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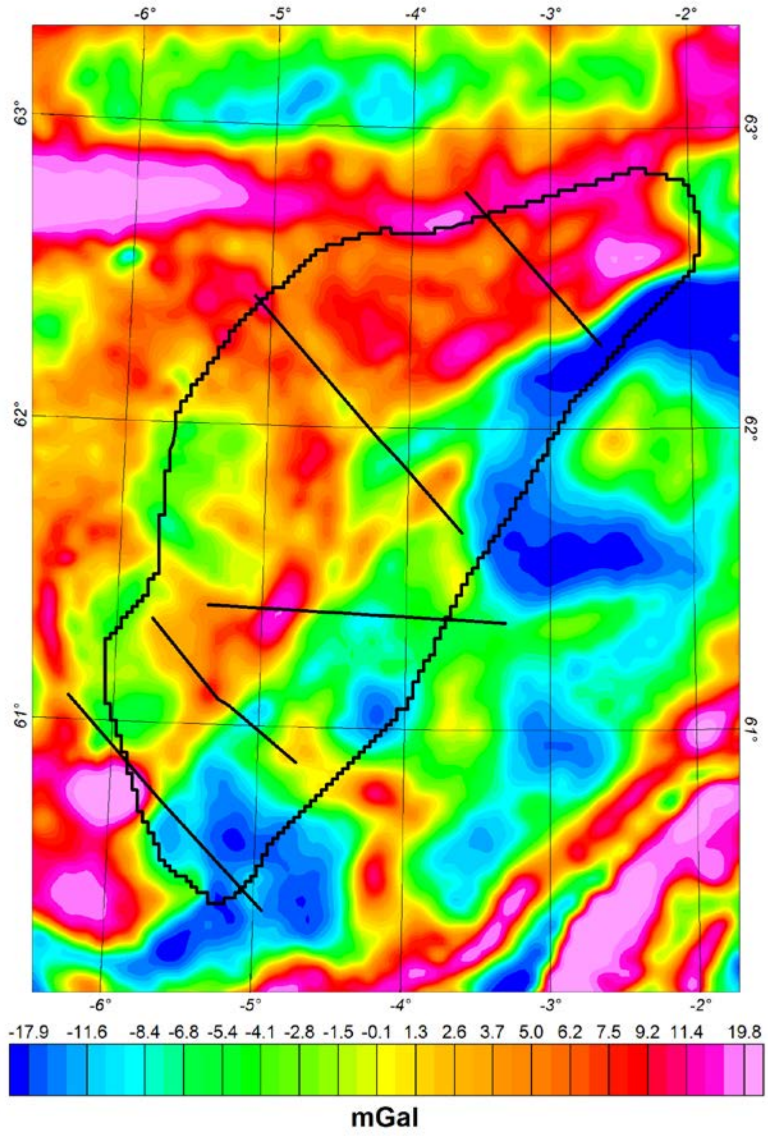
A new look at the structure of the Faroe-Shetland Basin southeast of the Faroe Islands

Energy Systems & Basin Analysis Programme

Commissioned Report CR/18/038



BRITISH GEOLOGICAL SURVEY

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COMMISSIONED REPORT CR/18/038

A new look at the structure of the Faroe-Shetland Basin southeast of the Faroe Islands

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Keywords

Faroe-Shetland Basin; seismic; gravity; magnetic.

Front cover

Residual gravity anomaly after removal of the 10 km upward-continued field.

Bibliographical reference

WILLIAMSON, J P AND ZISKA, H 2018.
A new look at the structure of the Faroe-Shetland Basin southeast of the Faroe Islands. *British Geological Survey Commissioned Report*, CR/18/038. 37pp.

Keyworth, Nottingham British Geological Survey 2017

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Foreword

This report is the result of a joint study by the British Geological Survey (BGS) and Jarðfeingi (the Faroese Earth and Energy Directorate) on behalf of the Faroe-Shetland Consortium (FSC) and presents a re-evaluation of the structure southeast of the Faroe Islands. The study is based on a reprocessing and reinterpretation of five regional seismic lines, together with along-line potential field modelling.

Acknowledgements

This report was commissioned by the BGS/Jarðfeingi/Industry Faroe-Shetland Consortium, which includes the following six oil company sponsors: Chevron, INEOS, Maersk Oil UK Ltd, Nexen Petroleum, Shell and Total. In addition, E.ON originally a sponsor, left the FSC in 2016 following its acquisition by Premier Oil. The co-funding support and interest of all these companies and their representatives is gratefully acknowledged. Responsibilities of individual authors during the production of the report have been as follows:

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Summary

This report describes a project to evaluate, in the area southeast of the Faroes, the structural element map of the Faroe-Shetland Basin (FSB) produced during Phase 2 of the consortium (Quinn et al., 2014) in the light of new interpretations of reprocessed seismic data and taking into consideration the potential field anomalies in the area.

Interpretations were made along five reprocessed seismic lines across the area, which placed the base basalt reflector considerably deeper than has been done previously. Identification of reflectors beneath base basalt is very patchy, with little evidence of basement highs. Within the basalts, identification of different volcanic facies was made.

Potential field models were constructed along each of the five profiles, and illustrate that the anomalies in the area can be accounted for by geometry and property variations within the lava succession, although these are not always supported by seismic evidence.

Taken together, the seismic and potential field interpretations do not strongly support the existence of previously mapped basement highs under the lavas, and suggest that some revision of the structural elements map is necessary in the area southeast of the Faroes.

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1 Introduction

This report describes a project to evaluate, in the area southeast of the Faroes, the structural element map of the Faroe-Shetland Basin (FSB) produced during Phase 2 of the consortium (Figure 1) (Quinn et al., 2014) in the light of new interpretations of reprocessed seismic data and taking into consideration the potential field anomalies in the area.

Figure 2 shows the top basement as derived by optimisation of a 3-D crustal model of the Faroe-Shetland area (Kimbell, 2010). The correspondence between the basement structure derived from inversion of gravity anomalies and that derived by mapping is good in general, but in the area of thick basalt southeast of the Faroe Islands the agreement between the gravity results and the mapped structure is less clear. The basement structure in this region has been examined using five reprocessed and reinterpreted seismic profiles with associated gravity and magnetic profile models.

2 Seismic interpretation

2.1 SEISMIC DATA

Within the area of interest, numerous seismic datasets have been acquired over several years. The more areally-extensive surveys were acquired in the 1990s, while more area-specific surveys, generally conducted in connection with exploration licence commitments, were acquired between 2002 and 2009. Over the time period in which the surveys were acquired, advances in acquisition and processing has resulted in a significant uplift in data quality (e.g. Gallagher and Dromgoole, 2009; White et al., 2005). One of the key aspects learned from early exploration in the area was that seismic acquisition should focus on maximising the lower frequency range of the signal, which was achieved in the acquisition phase by towing both source and receivers deeper than previous industry standards would indicate. Screening of all available data within the research area resulted in the selection of twelve different 2-D surveys (Table 1 and Figure 1), which were used for this project.

The key datasets are the ST-surveys, which were acquired by Statoil and partners as part of their exploration license commitments. These were all acquired with both source and receivers towed below 15 meters, with the exception of the oldest survey (ST0107), where the source was towed at 10 m depth. Examples of the quality of the seismic data can be seen in Figures 2 – 5.

Dataset	of Year	Streamer		source		sample rate	record length	shot interval	Filter cutoffs	
		Length (m)	Depth (m)	Size (in^3)	Depth (m)	(ms)	(s)	(m)	Low (Hz)	High (Hz)
OF94	1994	6000	10	5280	8	2	8.192	25	8	128
OF95	1995	6000	8	4500 6000	6	2	8.192	25	2	196
OF96	1996	4800 m	8	5070	6	2	8		8	180
AMG96	1996	4500/6000	11	4736	9	2	8	25	3	125
GFA	1999	11,400	14	4986	10	4	9.8	25	3	100
IS-FST	2001/2002	10,050	8	4240	6	2	10	25	out	200
ST0107	2002	11,987.5	15	5525	10	2	12.288	37.5	3 Hz	206
ST0510	2005	8100	18	6060	15	2	8.192	25	4.3	200
ST0513	2005	8100	18	6060	15	2	8.192	25	4.3	200
ST0514	2005	8100	18	6060	15	2	8.192	25	4.3	200
ST09004	2009	8100	18	6180	15	2	8.192	25	4.4	214
CV05 o/u*	2005	12,400	30	5085	20.25	2	10	25	out	200

Table 1 Seismic surveys in the study area and their acquisition parameters

2.2 SEISMIC HORIZONS

The key horizons that have been picked are:

- Sea Bed
- Top Basalt: represents the top of the Palaeogene lavas which cover most of the area where the modelled profiles are located
- Base syn-breakup volcanics: the base of the younger lava sequence.
- Lamba formation: a marine sedimentary unit, which in well 6104-21/2 (Brugdan II) was seen to be intruded by a number of basaltic sills.
- Top of the pre-breakup volcanics: this horizon is only discernible in the Judd Basin (on Profile 1)
- Base Basalt: the interpreted oldest occurrence of extrusive basaltic lithology.
- Basement: the oldest unit, which can be mapped across the eastern part of the Fugloy Ridge and is assumed to represent metamorphic basement.

2.2.1 Top Basalt

Top Basalt (represented on all seismic sections by a green horizon) is in most places characterised by a strong positive reflection (Figure 4 and Figure 5). In some places (e.g. Figure 4), the surface exhibits a rugose nature, which is either a result of emplacement or post-emplacement erosion and/or weathering. The reflection is generally continuous, but in some areas, there are sudden depth changes, which can be attributed to faulting (Figure 5), termination of flows (Figure 4) or palaeoshorelines (Figure 7).

The top basalt reflects a change in seismic reflectivity from an almost amorphous overlying unit (although with some evident layering) to a dominantly plane-parallel basalt unit underneath (e.g. Figure 5). In some areas, the clinoforms associated with palaeoshorelines come close to the top basalt surface (Figure 4).

2.2.2 Base syn-breakup volcanics

This horizon encompasses the transition from the first phase volcanics, through the sedimentary Hvannhagi formation to the second phase volcanics. The Hvannhagi formation is only a few meters thick onshore Faroe Islands, and it is only in the Judd Basin, that these pre- and syn-breakup volcanics diverge to a point where the thickness of sediments between these units can be mapped.

The base syn-breakup volcanics horizon was calibrated to seismic data by Petersen et al. (2006), who demonstrated a distinct change in reflectivity between the overlying Malinstindur Formation (the lower part of the syn-breakup volcanic section) and the underlying Beinisvørð Formation (the upper part of the pre-breakup volcanic section). They correlated base syn-breakup volcanics to a strong positive reflection. The reflection (Figure 3 and Figure 4) can be traced into the Faroe Shetland Basin. The interpreted reflection is traced until it reaches the older parts of the Faroe Shetland Escarpment (clinoforms on Figure 3 and Profile 4). At this point the mapped reflection continues into steeply dipping reflections, which, based on the reflection configuration, is expected to represent hyaloclastite deposits. Attempts to follow the reflection across the palaeoshoreline were unsuccessful, due to the progressively overstepping nature of these units. Mapping one single chronological surface in such an area requires either a very dense grid of 2D seismic data or 3D seismic data, neither of which was available for this project. The maximum easterly extent of the base of the interpreted syn-rift volcanics is thus the point where the unit reaches the palaeoshoreline.

Furthest south in the research area (Figure 3), the reflection is interpreted to merge with the top basalt, and thus defines the edge of the post-breakup basalt section in this area.

2.2.3 Lamba Formation

The starting point of the interpretation of the Lamba Formation was well 6104/21-1 (Brugdan II), which drilled into the formation at the base of the well. Seismic data north of well location (Profile 3) shows the transition from the overlying hyaloclastite section to the Lamba Formation to be characterised as a transition from a section with medium strength sub-parallel to slightly dipping reflections to a section that exhibits strong chaotic to hummocky reflections. In other areas (Figure 3 and Figure 4 and Profile 5), the seismic character of the underlying unit only demonstrates a thin section with hummocky reflections overlying dominantly plane parallel units.

