

Porcupine Studies Group
Project PSG 00/4b Phase 3

Gravity and Magnetic Modelling in the Porcupine Basin

Final Report

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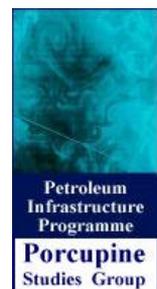
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Executive summary

The Porcupine Basin, which developed during the Mesozoic Era, is situated between the highly stretched crust of the Rockall Basin and the crust of the Irish mainland. Marine gravity and magnetic surveys around Ireland together with satellite gravity data from the deeper ocean are used to investigate the larger-scale crustal structure of these two sedimentary basins. Vertical incidence seismic reflection data is used to constrain the structure of the syn-rift to post-rift sedimentary succession, in order to isolate the gravity and magnetic responses of the crust and mantle. Crustal structure derived from wide-angle and vertical incidence seismic data is used to control the interpretation and modelling of gravity data. Comparison with the Rockall Basin where an axial NE–SW-trending gravity low caused by a seismically defined crustal thickening towards the centre of the basin is also present, shows that in the southern part of Porcupine Basin the crust has been extended by similar amounts. In contrast, the amount of extension is less across the narrower northern sector of the Porcupine Basin, where a north–south-trending axial gravity high, due to poorly understood anomalous density variations in the crust/upper mantle is present. A preliminary new model for the large-scale structural development of the Porcupine Basin is presented. This new structural model is part of on-going work at the Dublin Institute for Advanced Studies, and is not specifically a part of the work undertaken on behalf of the Porcupine Studies Group, but is outlined here as it is relevant to the discussion of the models produced in this study.

1. Introduction and background

The Porcupine Basin is a large sedimentary basin of Mesozoic age located to the southwest of Ireland (Figs 1 and 2). It developed in response to multiple continental rifting episodes (Shannon *et al.* 1995; Naylor *et al.* 2002) that also controlled basin subsidence in the neighbouring Rockall Basin and the sedimentary basins along the shelf and slope regions of the eastern margin of the Rockall Trough (Corfield *et al.* 1999). In this work the basin is sub-divided into three regions based mainly on seismic stratigraphic and bathymetric criteria, as described below and indicated in Fig. 1.

Following the nomenclature system of Naylor *et al.* (2002), the North Porcupine Basin (NPB) and the Porcupine Basin (PB) were previously interpreted as being separated by an east–west-trending wrench fault system at *ca* 51° N from the Porcupine Seabight Basin (PSB) as defined by Tate (1992). This system of wrench faults was based on the interpretation of the available potential field data sets (Masson & Myles 1986) as the ‘Clare Lineament’ (CL), a postulated splay or continuation of the Charlie Gibbs Fracture Zone (CGFZ) across the Porcupine High into the Porcupine Basin (Tate 1992). Since then this interpretation of lineament patterns from potential field data has changed (see e.g. McGrane *et al.* 2001; Johnson *et al.* 2001a) largely because of the availability of high quality satellite free-air gravity data. The path, or perhaps even the existence of the Clare Lineament as the geophysical expression of a major crustal fracture system in the Porcupine Basin, has become controversial in recent interpretations of the potential field data now available for the basin.

Towards the south, the Porcupine Basin broadens and deepens from 250 m to about 3000 m into the bathymetric trough which overlies the Porcupine Seabight Basin (Johnson *et al.* 2001b) south of the proposed trace of the Clare Lineament. Farther south, the PSB passes into the late Cretaceous oceanic crust of the Porcupine Abyssal Plain. A detailed account of the nomenclature used to describe important structural features within the Rockall and Porcupine Basins is given in Naylor *et al.* (1999, 2002). In this report however, the Porcupine Basin as defined by Naylor *et al.* (2002) is sub-divided into a northern section which is still named the Porcupine Basin and a southern section south of *ca* 51°N named the Porcupine Seabight Basin (PSB), after Tate (1992) (see Fig. 1).

The geographical and structural position of the Porcupine Basin between the highly stretched crust of the Rockall Basin (where the crustal stretching factor, $\beta = 5$ to 6) and the Irish mainland and shelf, where the crust is about 30 km thick (O’Reilly *et al.* 1996), suggests that there is a structural relationship between the two basins at a whole crustal, or possibly lithospheric scale. Knowledge of the geometry of the crust, particularly the depth to the Moho, is important towards understanding the tectonic relationship between the two basins. Information about the gross crustal structure can be obtained by modelling potential field data, especially gravity if the gravity affects the basin sediment fill and the water column can be successfully removed from the total field. The vertical seismic velocity structure of the dominantly Mesozoic and Tertiary basin-fill sediments of the basin is known from conventional vertical seismic profiles which are stratigraphically constrained by exploration wells (Shannon *et al.* 1995; Naylor *et al.* 2002).

However, unlike the Rockall Basin, the seismic properties of the crust and the upper mantle across the axial region have not been investigated in the Porcupine Basin using

wide-angle seismic techniques. Deep vertical seismic reflection profiles processed to beyond 10 s exist, but these have failed to clearly image the Moho reflection below the basin-fill sequence (England & Hobbs 1997). A previous investigation using wide-angle seismic methods was focussed on the basin margins, specifically the continent-ocean transition at the mouth of the Porcupine Seabight Basin and part of the eastern margin across the Irish Mainland Platform (Makris *et al.* 1988), but it did not cover the central part of the basin.

In the work presented here the results of gravity modelling along five, and magnetic modelling along two, seismic reflection transects (Figs 1 and 2) are described for the sedimentary basin-fill and the crustal structure below the sedimentary basin. These cross the entire Porcupine Basin between the latitudes 50° and 53° N. The work is partially based on the interpretations of the seismic reflection profiles described in PSG Project P00/1 (Naylor *et al.* 2002) as well as our knowledge of the regional crustal structure of the surrounding area based on wide-angle refraction/reflection and vertical reflection seismic data.

2. Data sources

The free-air gravity anomaly maps produced by PGW Europe Ltd (PGW) for the region is shown in Fig. 3. This is primarily based on the satellite-derived grids of Sandwell & Smith (1997) with some additional surface measurements (for the data coverage, see PSG Project P00/4 Map 3). It was intended to extract the profile data from the digital grids used to produce these maps, but the data supplied was unable to be used. It was noted however that the addition of the surface data has very little effect on the final gravity map produced, and does not add useful detail for modelling on the scale of this project. The project was therefore started using gravity profiles extracted directly from the satellite-derived marine free-air anomaly grid. The free-air anomaly map produced from this grid is shown in Fig. 4.

