overview of the sub-basins, highs, lineament zones and igneous centres in the Faroe-Shetland area (modified from Ritchie *et al.*, 2011). S = Suðuroy, V = Vágoy, M = Mykines. WTR = Wyville-Thompson Ridge, EFHs/c/n = East Faroe High south/central/north, FP = Faroe Platform,

MGR = Munkagrunnur Ridge, FR = Fugloy Ridge, FB = Faroe Bank, FBCK = Faroe Bank Channel Knoll (volcanic centre), HH = Heri High, TH = Tróndur High, FVC = Frænir Volcanic Centre, RS = Regin Smiður Volcanic Centre, DE = Drekaeyga Volcanic Centre, SH = Sjúrður High, MFH = Mid Faroe High.

Figure 2: Reduced to pole aeromagnetic data, with basement features. MA = Mykines Anomaly, SA = Suðuroy Anomaly AA = Annika Anomaly. Profile a = Figure 4, Profile b = Figures 6&7, Profile c = Figure 8, Profile d&e = Figure 9. See Figure 1 for structural element abbreviations.

Figure 3: Lithostratigraphic column of the Faroese onshore geology, with magnetic polarity inferred from published palaeomagnetic analyses (modified from Rasmussen and Noe Nygaard, 1969). Interpreted correlations with the timescale of Gradstein et al. (2012) are shown.

Figure 4: Seismic line across the Mykines Anomaly (profile a on Figure 3) with marine magnetic data acquired along the line (yellow line). Green line: top volcanic reflection, orange lines: intravolcanic reflections.

Figure 5: Comparison of interpreted subcrop pattern with the observed Mykines Anomaly. Left: contours on top Beinisvørð after Passey and Varming (2010) and outcrop of the A-horizon (green) superimposed on the predicted offshore subcrop of the magnetostratigraphic units below this horizon (black arrow on the type section). Right: total field magnetic anomalies with white dashed lines showing the upper edges of the two normal polarity zones. Black dotted line: location of proposed Skopunarfjørður Fault

Figure 6: Seismic line across Munkagrunnur Ridge (MR) (profile b on Figure 3) with marine magnetic data acquired along line (yellow line). Green line: top basalt, red line: Top Beinisvørð Formation. Seismic data courtesy of TGS.

Figure 7: Magnetic model of a SW-NE profile SE of Suðuroy along seismic line OF95-108. Reversely magnetised lavas of the Faroe Islands Basalt Group are shown in light grey (NRM magnitude = 3 $A.m^{-1}$, inclination = -61°, declination = 188°) and normally magnetised lavas in dark grey (NRM magnitude = 3 $A.m^{-1}$, inclination = 61°, declination = 8°) . The bulk susceptibility of the lavas is 0.025 SI units.

Figure 8: Magnetic model of a NW-SE profile SE of the Faroe Islands, coincident with seismic line OF95-145. Reversely magnetised lavas of the Faroe Islands Basalt Group are shown in light grey (NRM magnitude = 3 $A.m^{-1}$, inclination = -61°, declination = 188°) and normally magnetised lavas in dark grey (NRM magnitude = 3 $A.m^{-1}$, inclination = 61°, declination = 8°) . The bulk susceptibility of the lavas is 0.025 SI units. Non-magnetic post-basalt sedimentary rocks are shown in light brown. Hyaloclastites, volcaniclastic rocks and volcanogenic sedimentary rocks are interpreted to extend to a depth of up to 8 km beneath the magnetic lavas (green line at the bottom).

Figure 9: Seismic line across the Regin Smiður Volcanic Centre (RSVC) and Faroe Bank Channel Knoll (FBCK) (profiles d and e on Figure 3) with marine magnetic data acquired along line (yellow line). Green line: Top basalt, Red line: Top Beinisvørð Formation. Red box indicates interpreted location of the central part of the igneous centre. Seismic data courtesy of TGS.

Table 1: Published values for magnetic properties of basalts onshore Faroe Islands.