In the area with steeply dipping hyaloclastites (representing palaeoshorelines with significant water depth), the hyaloclastites downlap onto the Lamba Formation, but detailed analysis of this downlap reveals downlapping units extending to a varying extent into the hummocky reflections of the Lamba Formation (e.g. Figure 3).

On the Fugloy Ridge (Profile 5 in Figure 7), it is possible to map the downward extent of the hummocky reflections characterising the Lamba Formation. In other locations, e.g. Figure 3 the interpreted Top Lamba horizon represents a transition between two volcanic units, which has prevented the mapping of the thickness of the Lamba Formation on a basin-wide scale.

Towards the west of the research area, the distinct character of the Lamba Formation terminates (Profile 3, Figure 5). This termination, which runs along the northwestern side of the East Faroe high, does not coincide with any discernible change in data quality or rapid geological changes in the overlying units, which could mask the reflections from the Lamba Formation. It is therefore proposed, that the termination reflects the maximum lateral extent of the Lamba Formation in the area.

2.2.4 Base Basalt

According to the well completion logs, base-basalt was drilled in wells 6005/15-1 (Longan) and 6004/8a-1 (Anne Marie). Both wells are, however located in areas with limited thicknesses of volcanic rocks, which due to the episodic nature of volcanic eruptions makes it challenging to trace the base into an area with an increasing thickness of extrusive basalt. The chosen base-basalt is therefore based on a change in internal reflection character (Figure 4). The figure shows a homogeneous dominantly parallel-bedded section overlying a section dominated by hummocky reflections of high reflectivity.

The internal reflection character varies throughout the area. There is a sudden change in reflection character at the northwest side of the southern part of the East Faroe High (Profile 3, Figure 5), which coincides with the maximum northwestwards extent of the Lamba Formation. Northwest of the East Faroe High, it is dominated by a uniform, mostly parallel reflection character, in some areas with more amorphous sections, which in well 6104/21-2 (Brugdan II) were shown to represent a section dominated by volcaniclastic deposits. The presence of volcaniclastic sediments at the base of the volcanic section, presumably overlying non-volcanic sediments, does provide an explanation for the lack of a clear seismic reflection at this level across the southern part of the East Faroe High.

Interpreting the base of the volcanic section northwest of the Corona High (Profile 2, Figure 4 and Profile 3, Figure 5), is complicated by what seems to be a gradual transition from a dominantly non-volcanic section adjacent to the ridge to an increasingly volcanically dominated section further west, until it is most likely purely volcanic across the East Faroe High. In order to be able to provide relevant units as input to potential field modelling, the base of the volcanic section has been chosen as the base of what is seen as the volcanically dominated section.

2.2.5 Basement

On the Fugloy Ridge (Profile 5, Figure 7), a reflection at 6-7 seconds TWT can be interpreted on survey ST09004, which covers the eastern part of the Fugloy Ridge. This unit is faulted, and is assumed to represent metamorphic basement.

2.3 DEPTH CONVERSION

Within the study area, depth conversion of the seismic data presents a significant challenge due to the presence of a number of volcanic facies with differing seismic properties. As well as being comprised of subaerially-emplaced basalt flows, the lava succession includes units which flowed into water to form hyaloclastites, or else were emplaced under water to form pillow lavas. In conjunction with these processes arising from lava emplacement, ash and other ejected material often accompanied the volcanic eruptions. Further heterogeneity was introduced when volcanic deposits were exposed to weathering and sediment transport processes in the intervals between episodic volcanic activity.

Detailed depth conversion requires mapping the 3-D complexity of individual facies and construction of a corresponding seismic velocity grid. The construction of such elements requires interpretation over a dense network of seismic profiles, either a grid of 2-D lines or (preferably) 3-D seismic data, neither of which was available for this project. The depth conversion that was used is based on constant velocities within the mapped units, adjusted for regional facies variations (such as the transition from basalt to volcaniclastic units northwest of East Faroe High).

2.4 MODEL PROFILES – DISCUSSION OF INTERPRETATION

Five seismic profiles were selected for 2½ D potential field modelling based on location relative to structural features and availability and quality of regional seismic data long the profile.

2.4.1 Profile 1

Profile 1 (Figure 3) is located along a composite line, where the northwestern section is acquired as part of the ST0510 survey, and the southeastern section is part of the IS-FST-01 survey (Table

1). The line ties three key wells on the Faroese Continental Shelf, which intersected a southeastward-decreasing amount of basalt. Well 6005/13-1 (William) was terminated within the volcanic section after drilling more than 1.4 km of basaltic lithology, well 6005/15-1 (Longan) drilled two thin sections of basalt with thick siliciclastic sediments between, and well 6004/16-1z (Marjun) did not drill any extrusive volcanic units.

The base of the syn-breakup volcanic sequence has not been interpreted on the northeastern part of the profile due to poor data quality, but based on the regional interpretation only minor thickness variations are expected.

The top of the older basalt section (orange horizon) shows that the older basalt section thickens gradually between well 6005/15-1 (Longan) and 6005-13/1 (William). This unit is interpreted on the basis of changes in internal reflection character on either side, with the interpreted siliciclastic units exhibiting a dominantly layered section compared to a more chaotic reflection character of the interpreted volcanic units.

Base Basalt is seen as a higher reflectivity package unit underlying the pre-breakup volcanic section. The interpretation of this line is steered strongly by crossing seismic lines. Base basalt has only been interpreted towards the middle of the profile due to degrading data quality towards the northwest.

Data quality does not permit interpretation of deeper units.

2.4.2 Profile 2

Profile 2 (Figure 4) is located along a composite of two lines. The northwestern section is from the ST0510 survey, while the southeastern section is from the ST0107 survey (Table 1). There is a small data gap between the two profiles. No rapid depth and/or thickness changes are anticipated in the gap, which means that it does not present a weakness with regard to the input model for the potential field modelling.

The syn-breakup volcanic sequence (lying between the green and light blue horizons) exhibits only minor thickness variations across the profile. The base is constrained towards the northeast by a strong positive reflection and towards the southeast as a transition from plane-parallel unit above to a discontinuous unit below.

Base basalt (red horizon), is seen as a strong, relatively continuous reflection across the Heri High. Towards the southeast, the reflection character becomes more broken, but the transition is still quite easy to follow.

Data quality does not permit interpretation of deeper units.

2.4.3 Profile 3

Profile 3 (Figure 5) is located along a seismic line that was acquired as part of the IS-FST survey (Table 1).

The syn-breakup volcanic section only exhibits minor thickness variations on the northwestern part of the line, where the base (light blue horizon) is constrained by a high amplitude continuous reflection. Larger variations are expected towards the southeast due to the interpreted horizon reaching a hyaloclastite sequence. The transition from subaerial emplacement to shelfal deposition cannot be interpreted consistently on the available grid of 2D seismic data.

The pre-breakup volcanic section can be subdivided into a solid basalt section and a dominantly volcaniclastic section. The Lamba formation was drilled in the nearby Brugdan well, where the underlying volcanic section was shown to consist of volcaniclastic material. The volcaniclastic section only exhibits minor internal reflectivity. The base of the volcanic section (red horizon) is seen as a relatively strong reflection towards the northeast. This becomes less pronounced where the overlying basaltic unit consists of volcaniclastic material, most likely due to lower impedance contrast between the volcaniclastic section above and expected siliciclastic sedimentary section below. From the East Faroe High (structural high on all interpreted units) and southeastwards, the base of the basalt is interpreted as a facies change from a section dominated by volcanic material, to a section dominated by non-volcanic material. The horizon is therefore not expected to represent a chronostratigraphic surface in this area.

There are hints of deeper units, but it has not been possible to map these in detail in this area.

2.4.4 Profile 4

Profile 4 (Figure 6) is located along a composite line, where the northwestern section was acquired as part of the ST0513 survey while the southeastern section is acquired as part of the ST0514 survey (Table 1).

The base of syn-breakup section (blue horizon) is only clearly visible in the southeastern slope of the Fugloy Ridge. A dashed line shows where adjacent lines indicate it is. There are only minor variations in the thickness along the profile. Larger variations are expected towards the southwest due to the interpreted horizon reaching a hyaloclastite sequence. The transition from subaerial emplacement to shelfal deposition cannot be interpreted consistently on the available grid of 2D seismic data.

On the northwestern section of the profile, the base basalt horizon is seen as a slight change to a unit with stronger reflections. On the southeastern section, it is seen as a strong continuous reflection until it disappears in a hummocky reflection unit at that end of the line. An intra-volcanic mounded unit can be interpreted on a few lines. The seismic data do not permit further characterisation of this unit.

Deeper units cannot be interpreted consistently along the profile. A sub-basalt feature (light purple horizon) across the east Faroe High is based on crossing seismic lines from another survey. The interpretation has not been extended away from the East Faroe High because it is difficult to distinguish between signal and noise (primarily multiple energy) in those areas.

2.4.5 Profile 5

Profile 5 (Figure 7) is located along a seismic section from the ST09004 survey (Table 1)

The base of the syn-breakup volcanic sequence is seen as a continuous reflection along most of the profile. At the northwestern end it is intersected by the inner seaward dipping reflection sequence, which marks the start of the transition to oceanic crust. The interpretation is discontinued at the southeastern end due to uncertainty of whether it continues on top of the hyaloclastite sequence or follows a palaeoshoreline to the base of the hyaloclastite sequence as seen on profiles 4 and 5.

The pre-breakup sequence can be subdivided into three discrete units. The top of the Lamba Formation is seen as a strong reflection across the profile. Between the syn-breakup volcanics and the Lamba formation, most of the section consists of hyaloclastites. It is possible to map a unit between the top Lamba Formation (light blue-green horizon) and the base basalt (red horizon). This is tentatively referred to as the base-Lamba Formation (dashed orange horizon). It is not possible to characterise this unit further based on seismic data. Base Basalt is seen as a transition into a series of strong reflections. At the central part of the ridge, these seem to consist of intrusive units.

A pre-breakup unit has been interpreted (light purple horizon) on this seismic survey. This unit is the deepest mappable unit, and is therefore referred to as basement.

3 Potential field interpretation

3.1 GRAVITY AND MAGNETIC DATA SOURCES

The gravity compilation employed was generated by Kimbell et al. (2010) as part of the process of building a 3-D gravity model of the Faroe-Shetland region. Data for the study area were extracted from grids derived from the FSC gravity compilation, and along-line data for each of the profiles was sampled from the grids..

The magnetic compilation that was used is a combination of aeromagnetic and marine data assembled in Phase 2 as part of the project to examine the magnetic signatures of Palaeogene igneous rocks in the Faroe-Shetland area (Kimbell, 2014). Gravity and magnetic data along each model profile were extracted from a grid of these data.

3.2 PHYSICAL PROPERTIES

3.2.1 Post-basalt sediments

Kimbell et al. (2010) reviewed wireline measurements of the density of Cenozoic sediments when building the 3-D gravity model of the Faroe-Shetland area. Given the evident effects of compaction seen in those wells, they established a methodology for extending the values across the entire region.

The end-result of this process is a density distribution for post-basalt sediments that varies both laterally and vertically, approximated in the 3-D model by a number of grids that when taken together make up the model of this sedimentary sequence. In terms of 2-D modelling, this structure of variation is difficult to incorporate into a model where the polygons represent areas having a constant density and therefore requires a different approach. The 3-D model was therefore used to compute the gravity anomaly with both constant and laterally-varying densities, and to take the difference between these responses. The difference grid was then subtracted from the observed anomaly grid to give a reduced gravity anomaly in which the effect of compaction in has been removed and can be modelled with a single density, which was set at 2.0 $Mg.m^{-3}$.

3.2.2 Volcanic rocks

The 3-D model of the Faroe-Shetland Basin uses a laterally-varying lava density based on a compaction trend established for the volcanic rocks. This approach of using a laterally-varying basalt density was not taken for the profile modelling because the thickness control is better established, and there is therefore a reduced need to account for varying proportions of low density material by varying the bulk density (this is especially true where the lavas become thin approaching the feather-edge). The density of the volcanic rocks was taken as a constant value of 2.7 $Mg.m^{-3}$ or 2.8 $Mg.m^{-3}$.

