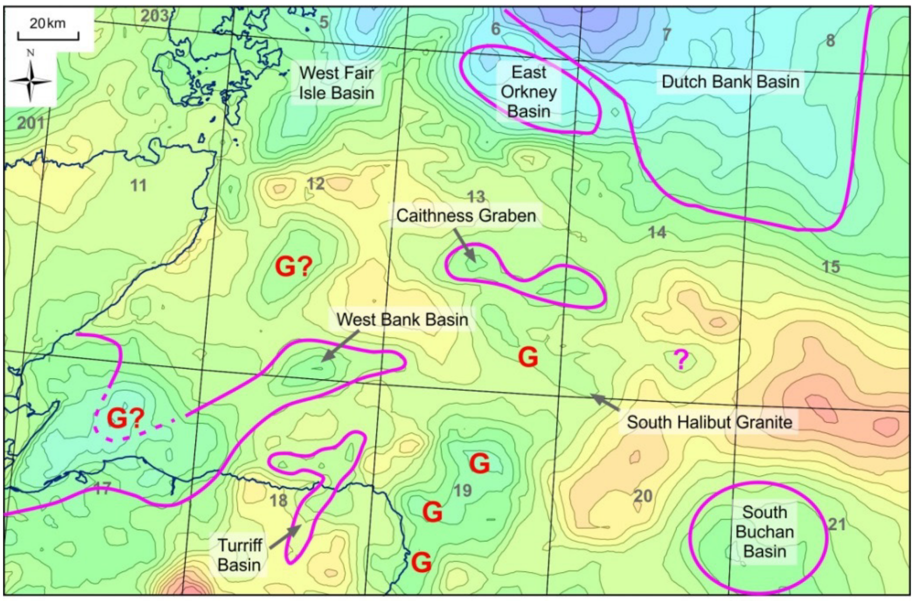
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

A gravity interpretation of the Orcadian Basin area

Energy and Marine Geoscience Programme

Commissioned Report CR/16/034



BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCE PROGRAMME

COMMISSIONED REPORT CR/16/034

A gravity interpretation of the Orcadian Basin area

G S Kimbell and J P Williamson

Contributor

S Arsenikos

Keywords

Gravity; interpretation; modelling; Orcadian Basin; Moray Firth; Palaeozoic; magnetic.

Front cover

A gravity map in which the contribution from the Mesozoic and younger sedimentary sequence has been removed, leaving a clearer impression of the gravity effect of deeper structure. Areas of apparent Palaeozoic thickening are outlined in pink and likely offshore granites are indicated by a red 'G'

Bibliographical reference

KIMBELL, G S, AND WILLIAMSON, J P. 2016. A gravity interpretation of the Orcadian Basin area. *British Geological Survey Commissioned Report*, CR/16/034. 50pp.

Keyworth, Nottingham British Geological Survey 2016

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of the Natural Environment Research Council.

British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
email enquiries@bgs.ac.uk

Environmental Science Centre, Keyworth, Nottingham NG12 5GG
Tel 0115 936 3241 Fax 0115 936 3488
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP
Tel 0131 667 1000 Fax 0131 668 2683
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road, London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB
Tel 028 9038 8462 Fax 028 9038 8461

www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Requests and enquiries should be addressed to Alison Monaghan, 21CXRM Palaeozoic Project Leader, als@bgs.ac.uk.

Foreword and acknowledgements

This report is a published product of the 21st Century Exploration Road Map (21CXRM) Palaeozoic project. This joint industry-Government-BGS project comprised a regional petroleum systems analysis of the offshore Devonian and Carboniferous in the North Sea and Irish Sea. The report describes an interpretation of gravity data from the Orcadian Basin study area, integrated with magnetic data and with the results of seismic interpretation resulting from a companion task (Arsenikos et al., 2016).

Jo Bagguley (Oil and Gas Authority) is thanked for technical review of this report.

Contents

FIGURES

TABLES

Summary

A gravity investigation of the Orcadian Basin area has been conducted which involved the following stages:

- compilation, imaging and qualitative interpretation of BGS gravity and magnetic data from the region;
- compilation of rock densities from geophysical well logs and modelling of density variations within the sedimentary sequence;
- construction of a structural model of the cover sequence down to the top of the Permian, based on depth-converted seismic interpretation;
- calculation of the gravity effect of the sequence to top Permian using the structural and density models;
- removal of this calculated gravity effect and a regional background field from the observations to leave a residual stripped gravity anomaly;
- analysis of the signatures within the residual stripped gravity anomaly map, integrated with seismic evidence of Upper Palaeozoic structure and magnetic imaging.

The residual stripped gravity anomaly map reveals features that can be correlated with the West Bank Basin and the eastern end of the Caithness Graben of Arsenikos et al. (2016), and with the thickened Upper Palaeozoic sequence in the East Orkney Basin inferred by those authors. Gravity signatures indicative of a thickening of the Upper Palaeozoic sedimentary rocks are also identified in the Dutch Bank Basin and the South Buchan Basin, areas in which seismic interpretation of Palaeozoic structure was difficult because of problems with data quality and line spacing.

The influence of granitic intrusions is seen in a belt that extends in a north-north-east direction from Quadrant 19 into Quadrant 13, although the magnetic characteristics of the bodies might indicate separate post-tectonic and late-tectonic suites of Caledonian intrusions. Further granites are inferred in the Inner Moray Firth, in Quadrants 12 and 17. A Caledonian age is possible for these but an alternative interpretation invokes Palaeoproterozoic calc-alkaline basement, at least for the more magnetic component. Gravity signatures in the Inner Moray Firth are also influenced by low density Dalradian (Grampian Group) basement and Devonian sedimentary rocks, making it difficult to partition the response accurately between the different sources.

Positive gravity signatures are associated with the Buchan Block and its offshore extension, and with Jurassic intrusives beneath the Forties Volcanic Province. Dense/shallow basement extends in a west-north-west direction from the Forties area in a broad axis, and this is an important component of the long-lived structural configuration of the region that may be linked to an early transform offset in the Laurentian margin.

Recommendations for further work include more detailed and extensive gravity modelling, quantitative magnetic modelling and a geochemical/isotopic study of the samples available from offshore granite well penetrations.

1 Introduction

The 21CXRM Palaeozoic Project aimed to stimulate exploration of the Devonian and Carboniferous plays of the Central North Sea - Mid North Sea High, Moray Firth - East Orkney Basin and in the Irish Sea area. The objectives of the project included regional analysis of the plays and building of consistent digital datasets, working collaboratively with the Oil and Gas Authority (OGA), Oil and Gas UK and industry.

The project results are delivered as a series of reports and as digital datasets for each area. This report describes the interpretation of gravity data in the Orcadian Basin area. The original focus was an area including the Inner and Outer Moray Firth basins and extending northwards to encompass the East Orkney Basin and Dutch Bank Basin, and this was subsequently extended slightly to the east to incorporate the Witch Ground Graben (Figures 1 and 2). Gravity and magnetic data were compiled, imaged and interpreted qualitatively over the full area shown in Figure 1, and 3D gravity stripping was conducted over a subarea for which depth converted horizons were available from seismic interpretation undertaken in a companion task (Arsenikos et al., 2016).

2 Gravity and magnetic data

2.1 DATA SOURCES

This study has employed BGS gravity and magnetic data. The gravity compilation (Figure 3) comprised marine tracklines and onshore gravity stations, with the former including both digitally acquired data and digitised analogue data. The offshore component comes from the BGS 'adjusted' marine gravity database, which does not include all available survey lines (some segments have been removed because of noise or crossover errors). The magnetic compilation (Figure 4) was based on marine tracklines in the east and the national aeromagnetic survey in the west (the area shown in the figure was flown in 1964-1965). The north-western corner of the area was covered using aeromagnetic data originally flown by Huntings Geology and Geophysics Ltd. and subsequently acquired by BGS. There is alternative aeromagnetic coverage of the North Sea (originally flown by Aeroservice Corporation; now owned by Fugro Airborne Surveys Ltd.), which has been used in BGS published geophysical maps. Those maps informed the present study but the digital data were not employed for confidentiality reasons.

The gravity and magnetic survey data were imported into Geosoft (Oasis Montaj) databases for detailed examination and gridding. They were interpolated onto regular grids with a 1 km node spacing and these were used in the generation of a range of georeferenced geophysical images, including the Bouguer gravity anomaly, residual Bouguer anomaly, total magnetic intensity, reduced-to-pole magnetic field and residual pseudogravity, which are shown in Figures 5-9 respectively. The full set of images provided in the digital deliverables is described in Appendix 1.

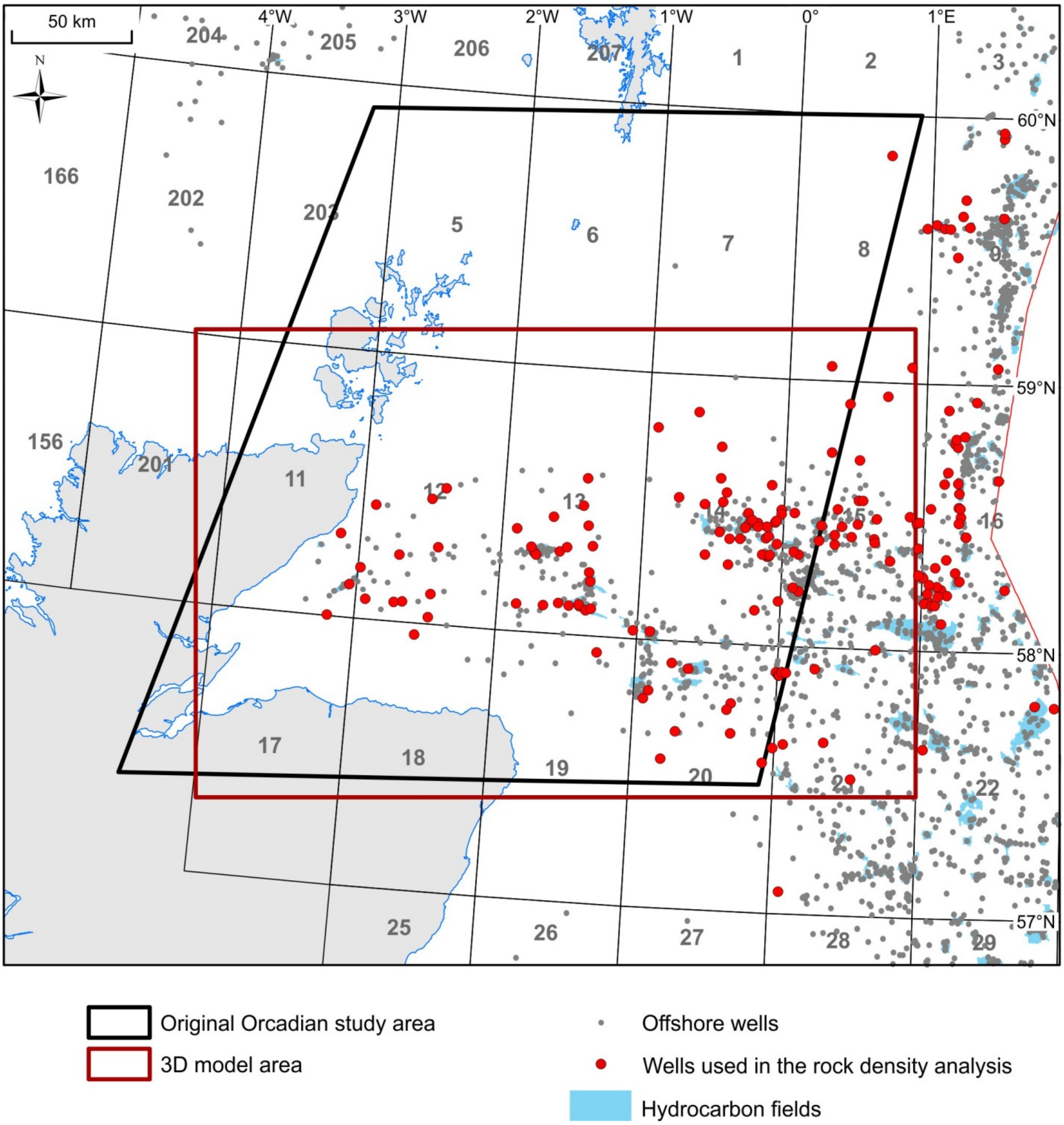


Figure 1 Location map and well distribution for the gravity investigation of the Orcadian Basin area

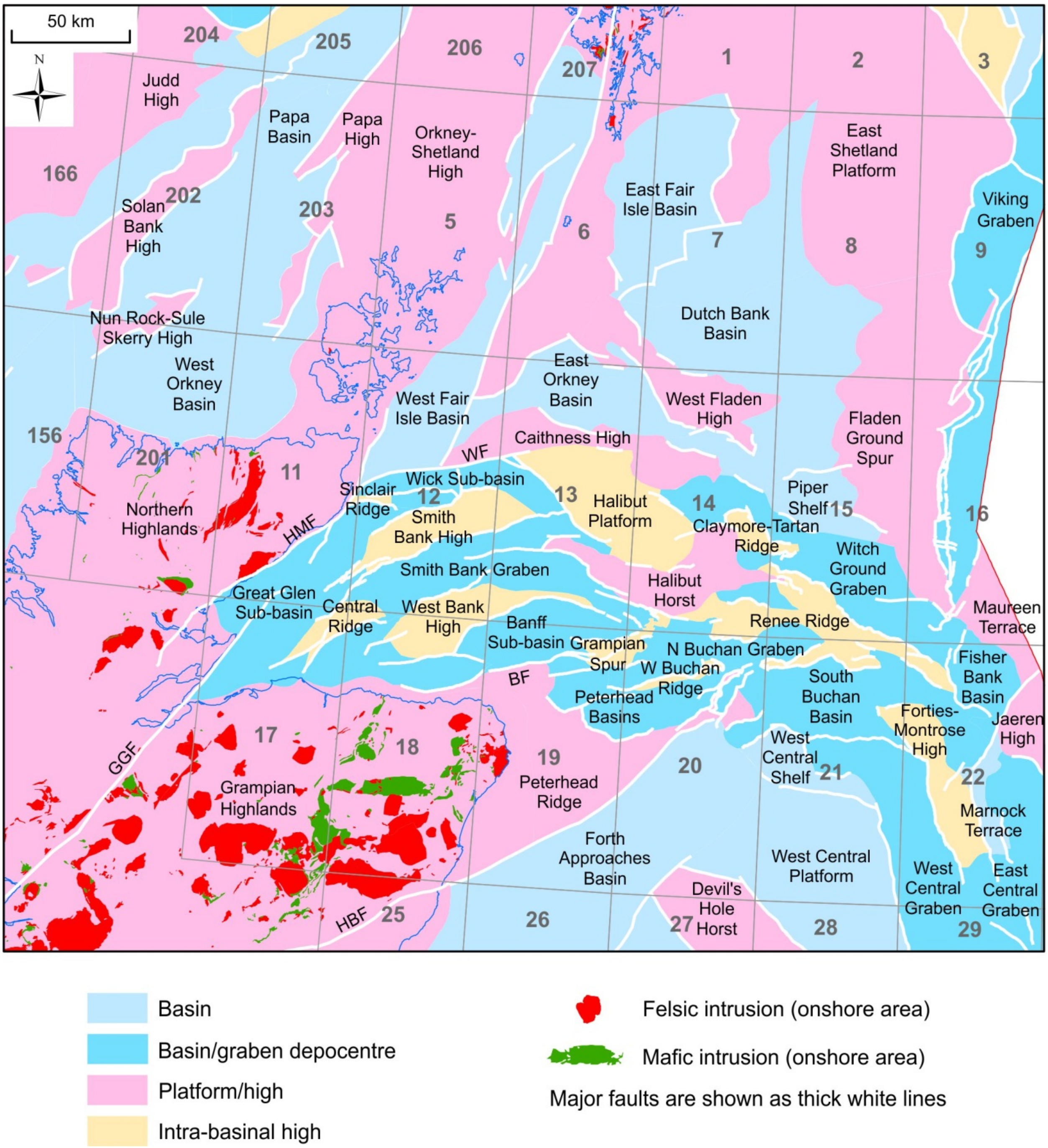


Figure 2 Structural elements from BGS Offshore Reports (mainly Andrews et al., 1990). BF = Banff Fault; GGF = Great Glen Fault; HMF = Helmsdale Fault; HBF = Highland Boundary Fault; WF = Wick Fault.

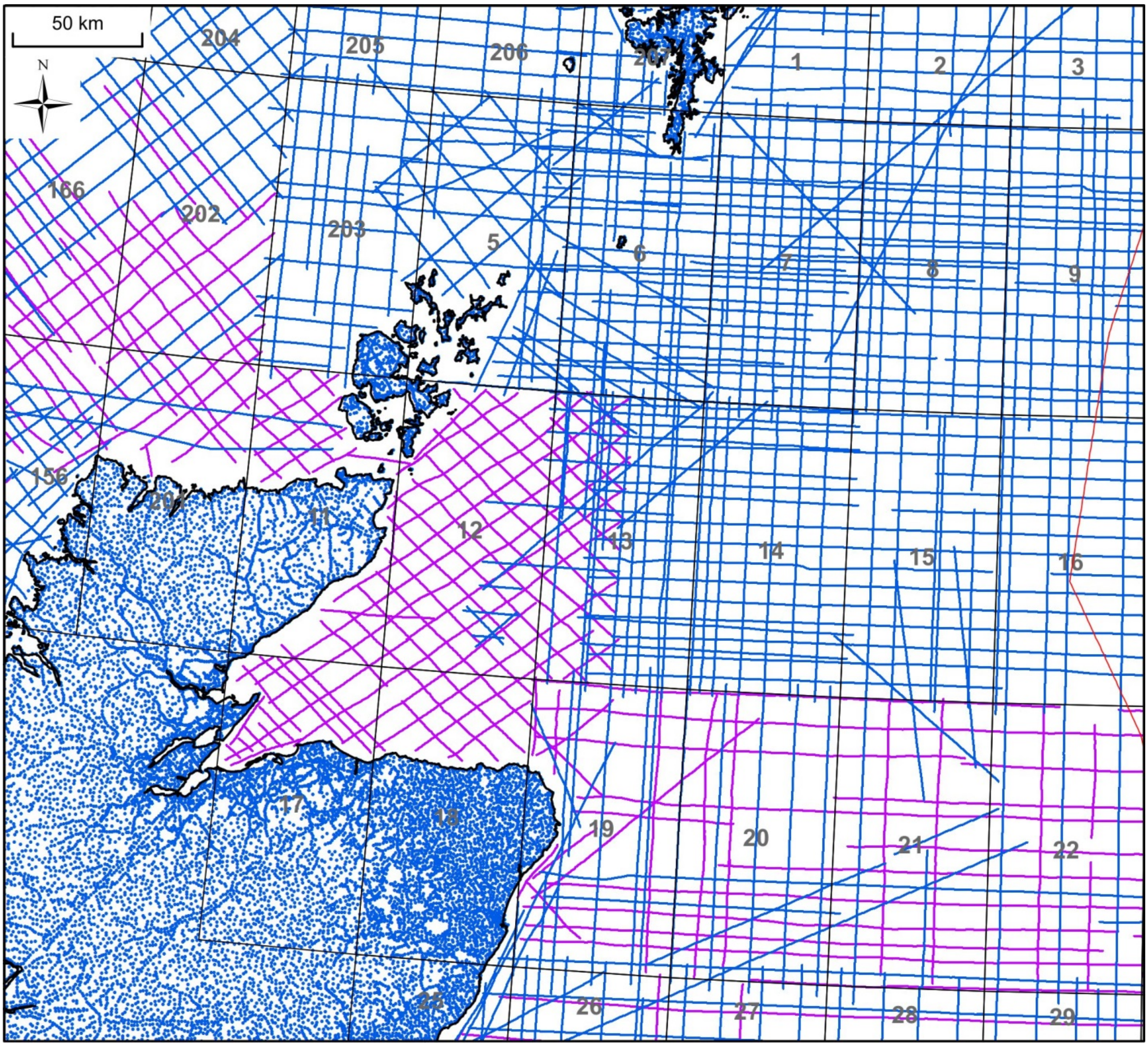


Figure 3 Locations of gravity observations from the BGS database. Blue lines and dots are marine tracklines (digitally acquired) and land gravity stations respectively. Purple lines are marine surveys that were acquired in analogue form and subsequently digitised.

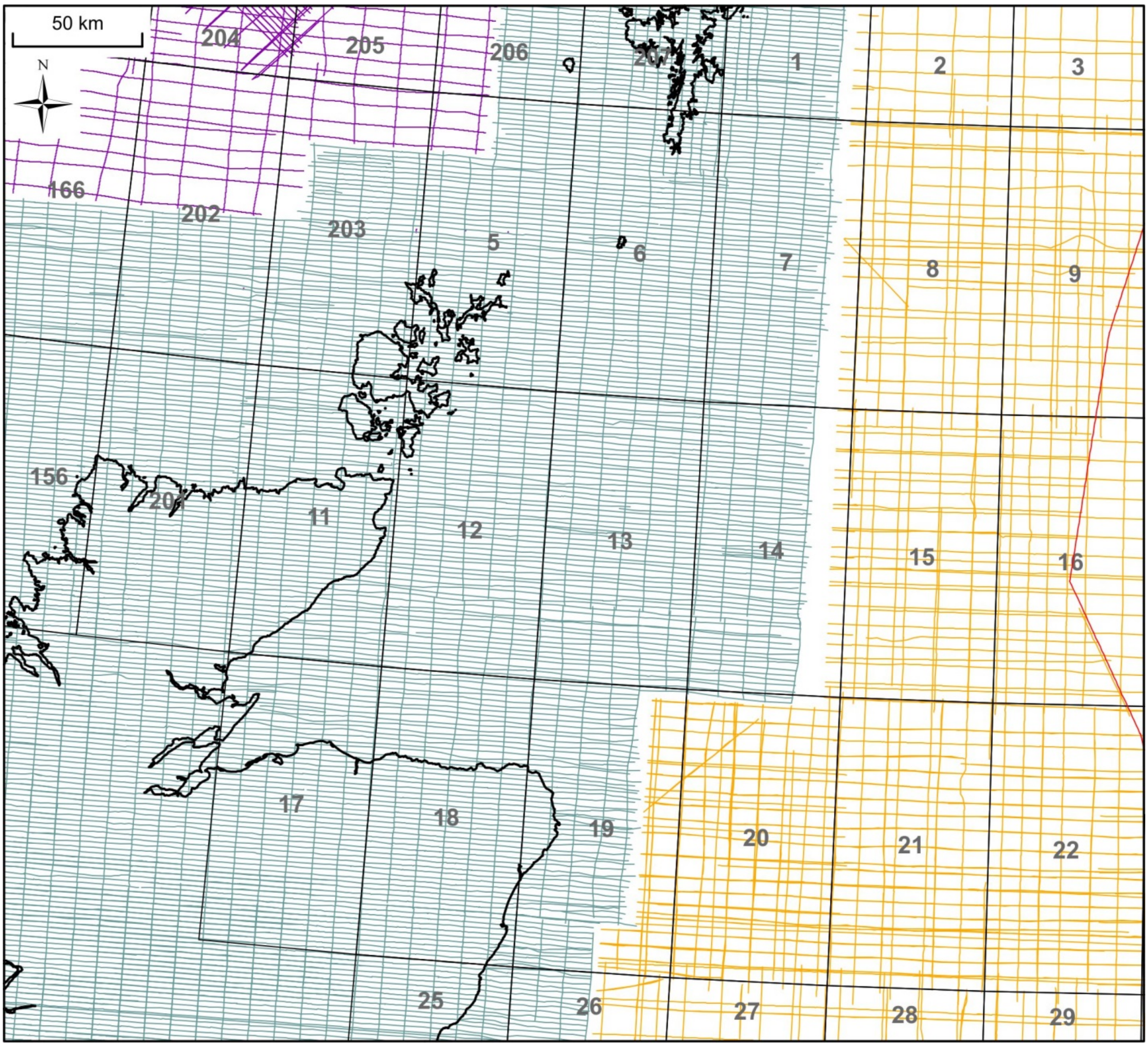


Figure 4 Magnetic survey locations. Green and purple lines are from BGS and Huntings aeromagnetic surveys respectively. Yellow lines are BGS marine magnetic surveys.