For the magnetic data (Fig. 5) on the other hand, there are large areas where high resolution surface magnetic field data has added considerably to the detail of the magnetic anomaly map over that which is in the public domain. Data extending well beyond the ends of the profiles are required to avoid severe end-effects, particularly for the gravity modelling. Unfortunately extraction of the data was done incorrectly along three of the profiles. As the satellite-derived gravity profiles are virtually identical to those extracted by PGW it was decided, and agreed by the PSG, to continue with the use of the satellite-derived gravity along the five profiles. The magnetic anomaly data was modelled along the two profiles for which data was extracted correctly. However the lack of magnetic data does not have a serious effect on the overall structural interpretation for the region which is based primarily on the results of the gravity modelling.

3. Seismic profiles

The location of the profiles, which all span the width of the basin and are approximately transverse to its axis, are shown on Figs 1, 2 and 4. These profiles were chosen by the PSG to cross significant features that had been identified in PSG Project P00/1 dealing with the structural elements (Naylor *et al.* 2002) and with regard to the gravity map (Fig. 3) after consultation with DIAS. In the northern part of the Porcupine Basin, Transect T (seismic profile SPB97-103) crosses the Porcupine Arch and Transect R (PW93-304) is just to the north of this feature on the edge of the gravity anomaly high correlating to the Porcupine High. Transect Q (seismic profiles PD93-170, MS81RE-78 and PW93-162) is in the northern tip of the Basin (the North Porcupine Basin of Naylor *et al.* (2002)). In the southern part of the Porcupine Basin, Transect VW (SPB97-121 and 138) crosses the Porcupine Median Volcanic Ridge System, and Transect X (SPB97-35a) spans the basin at about its maximum width about 100 km from the entrance to the Porcupine Abyssal Plain.

3.1 Time-depth conversion

The seismic profiles interpreted by Naylor *et al.* (2002) were depth-converted using seismic velocities for the Tertiary, Cretaceous and pre-Cretaceous sequences listed in Table 1. These velocities are based on comparing the two-way travel times to the picked horizons with a depth-converted section for profile PSB97-103 provided by M. Norton on behalf of the PSG, which was tied to exploration wells. The velocities listed for the various profiles are comparable to those used by Johnson *et al.* (2001a) to depth convert nearby (within 20 km) seismic reflection profiles in the basin. Changes in the velocity structure will reflect variation in burial depth as well as lateral facies changes within individual stratigraphic units, which the currently available seismic and borehole data cannot resolve. However, the variation in the interval velocities used for these stratigraphic units is consistent with such facies variations in areas where well data exists (Moore & Shannon 1995).

3.2 Velocity-density conversion

Densities for the syn-rift and post-rift sedimentary layers were calculated from the interval velocities using an empirical formula published for sediments of similar stratigraphic age in the Shetland-Faeroe Basin (see Fig. 6 and Hughes *et al.* 1998). This relationship is based on several tens of thousands of borehole sonic velocity and density measurements and is given by the following polynomial equation

$$d = 0.295 + 1.337V - 0.273V^2 + 0.019V^3$$

where d is density (g cm^{-3}) and V is P-wave velocity (km s^{-1}). The estimated densities are in general agreement with those obtained from the Nafe-Drake curve as summarized by Barton (1986) and are close to those used by Masson & Myles (1986), Conroy & Brock (1989) and by Johnson *et al.* (2001a) in their seismic and gravity studies of the Porcupine Basin along nearby transects to those presented in this work.

4. Gravity modelling procedure

The results of gravity modelling are inherently non-unique (e.g. see Parasnis 1997, pages 84 - 87) and so to avoid an over-complex final model the minimum number of layers that can be justified on geological and geophysical grounds are used to construct the gravity models. The results of the gravity modelling and the sensitivity of the models to parameter changes (layer depths and densities) for each of the seismic transects are described and presented later.

The seismic stratigraphic information provided by the Porcupine Studies Group (Naylor *et al.* 2002) was used to remove the gravitational effects of the basin syn-rift and post-rift sequences and so to isolate the free-air gravity anomaly due predominantly to the depth and shape of the Moho below the Porcupine Basin. The modelling of the gravity field across the basin is further constrained by previous work on the regional wide-angle and vertical incidence seismic structure of the crust in the Celtic Sea Basins, the Rockall Basin and the Irish mainland (O'Reilly *et al.* 1991; Klempner & Hobbs 1991; Hauser *et al.* 1995). This body of work demonstrated that the crust onshore Ireland is about 30 km thick, similar to that found below the Porcupine Bank (Whitmarsh *et al.* 1974) and consists of three layers each about 10 km in thickness, resolved at relatively low seismic frequencies (i.e. about 6 Hz). The seismic velocities for the crust were used as a basis for assigning densities to the three crustal layers using relationships published by Christensen & Mooney (1995) for crystalline basement rocks with mineralogies typical of the upper and lower crust.

No long wavelength regional gravity trend was removed from the profile data prior to modelling the structure along the selected seismic profiles. Typically, the Mesozoic lithospheric stretching episodes and crustal thinning that occurred within the basins of the North Atlantic region have left permanent topographic relief on the Moho, which is generally in approximate isostatic balance with the low-density syn-rift and post-rift basin-fill sediments (see for example, Smallwood *et al.* 2001). Regional long wavelength effects due to variations in the deep thermal structure of the lithosphere and upper mantle are only apparent over very large distances (see for example, O'Reilly *et al.* 1998). The preserved Moho topography survives long after thermal relaxation of the lithosphere has occurred when extension ceases. The surviving topography has a dramatic effect on the behaviour of gravity along the basin margins because of the very large density difference (*ca* 450 kg m⁻³) between the crust and the mantle. This effect is also apparent in many other deep-water basins and along some continental margins (Karner & Watts 1983; O'Reilly *et al.* 1998).

The depth converted post-rift and syn-rift stratigraphy was used to build the gravity model for the basin structure. As the geometry of the post-rift sequence (Cretaceous and Tertiary) is very well constrained in the seismic interpretations (Naylor *et al.* 2002) no change to the base Cretaceous and intra-Tertiary layers was made while modelling the seismic profiles. The 2-D modelling program GRAVMAG (Pedley *et al.* 1993) was used to calculate the gravitational response. This 2-D approach can be inaccurate particularly where the profiles cut across the edge of major deep-seated anomalies and off-line or 3-D effects become important. These 3-D effects must be borne in mind when the results of 2-D gravity modelling are been discussed and interpreted.

While modelling the shorter wavelength part of the gravity field, changes to the pre-rift basement interface were only permitted in cases where these were not well defined by the

seismic interpretations. Longer wavelength parts of the gravity field were fitted by adjusting the geometry of the crust, particularly the trajectory and depth of the Moho. Varying the geometry of the syn-rift sequence and the intra-crustal layers has only a slight effect on the calculated gravity anomalies due to the lower density contrasts involved (see Table I).