In terms of magnetic properties, the lavas were modelled as strongly remanent bodies (remanent field strength of 3 $A.m^{-1}$) with a reverse-normal-reverse magnetic stratigraphy for the main formations (Kimbell, 2014). A susceptibility of 0.02 SI was also assigned to the lavas to reproduce the magnetisation component induced in the direction of the Earth's present field. In places, the lavas are of hyaloclastite facies, characterised by having no remanent magnetisation and low magnetic susceptibility.

3.2.3 Pre-basalt sediments

There is limited information on the sedimentary rocks occurring at depth beneath the basalts. These were assigned a constant density of 2.5 $Mg.m^{-3}$, which is a value that is more appropriate to porous sandstones at depths greater than 3 km than to mudstones, and arguably may be on the low side.

3.2.4 Upper crust

Following the 3-D gravity model, the basement was assigned a constant density of 2.75 $Mg.m^{-3}$ and a susceptibility of 0.02 SI. It is assumed that the basement is magnetised in the direction of the Earth's present-day field.

3.2.5 Lower crust

Consistent with the 3-D model, the lower crust was given a constant density of 2.95 $Mg.m^{-3}$.

3.2.6 Upper mantle

In the 3-D model of the Faroe-Shetland region, upper mantle densities vary across the transition between oceanic and continental temperature regimes across a ramp extending from 75 km oceanward of the continent-ocean boundary to 100 km landward of the boundary, with the base of the zone of variable upper-mantle densities being set at a depth of 125 km. Analogously to how the effects of post-basalt sediment compaction were allowed for, the gravity response of the model was calculated for both variable and constant mantle densities, with the difference being subtracted from the compaction-corrected anomaly grid. The models were built using this reduced anomaly with a constant mantle density of 3.3 $Mg.m^{-3}$.

3.3 ASSEMBLING THE PROFILE MODELS

For each of the five model profiles, depth-converted interpretations of the reflection seismic data were supplied in digital form. The top and base basalt picks were uniformly present, with other picks being present to a greater or lesser extent along the length of the profile, depending on the quality of the data. These picks were georeferenced and imported into Geosoft GM-SYS Profile. The interfaces arising from seismic interpretation are very closely-sampled, and a line-simplification algorithm was selectively applied in order to reduce the number of model vertices while retaining the overall geometric character of the horizons. Deep crustal horizons (modelled top basement, mid-crust and Moho) along each profile were set by sampling the 3-D model of the Faroe-Shetland area (Kimbell et al., 2010). The top basement obtained by this method was in each case used only as the starting point for subsequent 2-D modelling and in each case was modified significantly during the modelling process to honour the new seismic interpretation.

3.4 MODELS

3.4.1 Profile 1

Profile 1 (Figure 8a) extends NW-SE from the margins of the Munkagrunnur Ridge southwest of Suðuroy into the Judd Basin. Elevated basement of the Munkagrunnur Ridge lies at the extreme NW end of the profile, which falls away to the Grani Fault Terrace. The pronounced gravity anomaly near km 50 is associated with the Frænir Igneous Centre (FIC), which lies just off line to the southwest. In order to account for this it has been modelled as a "2-¾-D" feature, with most of the body that gives rise to the gravity anomaly lying off profile. As is evident from the magnetic profile, and confirmed by the map data, there is little evidence of a magnetic anomaly associated with this intrusion. Southwest of the FIC the basement is modelled as stepping down into the basin, with the Sjúrður Ridge forming a basement high around km 98, before the line terminates in the Judd Basin.

Well 6005/13-1 (William), three kilometres off-profile to the SW at km 68, terminates in hyaloclastite lavas at 3358 m TVDSS, with the interpreted base of the lavas at the projected location of this well at about 5600 m from seismic interpretation. Well 6005/15-1 (Longan) lies very close to the profile at km 98, on the interpreted crest of the Sjúrður Ridge. This well shows two basalt layers separated by volcaniclastic sedimentary rocks, before terminating in volcanic rocks at 3994 m TVDSS. The seismic interpretation above places this close to the base of the lavas, which have an interpreted base of about 4000 m at this location. Finally, well 6004/16-1

(Marjun), which lies close to the SW end of the profile, proves a thick sedimentary succession with no volcanic rocks.

The prominent magnetic anomaly at km 28 is the expression on this profile of the Annika anomaly. Modelling of this feature has followed Smallwood et al. (2001) by accounting for it in terms of variations in thickness of a normally-magnetised package of lavas within a reversely-magnetised sequence. Seismic interpretation shows no reflection features that may be directly associated with this thickness-change interpretation, however, although changes in reflection character may give indications of a change in magnetic properties within the basalt sequence.

3.4.2 Profile 2

Profile 2 (Figure 8b) is a NW-SE trending profile that originates in the Annika Sub-Basin, crosses the Heri High and the Grimhild Sub-Basin before terminating on the Mid Faroe High. Well control on this profile is from 6004/8a-1 (Anne Marie) which lies close (12 km) to the SE end of the seismic profile (2 km from the end of the model). This well penetrated a 319 m thick upper lava sequence separated from a 233 m thick lower lava sequence by a 429 m thick sequence of tuffs and volcaniclastic sediments.

The interpretation of the magnetic anomalies along the profile is guided by models E and F from the 'magnetic signatures' report (Kimbell, 2014), lying respectively to the southwest and northeast of the profile. The model shows the lowermost part of the lavas as hyaloclastites from about km 53 to the end of the profile. The Annika anomaly at around km 24 is modelled in terms of thickness variations of a normally-magnetised package of lavas sandwiched between reversely magnetised units, although a greater thickness of these is required in this profile in comparison to Profile 1.

Elevated magnetic basement of the Heri High is indicated at around km 42, and the model terminates at its SW end on the Mid-Faroe High. With a susceptibility of 0.02 SI, at the modelled basement depths of around eight to ten kilometres, the effect of variations in the basement level is to generate comparatively long-wavelength anomalies that are superimposed on the higher-frequency anomalies that arise from structures close to the seabed (for example within the lavas, or due to variations in the surface topography of the basalts). Modelling the basement at such depths is mandated by interpretation of the base basalt at depths of up 9000 m at the NW end of the profile

3.4.3 Profile 3

Profile 3 (Figure 9a) is a roughly east-west profile originating in the Annika Sub-Basin, crossing the Tróndur High and the Brynhild Sub-Basin and terminating on the flanks of the Corona High. There is no well control on this line, although some constraint is provided by well 6104/21-1 (Brugdan) lying about 12.5 km to the south at km 34. The start of the profile is marked by high magnetic anomaly values associated with the Annika anomaly and the magnetic high at the end of the profile is associated with elevated magnetic basement of the Corona High,

In between the extremes of the profile, the magnetics form a relative high near km 65 that is not associated with a gravity anomaly, and this has been modelled as due to elevated basement, with the basement high helping to match the slope of the gravity anomaly.

The gravity high that is observed near km 30 is associated with the mapped East Faroe High (EFH) and is associated not with a magnetic high, but rather a magnetic low. This is difficult to explain in terms of relative elevations of (normally) magnetised basement, and the approach taken has been to place its source in property variations within the lavas, i.e. a relatively thick sequence of reversely magnetised basalts beneath the EFH, including a substantial pre-Lamba component.

3.4.4 Profile 4

Profile 4 (Figure 9b) extends NW-SE from the Fugloy Ridge into the Steinvar Sub-Basin, crossing the Tróndur High (TH) and the East Faroe High (EFH) into the Corona Basin. There is no well control of this profile.

The profile crosses the interpreted TH at km 80, where the interpreted base basalt is at about 7500 m, and there is no significant gravity anomaly. The mapped EFH lies at about km 98 beneath some 6000 m of basalt. The gravity anomaly associated with this feature is seen to coincide with a topographic high in the top basalt surface, which is also spatially coincident with a magnetic high. This apparent contradiction is resolved by thickening the hyaloclastite sequence beneath the basalt high, and there is some evidence to support this in the seismic data, which show intra-basalt seismic progrades (Figure 6),

There is little potential field evidence for the TH on this profile, and although it is shown as a basement feature it acts to generate relatively long wavelength anomalies. The gravity anomaly associated with the EFH is seen to be largely accounted for by variation in the top basalt surface, and hence the magnetic anomaly is modelled as arising from variations in the magnetic properties of the lavas.

3.4.5 Profile 5

Profile 5 (Figure 10; Figure 7) extends NW-SE across the Fugloy Ridge, from the continent-ocean transition zone into the northwest Corona Basin. The northwest end of this profile is marked by a thick volcanic sequence that is interpreted to extend to over 10 km depth, while at its southeast end the base of the lavas is still at around 6 km. There is no well control of this profile. The pattern of gravity anomalies observed along the profile is largely accounted for by crustal thickness variations and inferred lower-crustal density changes associated with the zone of transition between continental and oceanic crust. The interpretation of crustal density variations is guided by the velocity structure determined for the iSIMM profile (Roberts et al., 2009) lying some 50 km to the SW. Here, layered high-velocity lower crust in the zone between continental and oceanic crust was interpreted as due to intrusions into lower crust of continental type. On the iSIMM profile, the zone of transition is seen to be only 50 km wide, and the interpretation of the profile has sought to honour this observation.

Along its strike, the Fugloy Ridge is seen to be generally characterised magnetically by a magnetic low, which in terms of reversely magnetised lavas qualitatively suggests a thickening of the reversely-magnetised sequence (shown in blue). It should be noted that there is poor magnetic data in this area that mean that any sharp inflections of the observed magnetic data will have been missed. Given the interpreted picks of the base of the post-rift lavas along this profile, which are assumed to mark the top of normally-magnetised basalts, this is hard to model quantitatively using the generally assumed properties for volcanic rocks. This was modelled by effectively thickening the upper sequence of reversely-magnetised rocks by insertion of a non-magnetic unit that thickens towards the ends of the profile - this is not directly supported by seismic interpretation, but is inserted to account for the magnetic signature. The lower basalt sequence has also been reduced in remanent magnetisation, from 3 $A.m^{-1}$ to 1 $A.m^{-1}$. This interpretation could be contrasted with the interpretation of profiles L and M in the magnetic signatures project (Kimbell, 2014), where a similar configuration was modelled in terms of a change in magnetic polarity within the seaward-sipping reflectors, but the common feature of both is the identification of reversely magnetised basalts on the Fugloy Ridge.

4 Discussion

4.1 THE HERI HIGH, TRÓNDUR HIGH AND EAST FAROE HIGH

On the structural elements map (Figure 1), the Heri High (HH), Tróndur High (TH) and East Faroe High (EFH) form a branching network of narrow basement highs oriented approximately SW to NE. The TH and EFH are described by Keser Neish (2005), where the base basalt reflector on their profile E is at about 2.5 s and 3 s TWT over the TH and EFH respectively, with the deepest sub-basalt reflector (tentatively identified as the basement) at about 4.25 s TWT. In contrast, the current interpretation of the reflection seismic data places the base basalt over the TH at 3.5 s TWT on Profile 3, with no reflectors interpreted beneath the base basalt. On Profile 4 the base basalt over the TH and EFH is at about 4 s TWT, with a reflector at 5 s TWT possibly forming the basement underneath the EFH. There is therefore limited seismic evidence for these structural features.

The residual gravity anomaly maps (Figure 10 and Figure 11) show a belt of positive anomalies that have been correlated with the HH, EFH and TH and help to inform their position. Comparison of the top basalt surface from the current interpretation with the residual gravity anomaly map shows that the positive anomalies coincide spatially with ridges in the top basalt that give rise to gravity highs due to the (assumed) high density contrast between the lavas and the overlying sediments. Examination of the magnetic anomaly maps (Figure 13 and Figure 14) show that a belt of negative magnetic anomalies is broadly coincident with the residual gravity highs: intuitively this seems logical, in that elevated reversely-magnetised lavas give rise to a negative anomaly, but quantitatively it is difficult to explain without varying the properties of intra-basalt facies. It is also noted that an elevated normally-magnetised basement ridge lying below the basalt will not in general give rise to a negative magnetic anomaly

In fact the 3-D gravity model of Kimbell et al. (2010) illustrates the uncertainty around the definition of the basement highs in the area of interest (Figure 2). In this three-dimensional model, the basement structure beneath the EFH is somewhat unclear on Figure 2, largely because the gravity anomaly that defines the EFH is accounted for by the relief on the top basalt surface, leaving little anomaly remaining to be optimised in terms of basement relief (his discrepancy is especially prominent towards the northeast of the EFH).