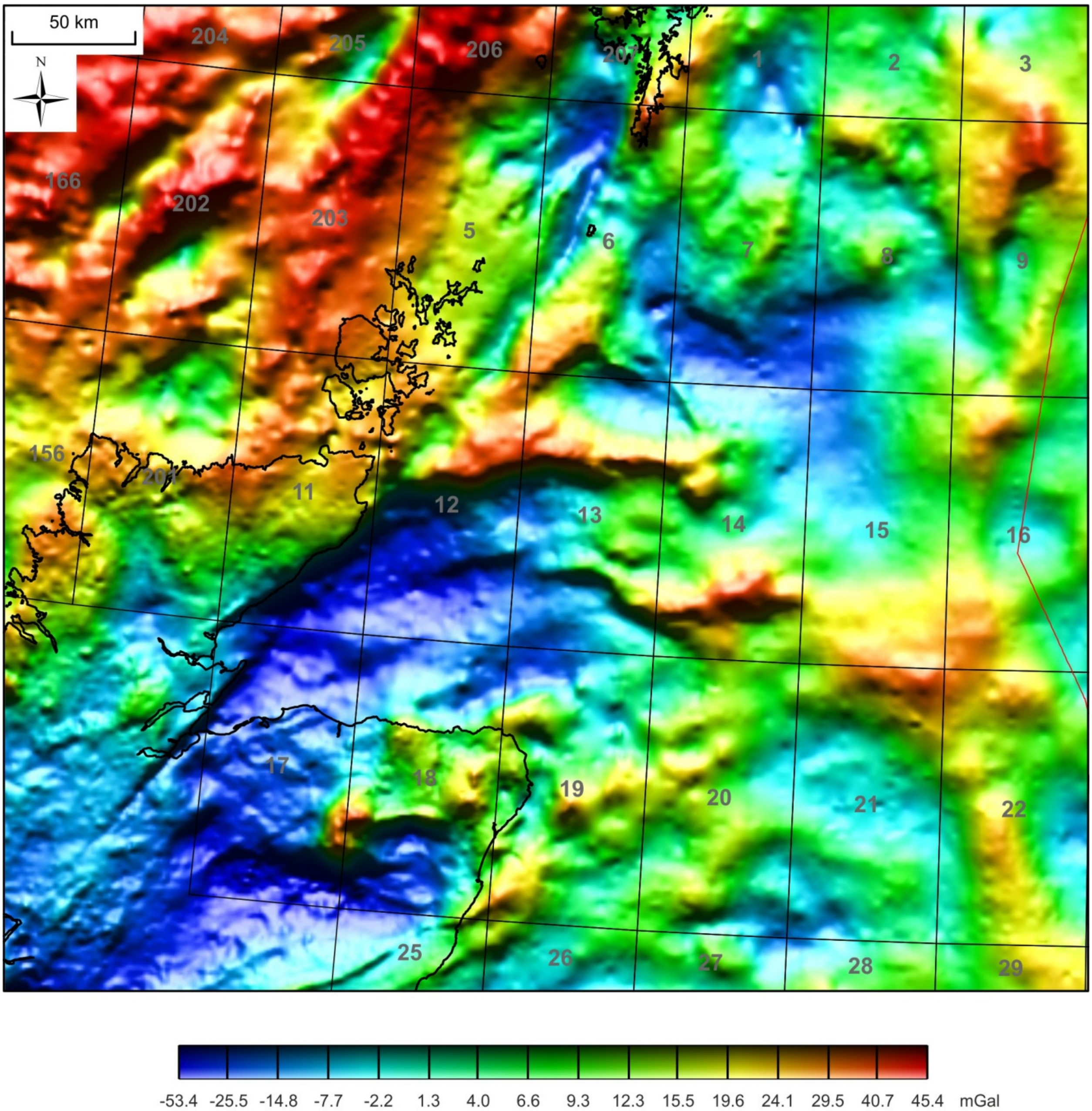


Figure 5 Bouguer gravity anomaly image with equal colour area and illumination from the north. Bouguer reduction density is 2.2 Mg/m^3 in the offshore area and variable (based on surface geology) onshore.

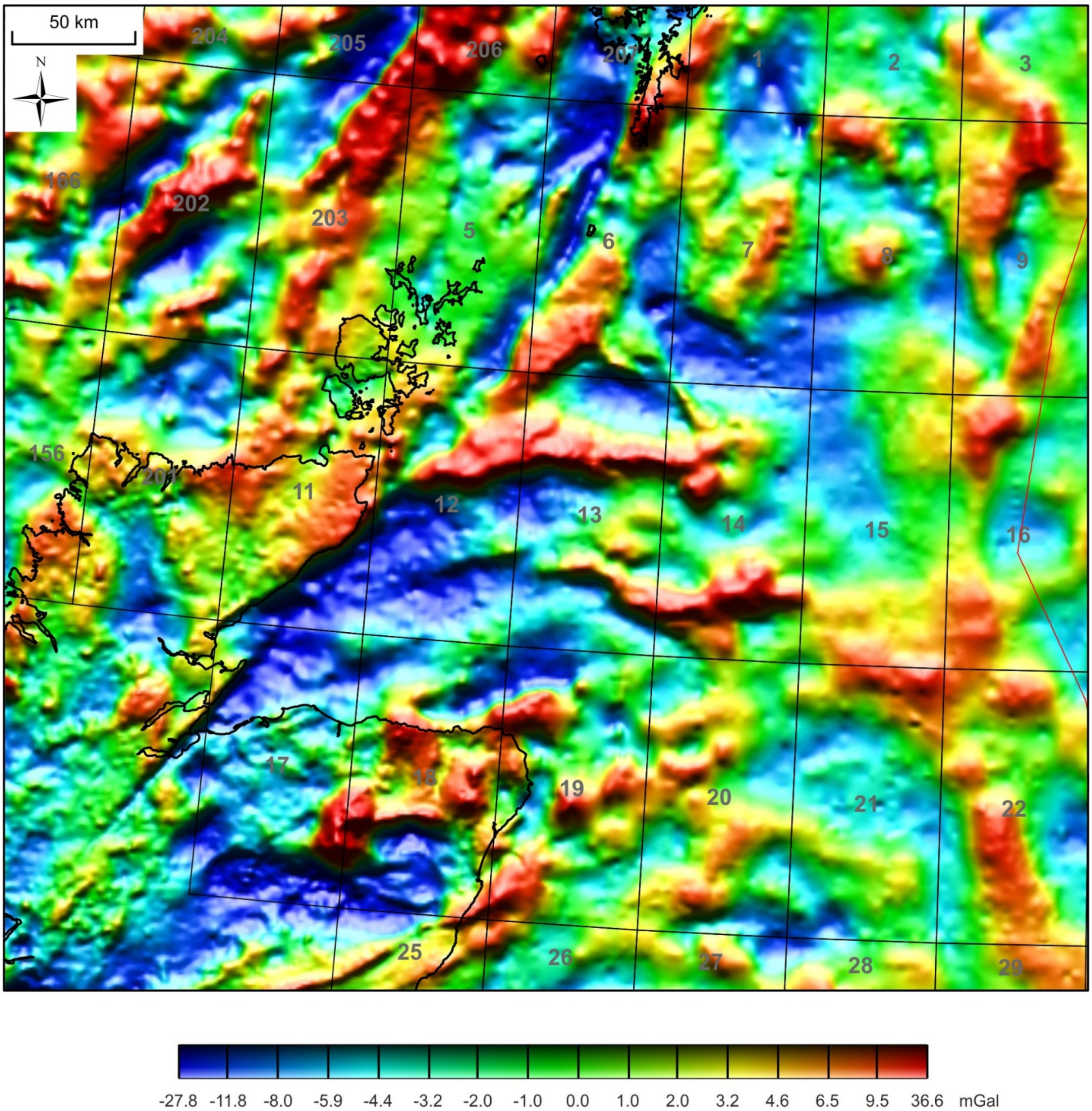


Figure 6 Residual Bouguer gravity anomaly, calculated by removal of a 10 km upward continuation. Equal colour area with illumination from the north.

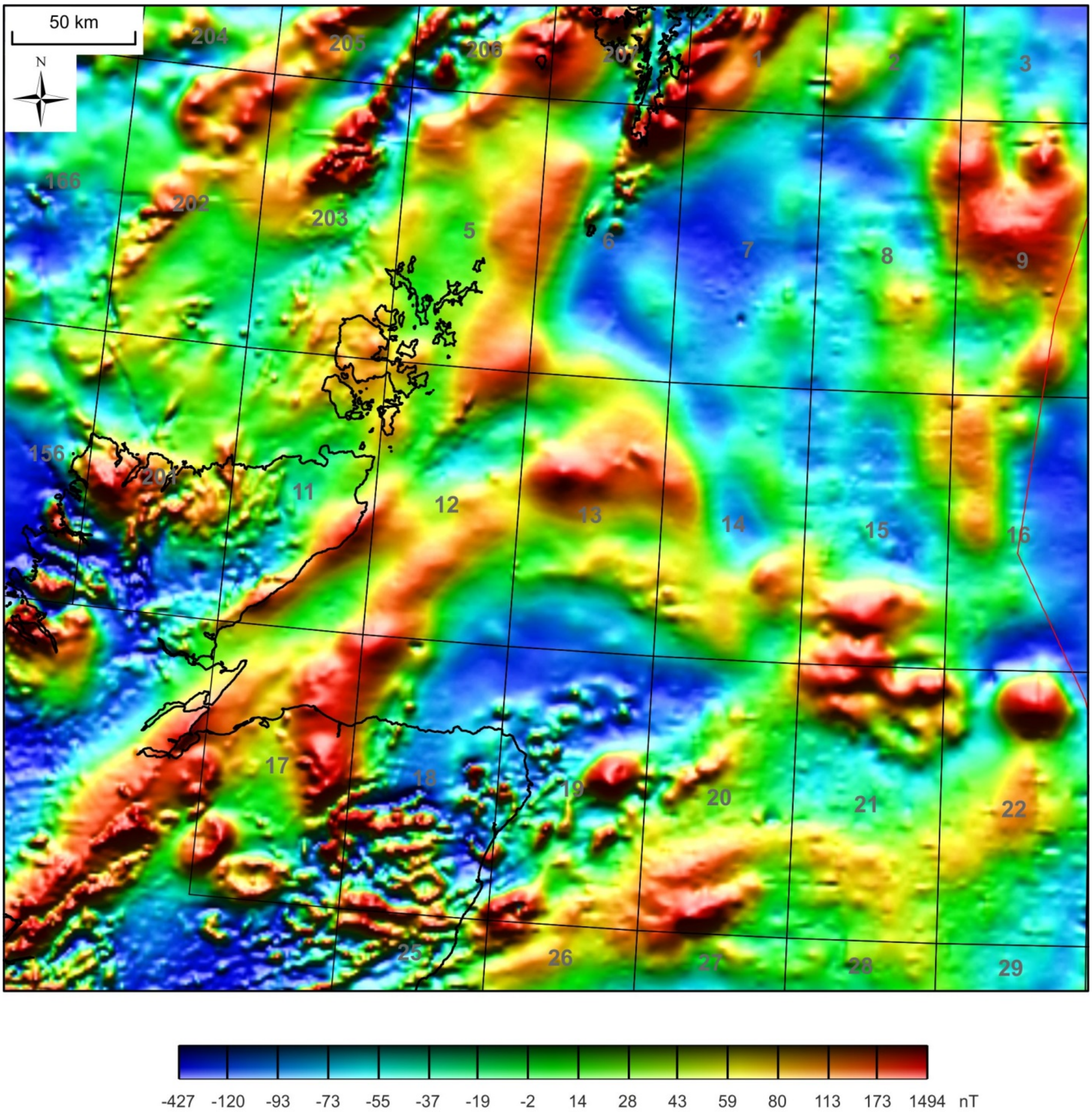


Figure 7 Total magnetic intensity image with equal colour area and illumination from the north.

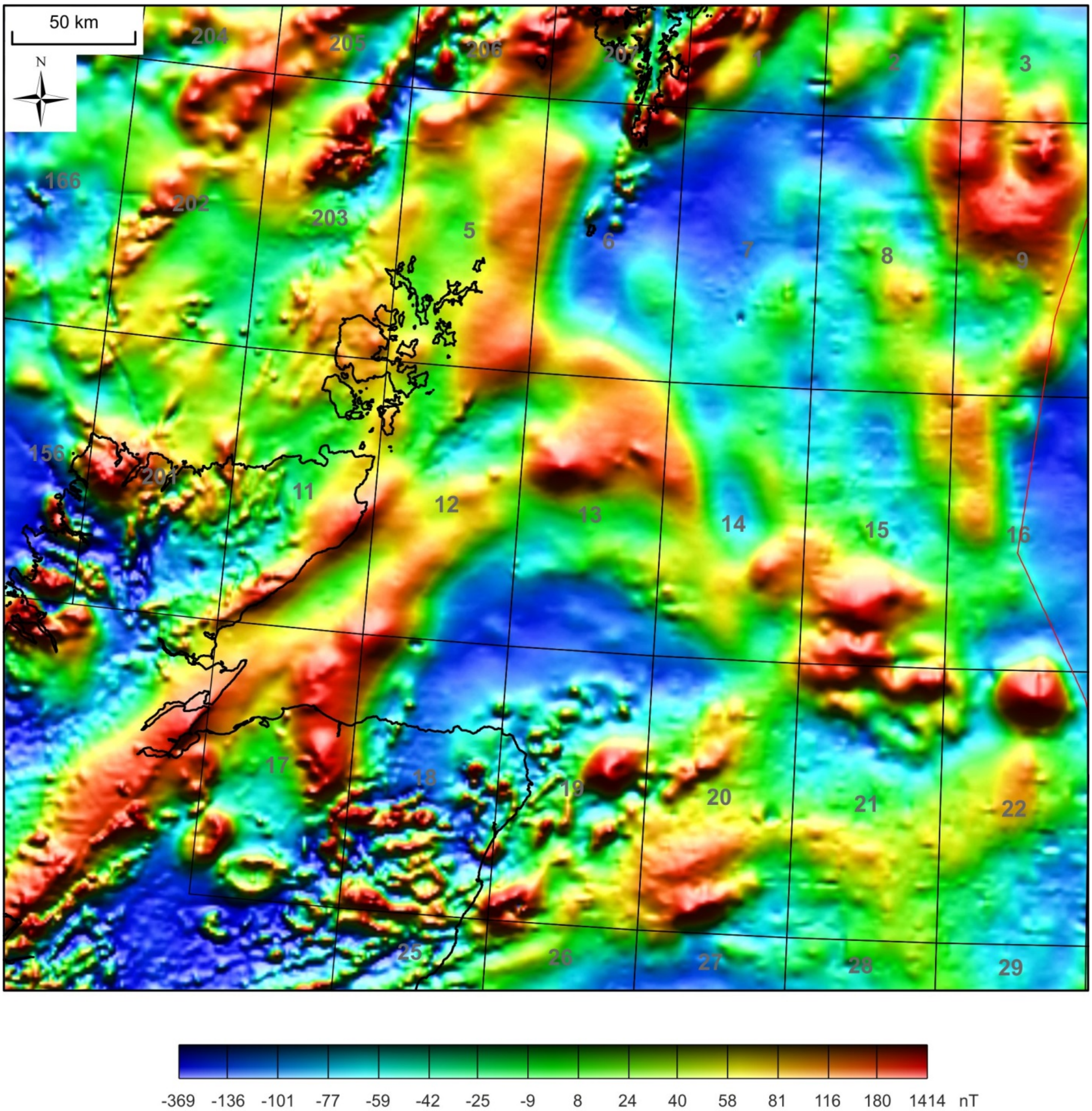


Figure 8 Reduced-to-pole magnetic image with equal colour area and illumination from the north

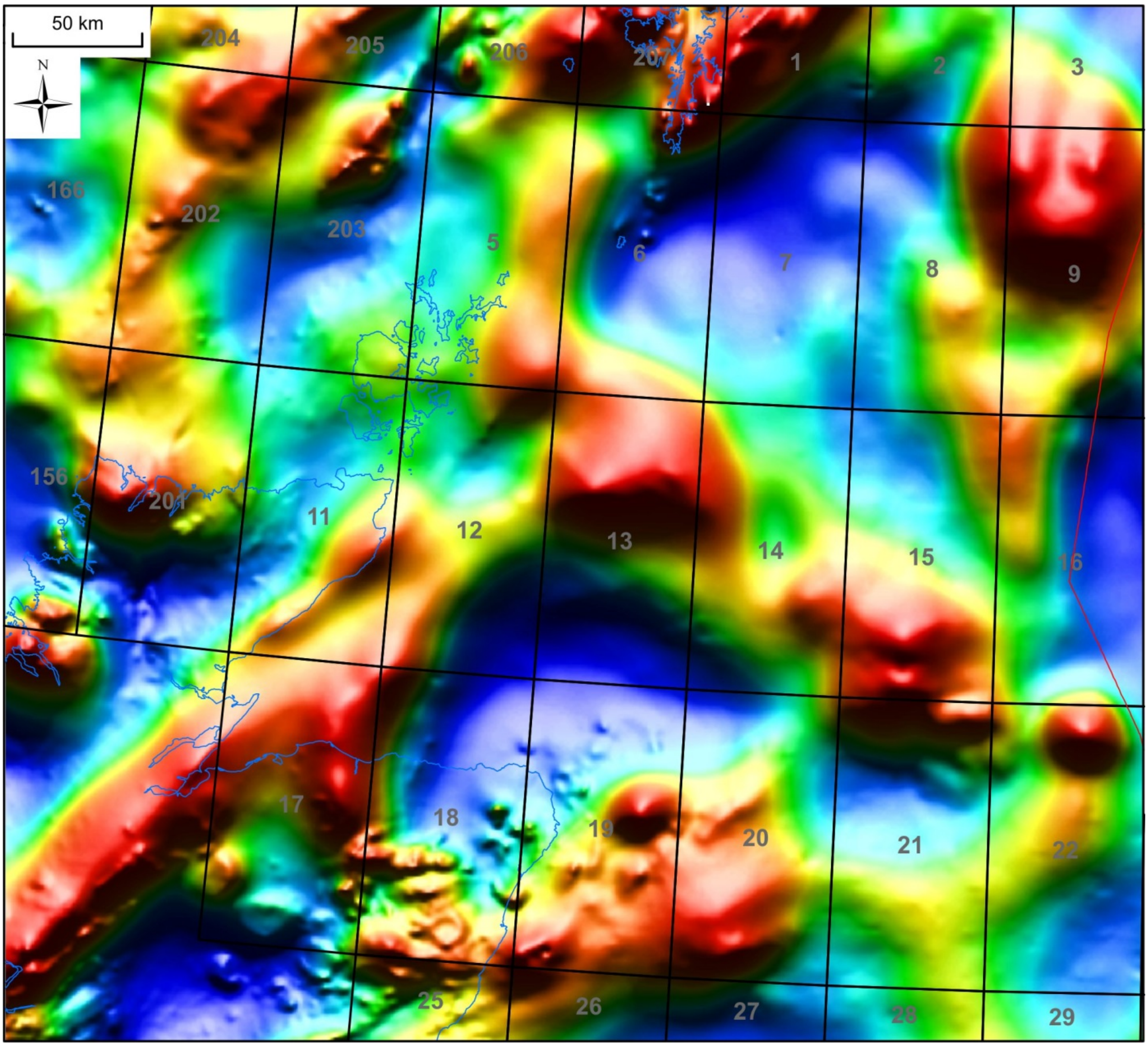


Figure 9 Residual pseudogravity transform, filtered using a high-pass Butterworth filter with a central wavelength of 200 km. Illumination is from the north.

2.2 QUALITATIVE DESCRIPTION OF REGIONAL GRAVITY FEATURES

Figure 10 is a residual gravity image on which selected structural features have been annotated. There is a close correspondence between many of the offshore features and structural elements established primarily during Mesozoic times (Figure 2), with the basins and structural highs being delineated by gravity lows and highs respectively. It is difficult to distinguish contributions from deeper sources (Palaeozoic sediments and basement density contrasts) where the Mesozoic signatures are strong, but in the north of the area there are anomalies over the East Shetland Platform that are indicative of such sources. The 'Lerwick anomaly' is a gravity low that spans the boundary between Quadrants 1 and 7. Its southern part extends over the East Fair Isle Basin (Figure 2), so may relate to Permo-Triassic sedimentary rocks proven in that area, but Devonian bedrock is mapped beneath its northern part, which is therefore more likely to be caused by a thickening of sedimentary rocks of that age. The BIRPS LERWICK profile (Klemperer and Hobbs, 1991; Snyder and Hobbs, 1999) displays synformal reflectivity that can be correlated with this feature. A positive gravity anomaly on its west side, spanning from the onshore to the offshore area, can be linked to the Shetland Ophiolite (Flinn and Oglethorpe, 2005).