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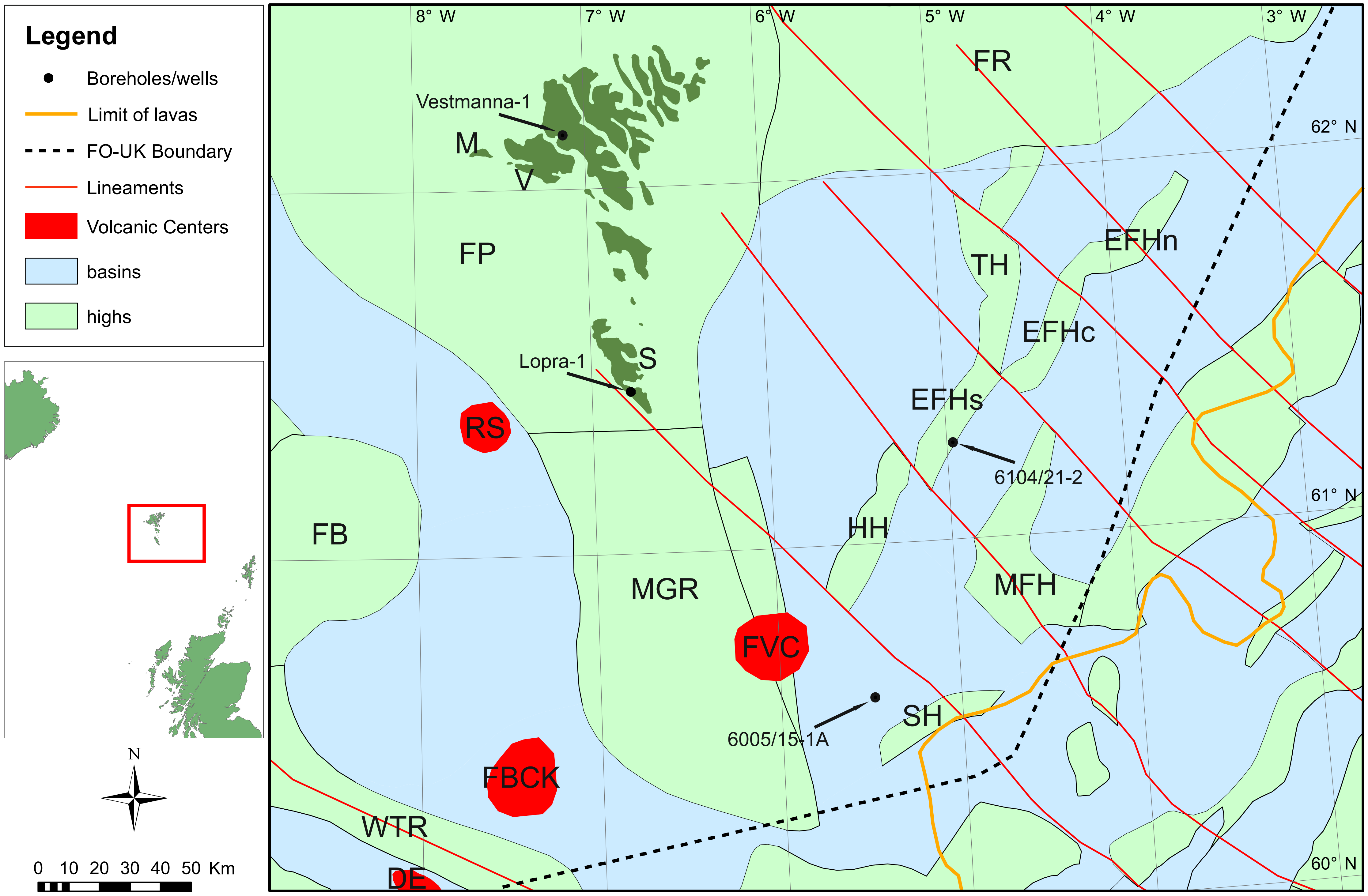