In conclusion therefore, from this modelling there is uncertainty about the definition of the EFH and associated structures as basement features, as they are not clear on seismic interpretations and on gravity grounds seem not to be necessary to explain the observed gravity anomalies.

4.2 THE ANNIKA ANOMALY

The ‘Annika Anomaly’ is a prominent positive magnetic feature that extends north-eastwards across the Annika Sub-basin (Figure 13 and Figure 14). It is approximately parallel with the mapped structural high marking the south-east side of the basin, but is offset to the north-west. The overall form of the anomaly is a magnetic high, more prominent in the southwest, superimposed upon a ‘step-down’ in magnetic values towards the southeast.

Previous attempts at modelling the source of the Annika Anomaly have included both deep-seated intrusive bodies (Sweetman, 1997) and variation of magnetic properties within a relatively thin volcanic sequence (Smallwood et al., 2001).

Modelling the anomaly in terms of a narrow, normally magnetised source is difficult, because such a source geometry would generate a magnetic low on its north-western side, which does not fit with the observations. A better fit is obtained if such a source extends towards the north-west, and given that there is good evidence for normally magnetised units within the upper part of the Beinisvørð Formation on the Faroe Platform it is persuasive to link the anomaly to the south-eastward truncation of such rocks. Those parts of the anomaly where the discrete high has a larger amplitude are difficult to explain using a simple ‘edge of sheet’ effect, suggesting local thickening of normally magnetised unit rocks (and/or thinning of reversely magnetised units) in such areas. The amplitude of magnetic lows on the southeast side of the Annika Anomaly suggests thickening of the reversely magnetised part of the volcanic sequence in this area.

In light of the above discussion, the Annika Anomaly has been modelled in terms of interaction between the normally and reversely magnetised parts of the volcanic sequence. The implication is that the anomaly marks the original location of a physical barrier to the spread of the basalts at the time of eruption of the normally magnetised sequence, and that the volcanic rocks extending farther to the southeast would be representatives of younger units that finally overspilled the barrier. As noted by Kimbell (2014), there is biostratigraphic evidence for lavas of Beinisvørð Formation affinity within the UK sector (205/9-1; Ellis et al., 2002), which require an alternative emplacement mechanism if the hypothesis is to be sustained (for example eruption from a local vent, or bypassing the barrier in some way).

4.3 MAGNETIC ANOMALIES SOUTHEAST OF THE EAST FAROE HIGH

The belt of positive magnetic anomalies southeast of the EFH (Figure 13 and Figure 14) is offset relative to the mapped basement high. The discussion in section 4.3 has indicated that the seismic evidence for the EFH is weak, and that the potential field data do not need the EFH as a basement high in order to match the anomalies. It is therefore possible that these anomalies arise from intra-basalt property variations (analogous to the modelled Annika anomaly). Kimbell (2014) demonstrated the presence of a R-N-R polarity of magnetisation in the onshore Faroes, and has shown how this can generate some of the major features of the observed magnetic anomalies. It is possible that the shorter-wavelength magnetic anomalies between the Annika Anomaly and the Corona High have their source in property variations within the basalts, but the origin of the longer wavelength component remains open to interpretation as due to deep basement features.

5 Conclusions

1. Interpretation of seismic profiles southeast of the Faroe Islands has indicated a thick sequence of basalts (base of basalt at about 4 s TWT), including units both above and below the Lamba Shale Formation. This interpretation contrasts with previous published interpretations (e.g. Keser Neish, 2005), which interpreted only one lava unit, placing its base at about 2.5 to 3 s TWT. Reflectors lying below the base basalt have not been identified
2. Potential field modelling along five of these profiles indicates that identification of the branching network of basement highs southeast of the Faroe Islands is not well supported by the observed gravity anomalies, which appear to be largely due to relief in the top basalt surface.
3. The present modelling suggests that the shorter-wavelength component of the belt of magnetic anomalies situated between the Annika anomaly and the Corona High is due to intra-basalt property variations, but the presence of a longer-wavelength component that is due to deeply-buried basement cannot be fully ruled out.
4. In the light of these results, the structure map in the area SE of the Faroe Islands may need revision in terms of the location of the HH, TH and EFH.

Appendix 1 Abbreviated names of structural features

The table below listing abbreviations for structural features in the study area uses nomenclature from Quinn et al (2014).

ANB	Annika Sub-Basin
BB	Brynhild Sub-Basin
CB	Corona Basin
CH	Corona High
CLB	Clair Basin
COT	Continent-Ocean transition
EFH	East Faroe High
FH	Flett High
FIC	Fraenir Igneous Centre
FLB	Flett Sub-Basin
FOB	Foula Sub-Basin
FOH	Foula High
FT	Flett Terrace
FYR	Fugloy Ridge
GB	Grimhild Sub-Basin
GDN	Guðrun Sub-Basin
GFT	Grani Fault Terrace Terrace
HH	Heri High
JB	Judd Basin
MFH	Mid-Faroes High
MR	Munkagrunnur Ridge
SR	Sjúrður Ridge
STB	Steinvar Sub-Basin
TH	Tróndur High
WH	Westray High
WSH	West Shetland High
WSHB	West Shetland Basin

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The British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

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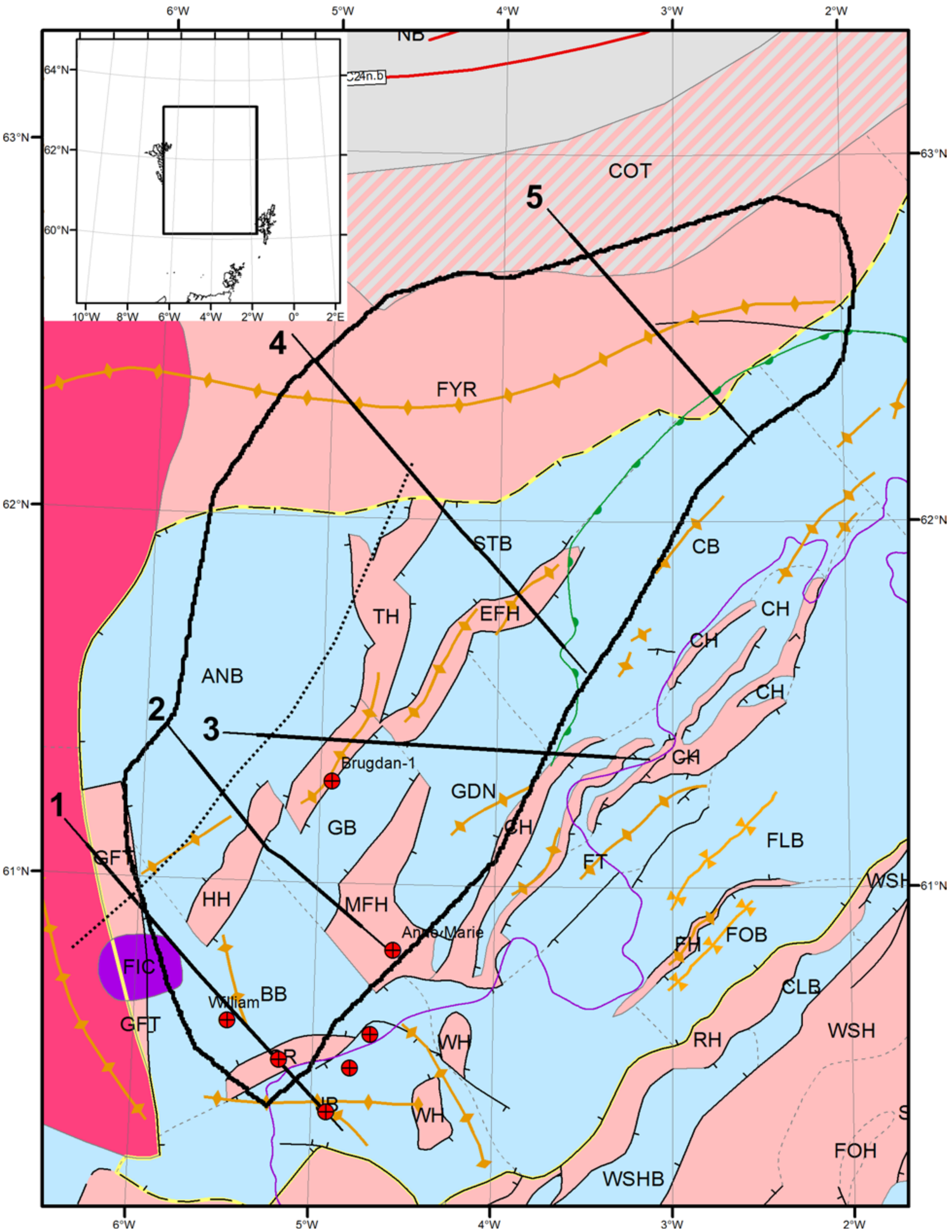


Figure 1 Structural element map (after Quinn et al., 2014) showing the locations of the five modelled profiles SE of the Faroe Islands: the thick line style illustrates the extent of seismic coverage on each line. See Appendix 1 for explanation of abbreviations. The polygon shows the areal extent of basalt top and base information from new seismic interpretation, and the dashed line shows the extent of the 'Annika Anomaly'. The inset shows the general location of the study area)

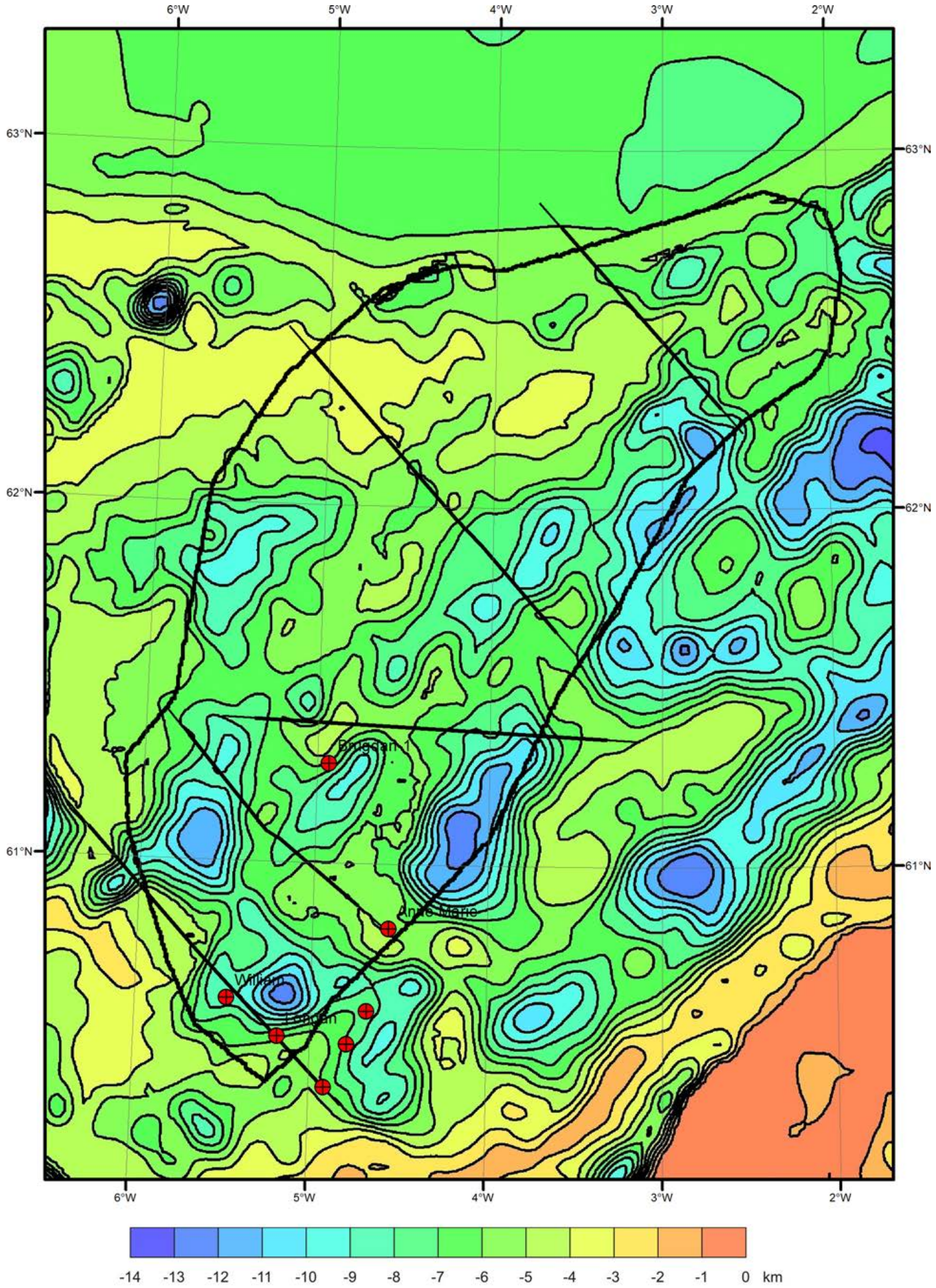


Figure 2 Optimised depth to top basement from the 3-D gravity model of the Faroe-Shetland area. The polygon shows the extent of basalt top and base information from new seismic interpretation.