The effect of the crust and Moho topography can be seen by calculating the gravity response of the post and syn-rift stratigraphy assuming a simple one-layer crust and flat Moho. The results, shown in Figs 7a – 11a, show discrepancies of up to about 200 mGal between the calculated and observed values of the gravity anomaly. This cannot be accounted for by any change in the topography of the basement or overlying stratigraphy, indicating that it must be due to topography or density variations deeper in the crust, and particularly to the topography of the Moho across which there exists the largest density contrast (about 450 kg m^{-3}). This implies a very significant crustal thinning beneath the deeper parts of the basin; as the water depth increases the discrepancy increases from about 100 mGal in the North Porcupine Basin (see Fig. 7a) where the water depth is about 400 m to over 200 mGal in the Porcupine Seabight Basin (see Fig. 11a) in the south, where the water depth reaches 2300 m.

A description of the modelled profiles follows. **Transect Q** extends the shortest distance across the Northern Porcupine Basin and is coincident with seismic reflection profiles PD93-170, MS81-RE78 and PW93-162; **Transect T** (seismic profile SPB97-103) extends east-west across the Porcupine Arch (Naylor *et al.* 2002) and **Transect R** (PW93-304) is situated just to the north of the Porcupine Arch. The remaining transects (**Transect VW**, comprising SPB97-121 and SBP97-138) and **Transect X** (SPB97-35a) extend across the deeper water Porcupine Seabight Basin (Tate 1992) between the Canice Basin and the Celtic Platform. The letters ascribed to the profiles are those used by Naylor *et al.* (2002) (thus Transect Q comprises the three profiles Q1, Q2 and Q3, and Transect VW comprises the two intersecting profiles V and W). Figures 7 – 11 show the results of various stages in the gravity modelling and Figure 12 summarises our preferred models for the five transects.

4.1 Profiles in the northern part of the Porcupine Basin

The gravity model for the southernmost profile, Transect T (seismic profile SPB97-103), is described first. This profile crosses the free-air gravity anomaly maximum which is relatively simple with its long axis perpendicular to the profile, thus making the 2-D assumption realistic. This contrasts with the location of the more northerly profile, Transect R (PW93-304), which is situated on the northern edge of this anomaly making interpretations of 2-D models less rigorous. Transect Q, a composite of seismic profiles PD93-170, MS81-RE78 and PW93-162, is further north in the North Porcupine Basin and close to the basin edge where, again, 2-D interpretation has limitations. For the locations of the profiles, see Figs 1 – 4. The nomenclature scheme used follows that of Naylor *et al.* (1999, 2002).

4.1.1 Transect T - seismic profile SPB97-103 (Figure 7)

This transect crosses the free-air gravity maximum of the gravity anomaly high which is spatially coincident with the Porcupine Arch. The anomaly pattern consists of the central axial high flanked by two gravity lows with the mean value of the gravity anomaly along the

profile significantly greater than zero (Fig. 4). This implies that the crust is not in isostatic compensation and/or that both surface and sub-surface loads are being supported by an increase in strength, or effective 'elastic thickness', of the lithosphere.

Along the corresponding seismic profile (Profile SPB97-103) the interpretations of the Cretaceous to Recent post-rift sequence are well defined (Naylor *et al.* 2002), but the thickness of the pre-Cretaceous syn-rift succession and the depth to pre-rift basement appears not to be traceable with any confidence in the region east (70 – 110 km on Fig. 7) of the Porcupine Arch. In this region the depth-to-basement was constructed and varied in the gravity model. However since the density contrast between the syn-rift sequence and the basement is relatively low (*ca* 150 kg m⁻³) compared to that across the crust-mantle boundary (*ca* 500 kg m⁻³), changes in the depth to this boundary have a relatively minor effect on the calculated anomaly.

The starting model consisting of the interpreted Tertiary, Cretaceous and pre-Cretaceous seismic stratigraphy is shown in Fig. 7a. Densities assigned to these layers are given in Table I. The crust consists of a layer of uniform density with a flat Moho. This model produces a large negative anomaly (–170 mGal) over the centre of the basin, contrary to the observed positive anomaly of +60 mGal. Varying the depth-to-basement where it is not defined in the interpretation of the seismic stratigraphy (Naylor *et al.* 2002) cannot account for this very large discrepancy. It therefore must be due to density variations within the crust and particularly to the topography of the crust-mantle boundary where the density contrast is several times greater than that across the sediment-basement interface.

Figure 7b shows a model where there are still no density variations in the crust and the central anomaly high is fitted solely by raising the Moho interface. This model has an extremely thin, *ca* 2 km, crust beneath the centre of the basin, somewhat thinner than *ca* 5 km as proposed by Johnson *et al.* (2001a) in a gravity and seismic interpretation of a profile across the same anomaly slightly further to the north. Introducing a three-layer crust (Fig. 7c) as indicated from the results of wide-angle and vertical seismic reflection studies carried out on the Porcupine Bank, Celtic Sea platform and the onshore Irish region over the past two decades (Klemperer & Hobbs 1991; Jacob *et al.* 1985; Lowe & Jacob 1989) does not significantly affect the model. Slight changes in the Moho topography are also not significant since there is no independent control, such as wide-angle seismic data, to constrain such changes.

Our final preferred model, shown in Fig. 7d, includes a body beneath the centre of the basin with a density (3200 kg m⁻³) intermediate between the crust and mantle, with no crust of 'normal' density in this region. This is similar to the model derived by Tate *et al.* (1993) to account for the same gravity feature along a neighbouring seismic profile (WI-13), except that in their model the body has narrower dimensions and a more pronounced triangular shape.

An entire suite of gravity models exist that are intermediate between those shown in Figs 7a and 7d that can satisfy the gravity observations, but they all require the presence of a high density body with a density intermediate between the crust and mantle positioned between the base of the syn-rift sequence, as defined in the seismic interpretation of Naylor *et al.* (2002), and the mantle lithosphere. If 'normal density' crust does indeed exist it must be extremely thin (<< 5 km) in these gravity models. A means of discriminating between the

alternative models would be to acquire wide-angle seismic data across the gravity feature, preferably along an axial profile.

4.1.2 Transect R - seismic profile PW93-304 (Figure 8)

The seismic profile PW93-304 lies just to the north of the Porcupine Arch and extends eastwards towards the Moling Sub-basin and the Clare Basin (Fig. 1). It crosses the northern edge of the gravity anomaly high that is associated with the Porcupine Arch.