Legend
Boreholes/wells
Limit of lavas
FO-UK Boundary
Lineaments
Volcanic Centers
basins
highs
N
0 10 20 30 40 50 Km
8° W
7° W
6° W
5° W
4° W
3° W
62° N
61° N
60° N
FR
Vestmanna-1
M
V
FP
EFHn
TH
EFHc
Lopra-1
S
EFHs
RS
6104/21-2
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SH
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FBCK
WTR
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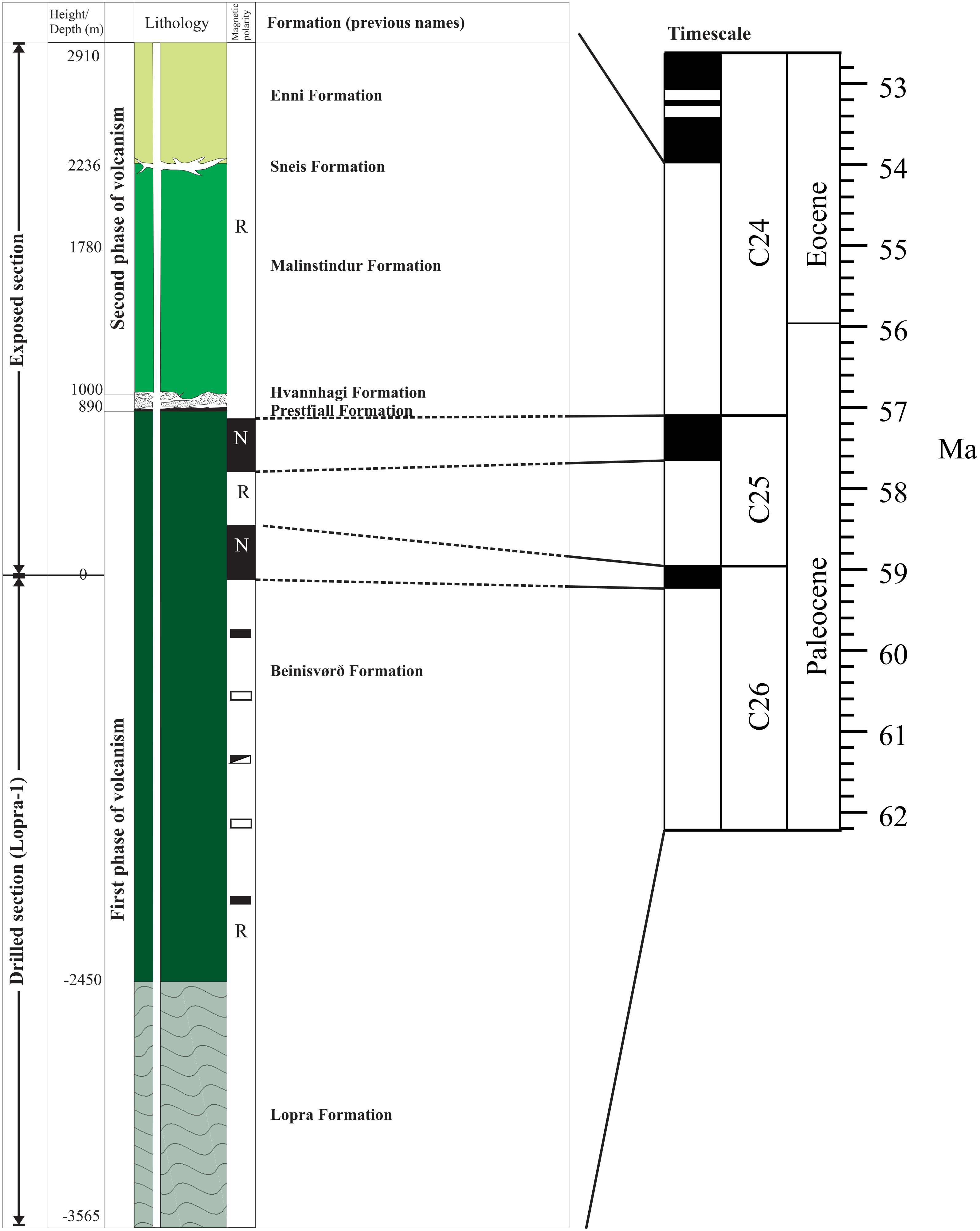
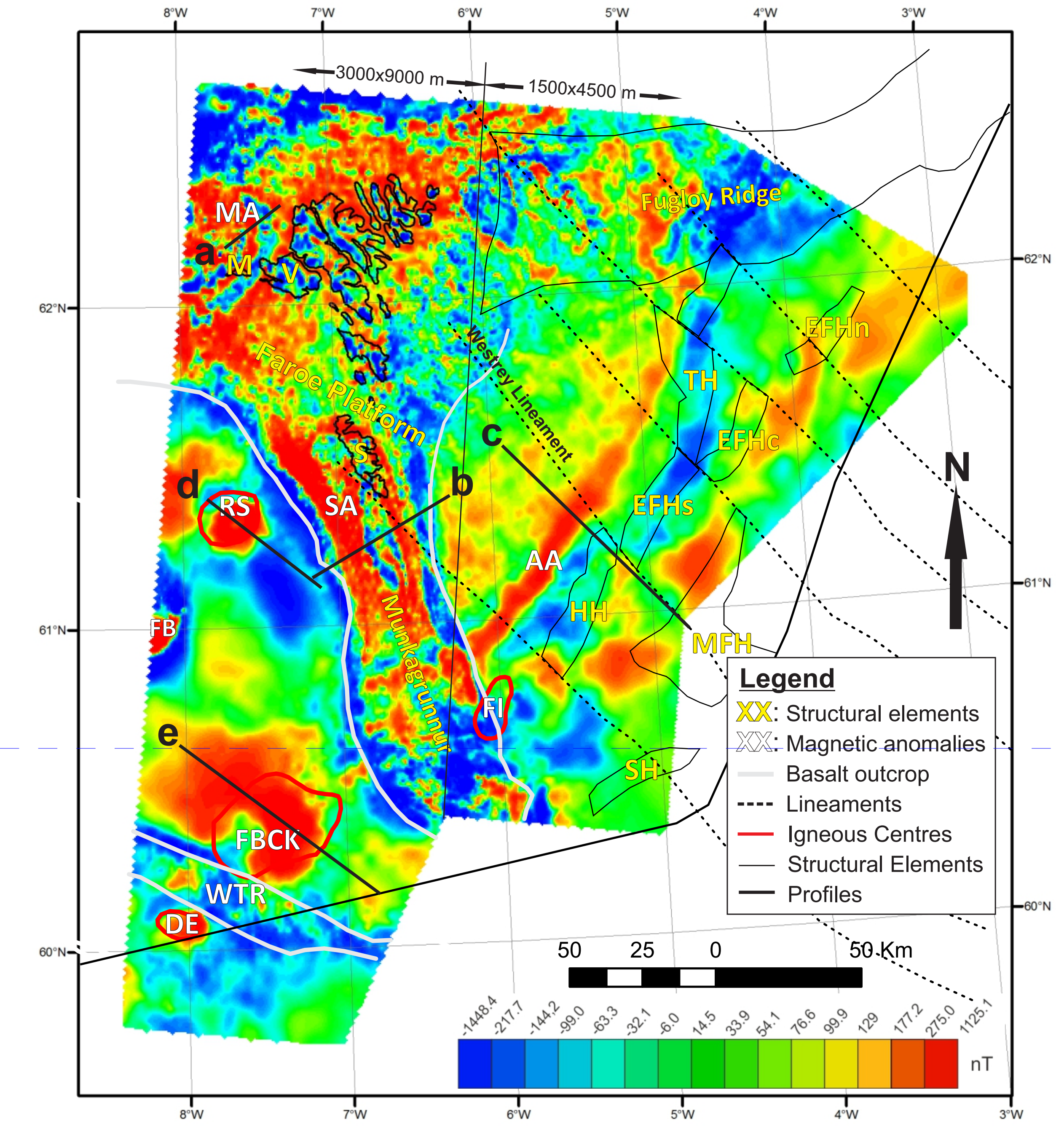
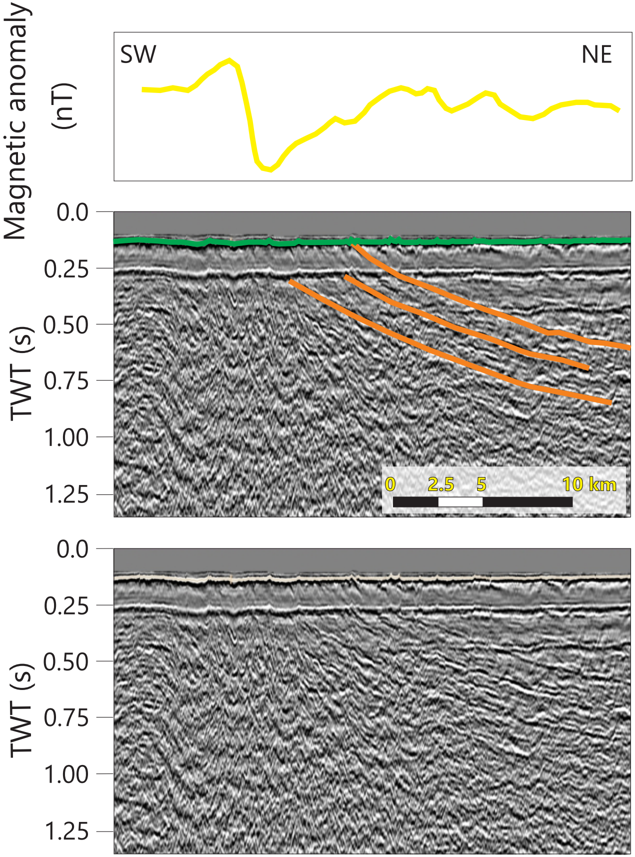