The gravity anomalies around the junction between Quadrants 2, 3, 8 and 9 were interpreted by Donato and Tully (1982) as being caused by a large (c. 40 x 40 km) granitic intrusion, most likely of Caledonian age, with magnetic anomalies in the vicinity attributed to a magnetic intrusive phase or interactions with the surrounding basement rocks. However, Holloway et al. (1991) demonstrated that the area of lower gravity close to the meeting point of the Quadrants can be correlated with seismically-imaged synclinally folded sediments of presumed Devonian age. They substantially reduced the size of a potential granite and questioned the interpretation of cuttings from well 9/3-1 as evidence of this rock type. The magnetic anomalies were interpreted as being due to sources within a heterogeneous crystalline basement.

The offshore gravity anomalies do not correlate closely with the known Mesozoic sedimentary architecture in the area from the Witch Ground Graben to the Fisher Bank Basin (southern Quadrant 15 to northern Quadrant 22; Figure 2). The Witch Ground Graben depocentre coincides with only subtle gravity variation and the Fisher Bank Basin coincides with a local gravity high (Figure 10). These uncharacteristic responses can be explained by the influence of magmatic rocks associated with the Forties Volcanic Province (Ritchie et al., 1988; Smith and Ritchie, 1993), which also have a clear magnetic expression (Figure 11). Although the well intersections are dominated by extrusive rocks (outline shown in Figure 11), the gravity and magnetic data point to the likelihood of intrusive bodies underlying these. The Fisher Bank centre is marked by coincident circular gravity and magnetic anomalies that strongly suggest an intrusive centre, and an axis of coincident anomalies along the Renee Ridge may be related to intrusive rocks associated with the Glenn centre (Smith and Ritchie, 1993). A magnetic high over the Witch Ground Graben was tentatively linked by Smith and Ritchie (1993) to their Ivanhoe volcanic centre and this coincides with an area where the gravity low expected over the thick sediments has been replaced by a residual high or 'terrace'.

Gravity variations in the onshore area are dominated by the effects of intrusive rocks. The numerous Caledonian granites present in the region typically give rise to negative gravity anomalies. These are particularly conspicuous over the voluminous 'Newer' or post-tectonic granites (400-425 Ma), such as Monadhliath, Cairngorm, Lochnagar and Mount Battock, whereas the late-tectonic (c. 470 Ma) granites such as Ardclach, Grantown and Strichen have a more subdued response (Figures 10 and 12a; Stephenson and Gould 1995, their fig. 26). In some cases the difference in response may relate to mineralogy (for example where denser, dioritic units are present), but in others the primary cause is likely to be differences in depth extent. There are exceptions to the pattern: for example the late-tectonic Moy Granite has a more pronounced gravity response than the post-tectonic Ben Rinnes Granite (Figure 12).

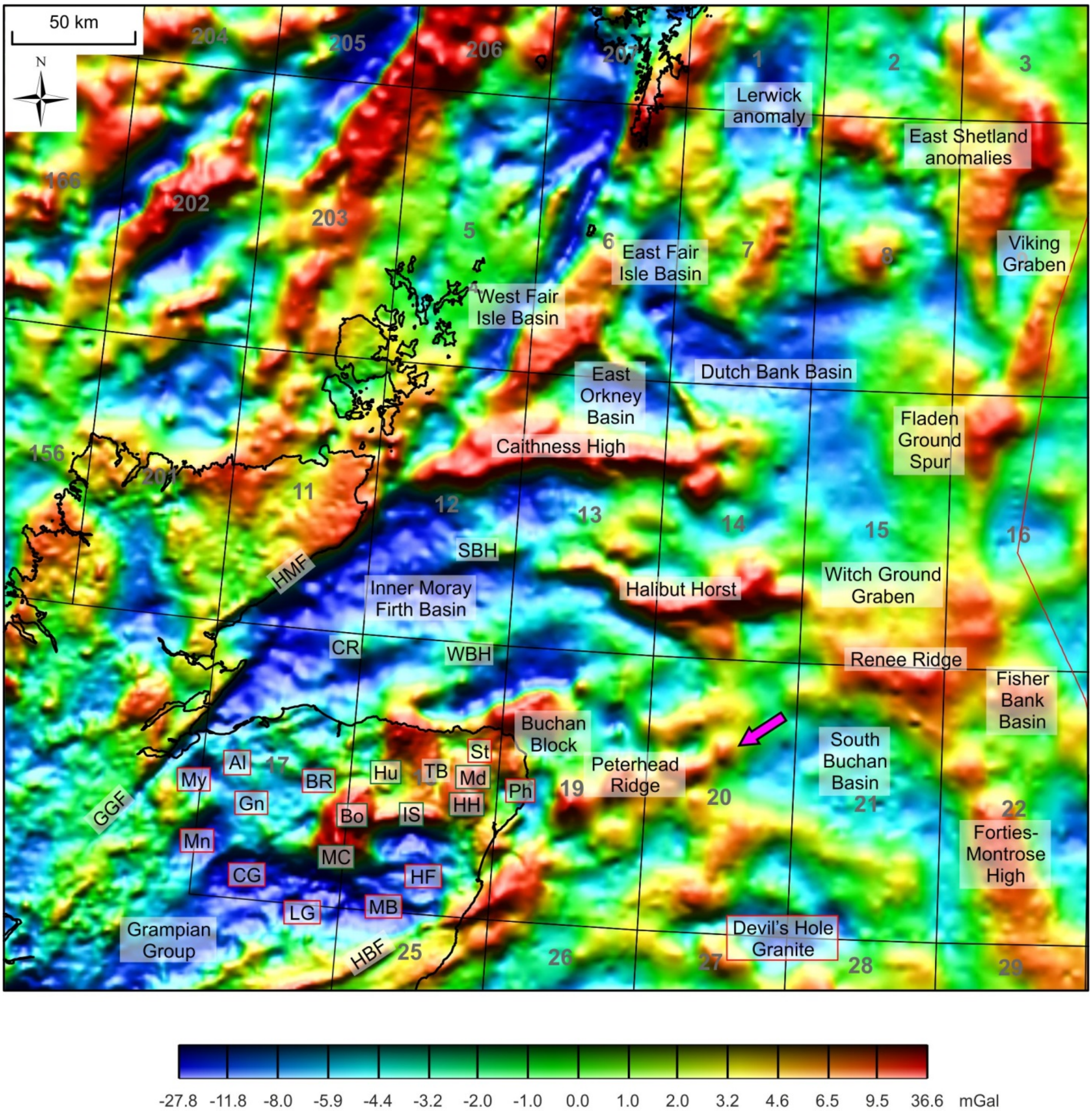


Figure 10 Annotated residual gravity image. Selected Grampian granites (labels outlined in red): Al = Ardclach; BR = Ben Rinnes; CG = Cairngorm; Gn = Grantown; HF = Hill of Fare; LG = Lochnagar; MB = Mount Battock; Mn = Monadhliath; My = Moy; Ph = Peterhead; St = Strichen. Selected Grampian basic masses (labels outlined in green): Bo = Bogancloch; Hu = Huntly; IS = Insch; MC = Morven Cabrach; Md = Maud; HH = Haddo House. Other abbreviations: CR = Central Ridge; GGF = Great Glen Fault; HBF = Highland Boundary Fault; HMF = Helmsdale Fault; SBH = Smith Bank High; TB = Turriff Basin; WBH = West Bank High. See Figure 2 for further structural annotations.

When the granite outcrop pattern is compared with the broad gravity anomaly pattern across the north-east Grampian region it becomes clear that there is another contributor to the regional gravity low that characterises that region. It is most clearly expressed as a gravity gradient zone (decreasing to the north-west) adjacent to the Boundary Slide in the area south-west of Cairngorm (Figure 12a). Density measurements and modelling indicate that the gravity effect can be explained by the relatively low density of the quartz-rich Grampian Group, when compared with the younger Dalradian units (Rollin, 2009; Table 1).

Unit	Mean saturated density (Mg/m^3)	Standard Deviation	Number of sites
Southern Highland Group	2.78	0.09	67
Argyll Group	2.77	0.14	49
Appin Group	2.75	0.08	57
Grampian Group	2.70	0.06	63
Central Highland migmatites (Badenoch Group)	2.73	0.07	15
All Dalradian	2.75	0.10	244

Table 1 Density data for Dalradian rocks (from Rollin, 2009)

The syn- to late-tectonic (490-470 Ma) basic and ultramafic intrusions of the Grampian region have high densities and are associated with positive gravity anomalies (Figures 10 and 12a). These are most numerous in the north-east corner of the region where they are present in the Buchan Block – an area with a distinctive structural and metamorphic history. The western edge of this block lies along the Portsoy (-Duchray Hill) Lineament (Figure 12a), which influenced Dalradian sedimentation patterns and subsequently acted as a regional shear zone during the Grampian Orogeny, during and after the emplacement of the basic masses (Gunn et al., 2015). In the central part of the Buchan Block the positive gravity effect is still present but no basic masses are observed at outcrop and there is no magnetic evidence for their continuation beneath the area. The implication is that the block is characterised by a relatively dense and thin Dalradian sequence. Fettes et al. (1986) suggest that the southern margin of the block originally lay at a lineament (the Deeside lineament; Figure 12), which has subsequently been overprinted by major post-tectonic granite intrusions that make up the East Grampian batholith.

Positive gravity anomalies in the offshore area just to the east and north-east of the onshore Buchan Block could be indicative of its offshore extension, although the responses are due in part to variation in the thickness of the sedimentary overburden over the Peterhead Ridge. Within this zone, relative gravity minima offshore Peterhead suggest the presence of offshore granite intrusions. A gravity high that follows the Highland Boundary Fault can be ascribed to dense mafic rocks within the Highland Border Complex, lying at the boundary between the Grampian and Midland Valley terranes. The anomaly can be traced offshore to the east where it broadens (on the Midland Valley side) to the extent that dense rocks within that terrane may also be implicated. These could be rocks formed by arc magmatism prior to collision of the Midland Valley Terrane with the Laurentian margin in the event interpreted to be responsible for the Grampian Orogeny at around 470 Ma (e.g. Dewey et al., 2015).

2.3 QUALITATIVE DESCRIPTION OF REGIONAL MAGNETIC FEATURES

Magnetic anomalies in the north-western part of the area shown in Figure 11 can be linked to Lewisian crystalline basement, both where it is present at outcrop onshore and where it forms the core of structural highs (e.g. the Solan Bank and Papa highs) in the West of Shetland area. The outcrop evidence shows that the basement is not uniformly magnetic, with zones of granulite facies metamorphism tending to have higher magnetisation than those of lower metamorphic grade that have been subjected to Laxfordian (Palaeoproterozoic) reworking (Powell, 1970; Bott et al., 1972). There is a relative magnetic low over the Moine rocks to the south-east of these outcrops, before anomaly values rise toward the Great Glen and Helmsdale faults. This response might be due to a shallowing of magnetic basement towards the faults (there is, for example, a

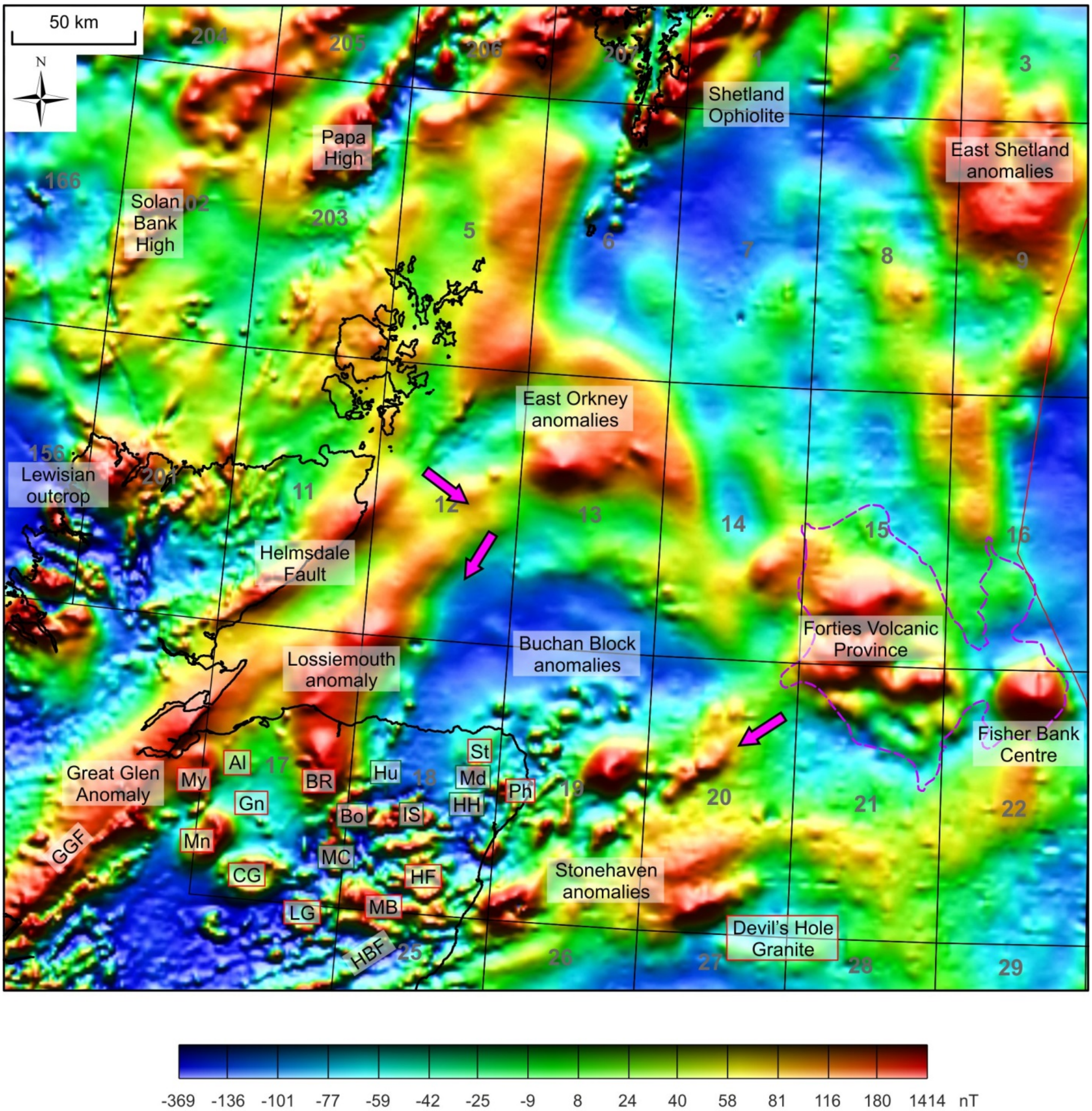
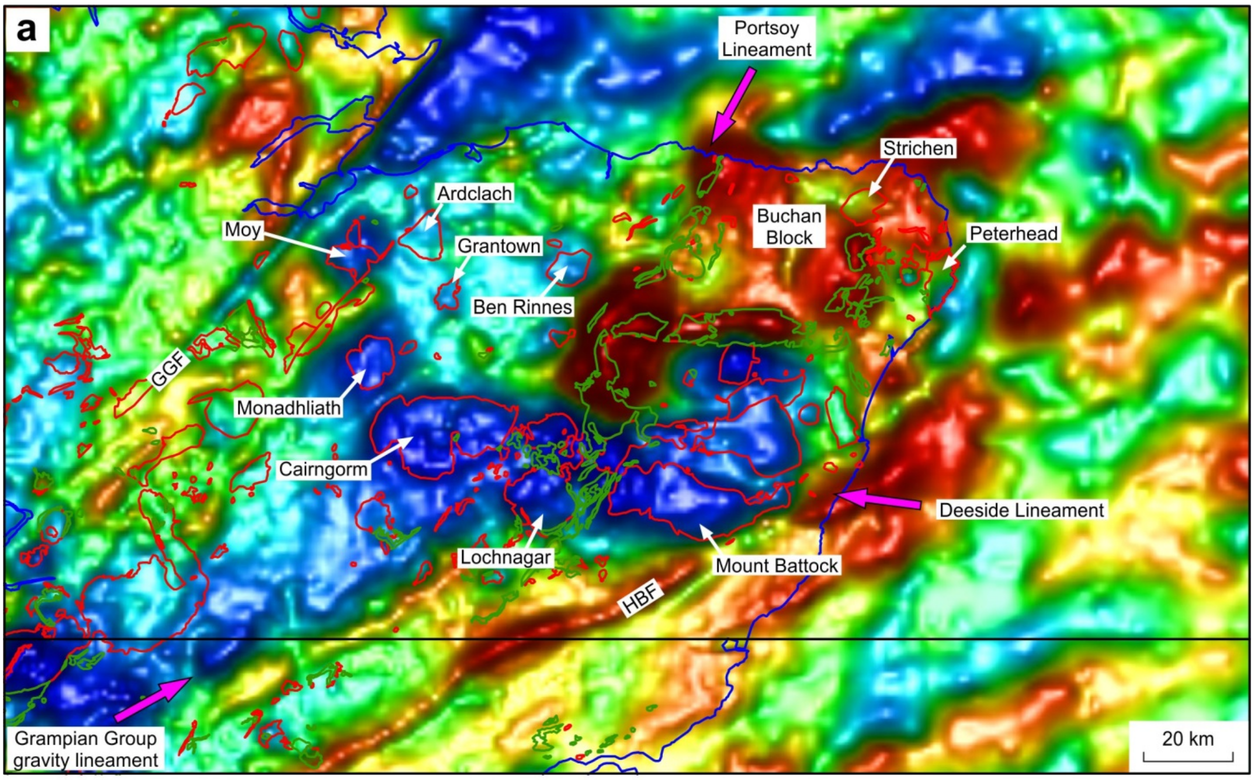


Figure 11 Annotated reduced-to-pole magnetic image. For abbreviations see Figure 10. The purple dashed line indicates the extent of the Jurassic volcanic rocks of the Forties Volcanic Province (after Smith and Ritchie, 1993). Pink arrows illustrate the intersecting NNE and WNW magnetic trends in the Moray Firth area and an alignment of magnetic anomalies along a possible extension of the Highland Boundary Fault.

Lewisian inlier at Rosemarkie on the Great Glen Fault), but the possibility of a discrete magnetic source beneath the Great Glen cannot be discounted.

The magnetic anomaly over the Great Glen is characteristic of a source that spans this near-vertical structure, dipping away both to the north-west and south-east (see the models of Rollin, 2009). This is not necessarily problematic in terms of the geological history of the structure, as its role as a terrane boundary has been brought into question (e.g. Stone et al., 1999). It is possible, however, that the magnetic basement beneath northern Scotland has been amalgamated from Archaean and Palaeoproterozoic blocks, with the latter formed during the widespread development of calc-alkaline arcs that occurred at that time along a belt associated with the



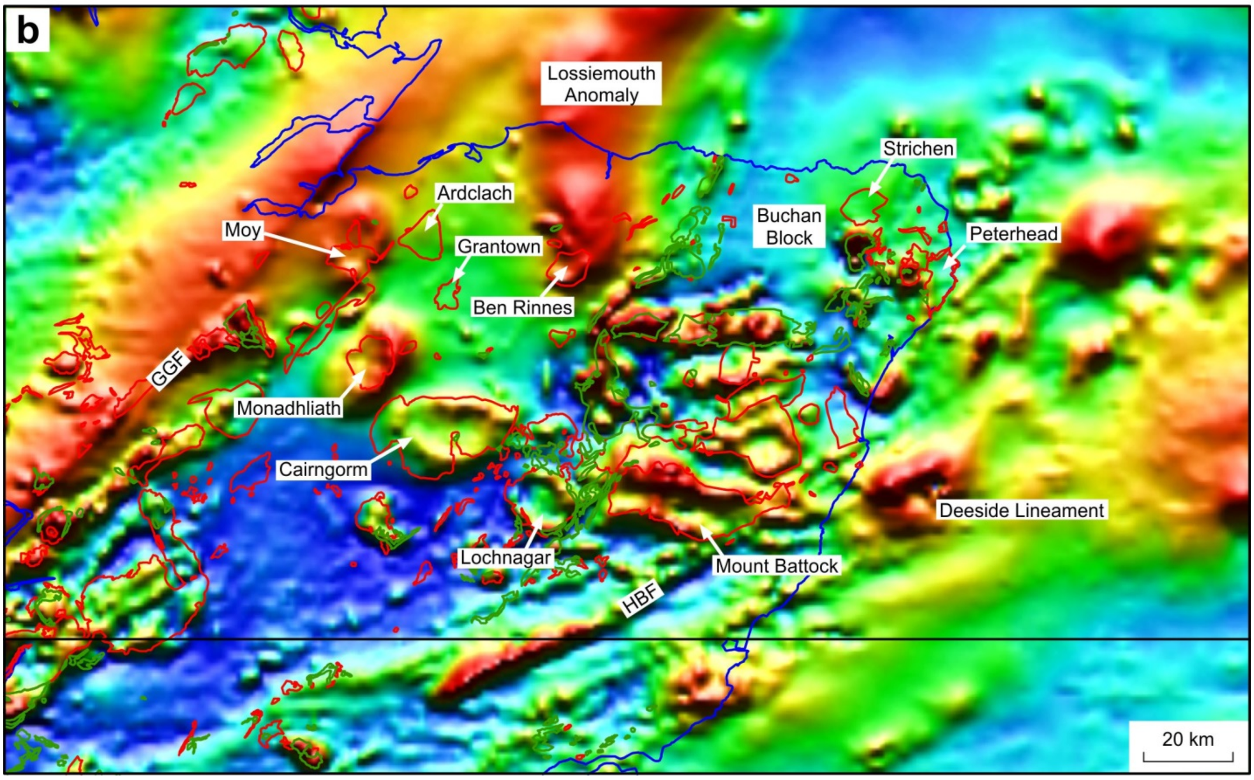


Figure 12 Gravity (a) and magnetic (b) images of the NE Grampian area illustrating the signatures associated with Caledonian granites (red outlines) and basic masses (green outlines). The gravity image shows the gradient zone associated with intra-Dalradian density contrasts (southern edge of the low-density Grampian Group) and the gravity high associated with the Buchan Block. The horizontal black line on the images is the southern edge of the study area shown in the previous figures. Moy, Ardclach, Grantown and Strichen are late-tectonic granites and Monadhliath, Cairngorm, Lochnagar, Mount Battock and Ben Rinnes are post-tectonic granites.

convergence that lead to the formation of the Columbia (or Nuna) supercontinent (Zhao et al., 2004; Rogers and Santosh, 2002, 2009). Examples of magnetic rocks of this type occur in southern Greenland to the west (the major Julianehåb batholith within the Ketilidean orogen of southern Greenland; Garde et al. 2002) and in the Transscandinavian Igneous Belt to the east (Gaál and Gorbatschev, 1987; Ebbing et al., 2012). Evidence for such rocks in the UK area is found in the Inner Hebrides and Stanton Banks (Dickin and Bowes, 1991; Ritchie et al., 2013) and has been assigned to the Rhinns Terrane, which has been inferred to extend north-eastwards beneath the northern part of the Grampian Terrane on the basis of the granite inheritance (Dickin and Bowes, 1991) and sedimentary provenance (Banks et al., 2013). On this evidence, the models of Rollin (2009) have invoked a composite magnetic basement, incorporating a Lewisian component to the north-west and a Rhinns component to the south-east.