The starting model comprising the interpreted Tertiary, Cretaceous and pre-Cretaceous seismic stratigraphic sequences is shown in Fig. 8a. This structure produces a negative gravity effect of 100 – 150 mGal with a crust of uniform density 2800 kg m^{-3} and densities for the post- and syn-rift sequences are given in Table I. Reducing the depth to the Moho beneath the basin produces a model (Fig. 8b) that satisfactorily explains the anomaly, but requires a high degree of crustal thinning (crustal stretching factor, $\beta = 4 - 5$) and a very steep slope (*ca* $30 - 40^\circ$) on the Moho. A three-layer crust has been assumed again, consistent with the known seismic crustal structure in the nearby region (Jacob *et al.* 1985; Lowe & Jacob 1989; O'Reilly *et al.* 1995, 1996) but this has little effect on the model calculations. Introducing a high density (3200 kg m^{-3}) body at the base of the crust somewhat reduces the overall thinning (assuming the body is part of the crust) but the effect on the slope is small (Fig. 8c). By moving the high-density (3050 kg m^{-3}) body higher within the crust the Moho topography and the crustal thinning is substantially reduced (to a slope of *ca* 25° and β of *ca* 2, respectively – see Fig. 8d). Without 3-D gravity modelling and further evidence such as obtained from wide-angle seismic refraction/reflection work it is not possible to distinguish between these alternative possibilities.

As the profile skirts the edge of the axial anomaly (see Figs 3 and 4) the gravity variation along it is unlikely to reflect the gravity effect of a long axial body such as assumed for the 2-D modelling approach used here. This further adds to the problems of non-uniqueness inherent in gravity studies and makes the determination of the geometry of this body uncertain. It is possible, for example that the body is not located directly beneath the profile, with the edge of the body being located to the south and the observed anomaly resulting from a 3-D effect.

4.1.3 Transect Q - seismic profiles PD93-170, MS81-RE78 and PW93-162 (Figure 9)

This is the most northerly profile in the study area (close to the North Porcupine Basin of Naylor *et al.* 2002) and consists of the two co-linear seismic profiles PD93-170 and MS81-RE78 continued eastwards by using the seismic profile PW93-162 located some 5 km to the south (see Figs 2, 3 and 4). The gravity anomaly data for PW93-162 was extracted along the eastward continuation of profiles PD93-170 and MS81-RE78, and the seismic structure approximated to that interpreted for PW93-162 (Naylor *et al.* 2002). This is considered reasonable since the quality of the seismic data along this section of the transect is considered poor (PSG *pers. comm.*) and there is no significant change in the nature of the gravity anomaly over the resulting offset of the modelled line.

Figure 9a shows the calculated anomaly assuming a flat Moho with a uniform crustal density of 2800 kg m^{-3} . To explain the -100 mGal discrepancy with the observed anomaly requires that the Moho be raised by about 10 km. However unlike the previously described

profiles, it is not possible to fit the anomaly pattern satisfactorily at the ends of the profile (e.g. see Fig. 9b) simply by this means. This is due mainly to the edge-effects resulting from the topography of the crust-mantle boundary. Figure 9c shows a model that does satisfactorily model the basin margin edge anomalies, but predicts a negative anomaly over the centre of the profile which is 10 – 20 mGal greater than that observed. This could be explained by introducing a high density body (3100 kg m^{-3}) into the crust as indicated in our preferred model shown in Fig. 9d. The exact form of this body is difficult to model using a simple 2-D approach but in general the fit with the observed anomaly is better if the body has a relatively narrow, inclined profile similar to that shown in the Fig. 9d.

4.2 Profiles in the Porcupine Seabight Basin

The Porcupine Seabight Basin (Tate 1992) underlies the widening bathymetric trough south of the putative trace of the Clare Lineament (also see Johnson *et al.* 2001a). Gravity modelling along two transects, VW and X across the basin was undertaken. The location of the profiles are shown on Figs 2, 3 and 4.

4.2.1 Transect VW - seismic profiles SPB97-121 and SBP97-138 (Figure 10)

This transect consists of a composite of two intersecting seismic reflection profiles (SPB97-121 and SBP97-138). The gravity shows little variation along this profile away from the basin edges although it crosses the Porcupine Volcanic Ridge System (PVRS) (see Fig. 2) at 50 – 60 km and 90 – 115 km distance along the profile. The fact that there is no significant gravity anomaly associated with the part of the PVRS named the Porcupine Median Volcanic Ridge (PMVR) suggests that this body is quite thin, and/or has a relatively low density.

The interpretation of the seismic reflection data by Naylor *et al.* (2002) used in this work does not extend to the top of basement from *ca* 40 – 130 km distance along the profile. The starting model with no crustal variations or Moho topography is shown in Fig. 10a, where a fairly smooth variation of the basement surface that is not defined by the seismic interpretation has been assumed. Deepening this surface will depress the calculated anomaly by approximately a further 8 mGal per km. The gravity effect of up to *ca* 200 mGal has to be explained by arching the Moho beneath the basin, and to a lesser degree by density variations in the crust.

As described in the previous models, a three-layer crust is assumed in subsequent modelling as it is consistent with the seismically defined crustal structure found in the surrounding regions (Jacob *et al.*, 1985; Lowe & Jacob, 1989; O'Reilly *et al.* 1995, 1996). To explain the observed anomaly the Moho must shallow from about 30 km to 18 km beneath the basin (Fig. 10b). However this leaves some smaller features of the anomaly pattern difficult to model in detail using only the interpreted seismic structure. Reducing the thickness of the Jurassic and Permo-Triassic at the eastern end of the basin (*ca* 110 – 130 km) whilst maintaining a thickness of 3 – 4 km beneath the PMVR goes some way towards reproducing the undulating pattern observed in the anomaly pattern in the centre of the profile.

To refine the model further to more closely explain the observed anomaly pattern without recourse to alteration of the geometry of the seismic-interpreted stratigraphy requires inclusion of further bodies (Fig. 10c). Low density bodies (granites?) at 10 km and 140 km along the profiles are required to shallow and steepen the slope of the gravity variation respectively at the western and eastern edges of the basin. A higher density body (2700 kg m^{-3}) is included within the Cretaceous to reproduce more closely the 10 mGal peak at 120 km. The peak at 50 km has also been sharpened by increasing the density of the causative body – part of the PVRS – from 2700 kg m^{-3} (in Fig. 10b) to 2900 kg m^{-3} . This preferred model is shown in Fig. 10c.