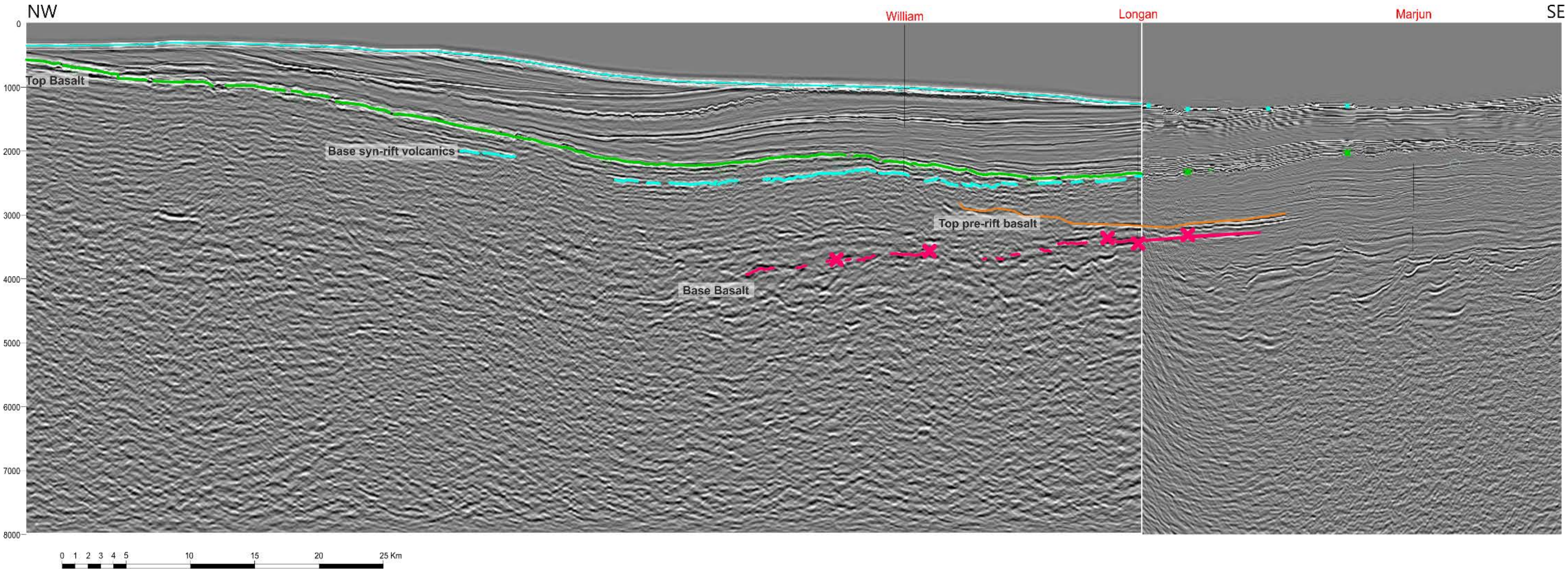


Figure 3 Seismic interpretation of profile 1

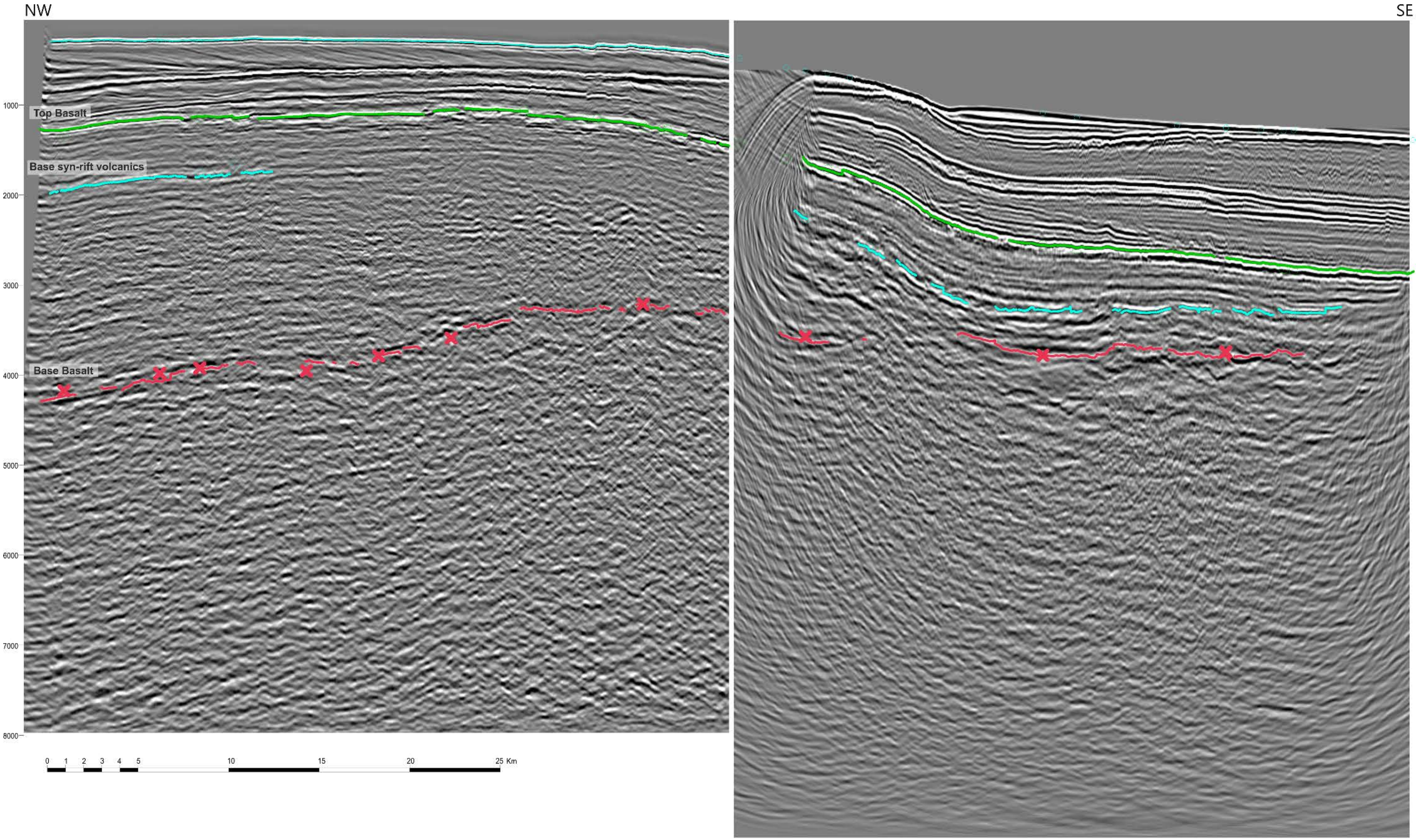


Figure 4 Seismic interpretation of profile 2

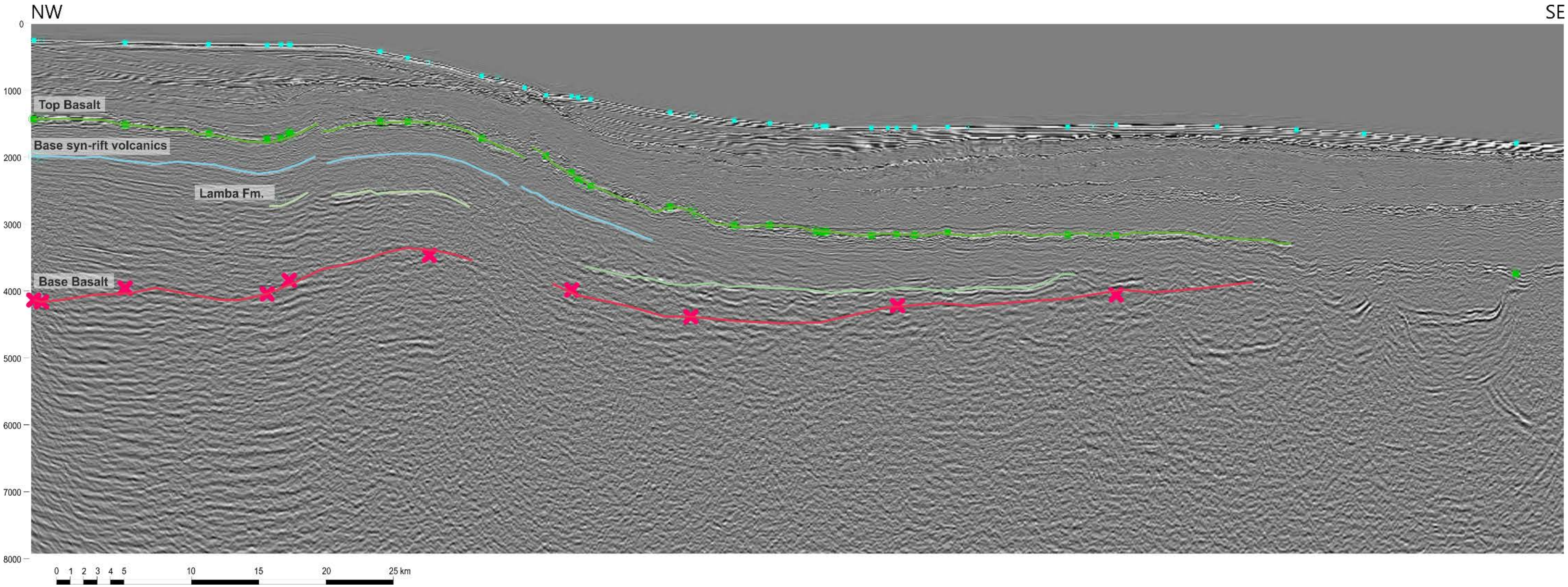


Figure 5 Seismic interpretation of profile 3