This interpretation has a bearing on one of the major magnetic anomalies in the present study area – the Lossiemouth anomaly, which extends northwards and north-eastwards from the onshore Grampian region into the Inner Moray Firth (Figures 11 and 12b). In the interpretation of Rollin (2009) this anomaly is caused by a relative high in the Proterozoic magnetic basement. An alternative interpretation, advocated by Dimitropoulis and Donato (1981) and Pilkington et al. (1995), is that the magnetic anomaly is associated with a major Caledonian granite pluton. In support of the latter hypothesis, those authors note a spatial correlation between the southern end of the Lossiemouth magnetic anomaly and the shallow magnetic anomalies associated with the Ben Rinnes intrusion (Figure 12b).

There are typically magnetic anomalies over post-tectonic granites in the north-east Grampian region, and these often have an annular form, indicative of relatively magnetic marginal phases (Figure 12b). The late-tectonic granites are often non-magnetic, or at least below the resolution of the regional aeromagnetic survey (e.g. Ardclach, Grantown, Strichen).

The Shetland and Highland Border ophiolitic rocks are associated with positive magnetic (as well as gravity) anomalies and the Highland Border trend can be traced into the offshore area as a discontinuous set of anomalies extending for about 130 km into the central part of Quadrant 20 (Figures 11 and 12b). There are magnetic anomalies to the south of this line ('Stonehaven anomalies' in Figure 11) indicating sources in the Midland Valley Terrane that might be associated with Lower Palaeozoic arc magmatism or later, Upper Palaeozoic magmatic activity. To the north of this line is a zone of short-wavelength magnetic anomalies over the possible offshore extension of the Buchan Block, with some of these clustered around the possible granites within this block suggested by the gravity data. The implication is that the magnetic anomalies might form annular features if covered by higher resolution magnetic survey data.

Conspicuous positive magnetic anomalies occur over the Jurassic volcanic rocks of the Forties Volcanic Province, and the coincidence of the strongest of these with positive gravity anomalies (e.g. over the Fisher Bank Volcanic Centre) suggest major intrusive bodies underlying the proven extrusive rocks.

To the north of the Forties province, magnetic anomalies extending northwards through Quadrants 16 and 9 are inferred to relate to relatively shallow magnetic crystalline basement (e.g. 'East Shetland anomalies' in Figure 11; Holloway et al., 1991), although its affinity is unclear. There are also magnetic anomalies to the east of Orkney that lie along a WNW-ESE axis that includes the Forties province. This alignment is highlighted by the pseudogravity transform shown in Figure 9. It appears unlikely that the features at the western end of the alignment are due to Jurassic magmatism, as they are distant from its focus in an area where there is little evidence of its products. An association with magnetic basement along trends established earlier (but adopted by the Jurassic activity) appears more likely. Johnson and Dingwall (1981) and Pegrum (1984) have projected the Tornquist Zone into this area and argued for its influence on later structural styles. Pegrum (1984) describes this extension as 'a transform belt bisecting the Caledonide orogen', and Johnson and Dingwall have described it as a 'system of deep-seated crustal weakness' and even linked it to the co-linear Wyville Thomson Ridge (although a pre- or syn- tectonic cause for such co-linearity would be surprising, given the evidence for subsequent transcurrent movements on the Great Glen Fault). This axis can be seen as forming a possible offset or dogleg between the Highland Border and Shetland ophiolitic belts, making a transform origin attractive. Rather than a direct link to the Tornquist Zone (which is associated with the convergence between Baltica and Eastern Avalonia) such a transform offset could have been established on the Laurentian margin and been in place during the collision of arcs with that margin during the Grampian orogeny, prior to subsequent interactions with Baltica/Avalonia.

Regardless of the details of these antecedent influences, it is clear that the study area lies in a region where the basement is characterised by an intersection of trends: with north-north-east (e.g. Portsoy Lineament) to north-east (e.g. Great Glen and Highland Boundary faults) structures intersecting with east-south-east trends associated with a transform offset of the Laurentian margin and/or the propagation of Tornquist trends into this area.

3 Rock densities

Digital density logs from 179 wells were used to investigate rock densities in the region (Figure 1). The logs were corrected to depth below seabed so that compaction trends could be compared. A set of individual logs is provided in a supplementary document, and the supplementary material also includes plots providing an overview of density-depth relationships in the different rock units and listings providing average values for each unit in each well (with the sequence divided both according to the main chronostratigraphic divisions and the layers employed in the gravity modelling; see Appendix 2 for further details).

Kimbell and Williamson (2015) have described the construction of a density model for the sedimentary sequence in the Central North Sea area which employed a predictive approach. Such an approach was used because of the large gaps in the available density control; it was based on lithology and compaction trends, including allowance for burial anomalies, and was calibrated by comparison with the control that was available. There is a better distribution of density control points in the Orcadian study area, or at least that part of it covered by the 3D gravity modelling (Figure 1), so a different approach has been adopted for the majority of the rock units employed in the modelling.

The density of the post-Chalk sequence is relatively poorly sampled, both in terms of areal distribution (Figure 13a) and the proportion of the sequence logged at the locations where density measurements are available. A predictive approach was therefore employed for this layer, and this was based on the compaction curves of Sclater and Christie (1980) combined with burial anomalies based on Japsen (1999, his figure 9a). These were used to predict the average densities in the intervals sampled by wells, which were compared with the observations. Different sets of values were predicted depending on the lithology assumed (shale, shaley sand or sand) and on the basis of the fit to the observations (Figure 13b) the shaley sand model was adopted, which is a reasonable reflection of the lithologies encountered in this part of the sedimentary sequence. The resulting map of predicted average post-Chalk density in the 3D model area is shown in Figure 13a.

The average densities of the underlying layers have been modelled directly from the observational data using empirical Bayesian kriging. Wells with noisy or unrepresentative density logs were not included in the input to the modelling. This kriging method provides a model which avoids excessive short wavelength variation and is appropriate for generating grids for use in gravity models. The corollary of this is that average densities in individual wells are not necessarily honoured by the density model. Figures 14 to 17 illustrate the kriged density models for the Chalk, Lower Cretaceous, Jurassic and Triassic units respectively, which are the layers that were employed in the gravity stripping described in the Section 4. More detailed plots, including posted mean values at the well locations are included in the supplementary material (Appendix 2)

Although they were not used in the gravity modelling described below (see Section 4), kriged density models for the Upper Permian (Zechstein) and pre-Zechstein units encountered in the available wells are also shown (Figures 18 and 19), as they have a bearing on the way the results are interpreted and would be relevant for further gravity modelling studies. Kimbell and Williamson (2015) used an inverse relationship between the thickness and density of the Zechstein sequence to guide the way it was modelled in the Central North Sea area. The relationship arises because the thicker sequences in that area tend to be dominated by low-density halite whereas the thinner sequences have a higher proportion of higher density dolomite and, particularly, anhydrite. Density-thickness plots for the Orcadian Basin area showed a less well-defined relationship, and this is explicable in terms of the more complicated facies variations in this area (see fig 23 of Andrews et al., 1990). A density model derived by kriging (Figure 18) correlates well with the mapped facies with, for example, a north-north-east-trending zone in which anhydrite is common coinciding with a high-density zone in the model. The Zechstein sequence is relatively thin in the modelled area so lateral variations in its density will generally only have a limited gravity effect. The exception is towards the south-east corner of the area, where the sequence is thicker and dominated by halite.

When modelled using empirical Bayesian kriging the pre-Zechstein rocks have a relatively narrow range of densities (Figure 19; note the different colour scale applied). This model includes all the rocks encountered (including some short granite and basement well penetrations), so a more selective dataset would have to be specified in order to build a density structure that could be employed in modelling. In practise that might not be the best approach, however, as the data available include short sections from the upper part of this sequence that will provide underestimates of its average density. The data for individual rock units provided in the supplementary material (described in Appendix 2) can be used for more detailed analysis. For example the average density of the Devonian sequence in wells where its thickness exceeded 500 m is 2.57 Mg/m^3 and the equivalent value for sequences more than 200 m thick is 2.56 - 2.57 Mg/m^3 (depending on whether a simple average of the site means is employed, or this is weighted according to thickness).

The very limited density sampling of metamorphic basement in the offshore wells is insufficient to provide reliable control, but the onshore sampling of the Dalradian sequence (see Section 2.2, Table 1) provides good justification for adopting the value of 2.75 Mg/m^3 previously used in the Central North Sea modelling study (Kimbell and Williamson, 2015). Density logs through the granite intersections encountered in the offshore area are also unlikely to provide a reliable sample, but where digital logs appear to extend into less weathered zones (e.g. in well 13/24b-3) the average density is similar to that (2.64 Mg/m^3) estimated by Rollin (2009) from 115 onshore sites.

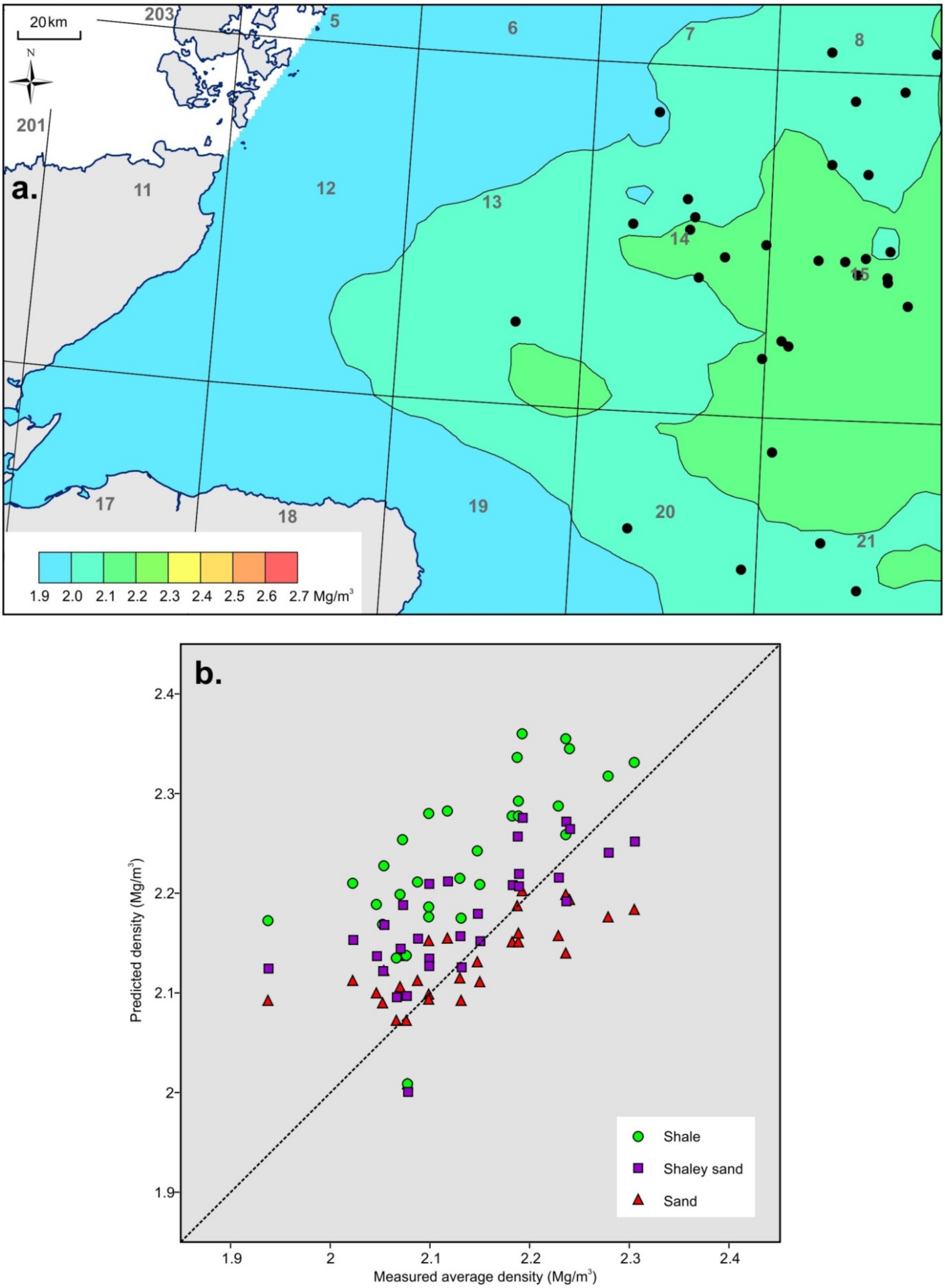


Figure 13 (a) Density model for the post-Chalk sequence, based on the assumption of a shaley sand lithology and employing the compaction trend of Sclater and Christie (1980) and burial anomalies of Japsen (1999). (b) Comparison of observed and predicted average densities at the well locations shown by black dots in (a), illustrating the effect of assuming different lithologies (Sclater and Christie, 1980).

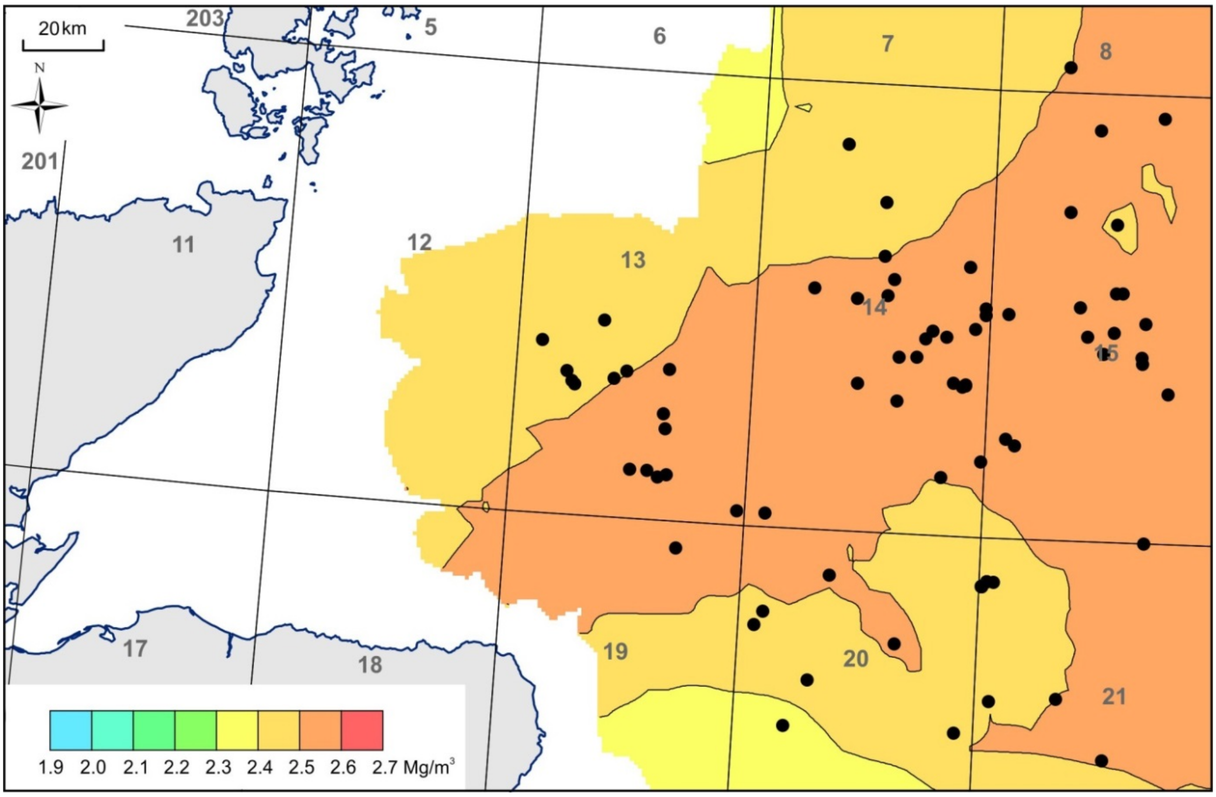


Figure 14 Density model for the Chalk, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

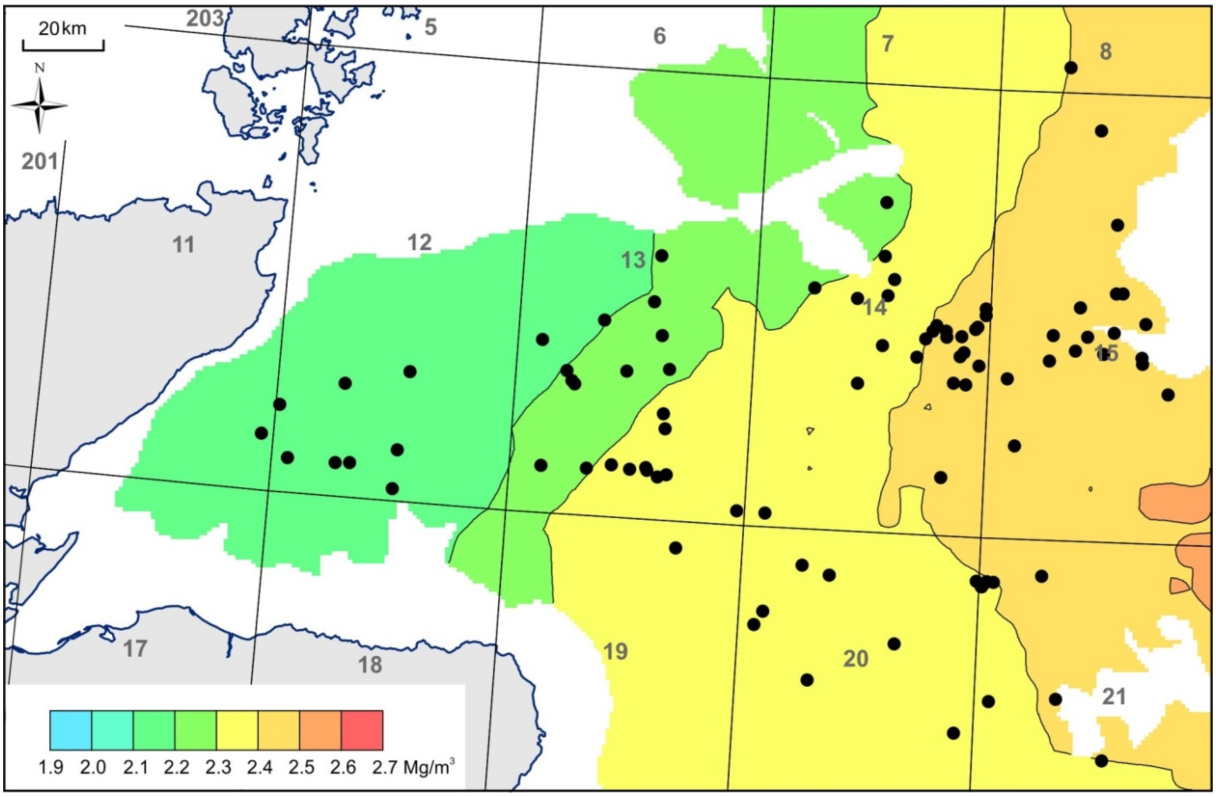


Figure 15 Density model for the Lower Cretaceous, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

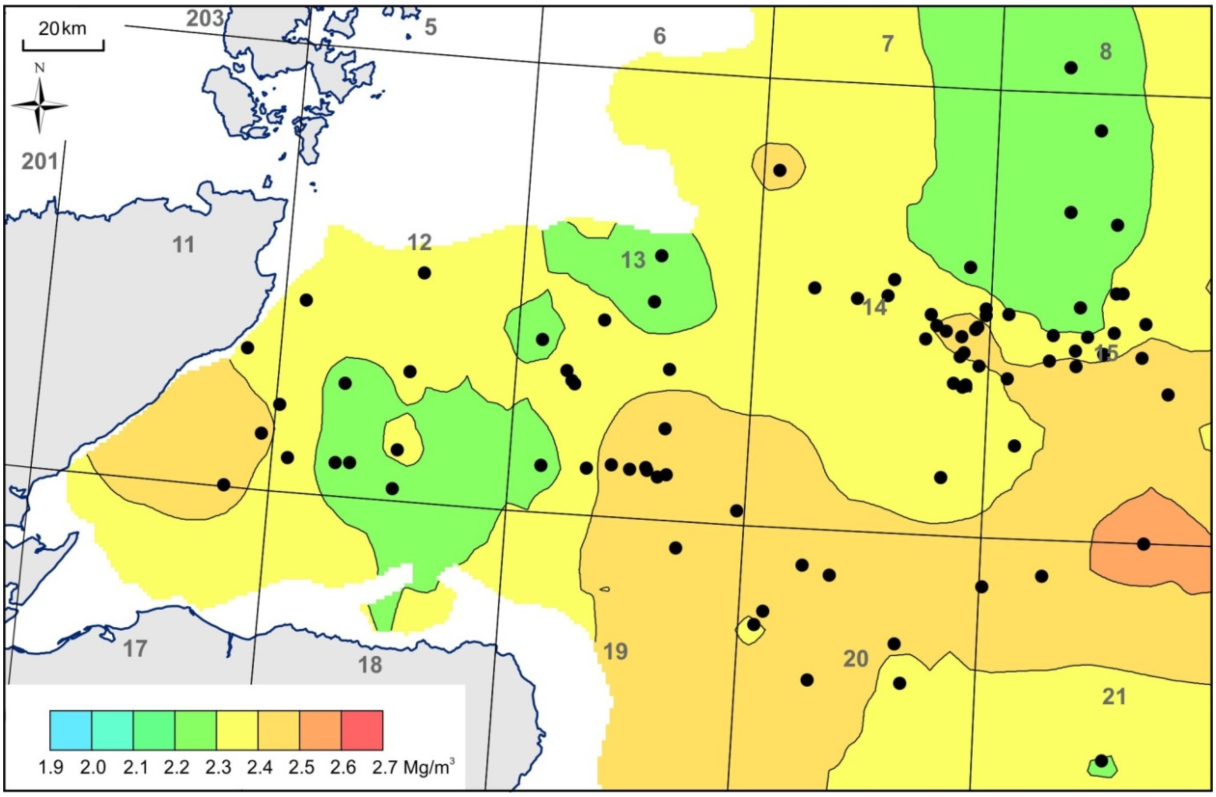


Figure 16 Density model for the Jurassic, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