4.2.2 Transect X - seismic profile PSB97-35A (Figure 11)

This is the longest transect modelled and consists of one seismic profile (PSB97-35A) running NW–SE across the region where the Porcupine Basin is widest. It extends from the Canice Basin in the west to the Celtic platform in the southeast. The geometry of the syn-rift and post-rift sequences are well constrained by the depth converted seismic profiles and the only uncertain horizon is that defining the pre-rift basement interface across part of the interpreted seismic profile (Naylor *et al.* 2002).

The anomaly pattern along the transect consists of paired high and low anomalies with amplitudes of about 30 mGal due mainly to the ‘edge effect’ along both the eastern and western margins of the basin. This profile crosses the deepest water parts of the basin with correspondingly steeper seafloor topography at the edges of the basin. Thus the topographic ‘edge effect’ is more prominent than in the other profiles. In contrast to the Porcupine Basin further north the very prominent axial gravity high anomaly is replaced with a pronounced gravity low of amplitude -15 mGal (compare Figs 7b and 11b). This symmetrical free-air gravity anomaly pattern is a very distinctive feature within the southern part of the Porcupine Seabight Basin. It is similar to the free-air anomaly pattern found across the Rockall Basin (O’Reilly *et al.* 1998) and may have a similar origin (see Discussion).

The magnitude of the crustal thinning can again be estimated, by reference to the anomaly produced by the simple starting model with uniform density crust and flat Moho (see Fig. 11a), to be around 20 km (i.e. the Moho raised by 20 km). A three-layer crust is again introduced with further modelling involving changes in the thicknesses of these layers and, more importantly the depth to the Moho. Adjustments were also made to the pre-rift basement interface where the seismic interpretation permitted this but these adjustments have little effect on the calculated longer wavelength part of the free-air gravity field as the density contrast between the syn-rift sediments and the upper crust is relatively small (see Table I). The behaviour at these wavelengths (i.e. $> 40 \text{ km}$), as in the case of the Porcupine Basin, is very much determined by the Moho topography.

The final preferred model (Fig. 11b) requires greater thinning of the crust by *ca* 2 km towards the basin margins. This geometry, with a thickening of the crust at the basin centre to 5 km is required by the central gravity low. An alternative model would involve reducing the density of the crust at the centre of the basin to produce the gravity low (e.g. see Fig. 11c where the crustal densities are reduced to 2600 kg m^{-3} and 2700 kg m^{-3} for the upper and lower crust respectively) but it is not possible to attain such a good fit to the observed anomaly using this approach. The preference for the model with axial crustal thickening is outlined in the discussion.

5. Magnetic modelling

Large scale magnetic anomaly maps are very useful in tectonic interpretations where they can be used to map structural features such as terrain boundaries and large-scale shear systems. However there is greater uncertainty in the magnetic properties appropriate for modelling the magnetic field variations than there is for the density values used in gravity modelling. The densities are a bulk property of the sedimentary and crystalline rock material but the magnetic properties are dependent on trace amounts of magnetic minerals and may show very little correlation with density variations within the crust. In the present study the magnetic signature across the Porcupine area is likely to be dominated by Tertiary and early Cretaceous volcanic rocks and by magnetic property variations in the older basement rocks. The magnetic variations over the sediment covered deeper water regions (Fig. 5) generally show smooth variations reflecting deep magnetization contrasts. In the shallower water-depth basin margin regions on the Irish Mainland Platform and the Porcupine High the variations are of higher frequency reflecting larger magnetic contrasts in the basement at shallower depths, and the presence of basic igneous bodies such as the Brendan Centre (Lefort & Max 1984; Masson & Miles 1986).

More weight is given to the gravity models than to the magnetic models due to the major uncertainties in magnetic properties and the magnetization history of the lithosphere over the geological period when magnetic remanence was acquired. For example, relatively thin layers of Tertiary basalts can have very strong magnetic effects with very little corresponding effect on the gravity values. Hence, the derived gravity models were used as the basis for modelling the magnetic field. No changes to the gravity models were made as a result of the magnetic modelling but additional bodies or layers were included within individual layers or polygons to satisfy the magnetic field data. Because of the difficulties encountered in the magnetic data extraction (see page 4) only two of the seismic transects (**Transect Q** – seismic profiles PD93-170, MS81-RE78 and PW93-162 and **Transect T** – seismic profile SPB97-103) were modelled.

5.1 Transect T - seismic profile SPB97-103 (Figure 13)

The dominant feature of this magnetic profile is the magnetic anomaly low of magnitude – 250 nT in the centre of the basin. This anomaly spatially correlates with the pronounced gravity anomaly high (see Fig. 13) and has a similar wavelength to the gravity anomaly. The strong correlation of the magnetic and gravity anomalies suggests that they originate from the same source, i.e. the high density body in the gravity profile (see Fig. 7d, polygon 14). It also suggests that the body is reversely magnetised. A reasonable fit to the observed anomaly is obtained by assuming that this body has a magnetisation of 2.40 A m^{-1} with zero magnetisation for all other sedimentary and crustal units (see Fig. 13). A more refined fit to the anomaly pattern, particularly on the margins of the basin, can be obtained by introducing magnetic bodies within the basin. However without additional geological and geophysical evidence these have little physical significance as there are no constraints on the magnetisation properties or geometry of these bodies.

5.2 Transect Q - seismic profiles PD93-170, MS81-RE78 and PW93-162 (Figure 14)

The major feature along this magnetic profile is the anomaly high of 350 nT associated with the inferred Brendan Igneous Centre (Croker 1995; Naylor *et al.* 2002) at *ca* 100 – 110 km

distance from the start of the seismic transect Q. This is beyond the extent of the seismic profile so there is no seismic constraint on the geometry of the causative body. Assigning a magnetisation of 2.2 A m^{-1} to the body (labelled 15 in the gravity model, Fig. 9d) produces an anomaly of the correct amplitude but spatially offset from the observed anomaly. This can be corrected by modifying the geometry of the eastern edge of the body and dividing it so that the western half has similar magnetic properties to the crust (Fig. 14).

6. Discussion

The results of the gravity modelling presented here show that sedimentary basin and crustal structure change dramatically from north to south along the axis of the basin. Figure 12 shows the preferred models displayed on similar scales going southwards from the North Porcupine Basin (top) to the Porcupine Seabight Basin (bottom). The change in structure is sharp and occurs at around 51.6° N between Transects T and VW. Recent work at DIAS suggests that a NW–SE-trending fault system expressed as a similarly trending gravity fabric is important in controlling large-scale structure and basin development in the North Atlantic region (Figs 15 and 16).