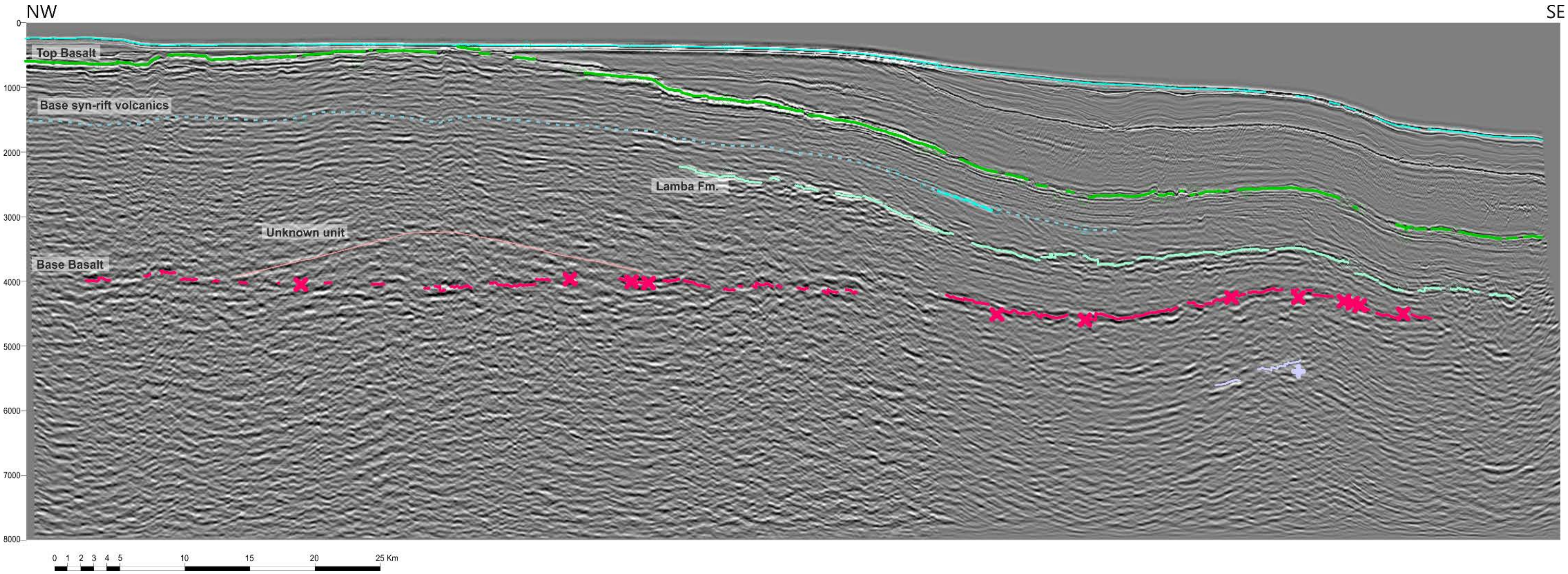


Figure 6 Seismic interpretation of profile 4

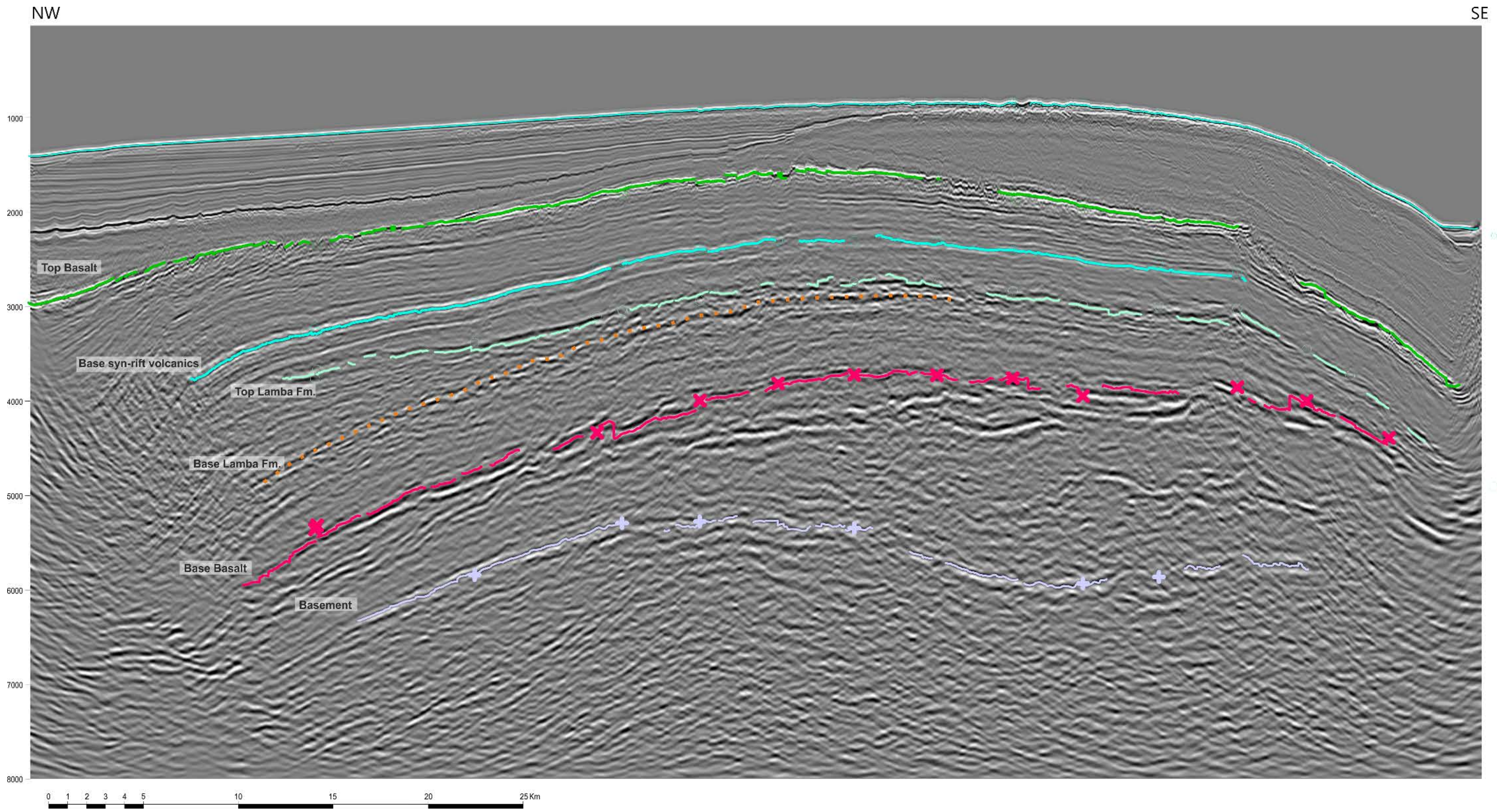


Figure 7 Seismic interpretation of profile 5

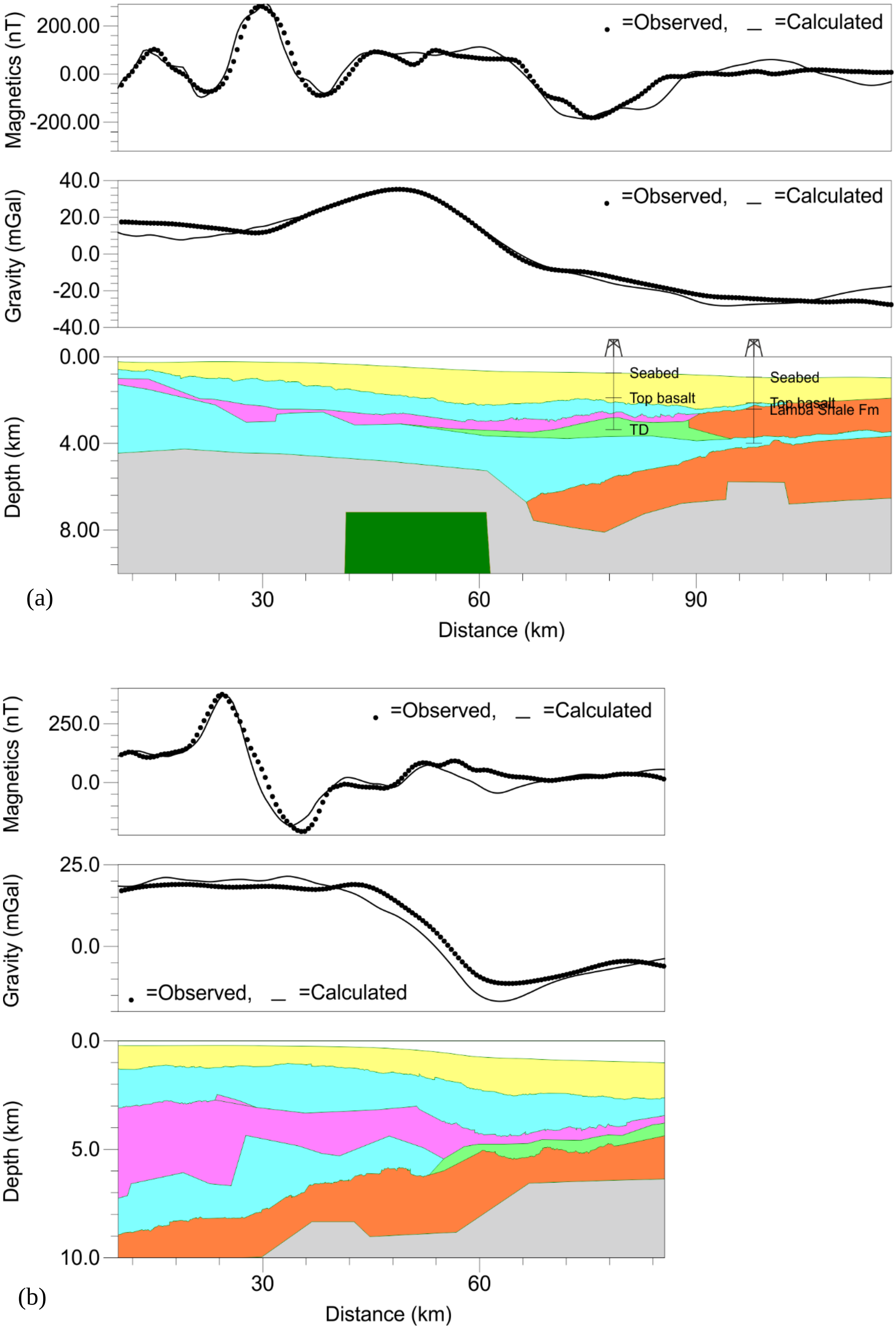
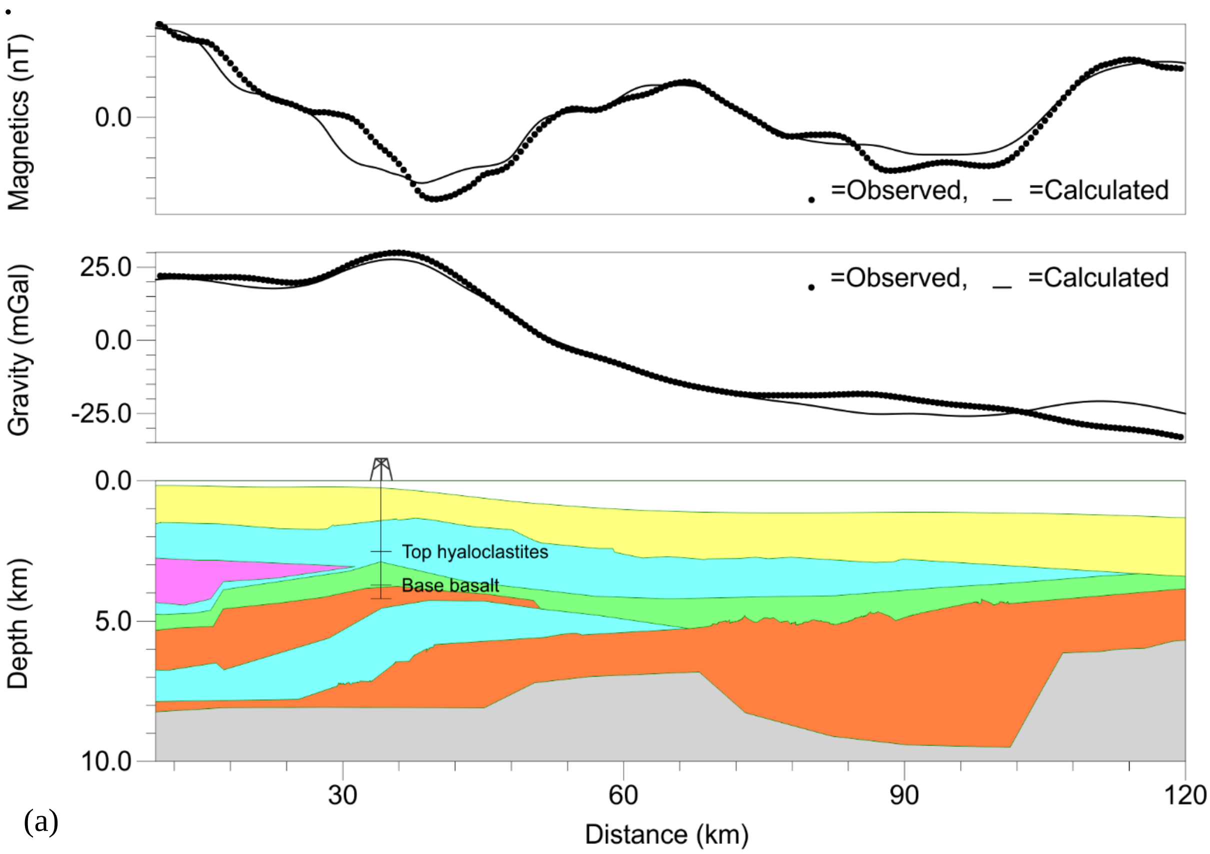
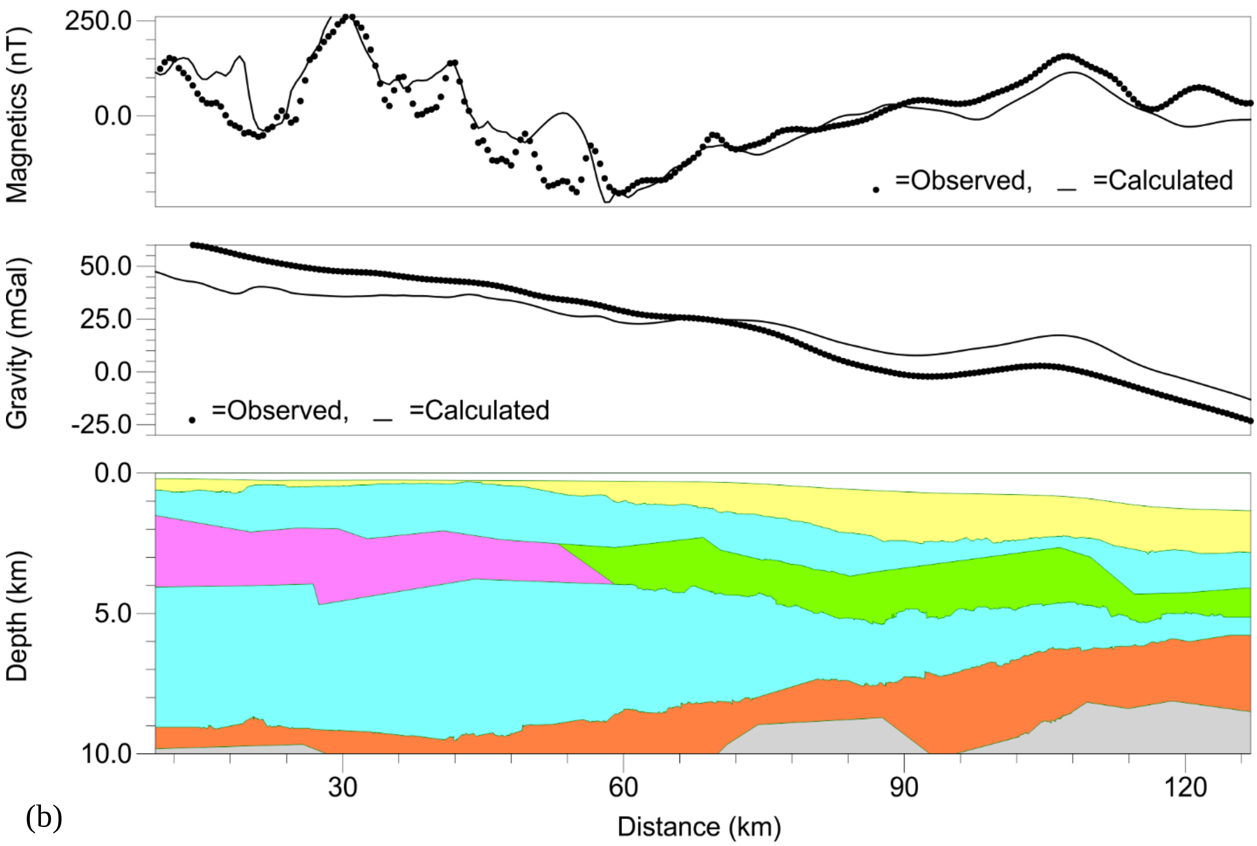