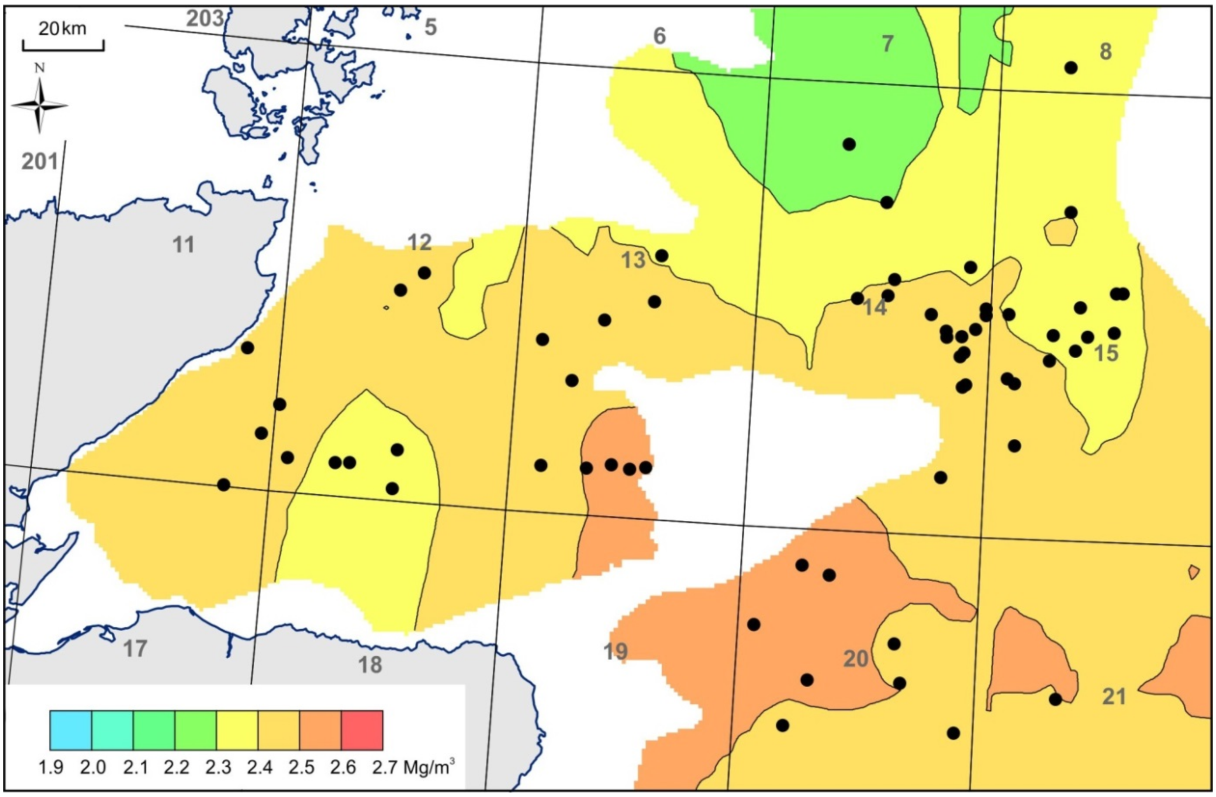


Figure 17 Density model for the Triassic, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

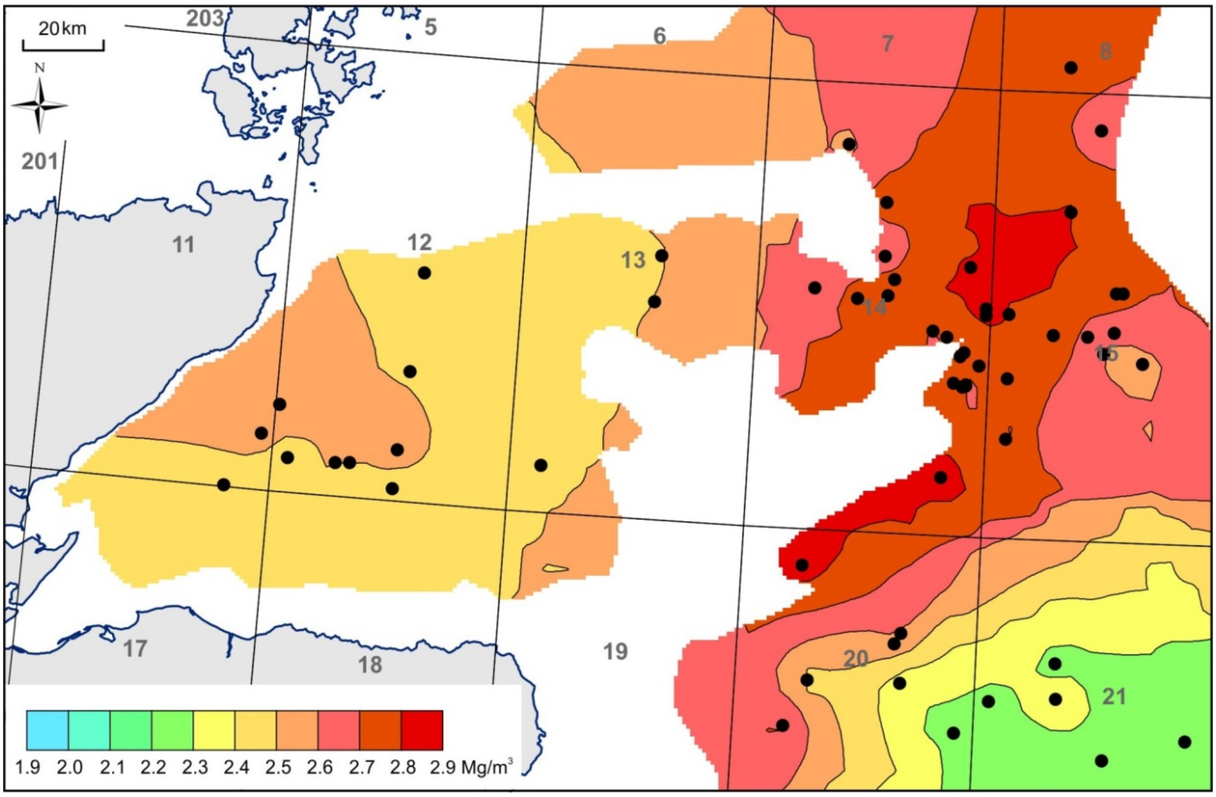


Figure 18 Average density of the Zechstein sequence, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

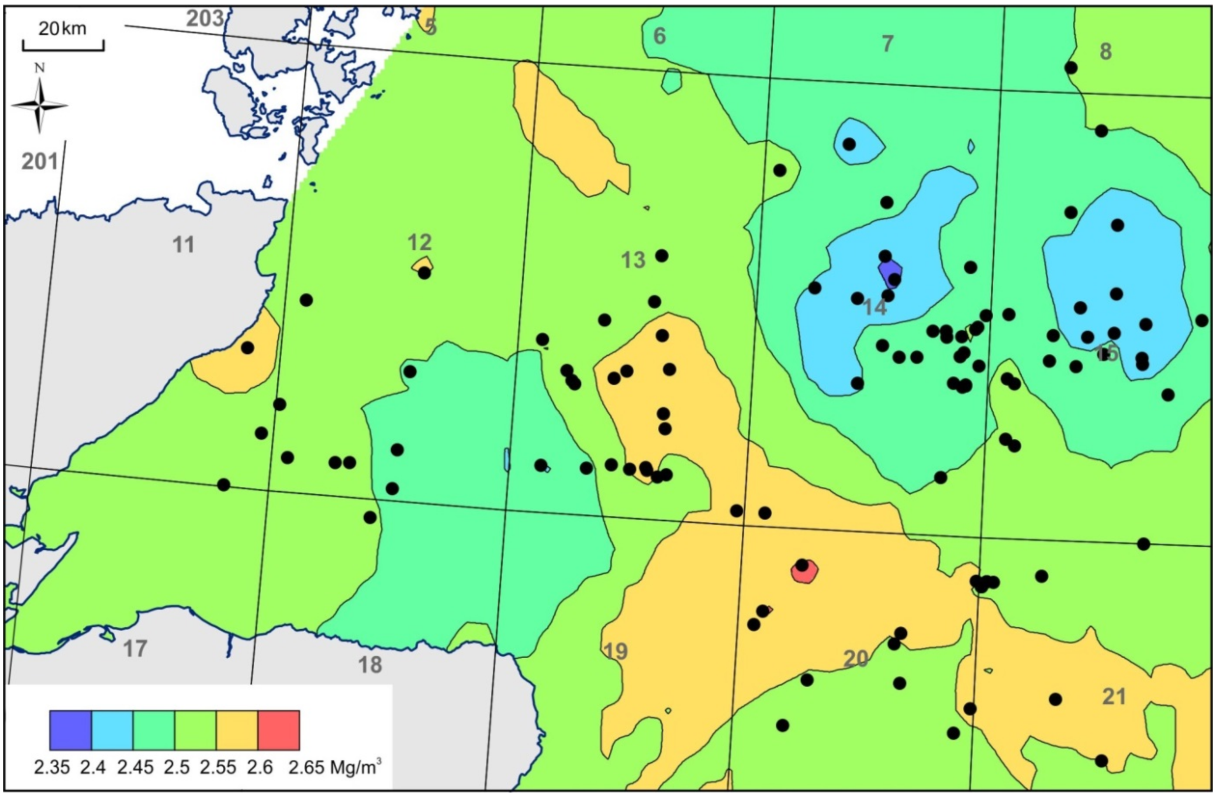


Figure 19 Average density of the pre-Zechstein sequence, based on empirical Bayesian kriging of the observed average densities at the well locations indicated by black dots

From the above discussion it appears likely that the density contrast between basement and a pre-Zechstein sequence dominated by Devonian rocks might be about 0.18 Mg/m^3 (2.57 Mg/m^3 vs. 2.75 Mg/m^3), which might be rounded down (to, say, 0.15 Mg/m^3) to allow for bias in the sampling of the Devonian rocks. For comparison, Ashcroft and Wilson (1976) adopted an average density for the Devonian sequence in the onshore Turriff basin (TB in figures 10 and 20) of 2.59-2.62 Mg/m^3 but employed relatively small density contrasts of 0.09-0.12 Mg/m^3 based on what appears to be an underestimate of the density of the Dalradian rocks of the Buchan Block. The model of Ashcroft and Wilson (1976) for the northern part of the Turriff basin was constrained, to a degree, by a seismic refraction experiment, but the isolation of its gravity effect was complicated by the effects of neighbouring igneous rocks.

4 Gravity modelling

The gravity modelling involved the construction of a forward model of the gravity effect of the sequence down to top Zechstein, the subtraction of the result from the observed anomalies and the analysis of the residuals in terms of the underlying geology. The initial intention was to extend the gravity stripping to the base of the Zechstein, but due to the variable character and extent of this unit it was not possible to obtain a reliable depth conversion of its base over the full model area (structural element map shown in Figure 20) within the scope of the project.

4.1 STRUCTURAL INPUTS

The structural inputs were interim depth-converted seismic picks resulting from a companion task (Arsenikos et al., 2016):

- Seabed (derived from DigBath250; http://www.bgs.ac.uk/products/DigBath250/home.html)
- Top Chalk
- Base Chalk
- Base Cretaceous/Cimmerian Unconformity
- Near Top Triassic
- Top Zechstein

These were initially supplied as 1 km grids, which were converted to data points, merged with additional control points and regridded at 5 km intervals in order to comply with agreements with seismic data companies on output grid resolution. For the gravity modelling, each surface was continuous across the full model area, clipping to the overlying horizon where the intervening rock unit was absent. The control points were designed to restrict layers to their mapped limits and, in places, to extrapolate units where the seismic mapping was impeded by lack of data. An example of the latter approach was in the footwall of the Banff Fault in the nearshore area (Figure 20) where the structure contours were extrapolated up to the fault to avoid the generation of an artefact at the edge of the seismic coverage. The basal surface of the modelled sequence is shown in Figure 21. Substantial smoothing has resulted from the generalisation of the structural data, and the original interpretation contained sharper thickness variations across faults. Note that the West Fair Isle Basin and the area west of Orkney was not included in the structural model (only the gravity effect of the sea water was calculated in that area).

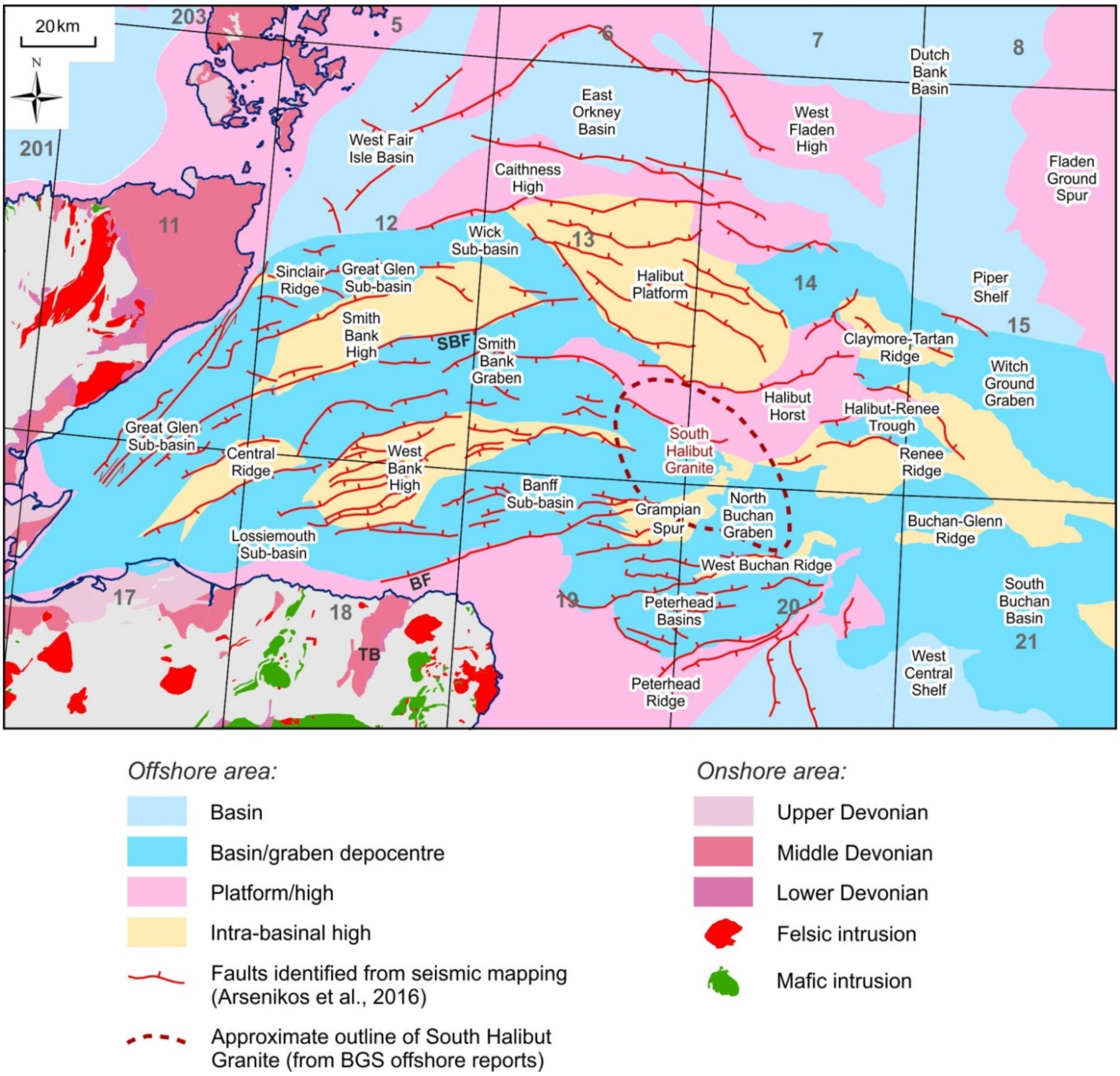


Figure 20 Structural elements over the 3D gravity modelling area. BF = Banff Fault; SBF = Smith Bank Fault; TB = Turriff Basin.

4.2 GRAVITY MODELLING PROCEDURE

The gravity calculations were made using GM-SYS 3D routines within the Geosoft Oasis Montaj software package. The structural grids with a 5 km node spacing were used as the basis for the initial modelling, but the final model resampled these at 2.5 km intervals, and employed an observed gravity field and bathymetric model that incorporated the wavelengths available with this closer sampling. This slightly improved the visual appearance of the modelled result but the limitations of the inherent seismic resolution need to be borne in mind when viewing the results. The basin structure is characterised by complex faulting which is necessarily highly generalised. The model explicitly included the seawater layer (with a density of 1.03 Mg/m^3) and thus simulates free-air gravity anomalies in the offshore area. The input field (Figure 22) was based on free-air gravity anomalies offshore and Bouguer anomalies onshore and the gravity calculation surface was at the sea level datum. The forward gravity calculation is shown in Figure 23.

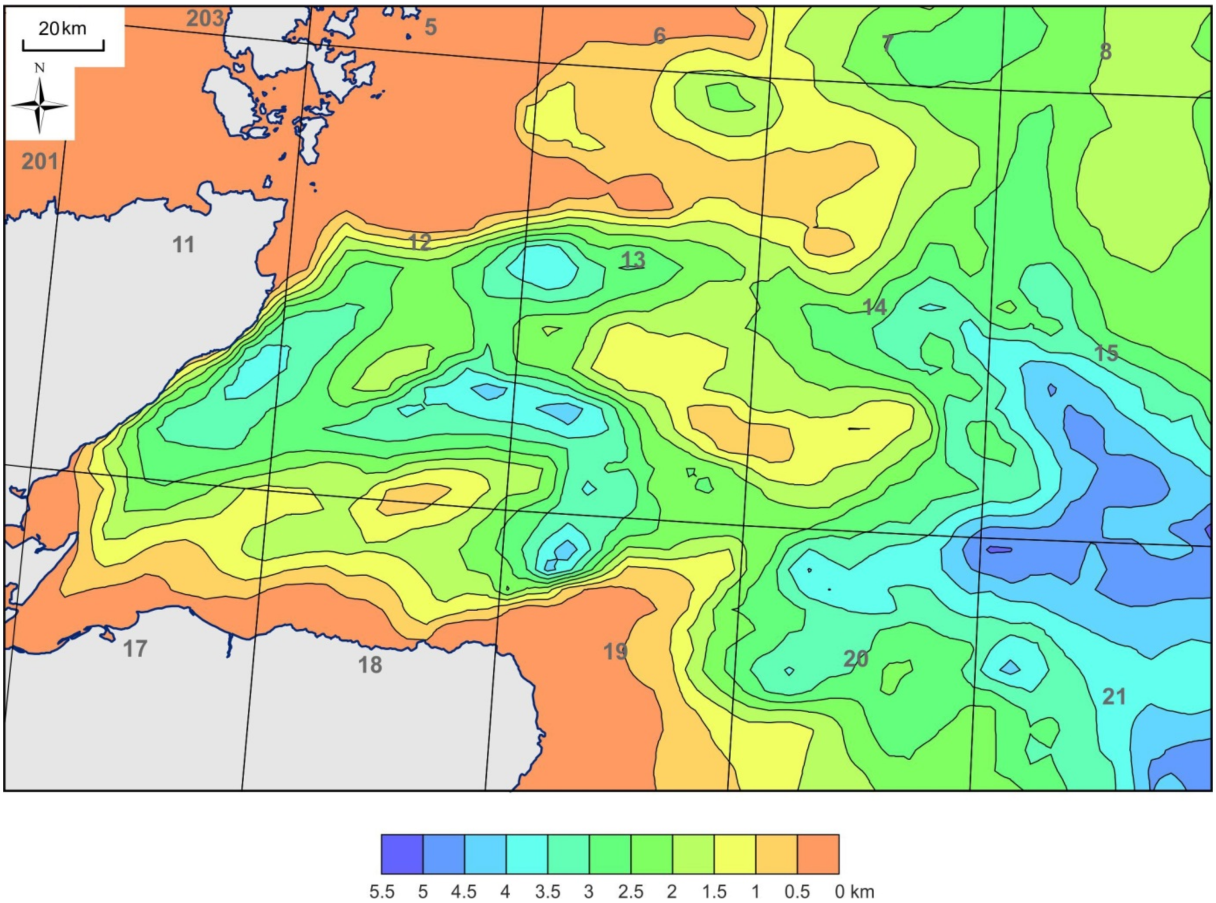


Figure 21 Basal surface of the sequence employed in the 3D gravity stripping (base Triassic / top Zechstein where present)