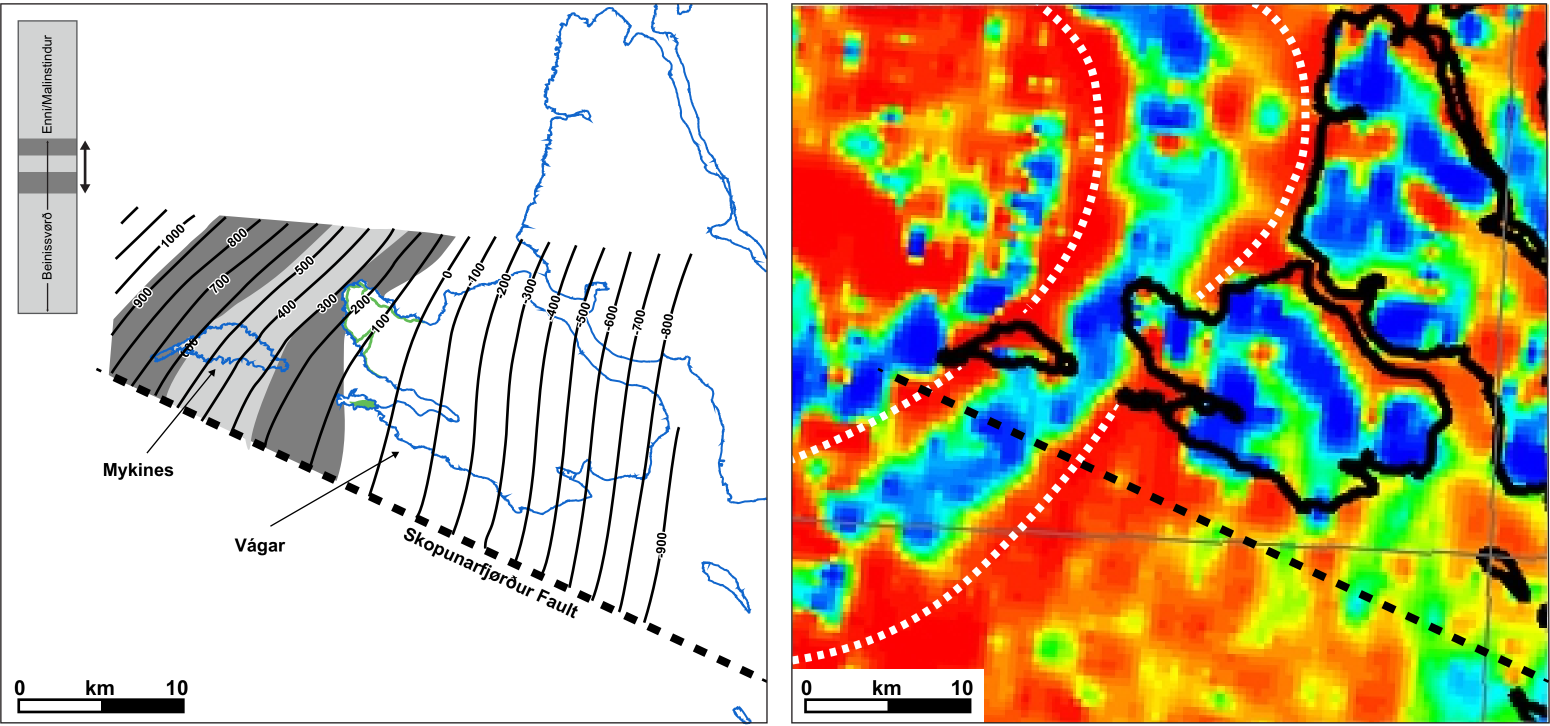
Height/ Depth (m)
Lithology
Magnetic polarity
Formation (previous names)
Timescale
2910
2236
1780
1000
890
0
-2450
-3565
Exposed section
Drilled section (Lopra-1)
Second phase of volcanism
First phase of volcanism
Enni Formation
Sneis Formation
Malinstindur Formation
Hvannhagi Formation
Prestfjall Formation
Beinisvørð Formation
Lopra Formation
R
N
R
N
R
C24
C25
C26
Eocene
Paleocene
53
54
55
56
57
58
59
60
61
62
Ma