The importance of NW–SE-trending fracture structures in controlling the structuring of the Porcupine Basin is not new but was proposed by Lefort & Max (1984) and also by Masson & Myles (1986) from regional gravity and magnetic and seismic data. They suggested that a suite of faults with a NW–SE orientation is of fundamental importance in understanding the structure of the Porcupine region, and inferred from the pattern of aeromagnetic and gravity anomaly data then available that up to six such fault systems cross the Porcupine area.

However later work has placed less emphasis on the role of these NW–SE-trending structures in controlling the geometry of the basins around and to the west of Ireland (for example Tate (1992), and Tate *et al.* (1993)). It is only since the mid-1990s that the general importance of the trend in the structural development of the sedimentary basins in the Northwest Atlantic has been re-emphasized (Readman *et al.* 1995; O'Reilly *et al.* 1996; McGrane *et al.* 2001; Johnson *et al.* 2001a). The main reason for this is that the earlier interpretations were limited by the vague nature of these transverse trends due to the low level of coverage and areal extent of marine gravity and magnetic data coverage then available across the Porcupine area (Masson & Miles 1986; Lefort & Max 1984). Even now the marine surface (ship) gravity and magnetic data coverage is still very poor south of about 51° N . It has only been since the mid 1990s that the large data gap in the gravity data has been filled-in by accurate satellite-derived gravity determinations (Sandwell & Smith 1997) for the deeper water part of the Porcupine Seabight Basin and the regions of the Irish Mainland Platform and Porcupine High south of 51° N .

The Clare Lineament is an ESE–WNW-trending structure that was first described by Dingle *et al.* (1982) at the southern boundary of the Rockall Trough, where it predates the Charlie Gibbs Fracture Zone, the largest transform fault in the North Atlantic region. A possible eastwards extension of the lineament into the Porcupine Basin was inferred from the sparse gravity and magnetic data then available and was termed the Clare trend (Naylor & Shannon 1982; Megson 1987). The trace of the Clare Lineament across the Porcupine Basin as drawn by Tate (1992) (see Fig. 1 in Tate 1992) passes approximately E–W through

ca 51° N, and runs south of the gravity anomaly high over the Porcupine Arch. A more recent interpretation (see Fig. 3 of Johnson *et al.* 2001a) of the higher resolution data now available places it at the southern extent of the Porcupine Gravity High (PGH in Fig. 4), with a more northwesterly trend that swings to an E–W trend towards the Celtic Platform. This interpretation is more consistent with the one recently presented by Readman & O'Reilly (2001) which re-introduces the NW–SE-trending cross-faulting as an important structural element in the Mesozoic extensional tectonics of the Porcupine and Rockall region.

To the north of our interpreted NW–SE-trending fault system (Fig. 16) the main feature of the model is a dense body that generates the gravity anomaly high across the basin axis along profiles PW93-304 and SPB97-103. The areal extent of this gravity high correlates broadly with the Porcupine Arch (Figs 2 and 16) and shows no correlation with the Porcupine Volcanic Ridge System (compare Figs 2 and 4). It also correlates with a pronounced magnetic low but the composition or nature of this body cannot be determined from gravity and magnetic studies alone. It is likely to be related to the extensional episode that formed the basin rather than have been emplaced later after the main crustal stretching episode(s). A significant observation is that the mean value of free-air gravity along these profiles is much greater than zero (Figs 7 and 8). This indicates that the crust is not in isostatic balance and the load created by the modelled dense body is supported by the lithosphere, perhaps because of intrinsic buoyancy related to mineralogical phase changes.

South of the NW–SE-trending fault system (Fig. 16) the basin broadens below the deep water of the Porcupine Seabight (Fig. 1) and the crust is probably more extended. The gravity anomaly pattern along profile Q (SPB97-35a) comprises an axial low flanked by highs. This is in complete contrast to the pattern observed along profile T (SPB97-103) and can be modelled as a rib of thickened crust along the basin axis. The anomaly pattern is remarkably similar to that imaged by wide-angle seismics in the Rockall Trough (O'Reilly *et al.* 1996) and may have a similar origin (see Fig. 17).

In our model a change in crustal geometry and gravity properties occurs across the distinctive set of NW–SE-trending gravity lineaments (Fig. 16). These are interpreted as a set of cross-basin syn-rift faults, which control large-scale segmentation of extensional deformation at mid to upper crustal levels. Currently published models based on well/subsidence and seismic refraction data for the formation of the Porcupine Basin and Seabight Basin involve a clockwise rotation of the Porcupine High away from the Irish Mainland and Celtic Platforms (Tate *et al.* 1993). As in this model the stretching occurs by pure shear this gives rise to an increase in stretching factor (along the basin axes from 2 in the north to about 6 in the south (Tate *et al.* 1993; Reston *et al.* 2001). This development model is least well constrained by the well/subsidence data south of 52° N but nevertheless there is still some indication that the stretching factor contours (see Fig. 6 in Tate *et al.* 1993) close towards 50° N, suggesting that the crust may thicken slightly towards the mouth of the Seabight Basin. A relatively small amount of crustal thickening is indicated on some of the earlier gravity models across the mouth of the Porcupine Seabight (Masson & Myles, 1986; Conroy & Brock 1989), although it is not entirely consistent with the available seismic wide-angle data from the basin (Makris *et al.* 1988) which only seem to require upper crustal thickening north of 50° N. The late Cretaceous stretching event which led to the formation of the continent/ocean boundary (Fig. 2) at the mouth of the Porcupine Seabight Basin would have led to further crustal thinning in the region prior to the onset of

seafloor spreading in the Santonian (Magnetic Anomaly 33). The crust (particularly the lower crust) may have been thicker prior to the late Cretaceous development of the Bay of Biscay margins and the onset of seafloor spreading.

In the basin development model outlined in our previous work (Readman & O'Reilly 2001; O'Reilly & Readman 2002) lithospheric stretching in the South Porcupine Basin involved a large anticlockwise rotation of the South Porcupine High, while to the north the stretching involved a smaller antipathetic clockwise rotation of the North Porcupine High (see Fig. 16). Restoration of the pre-rift crustal geometry requires that a large amount (10s of km) of cumulative sinistral motion on NW–SE-trending cross-basin faults accompanied these rotations, causing the southward broadening of the Rockall Basin. A tectonic linkage between the syn-rift development of the two basins and the smaller more numerous inboard basins in the Celtic Sea area to the east is required by this model. Regional changes in the distribution of strain in the crust is controlled by variations in the activity of NW–SE-trending transfer fault systems which compartmentalise the Mesozoic sedimentary basins throughout the north Atlantic region. The NW–SE-trending fault systems may have been important in focusing fluid flow in the lithosphere causing rheologically controlled serpentinisation of the mantle, inferred from earlier wide-angle seismic studies in the Rockall Basin. Similar linked rheological and fluid flow processes may perhaps also have occurred locally in the Porcupine Basin. Coincidentally low P_n and S_n seismic velocities in the Rockall Trough (O'Reilly *et al.* 1996) appear to be connected with the gravity anomaly high over the Porcupine Arch in the Porcupine Basin by such fault systems inferred from our earlier studies (Fig. 17).