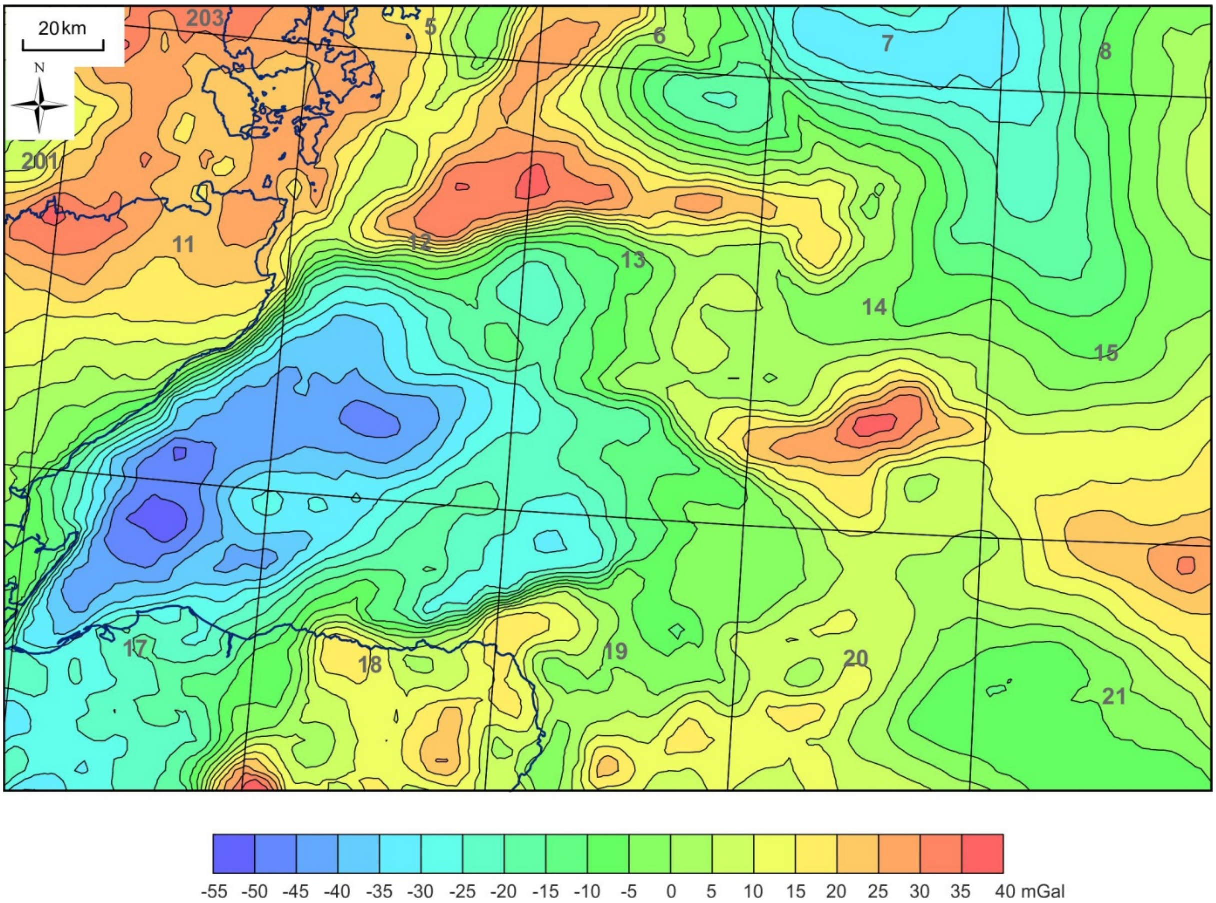


Figure 22 Observed gravity over the 3D gravity stripping area

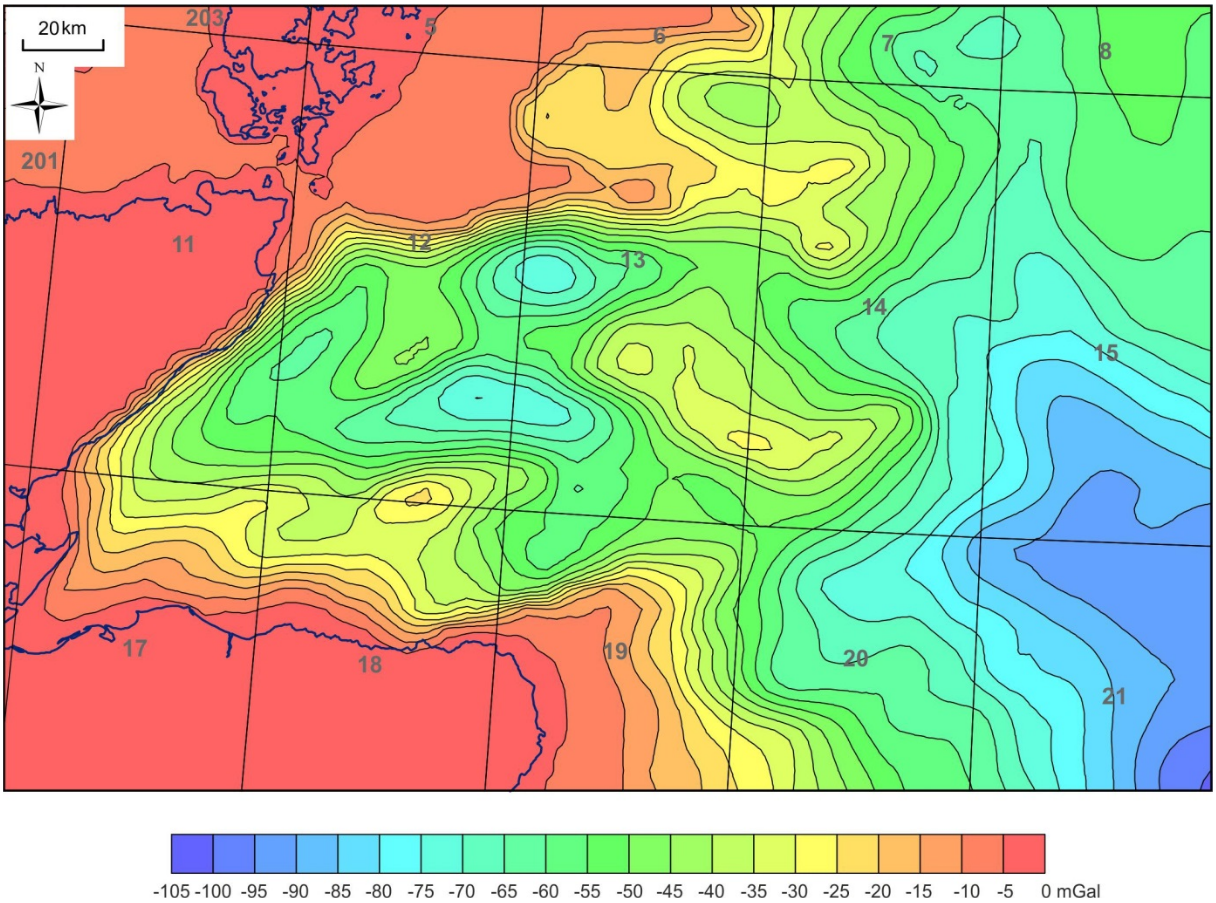


Figure 23 Calculated gravity effect of the sequence down to the surface shown in Figure 21

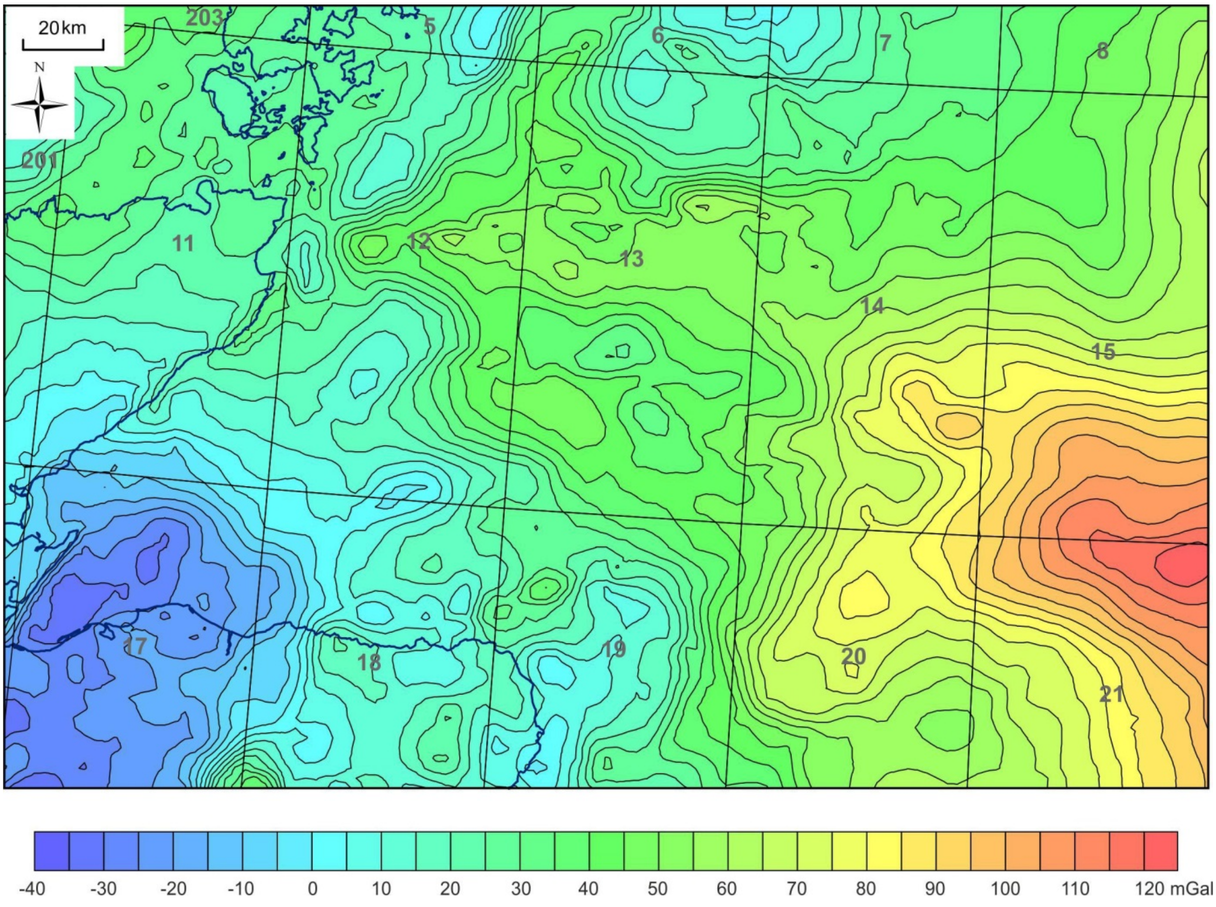


Figure 24 Stripped gravity field: observed field shown in Figure 22 minus the calculated field shown in Figure 23

The stripped gravity field (observed minus calculated) is shown in Figure 24. This contains long wavelength effects relating to deep crustal structure, which need to be removed in order to isolate the signatures of interest. A simple long wavelength background field has been defined on the basis of observations in the four corners of the model area. In the south-west and north-west it was guided by comparison with the onshore geological outcrop and also, in the latter area by gravity values observed over structural highs in the offshore area. In the north-east it was guided by control provided by the basement intersection observed in well 16/03a-11, just outside the modelled area. There was less constraint in the south-west, and a value was selected on the basis of the gravity stripping results and comparison with assumptions made in the area to the south (Kimbell and Williamson, 2015). The background field was simply allowed to vary smoothly between these corners (Figure 25), as it was not considered appropriate to attempt to incorporate shorter wavelengths at this preliminary modelling stage. Figure 26 shows the residual stripped gravity anomalies that result when the background field (Figure 25) is subtracted from the stripped gravity field (Figure 24). This display forms the basis of the analysis discussed in the following section. To aid with the correlation of gravity and magnetic features its contours are superimposed on a reduced-to-pole magnetic image in Figure 27.

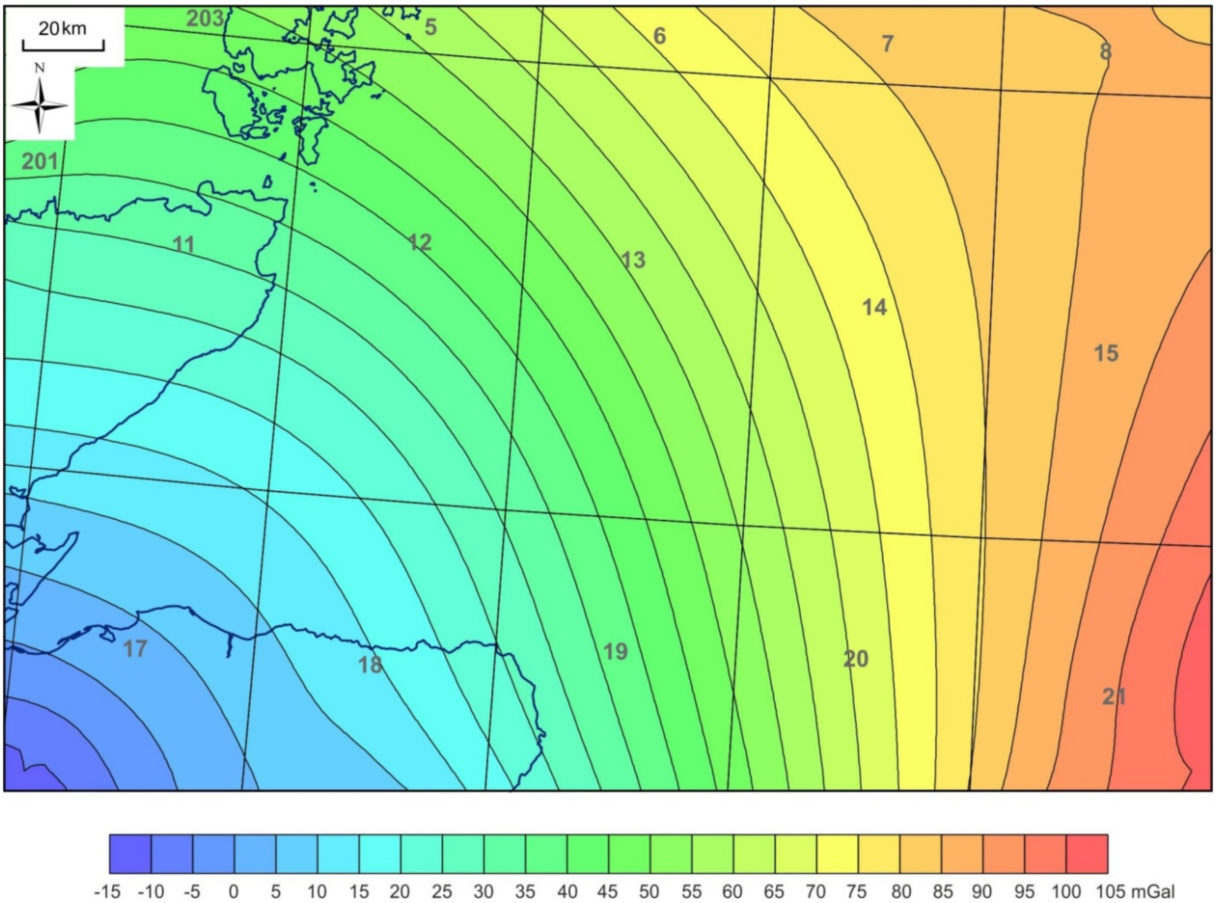


Figure 25 A simple 'background' field, based on limited constraints towards the corners of the modelled area and smoothly varying in-between (see text)

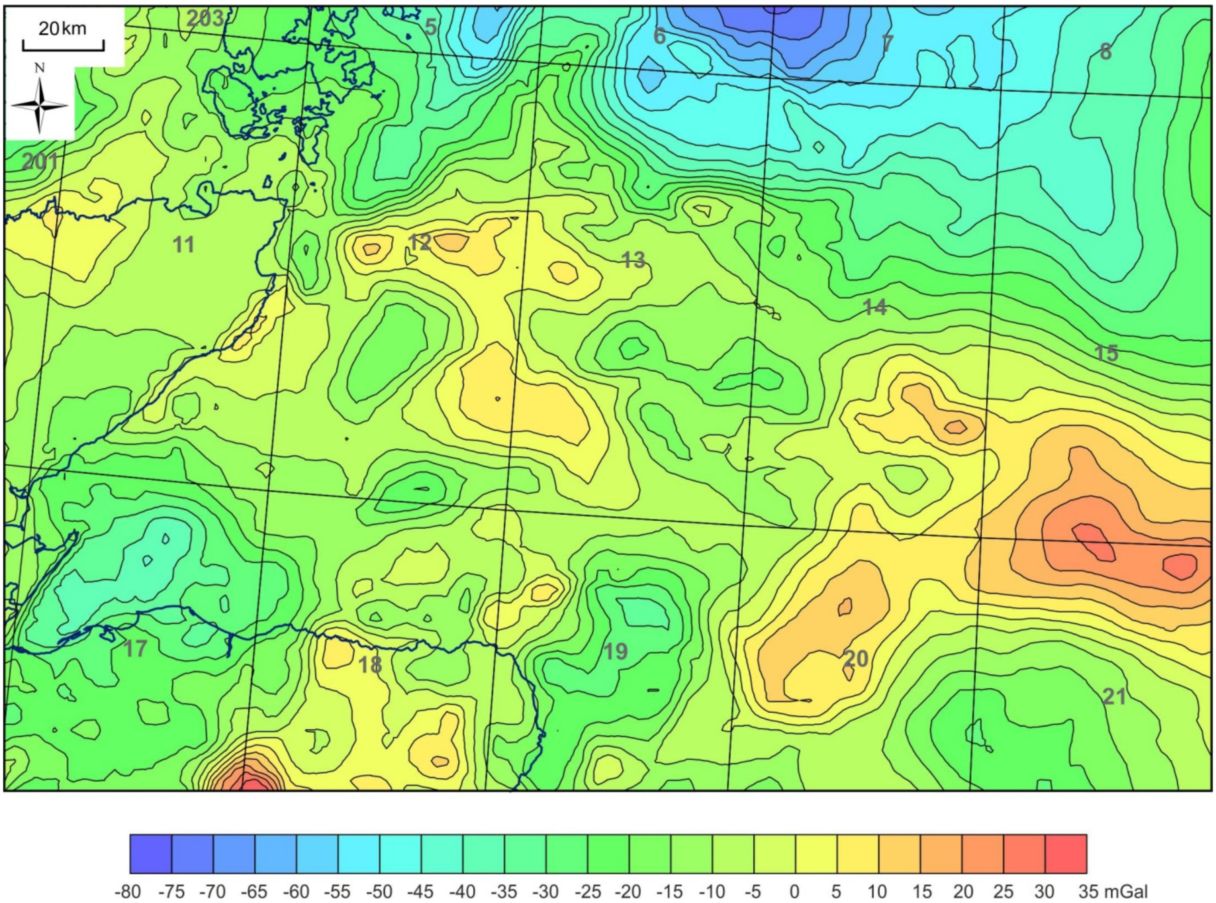


Figure 26 Residual stripped gravity: stripped field (Figure 24) minus background (Figure 25)

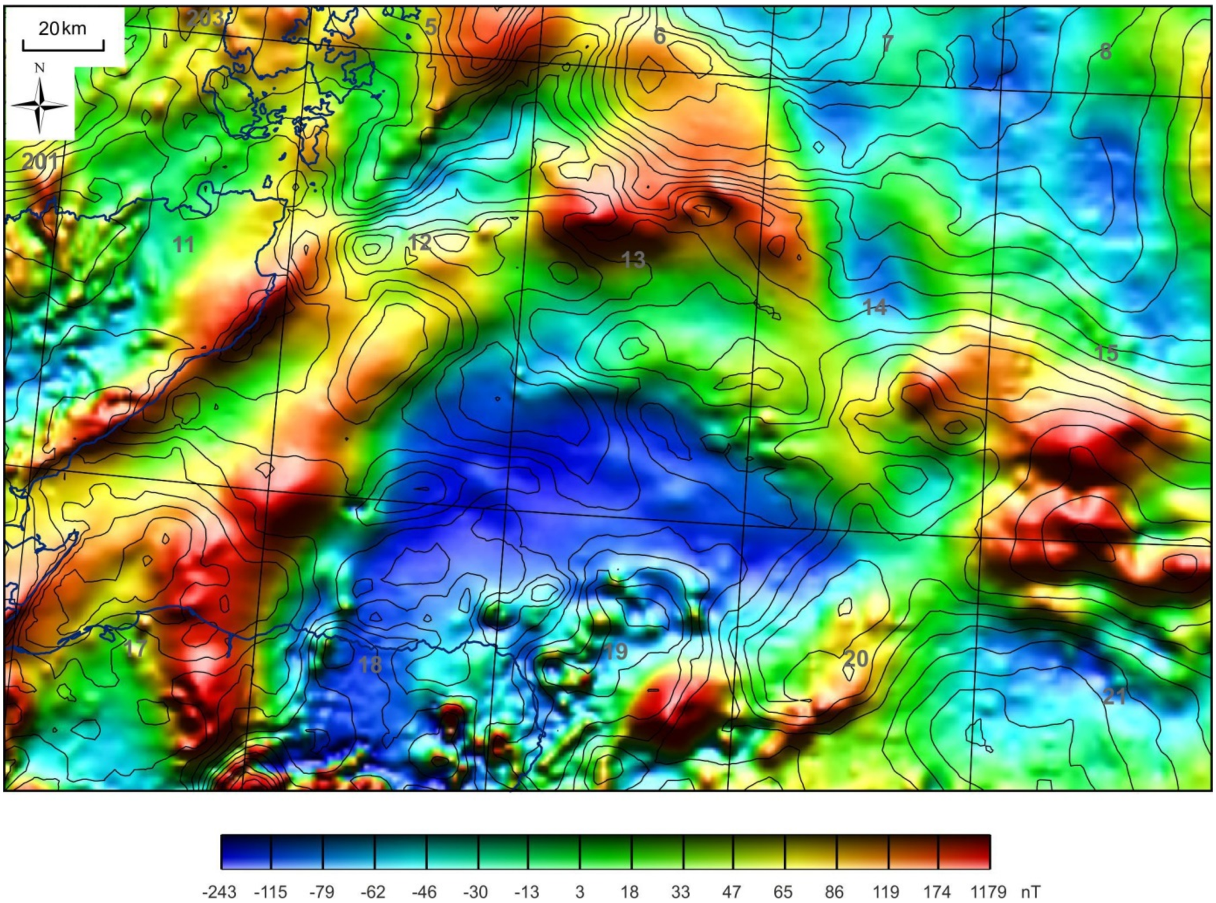


Figure 27 Residual stripped gravity contours superimposed on reduced-to-pole magnetic image

5 Discussion

In this section, the sources of the gravity variations revealed by the residual stripped gravity map (Figure 26) are discussed in relation to the following possible causes:

- Thickness variation in the Upper Palaeozoic sedimentary sequence
- Granitic intrusions
- Other basement density contrasts (e.g. intra-Dalradian density variation, mafic intrusions)
- Jurassic magmatism

5.1 PRIMARILY SEDIMENTARY FEATURES

An important and independent view of pre-Triassic sediment thickness variation is provided by the seismic mapping of intra- and base-Upper Palaeozoic horizons reported by Arsenikos et al. (2016). Figure 27 shows the thickness between the basal horizon used in the gravity stripping and a depth-converted top basement grid from the study of Arsenikos et al. (2016). There is a clear correspondence between these two lines of evidence in the West Bank Basin in the south-east corner of Quadrant 12, where vital ground truth is provided by well 12/29-2 (compare Figures 28 and 29). The well intersected a 2642 m thick pre-Triassic sequence (vertical thickness) before encountering metasedimentary basement. In the original interpretation, this sequence included a substantial (842 m) Lower Permian component, but reinterpretation has asssigned all but about 190 m of this to the Devonian (Marshall and Hewett, 2003; Whitbread and Kearsey, 2016). The residual stripped gravity anomaly at well 12/29-2 is -21 mGal which, in a simple 'Bouguer slab' calculation, is equivalent to a density contrast of -0.18 Mg/m^3 over the proven thickness. This is obviously a crude comparison, as it does not allow for the geometrical details, but the comparability to the estimated density contrast described in Section 4 does suggest good compatibility between the drilling, seismic and gravity stripping results.