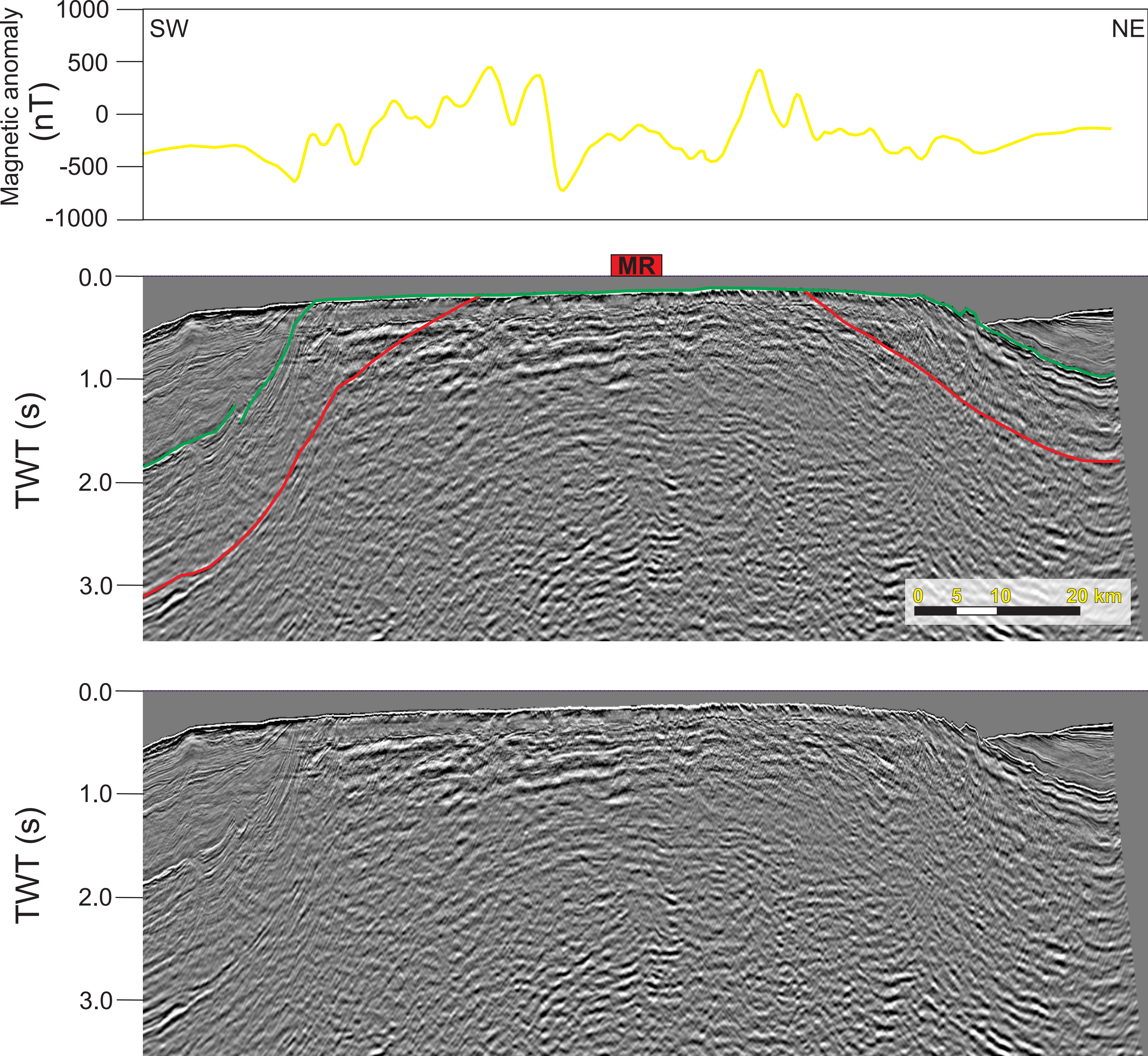
8°W
7°W
6°W
5°W
4°W
3°W
62°N
61°N
60°N
3000x9000 m
1500x4500 m
Fugloy Ridge
MA
a
M
V
Faroe Platform
Westrey Lineament
EFHn
TH
EFHc
c
S
d
b
RS
SA
EFHs
AA
HH
FB
Munkagrunnur
MFH
FI
e
SH
FBCK
WTR
DE
N
Legend
XX: Structural elements
XX: Magnetic anomalies
Basalt outcrop
Lineaments
Igneous Centres
Structural Elements
Profiles
50 25 0 50 Km
-1448.4
-217.7
-144.2
-99.0
-63.3
-32.1
-6.0
14.5
33.9
54.1
76.6
99.9
129
177.2
275.0
1125.1
nT