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TABLE I

Densities used in the gravity modelling, and seismic velocities used to depth convert the seismic profiles:

	Density kg m ⁻³	Velocity km s ⁻¹
Seawater	1030	1.485
Neogene	1900 - 1950	2.10
Paleogene	2070	3.00
(Neogene+Paleogene)	2000 - 2050	2.40 - 2.55
Cretaceous	2410	4.00 - 4.10
Pre-Cretaceous	2510 - 2550	4.50
Upper crust	2690 - 2700	
Mid-crust	2780 - 2800	
Lower crust	2900	
Granites?	2600 - 2630	
Igneous intrusions	2700 - 2900	
High density bodies?	3050 - 3200	
Mantle	3330 - 3350	

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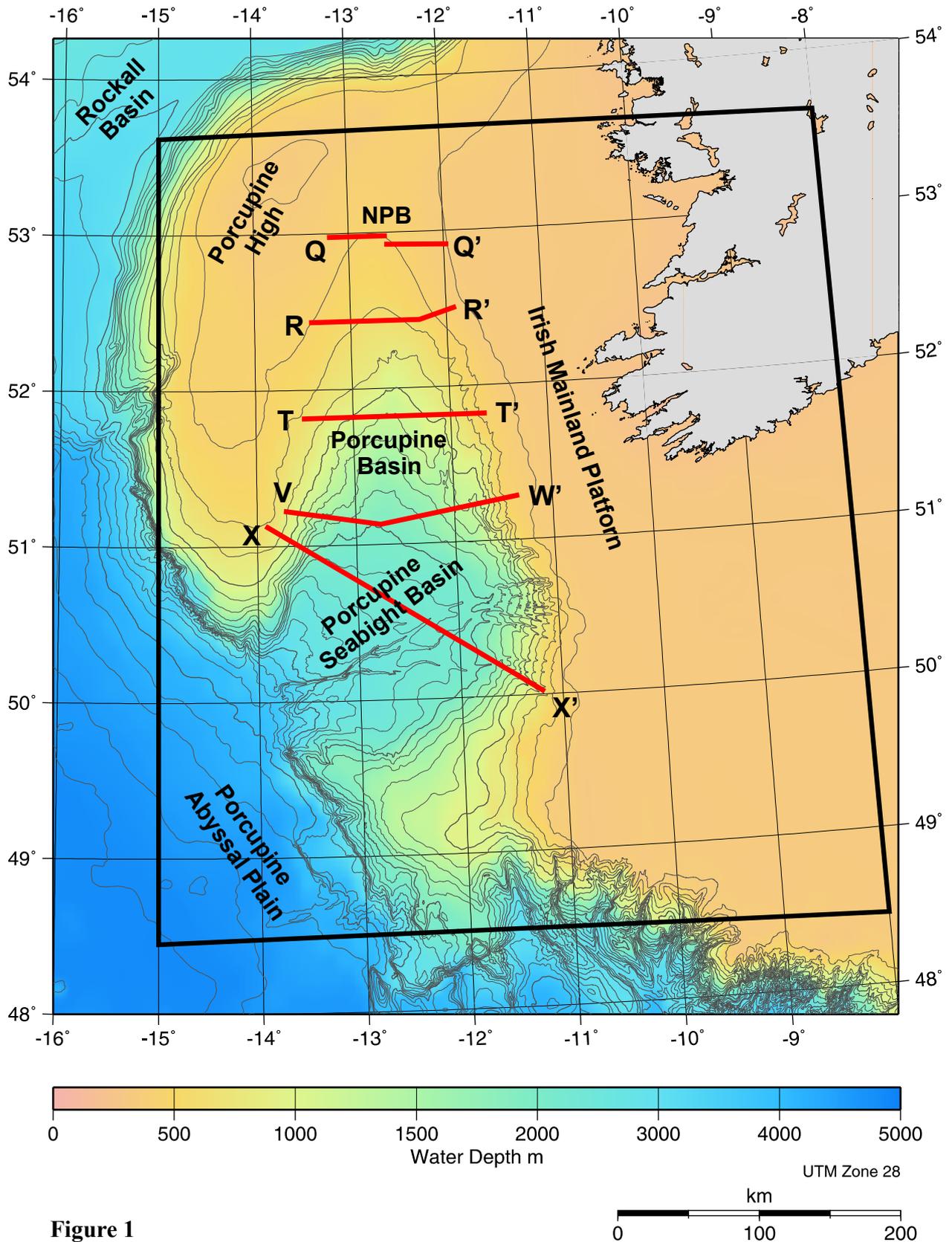


Figure 1

Bathymetry map of the Porcupine Basin region showing the location of the profiles. **Q - Q'**: Seismic profiles PD93-170, MS81RE-78, PW93-162; **R - R'**: Seismic profile PW93-304; **T - T'**: Seismic profile SPB97-103; **V - W'**: Seismic profiles SPB97-121 and SPB97-138; **X - X'**: Seismic profile SPB97-35a. **NPB** - North Porcupine Basin (Naylor *et al.* 2002). The Porcupine Studies Group project area is outlined in black. Depth contours, from GEBCO97 are at 200 m intervals.