A further probable area of pre-Triassic sedimentary thickening is suggested by both the seismic model and the gravity stripping about 30 km south of the sequence drilled by 12/29-2, along an axis which lies just to the north of the coast and in the hanging-wall of the Banff Fault. The presence nearby of the Turriff Basin (Figure 20) provides some supporting evidence, although the offshore feature is less well resolved as it occurs in an area with relatively poor gravity coverage (Figure 3).

There is a further close correlation between the gravity stripping results and seismic mapping in the East Orkney Basin in the north-east corner of Quadrant 13 (Figures 28 and 29). The calibration of the seismically-imaged sequence in this basin is poor because of lack of well control, so there is a degree of dependence between the two methods (an error in the level of the top Zechstein seismic pick would propagate into the stripped gravity). The gravity stripping does not reveal a clear signature that could be ascribed to the salt pillow described by Richardson et al. (2005), although the limited extent of that body makes it a difficult target with the coarse grids used in the modelling.

The West Fair Isle Basin was not included in the gravity stripping, so the map shown in Figure 28 refers to the thickness between seabed and seismic top basement in this area. Qualitative comparison with the gravity stripping results indicates reasonable agreement, although the continuity of the basin is clearer in the gravity data.

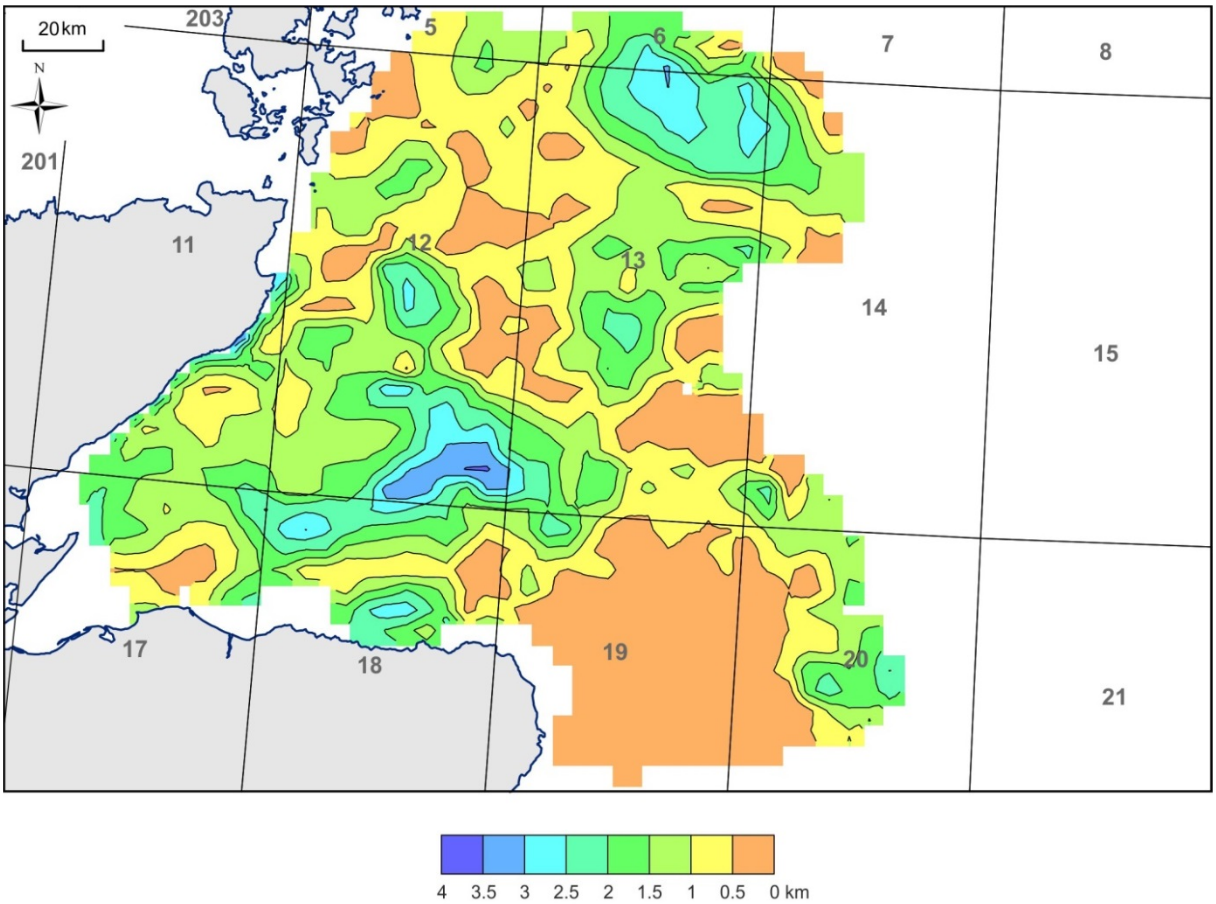


Figure 28 Thickness between base of the modelled sequence (Figure 21) and top basement from the seismic interpretation (Arsenikos et al., 2016)

The residual stripped gravity field decreases northwards in the north-east part of the modelled area, reaching a minimum on its northern edge at the boundary between Quadrants 6 and 7, on the eastern side of the Dutch Bank Basin. The peripheral location of this feature makes it susceptible to inaccuracies in the background field, so the absolute amplitude is not considered reliable, but there is supporting evidence for this sedimentary thickening in the magnetic data. Shorter wavelength magnetic anomalies over the Caithness Ridge can be assigned to the influence of relatively shallow magnetic basement, and the magnetic anomaly has a smoother (deeper) character over the East Orkney Basin before dropping away to lower values in a zone coincident with the residual stripped gravity low. Within the north-eastern corner of the modelled area there is detailed correlation between gravity and magnetic signatures, for example in axes that extend in a south-south-east direction through Quadrants 14 and 15. The evidence thus supports a thick, non-magnetic and relatively low density pre-Triassic sequence in the north-eastern part of the study area, which is considered most likely to be dominantly Devonian in age.

An axis of lower residual stripped gravity values extends eastwards and westwards from the vicinity of well 13/19-2 (Figure 29). That well intersected metamorphic (metasedimentary) basement beneath a relatively thin (234 m) Permo-Triassic sequence, but the lower gravity values to west and east may have a sedimentary cause. The western feature approximately coincides with a seismically defined sedimentary thickening at the eastern end of the Caithness Graben (Arsenikos et al. 2016), but top basement was not identified seismically in the area of the eastern extension (Figure 28). There is a further zone of possible Palaeozoic sedimentary thickening in the south-east corner of Quadrant 14 (Figure 29), although this lies in an area where the structural complexity of the overlying sequence is not well-resolved by the current low-resolution model and more detailed investigation is necessary.

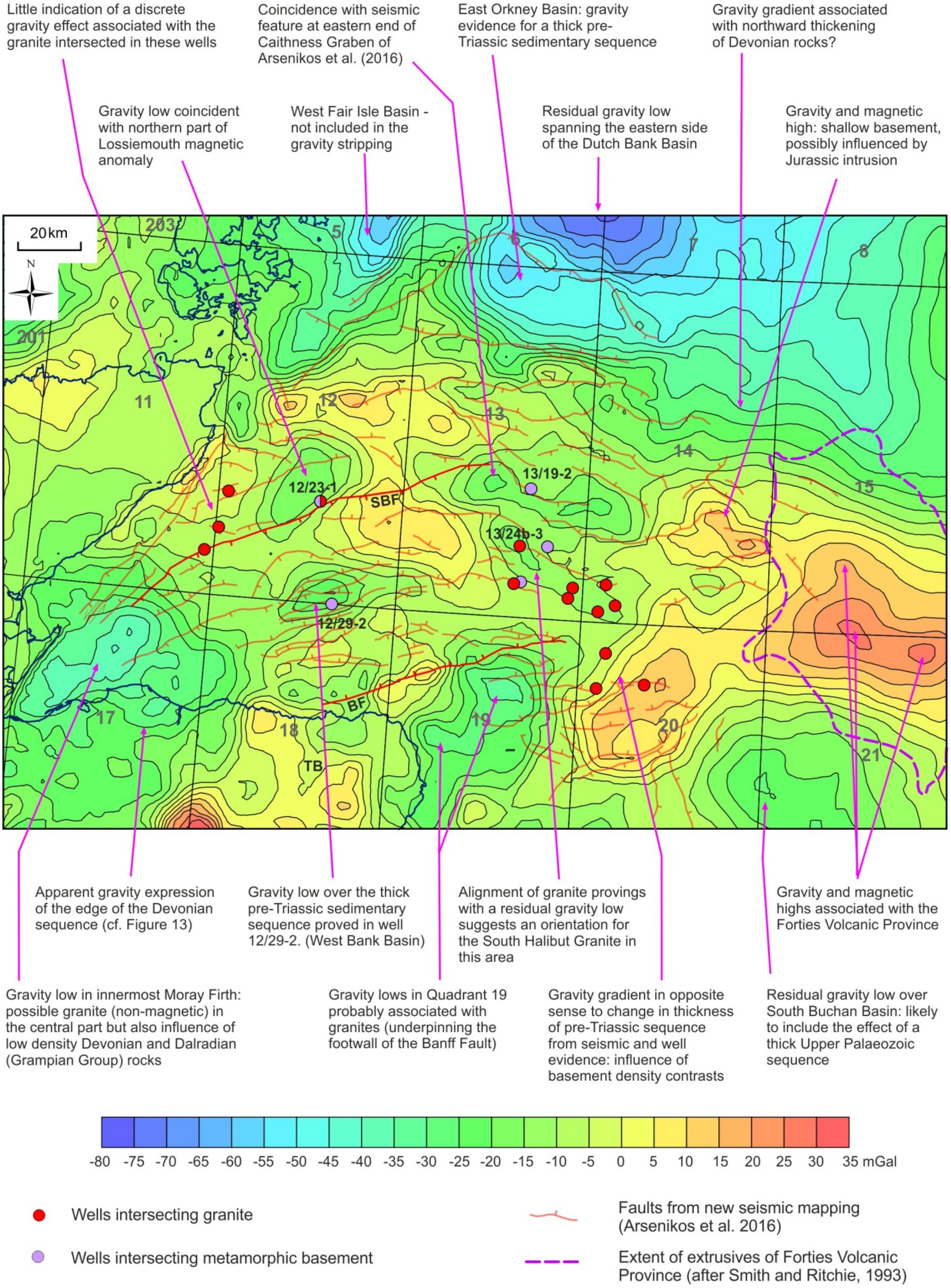


Figure 29 Annotated residual stripped gravity map. Wells intersecting granite and metamorphic basement are mainly after Bassett (2003). BF = Banff Fault; SBF = Smith Bank Fault; TB = Turriff Basin.

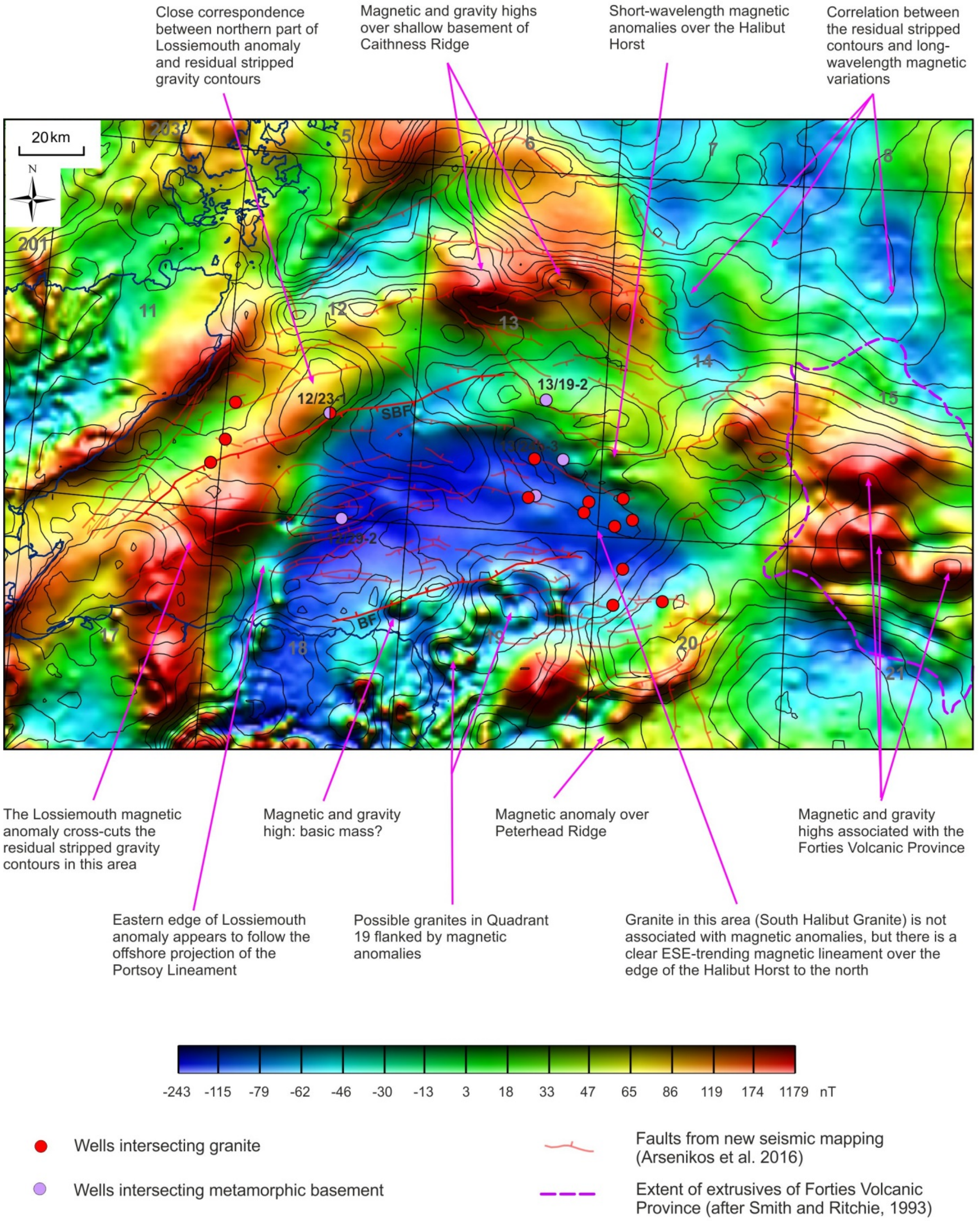


Figure 30 Annotated residual stripped gravity contours (cf. Figure 29) superimposed on reduced-to-pole magnetic image

A residual stripped gravity low over the South Buchan Basin in the SE corner of the study area is considered likely to indicate the effect of Upper Palaeozoic sedimentary rocks. A contribution to this will be due to low-density halite within the relatively thick Zechstein sequence in that area, which was not included in the gravity stripping, so it is difficult to quantify the contribution from the underlying Upper Palaeozoic sequence. At a qualitative level it is considered likely that the incorporation of the Zechstein would attenuate the residual gravity low in the extreme south-eastern corner of the area shown, but a low is likely to remain in the area around the boundary between Quadrants 20 and 21 farther west. Seismic mapping indicates a south-eastward thickening of Devono-Carboniferous sequence from the Peterhead Ridge into that area (Arsenikos et al., 2016) which is corroborated by the magnetic evidence (Figure 30).

There is also an area of pre-Triassic sedimentary thickening in the innermost Moray Firth (Quadrant 17), which is discussed in the following section because of the interrelationship with the effects of intra-basement density contrasts.

5.2 AREAS INFLUENCED BY GRANITIC INTRUSIONS AND OTHER BASEMENT EFFECTS

Possible granites were identified in Quad 19 on the basis of the initial qualitative analysis, and the results of the gravity stripping and seismic mapping support this interpretation. The seismically mapped basement is shallow in this area (Figures 21 and 28) and magnetic data indicate shallow sources which are poorly resolved but in places appear to be organised around the flanks of the gravity lows. The general disposition of this zone of granites appears to be along a north-north-east-trending axis, although there is some evidence of an east-south-east trend in its internal structure. The northernmost granite underpins the footwall of the Banff Fault. The combination of a pronounced gravity effect and marginal magnetic anomalies suggests that these granites most likely belong to the post-tectonic group, similar in age to the Peterhead granite in the onshore area (which is their closest neighbour).

An area of granitic basement, termed the South Halibut Granite, has been identified previously on the basis of well intersections (e.g. Andrews et al., 1990; the outline from previous publications is indicated in Figure 20). When the granite well penetrations are compared with the residual stripped gravity map there is a correlation along an axis extending east-south-east from well 13/24b-3. This provides an indication of a possible alignment of the granite(s), although caution is necessary because the gravity feature lies at the southern edge of the Halibut Horst so is prone to distortion resulting from the limited resolution of the structural model. There is little evidence of magnetic anomalies that can be correlated with this granite zone. Some short wavelength disturbance occurs just to the north of it, but appears more likely to be associated with other basement rocks.

Bassett (2003) shows three wells intersecting granite in the north-west corner of Quadrant 20 (Figure 29), although it has not been possible to validate the south-western of these with data available to the present project. The granite penetrations lie in an area where the residual stripped gravity field decreases towards the north-west but the thickness of the seismically-imaged pre-Triassic sedimentary sequence thins in that direction. It is clear, therefore, that the gravity gradient is primarily driven by basement density contrasts. Deeper-seated granites on the north-west side of the gradient zone contribute to the gradient, and it is unlikely that the granite proven on its south-east side (in well 20/07-2) is deep seated. This relatively thin granite has no clear magnetic expression (Figure 30), characteristics that are most common in the late-tectonic Caledonian granites (although further geochemical and isotopic investigation would be necessary to test this interpretation).

The combination of well, seismic, gravity and magnetic data therefore indicate a belt strongly influenced by granitic intrusion which extends in a north-north-east direction through Quadrant 19 into the south-east part of Quadrant 13, extending into the adjacent corners of Quadrants 20 and 14 on its eastern side. This may not represent a single magmatic episode, however, as the character of the granitic bodies (depth extent and magnetic signature) varies, and in the onshore area such variations show a relationship with magmatic episodes spanning a period of more than 50 million years.

A second area with evidence of granite intrusion lies in the Inner Moray Firth. Well 12/23-1 passed through a fine grained quartz-biotite gneiss and into severely fractured granite (Frost et al., 1981). Three further wells have intersected granite, or material interpreted to have been eroded from a nearby granite, close to the boundary between Quadrants 11 and 12 (Figure 29; Bassett, 2003). The intersection in 12/23-1 coincides with the SE flank of a residual stripped gravity low which coincides with the northern part of the Lossiemouth magnetic anomaly (Figure 30). This lends support to the contention of Dimitropoulis and Donato (1981) and Pilkington et al. (1995) that the Lossiemouth anomaly is associated with a large, magnetic granite intrusion. It should be borne in mind, however, that the alternative interpretation which associates the Lossiemouth anomaly with Palaeoproterozoic calc-alkaline rocks would also admit an association with relatively low density, as this is observed in similar rocks in, for example, the Transscandinavian Igneous Belt (Ebbing et al., 2012). Although the southern end of the Lossiemouth magnetic anomaly coincides with the Ben Rinnes granite in the onshore area (Figure 12b), the two sources are at different crustal levels so this does not demonstrate that they are coeval. On the other hand, the parallelism between the north-north-east-trending offshore part of the Lossiemouth magnetic anomaly and the granite belt identified in Quadrant 19, might be seen as supporting a Caledonian origin. This debate is clearly not going to be solved using geophysical data alone, but the availability of the sampling provided by the offshore wells does open the way for further investigation using modern geochemical and isotopic methods.

The granite intersections in the wells close to the boundary between Quadrants 11 and 12 do not correlate with a discrete residual gravity low and lie off the axis of the Lossiemouth magnetic anomaly (Figure 29 and 30). Farther south-west there is a distinct residual low in the innermost Moray Firth, but the contours associated with the north-eastern margin of this feature cross-cut the axis of the magnetic anomaly. In fact the more detailed imaging provided by residual magnetic anomalies (included in the supplementary material; see Appendix 1) emphasises the fact that there is a local high on the Lossiemouth anomaly axis just to the north-east of this gradient zone. Pilkington et al. (1995) used a model based on inversion of the magnetic data to define the top surface of a granite body which was then incorporated in gravity modelling. This approach carries risks because the density contrast associated with the igneous belt represented by the Lossiemouth anomaly may, on the above evidence, vary along its length. In detail, the minimum within the gravity low in offshore Quadrant 17 coincides with a basement high identified by seismic mapping (Figure 28; Arsenikos et al., 2016). There is a small half-graben on the south side of this feature that is not resolved by the low-resolution seismic model, but this is only a local feature superimposed on a general shallowing of the seismic reflectors (assumed to include top basement) into this area. A granite source therefore does appear a valid interpretation for this central anomaly, although the magnetic correlations indicate that it does not coincide with the Lossiemouth magnetic anomaly but rather lies between that and the Great Glen anomaly (Figure 30).

The poorly-calibrated contributions of low density igneous rocks and the influence of density contrasts in the Dalradian sequence (in particular the low-density Grampian Group; see Section 2.2) make it difficult to isolate the contribution of Upper Palaeozoic sedimentary rocks to the gravity low in the innermost Moray Firth. The south-western part of the Quadrant 17 gravity low is not well-defined in the residual stripped gravity map because the seismic mapping does not extend into that area, although at least a contribution from Devonian sedimentary rocks to this part of the anomaly appears probable on the basis of correlations with the onshore area. Similarly, the alignment of gravity contours with the margin of the onshore Devonian sequence on the south side of the anomaly indicates that part of it is due to this sequence. On current evidence, however, it does appear that the thickness of Devonian rocks in the Inner Moray Firth area is less than suggested by the gravity inversion of Pilkington et al. (2005).