Figure 8 Potential field interpretations of (a) Profile 1 and (b) Profile 2. Post-basalt sediments are shown in yellow, reversely-magnetised volcanic rocks in blue, normally-magnetised volcanic rocks in pink and older sedimentary rocks in orange. Hyaloclastite facies volcanic rocks (green) have no remanent magnetisation. Basement rocks are shown in grey.



(a)



(b)

Figure 9 Potential field interpretations of (a) profile 3 and (b) profile 4. Post-basalt sediments are shown in yellow, reversely magnetised volcanic rocks in blue, normally-magnetised volcanic rocks in pink and older sedimentary rocks in orange. Hyaloclastite

facies volcanic rocks (green) have no remanent magnetisation. Basement rocks are shown in grey.

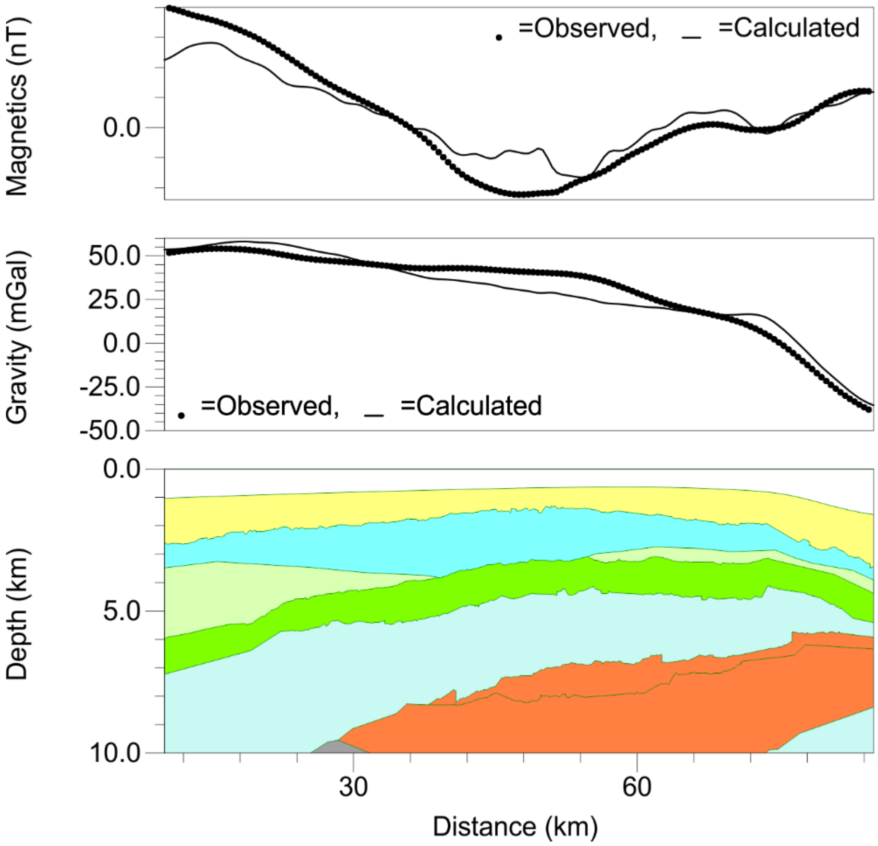


Figure 10 Potential field interpretation of profile 5. Post-basalt sediments are shown in yellow, reversely magnetised volcanic rocks in blue and older sediments in orange (includes the pre-basalt and pre-rift successions, separated by the line shown). Hyaloclastite facies volcanic rocks (green) have no remanent magnetisation - in order to explain the pattern of magnetic anomalies, the overlying pale green unit has been introduced that also has no remanent magnetisation. The lower lava unit (pale blue) has a lower value of reversely-oriented remanent magnetisation than the other profiles (1 A.m^{-1}).

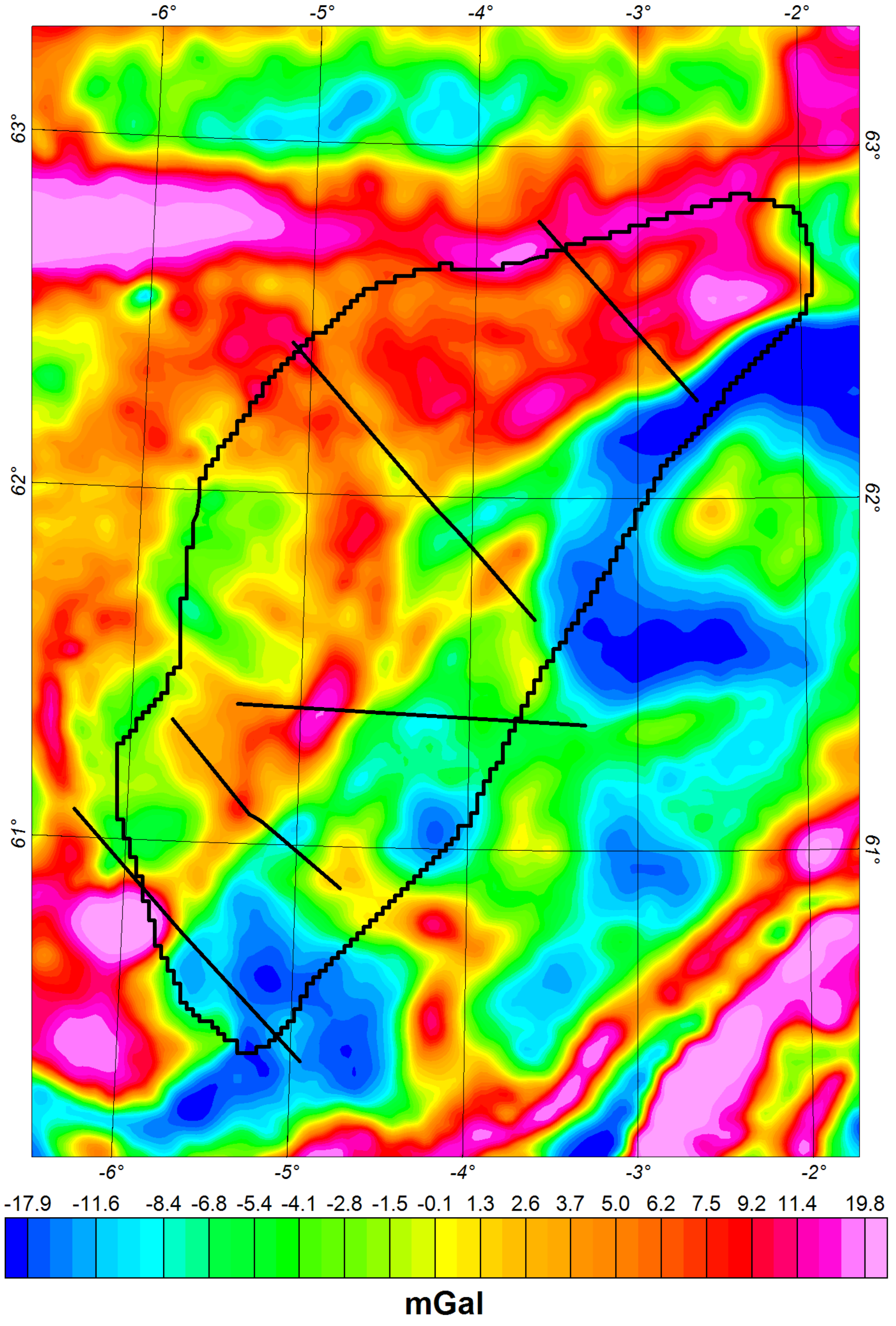


Figure 11 Residual gravity anomaly after subtraction of 10 km upward-continued field, showing the locations of the five profiles. The polygon indicates the extent over which basalt thickness was mapped for the present project.