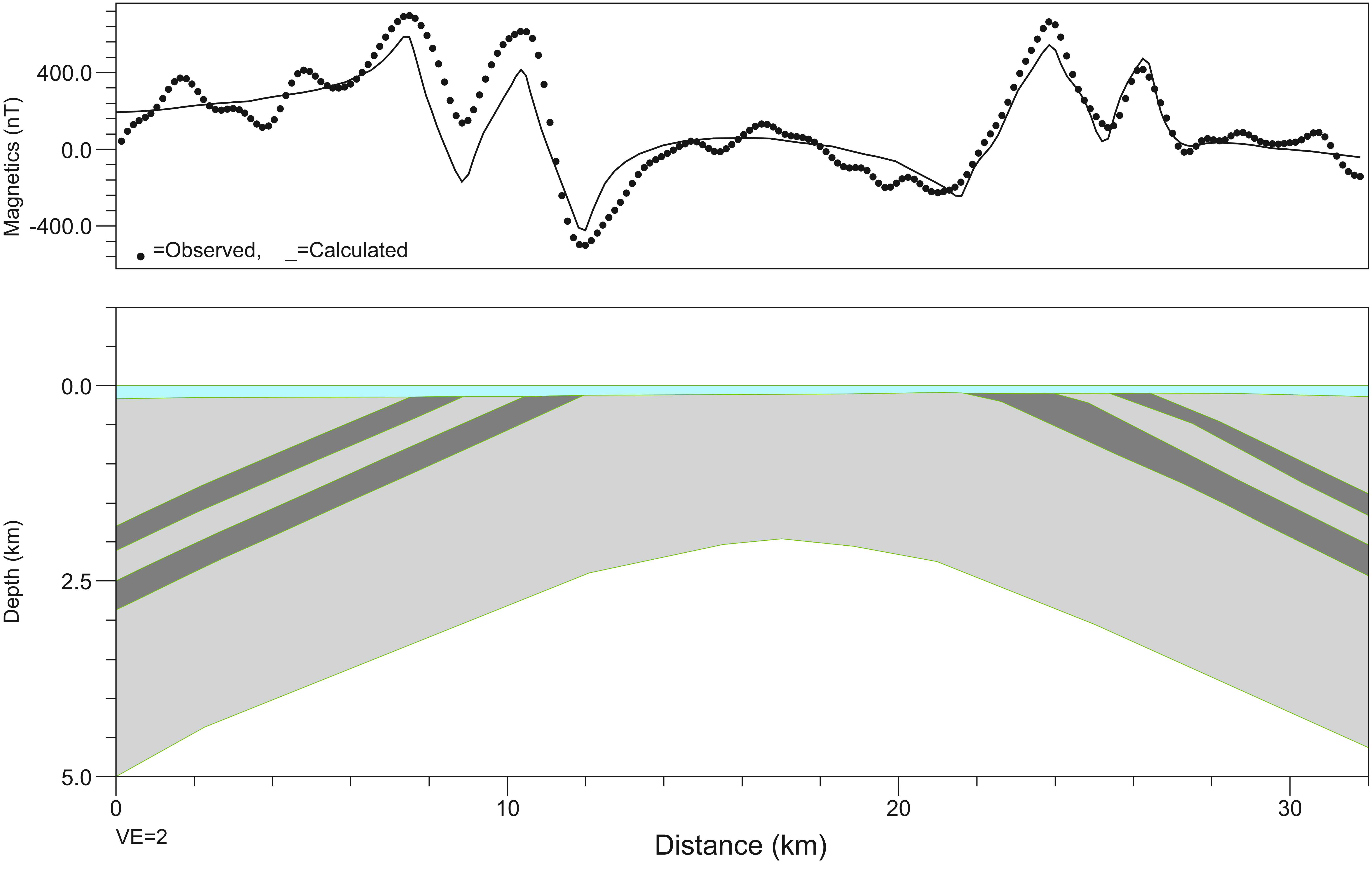


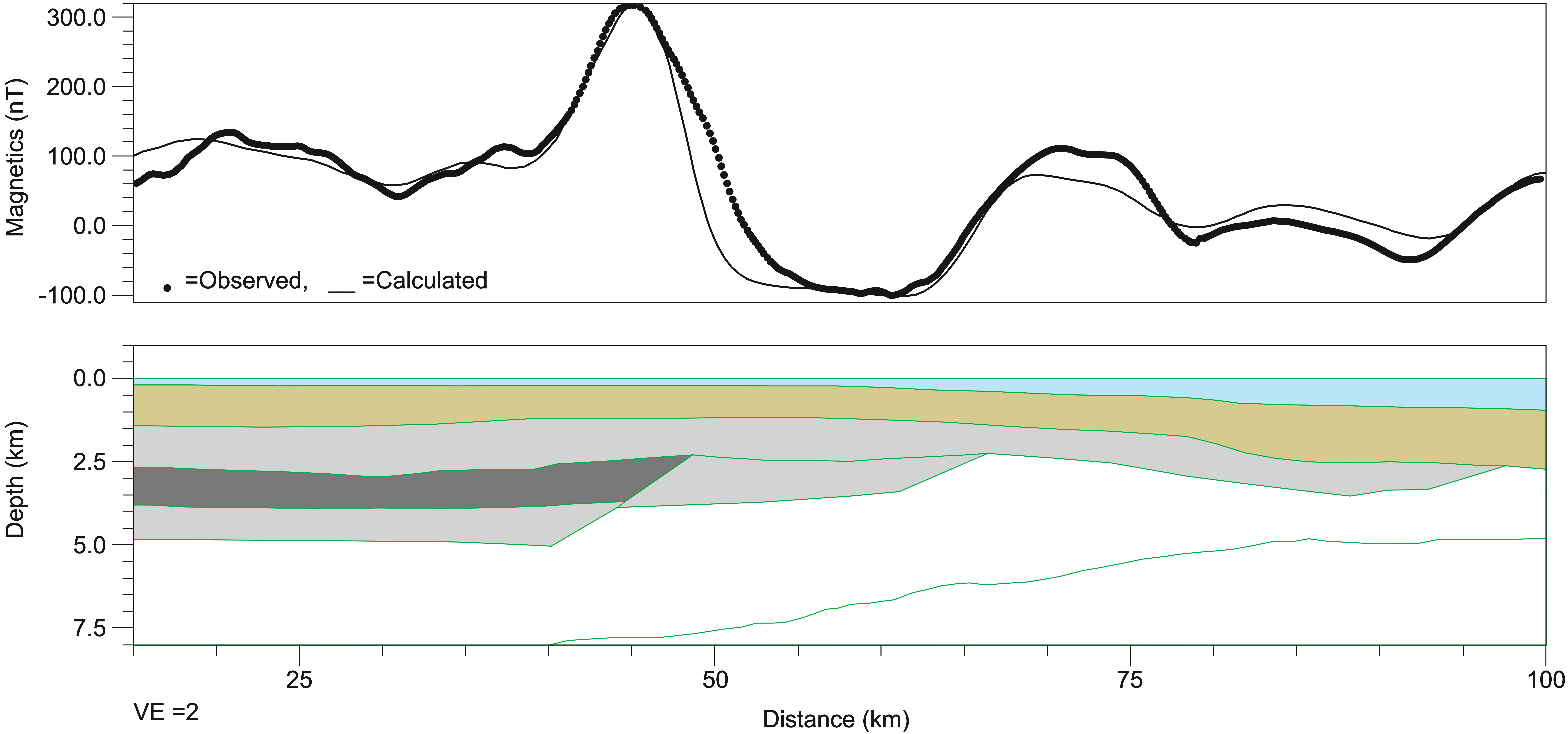
Magnetic anomaly (nT)
SW
NE
0.0
0.25
0.50
0.75
1.00
1.25
TWT (s)
0
2.5
5
10 km
0.0
0.25
0.50
0.75
1.00
1.25
TWT (s)