5.3 THE FORTIES VOLCANIC PROVINCE

The gravity stripping results confirm the presence of distinct gravity highs over probable intrusive centres underlying the Forties Volcanic Province, and the association of these centres with magnetic anomalies (Figures 29 and 30). A positive residual gravity and magnetic anomaly that extends into Quadrant 14, beyond the limit of the Jurassic extrusives, may be due to an intrusive body of that age, although an association with a basement feature along the long-lived WNW-ESE alignment appears more likely (it lies at the eastern end on the Halibut Horst; Figure 20). The positive anomaly that extends south-westwards from the Forties province is most probably a basement feature, which is associated with shallow magnetic basement in the Peterhead Ridge.

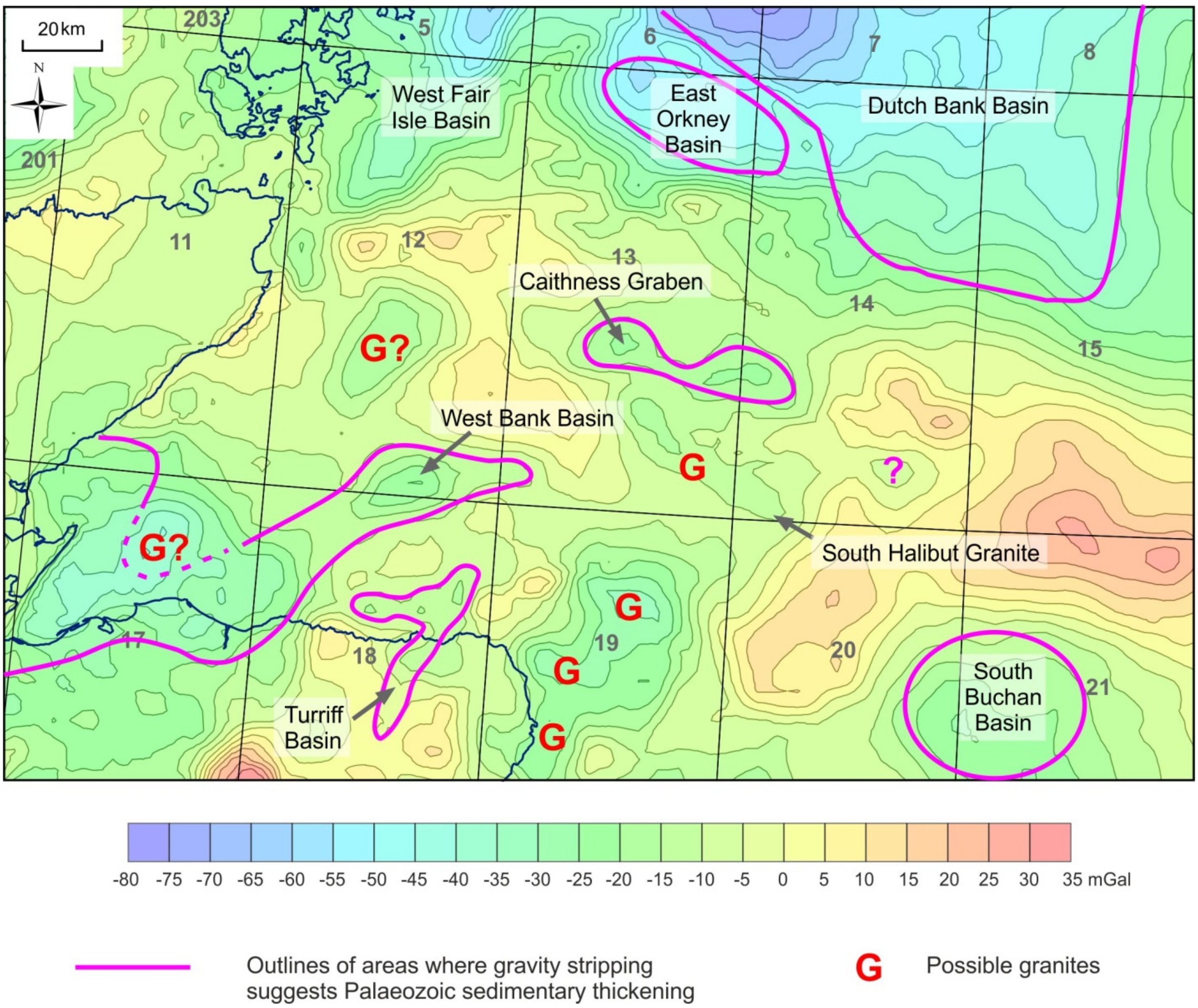


Figure 31 Summary figure showing the main areas of Palaeozoic sedimentary thickening and offshore granites indicated by the gravity stripping. The contour map shows the residual stripped gravity field.

6 Conclusions

This report describes an initial assessment of gravity and magnetic anomalies in the Orcadian Basin area. These anomalies have been interpreted qualitatively, both in the offshore area and onshore, in the East Grampian region, where the aim was to characterise the signatures associated with the basement that probably extends beneath the offshore basins. The gravity interpretation was taken further by constructing a quantitative model of the gravity effect due to the Mesozoic and younger strata and subtracting this from the observations in order to derive a stripped gravity field that can be interpreted in terms of a combination of Upper Palaeozoic sediment thickness variations and basement influences.

The stripped gravity map resolves the area of Upper Palaeozoic sedimentary thickening beneath the West Bank High, which was proved by well 12/29-2 (West Bank Basin; cf. Arsenikos et al., 2016). Further areas of Upper Palaeozoic sedimentary thickening are inferred beneath the East Orkney Basin, the eastern end of the Caithness Graben (Arsenikos et al., 2016), the Dutch Bank Basin and the South Buchan Basin (Figure 31). The last two of these (and a possible eastward extension of the Caithness Graben anomaly) lie in an area where seismic mapping of the Palaeozoic sequence is impeded by problems with data quality and survey line spacing.

A series of probable granite intrusions is identified in Quadrant 19 and south-east Quadrant 13, with extensions into Quadrants 14 and 20. The occurrences proven in wells in the north have previously been collectively termed the South Halibut Granite. The area affected by granite intrusion forms a belt with an overall north-north-east trend and internal structure which contains an east-south-east grain (Figure 31). Contrasts in the associated geophysical signatures (apparent thickness and magnetic expression), and comparison with geophysical anomalies over known onshore intrusions, suggest that both late-tectonic and post-tectonic Caledonian granites may occur within this belt, potentially spanning a period of more than 50 Ma.

A second granite belt is inferred to cross the Inner Moray Firth, and also has a north-north-east trend in the offshore area. The northern end of the belt can be correlated with the northern part of the Lossiemouth aeromagnetic anomaly but farther south there appears to be an offset between the magnetic anomaly and a gravity low with a possible granitic origin. Granites in this area may also be of Caledonian age, but an alternative interpretation invokes Palaeoproterozoic calc-alkaline basement. Although this belt contributes to negative gravity anomalies in the innermost Moray Firth there is evidence for contributions to the gravity minima in that area from Devonian sedimentary rocks and low-density rocks within the Dalradian sequence (the Grampian Group).

Positive gravity anomalies are identified over the Buchan Block and its probable offshore continuation and also over the Forties Volcanic Province where an association with intrusive centres underlying the extrusive sequence is inferred.

On a broad scale the structure of the region can be seen to be underpinned by the intersection between north-north-east (to north-east) and east-south-east trends. The former reflect the continuity of structural trends evident in the onshore Grampian region, which date back to the Grampian Orogeny (c. 470 Ma) or earlier. The latter lies on the projection of the Tornquist Zone, but might originate earlier than any influence from that direction, which would only have been ‘felt’ when Baltica and Avalonia converged with Laurentia later in the Lower Palaeozoic. One possibility is that the east-south-east trend represents the orientation of transform offsets in the Laurentian margin, one of which crosses the present study area and accommodates the offset between the ophiolites observed along the Highland Boundary and in Shetland.

The present gravity modelling only provides low-resolution coverage of a relatively restricted area. There are a number of ways in which the investigation could be taken forward:

- If appropriate seismic inputs become available it would be beneficial to model the gravity effect of the seismically-mapped cover sequence at higher resolution and over a larger area (in particular extending northwards from the present study area).
- The clear relationships between gravity and magnetic sources could be followed up by integrating quantitative modelling of depth to magnetic sources with the gravity modelling. Higher resolution magnetic surveying would aid with the characterisation of the magnetic signatures associated with granitic bodies.
- Profile modelling over selected targets employing seismic, gravity and magnetic data would help to calibrate and partition the overlapping responses associated with intra-basement and cover sequence structures.
- It would be particularly interesting to apply modern geochemical and isotopic methods to the granitic samples obtained from the offshore area, in order to place these within the context of the Caledonian and earlier evolution of the region.

Appendix 1 Digital deliverables

The digital deliverables comprise georeferenced geophysical images and grids resulting from the gravity modelling. All these are referred to UTM Zone 31 (ED50).

GEOPHYSICAL IMAGES

orc_grav_ba_csrn.jpg	Bouguer gravity anomaly, illuminated from the north. Reduction density is variable onshore and 2.2 Mg/m^3 offshore. Shown in Figure 5.
orc_grav_ba_resid_csrn.jpg	Residual Bouguer anomaly, illuminated from the north. Calculated by removal of a 10 km upward continuation. Shown in Figures 6 and 10.
orc_grav_ba_resid_csrs.jpg	Residual Bouguer anomaly, illuminated from the south. Calculated by removal of a 10 km upward continuation.
orc_grav_ba_2kmresid_csrn.jpg	Residual Bouguer anomaly, illuminated from the north. Calculated by removal of a 2 km upward continuation.
orc_grav_faba_csrn.jpg	Free-air gravity anomaly offshore, Bouguer anomaly onshore. Illuminated from the north; variable onshore reduction density.
orc_mag_tmi_csrn.jpg	Total magnetic intensity, illuminated from the north. Shown in Figure 7.
orc_mag_rtp_csrn.jpg	Reduced-to-pole magnetic field, illuminated from the north. Shown in Figures 8 and 11.
orc_mag_rtp_resid_csrn.jpg	Residual reduced-to-pole magnetic field, illuminated from the north. Calculated by removal of a 10 km upward continuation.
orc_mag_rtp_2kmresid_csrn.jpg	Residual reduced-to-pole magnetic field, illuminated from the north. Calculated by removal of a 2 km upward continuation.
orc_mag_pseud_csrn.jpg	Pseudogravity anomaly calculated from the magnetic field. Illuminated from the north.
orc_mag_pseud_resid_csrn.jpg	Residual pseudogravity anomaly, illuminated from the north. 8^{th} degree high-pass Butterworth filter with a central wavelength of 200 km. Shown in Figure 9.

MODEL GRIDS

The model grids all have a 2.5 km grid node spacing, but the structural inputs were derived by interpolation from versions with a 5 km node spacing. The grids are provided in ESRI (ArcGIS), ESRI binary (flt), Zmap, Geosoft, and ASCII (xyz) formats.

orc_v1_dep	Depth to base of the modelled layers (m). Shown in Figure 21.
orc_v1_gobs	Observed gravity field (free-air anomalies offshore, Bouguer anomalies onshore) (mGal). Shown in Figure 22.
orc_v1_gcalc	Calculated gravity effect of modelled layers (mGal). Shown in Figure 23.
orc_v1_gstrip	Stripped gravity field after removal of the modelled gravity effect (mGal). Shown in Figure 24.
orc_v1_bkgrd	Assumed background field (mGal). Shown in Figure 25.
orc_v1_gres	Residual stripped gravity field after removal of the calculated gravity effect and the background field (mGal). Shown in Figures 26, 29 and 31.

Appendix 2 Supplementary rock density information

The supplementary information on rock densities is contained in the files described below:

OrcBasin_WellDensityLogs.pdf	Plots of density logs from wells used in the study, with markers indicating tops from the DECC well stratigraphy datatbase. Q = top Quaternary, GN = top Tertiary, KU = top Upper Cretaceous, KL = top Lower Cretaceous, J = top Jurassic, T = top Triassic, PU = top Upper Permian (Zechstein), PL = top Lower Permian, C = top Carboniferous, D = top Devonian. Some plots are omitted because of confidentiality.
OrcBasin_SummaryMeanDensities.pdf	Plots of the mean densities of the chronostratigraphic units within individual wells. The values are plotted against mid-point depth below seabed, colour-coded according to subarea and superimposed on the compaction curves of Sclater and Christie (1980)
OrcBasin_SummaryDensities.pdf	Plots of all the density measurements within each chronostratigraphic unit. The values are plotted against mid-point depth below seabed, colour-coded according to subarea and superimposed on the compaction curves of Sclater and Christie (1980).
OrcBasin_LayerDensityMaps.pdf	Maps of interpolated (kriged) mean densities within chronostratigraphic layers, including posted values at the data locations
OrcBasin__MeanDen_Chronostrat.xlsx	Spreadsheet of well mean densities divided according to chronostratigraphy
OrcBasin__MeanDen_ModelLayers.xlsx	Spreadsheet of well mean densities divided according to model layers

References

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.

ANDREWS, I J, LONG, D, RICHARDS, P C, THOMSON, A R, BROWN, S, CHESHER, J A, and MCCORMAC, M. 1990. *United Kingdom offshore regional report: the geology of the Moray Firth.* (London: HMSO for the British Geological Survey.)

ARSENIKOS, S, QUINN, M F, JOHNSON, K, SANKEY, M, and MONAGHAN, A A. 2016. Seismic interpretation and generation of key depth structure surfaces within the Carboniferous and Devonian of the Orcadian Basin, Quadrants 7-9, 11-15 and 19-21 area. *British Geological Survey Commissioned Report*, CR/16/034.

ASHCROFT, W A, and WILSON, C D V. 1976. A geophysical survey of the Turriff basin of Old Red Sandstone, Aberdeenshire. *Journal of the Geological Society*, Vol. 132, 27-43.

BANKS, C J, PETERS, D P, WINCHESTER, J A, NOBLE, S R, and HORSTWOOD, M S A. 2013. Basement palaeogeography of late Neoproterozoic Scotland: constraints from exotic clasts within the lower Dalradian Supergroup. *Scottish Journal of Geology*, Vol. 49, 81-92.

BASSETT, M G. 2003. Sub-Devonian geology. 61-63 in *The Millenium Atlas: petroleum geology of the central and northern North Sea*. EVANS, D, GRAHAM, C, ARMOUR, A and BATHURST, P (editors and co-ordinators). (London: The Geological Society of London.)

BOTT, M H P, HOLLAND, J G, STORRY, P G, and WATTS, A B. 1972. Geophysical evidence concerning the structure of the Lewisian of Sutherland, N.W. Scotland. *Journal of the Geological Society*, Vol. 128, 599-610.

DEWEY, J F, DALZIEL, I W D, REAVY, R J, and STRACHAN, R A. 2015. The Neoproterozoic to Mid-Devonian evolution of Scotland: a review and unresolved issues. *Scottish Journal of Geology*, Vol. 51, 5-30.

DICKIN, A P, and BOWES, D R. 1991. Isotopic evidence for the extent of early Proterozoic basement in Scotland and northwest Ireland. *Geological Magazine*, Vol. 128, 385-388.

DIMITROPOULOS, K, and DONATO, J A. 1981. The Inner Moray Firth Central Ridge, a geophysical interpretation. *Scottish Journal of Geology*, Vol. 17, 27-38.

DONATO, J A, and TULLY, M C. 1982. A proposed granite batholith along the western flank of the North Sea Viking Graben. *Geophysical Journal of the Royal Astronomical Society*, Vol. 69, 187-195.

EBBING, J, ENGLAND, R W, KORJA, T, LAURITSEN, T, OLESEN, O, STRATFORD, W, and WEIDLE, C. 2012. Structure of the Scandes lithosphere from surface to depth. *Tectonophysics*, Vol. 536–537, 1-24.

FETTES, D J, GRAHAM, C M, HARTE, B, and PLANT, J A. 1986. Lineaments and basement domains: an alternative view of Dalradian evolution. *Journal of the Geological Society*, Vol. 143, 453-464.

FLINN, D, and OGLETHORPE, R J D. 2005. A history of the Shetland Ophiolite Complex. *Scottish Journal of Geolog*y, Vol. 41, 141-148.

FROST, R T C, FITCH F J, and MILLER, J A. 1981. The age and nature of the crystalline basement of the North Sea Basin. 43-57 in *The Petroleum Geology of the Continental Shelf of NW Europe*. ILLING, L V and HOBSON, G D (editors). (London: Heyden, on behalf of the Institute of Petroleum.)

GAÁL, G, and GORBATSCHEV, R. 1987. An outline of the Precambrian evolution of the Baltic Shield. *Precambrian Research*, Vol. 35, 15-52.

GARDE, A A, CHADWICK, B, GROCOTT, J, HAMILTON, M A, MCCAFFREY, K J W, and SWAGER, C P. 2002. Mid-crustal partitioning and attachment during oblique convergence in an arc system, Palaeoproterozoic Ketilidian orogen, southern Greenland. *Journal of the Geological Society*, Vol. 159, 247-261.

GUNN, A G, MENDUM, J R, and THOMAS, C W. 2015. Geology of the Huntly and Turriff Districts. Sheet description for the 1:50000 geological sheets 86W (Huntly) and 86E (Turriff) (Scotland). *British Geological Survey Open Report*, OR/15/026.

HOLLOWAY, S, REAY, D M, DONATO, J A, and BEDDOE-STEPHENS, B. 1991. Distribution of granite and possible Devonian sediments in part of the East Shetland Platform, North Sea. *Journal of the Geological Society*, Vol. 148, 635-638.

JAPSEN, P. 1999. Overpressured Cenozoic shale mapped from velocity anomalies relative to a baseline for marine shale, North Sea. *Petroleum Geoscience*, Vol. 5, 321-336.

JOHNSON, R J, and DINGWALL, R G. 1981. The Caledonides: their influence on the stratigraphy of the north-west European continental shelf. 85-97 in *The Petroleum Geology of the Continental Shelf of NW Europe.* ILLING, L V and HOBSON, G D (editors). (London: Heyden, on behalf of the Institute of Petroleum.)

KIMBELL, G S, and WILLIAMSON, J P. 2015. A gravity interpretation of the Central North Sea. *British Geological Survey Commissioned Report*, CR/15/119. 75pp.

KLEMPERER, S L and HOBBS, R W. 1991. *The BIRPS Atlas. Deep seismic reflection profiles around the British Isles*. (Cambridge: Cambridge University Press.)

MARSHALL, J, and HEWETT, T. 2003. Devonian. 65-81 in *The Millennium Atlas: petroleum geology of the central and northern North Sea.* EVANS, D, GRAHAM, C, ARMOUR A, and BATHURST, P (editors and co-ordinators). (London: The Geological Society of London.)

PILKINGTON, M, ADDOH, A, AND COWAN, D R. 1995. Pre-Mesozoic structure of the Inner Moray Firth Basin: constraints from gravity and magnetic data. *First Break*, Vol. 13, 291-300.

PEGRUM, R M. 1984. The extension of the Tornquist Zone in the Norwegian North Sea. *Norsk Geologisk Tidsskrift*, Vol. 64, 39-68.

POWELL, D W. 1970. Magnetised rocks within the Lewisian of Western Scotland and under the Southern Uplands. *Scottish Journal of Geology*, Vol. 6, 353-369.

RICHARDSON, N J, ALLEN, M R, and UNDERHILL, J R. 2005. Role of Cenozoic fault reactivation in controlling pre-rift plays, and the recognition of Zechstein Group evaporite-carbonate lateral facies transitions in the East Orkney and Dutch Bank basins, East Shetland Platform, UK North Sea. 337–348 in: *Petroleum Geology: North-West Europe and Global Perspectives—Proceedings of the 6th Petroleum Geology Conference.* DORÉ, A G and VINING, B A (editors). (London: The Geological Society of London.)

RITCHIE, J D, SWALLOW, J L, MITCHELL, J G, and MORTON, A C. 1988. Jurassic ages from intrusives and extrusives within the Forties igneous province. *Scottish Journal of Geology*, Vol. 24, 81-88.

RITCHIE, J D, NOBLE, S, DARBYSHIRE, F, and CHAMBERS, L. 2013. Precambrian basement. 47-53 in *Geology of the Rockall Basin and adjacent areas*. HITCHEN, K, JOHNSON, H & GATLIFF, R W, *British Geological Survey Research Report,* RR/12/03.

ROGERS, J J W, and SANTOSH, M. 2002. Configuration of Columbia, a Mesoproterozoic Supercontinent. *Gondwana Research*, Vol. 5, 5-22.

ROGERS, J J W, and SANTOSH, M. 2009. Tectonics and surface effects of the supercontinent Columbia. *Gondwana Research*, Vol. 15, 373-380.

ROLLIN, K E. 2009. *Regional Geophysics of Northern Scotland*. Version 1.0 on CD-ROM. (Keyworth, Nottingham: British Geological Survey.)

SCLATER, J G, and CHRISTIE, P A F. 1980. Continental stretching: An explanation of the Post-Mid-Cretaceous subsidence of the central North Sea Basin. *Journal of Geophysical Research: Solid Earth*, Vol. 85, 3711-3739.

SMITH, K, and RITCHIE, J D. 1993. Jurassic volcanic centres in the Central North Sea. *Geological Society, London, Petroleum Geology Conference Series*, Vol. 4, 519-531.

SNYDER, D, and HOBBS, R. 1999. *The BIRPS Atlas II, A Second Decade of Deep Seismic Reflection Profiling*. (London: The Geological Society.)

STEPHENSON, D, and GOULD, D. 1995. *British Regional Geology: The Grampian Highlands*. (London: HMSO.)

STONE, P, PLANT, J A, MENDUM, J R, and GREEN, P M. 1999. A regional geochemical assessment of some terrane relationships in the British Caledonides. *Scottish Journal of Geology*, Vol. 35, 145-156.

WHITBREAD, K, and KEARSEY, T. 2016. Devonian and Carboniferous stratigraphical correlation and interpretation in the Orcadian area, Quadrants 7-22. *British Geological Survey Commissioned Report* CR/16/032.

ZHAO, G, SUN, M, WILDE, S A, and LI, S. 2004. A Paleo-Mesoproterozoic supercontinent: assembly, growth and breakup. *Earth-Science Reviews*, Vol. 67, 91-123.