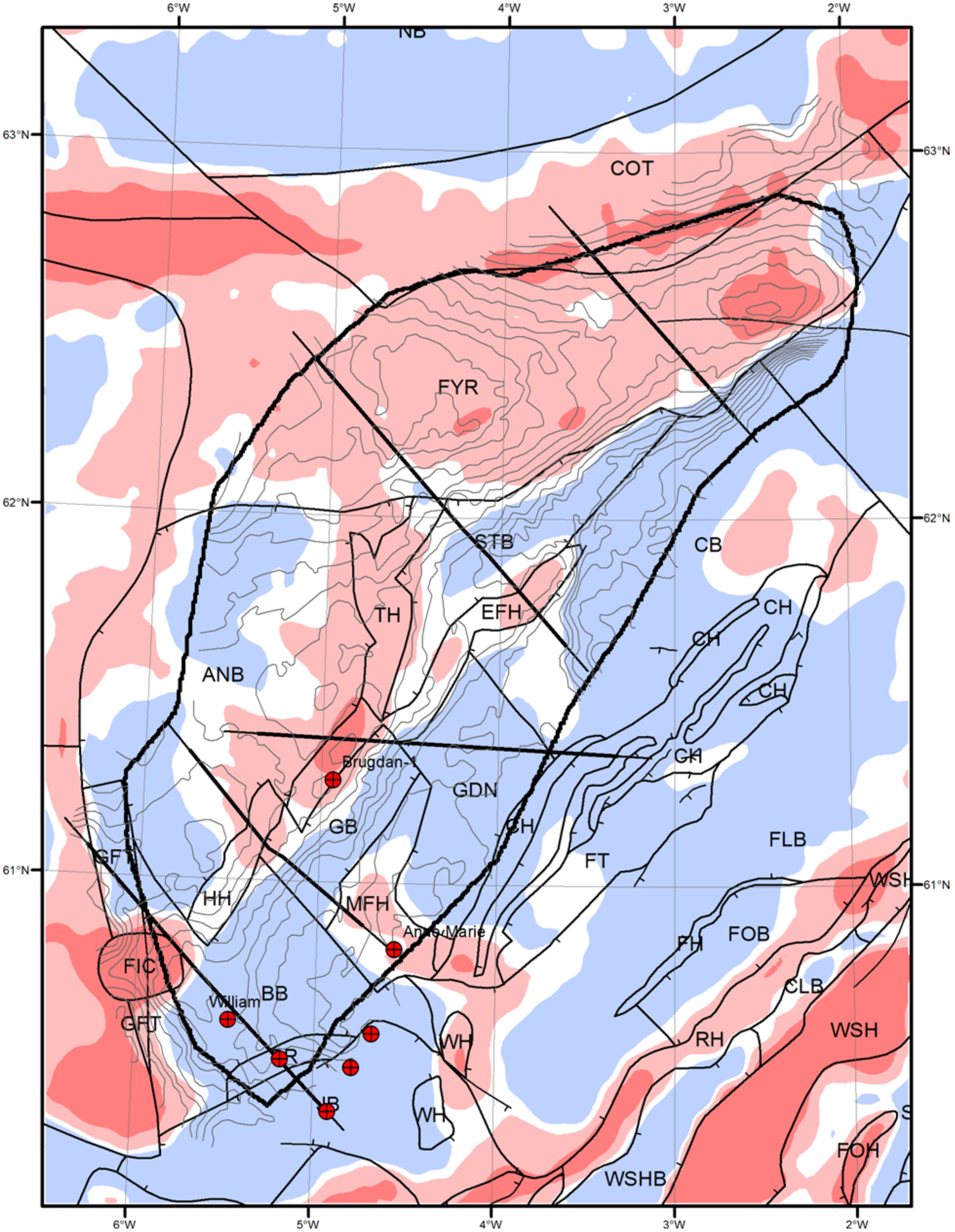


Figure 12 Summary of features on the residual gravity map, overlain by structural elements labelled as in Appendix 1. Red colours correspond to residual gravity highs and blue colours to residual lows. Wells are indicated by red symbols. Contours are at 200 m contours on the top basalt surface, showing the spatial coincidence between top basalt and gravity highs over the East Faroe High (EFH) the extent over which basalt thickness was mapped for the present project.

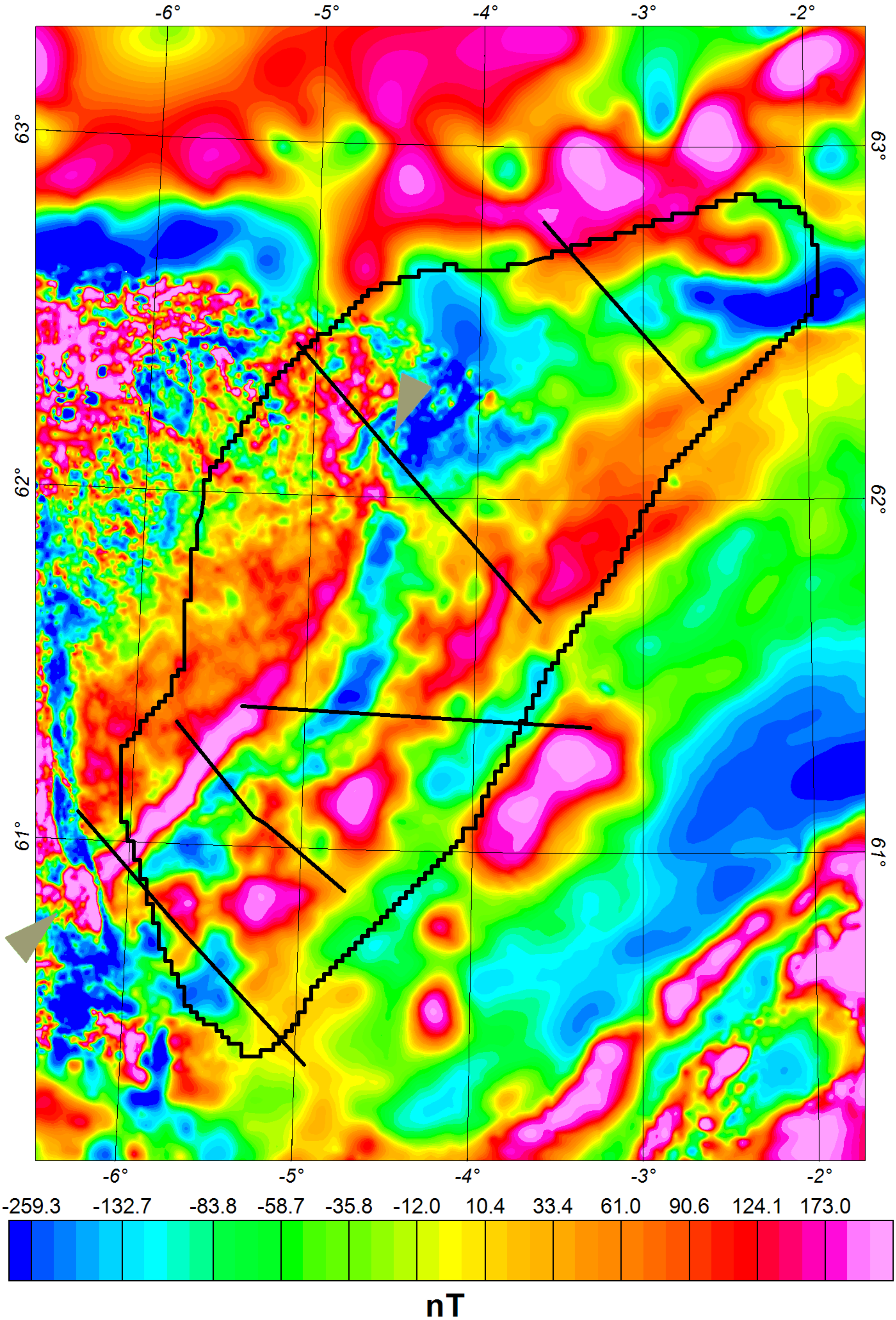


Figure 13 Observed magnetic anomaly (TMI), showing the locations of the five profiles. The polygon indicates the mapped extent of basalt thickness. Arrows indicate the extent of the 'Annika Anomaly' in the study area.

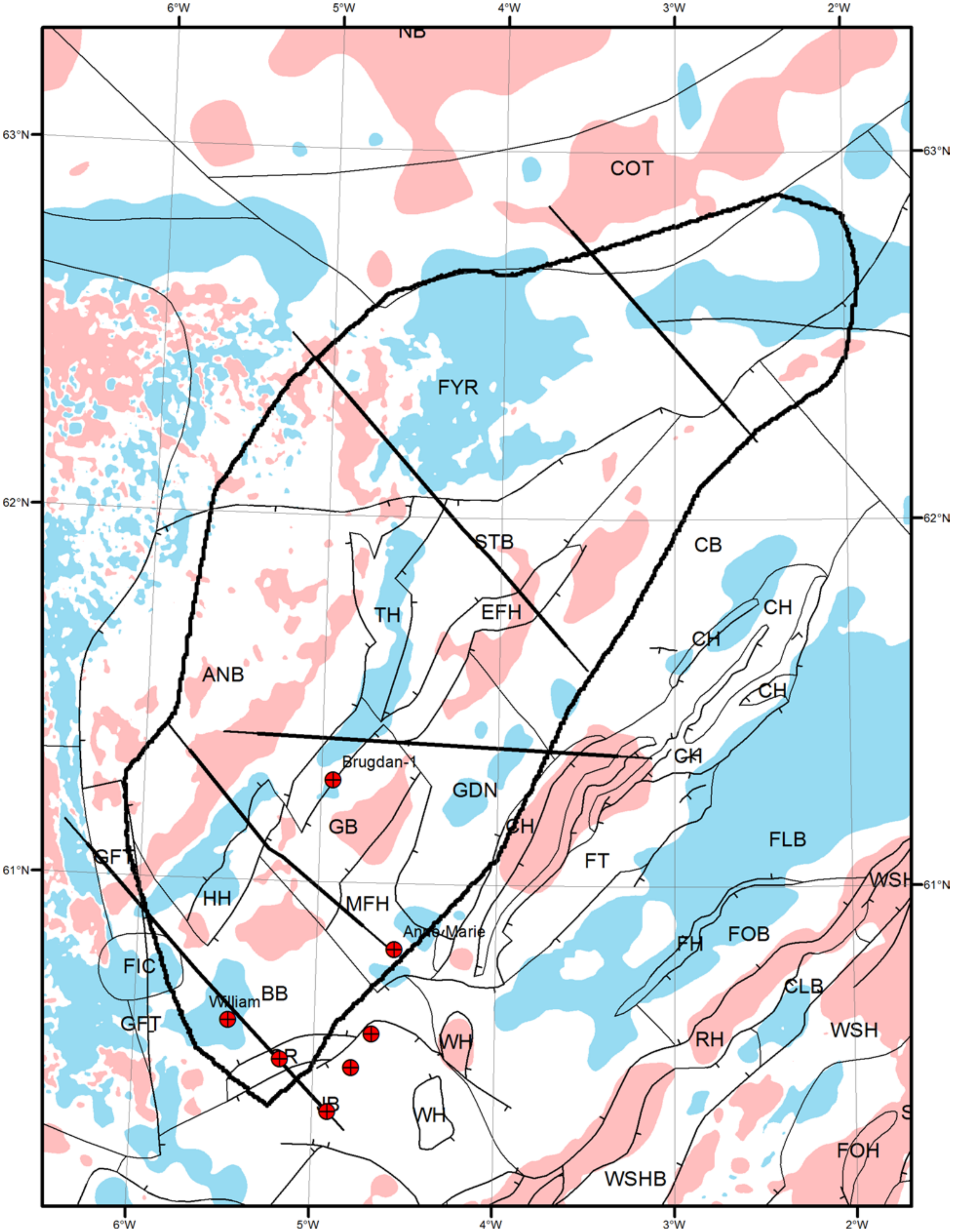


Figure 14 Summary of features on the magnetic anomaly map, overlain by structural elements labelled as in Appendix 1. Red colours correspond to residual magnetic highs and blue colours to residual lows. Wells are indicated by red symbols.