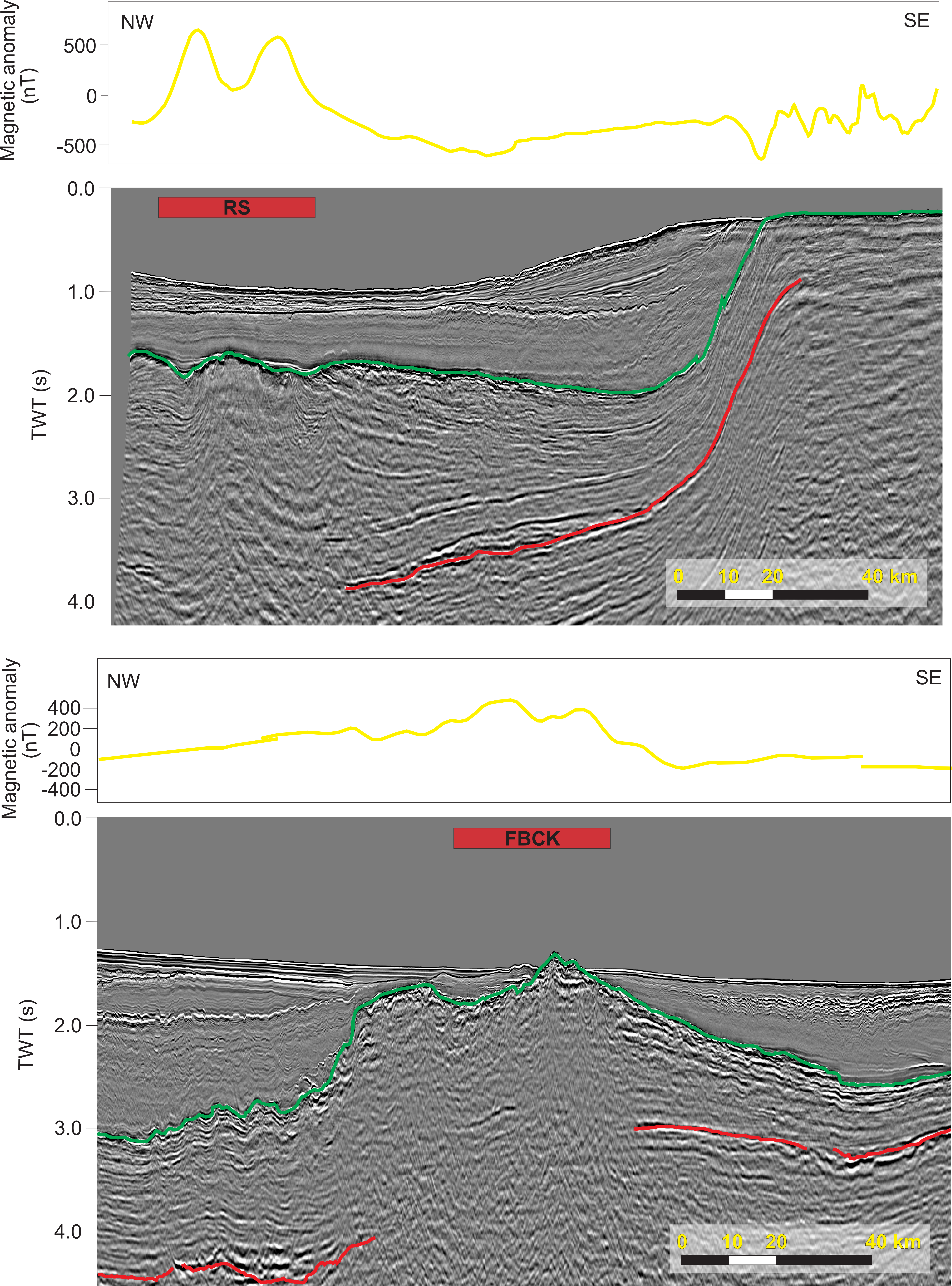


Enni/Malinstindur
Beinissvørð
1000
900
800
700
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
Mykines
Vágar
Skopunarfjørður Fault
0 km 10
0 km 10


1000
500
0
-500
-1000
Magnetic anomaly (nT)
SW
NE
MR
0.0
1.0
2.0
3.0
TWT (s)
0 5 10 20 km
0.0
1.0
2.0
3.0
TWT (s)


Magnetics (nT)
400.0
0.0
-400.0
● =Observed,
_=Calculated
Depth (km)
0.0
2.5
5.0
0
10
20
30
VE=2
Distance (km)


Magnetics (nT)
300.0
200.0
100.0
0.0
-100.0
● =Observed,
__ =Calculated
Depth (km)
0.0
2.5
5.0
7.5
25
50
75
100
VE =2
Distance (km)


NW
SE
Magnetic anomaly (nT)
500
0
-500
0.0
1.0
2.0
3.0
4.0
TWT (s)
RS
0
10
20
40 km
NW
SE
Magnetic anomaly (nT)
400
200
0
-200
-400
0.0
1.0
2.0
3.0
4.0
TWT (s)
FBCK
0
10
20
40 km

	Location/well	Interval (well) m (KB)	Susceptibility SI	Polarity	NRM A/m	Q	Source
Enni Formation				Reverse			
	various locations		$16.3*10^{-3}$				Hansen et al 1973
Malinstindur Formation				Reverse			
	Vestmanna-1:	410-556	$1-72*10^{-3}$	Reverse	0.8-27	0.4-48	Abrahamsen et al. 1984
	various locations		$14.7*10^{-3}$				Hansen et al 1973
Beinisvørð Formation				mixed			
	Hvannafelli		$22.6*10^{-3}$				Saxov 1971
	various locations		$30.8*10^{-3}$				Hansen et al 1973
	lower+middle			N/R			Riisager et al, 2002b
	Vestmanna 1	573-590 + 645-659		mixed		<3	Abrahamsen et al. 1984
	Vestmanna-1	558-659	$>= 20*10^{-3}$	mixed			Abrahamsen et al. 1984
	Lopra-1: Core 1	337.5-338.15	$31*10^{-3}$	Normal	3.25	1.9	Shoenarting and Abrahamsen 1984
	Lopra-1: Core 2	860.14-862.79	$16*10^{-3}$	Reverse	14.35	15.2	Shoenarting and Abrahamsen 1984
	Lopra-1: Core 3	1218.14-1219.94	$39*10^{-3}$	N/R	1.74	0.9	Shoenarting and Abrahamsen 1984
	Lopra-1: Core 4	1922.38-1923.10	$17*10^{-3}$	Reverse	4.46	5.3	Shoenarting and Abrahamsen 1984
	Lopra-1: Core 5	2177.28-2178.18	$22*10^{-3}$	Normal	4.65	4.1	Shoenarting and Abrahamsen 1984
	Lopra-1/1A: Core	2380-2381.1	$28.4*10^{-3}$	Reverse	2.256	2.44	Abrahamsen 2006
	Lopra-1/1A: SWC's	2219-3312.5	$16.23*10^{-3}$	Reverse	1,516	1.85	Abrahamsen 2006