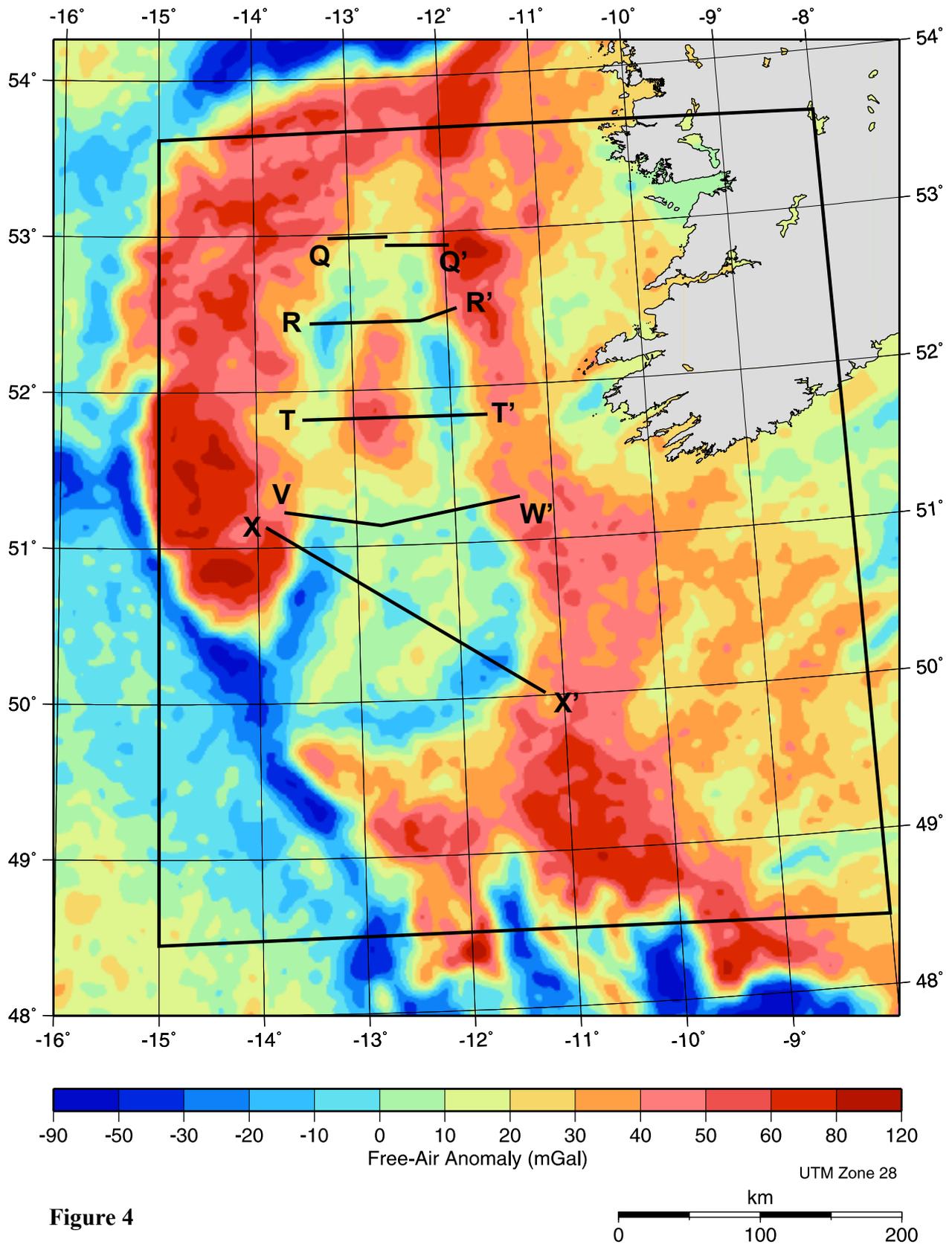


Figure 4

Free-air gravity anomaly map of the Porcupine area plotted from the satellite-derived 1-minute grid of Sandwell & Smith (1997). The profiles are labelled: **T - T'** - profile SPB97-103 (131 km in length); **R - R'** - profile PW93-304 (105 km); **Q - Q'** - profiles PD93-170, MS81-RE78 and PW93-162 (86 km in total); **V - W'** - profiles SPB97-121 and SBP97-138 (169 km in total); **X - X'** - profile SPB97-35a (230 km). The gravity profiles modelled in this report were extracted from the grid used to produce this map. Profiles were modelled for 100 - 200 km beyond the ends of the lines so that the edge effects of the ocean-continent transition were taken into account.

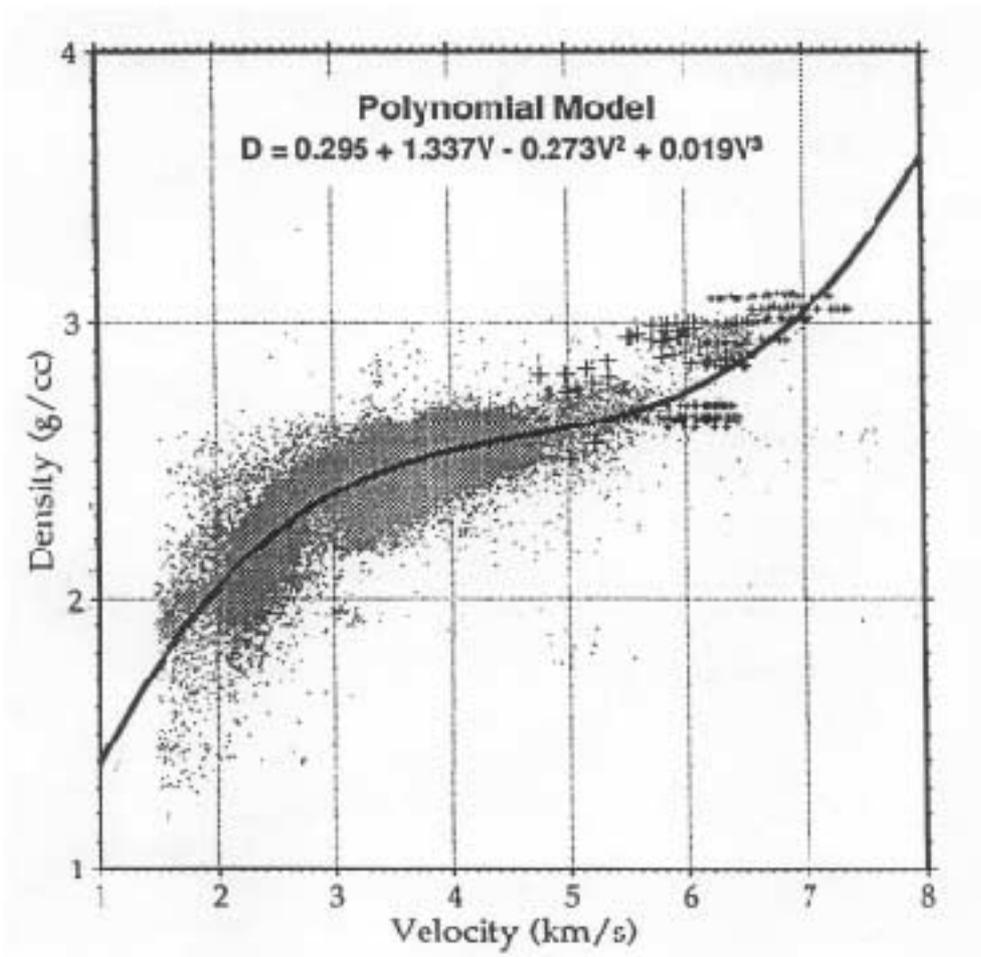


Figure 6

The seismic velocity - density relationship used as a basis for the estimation of the densities of the post and syn-rift sediments. This figure is taken from Hughes *et al.* (1998).

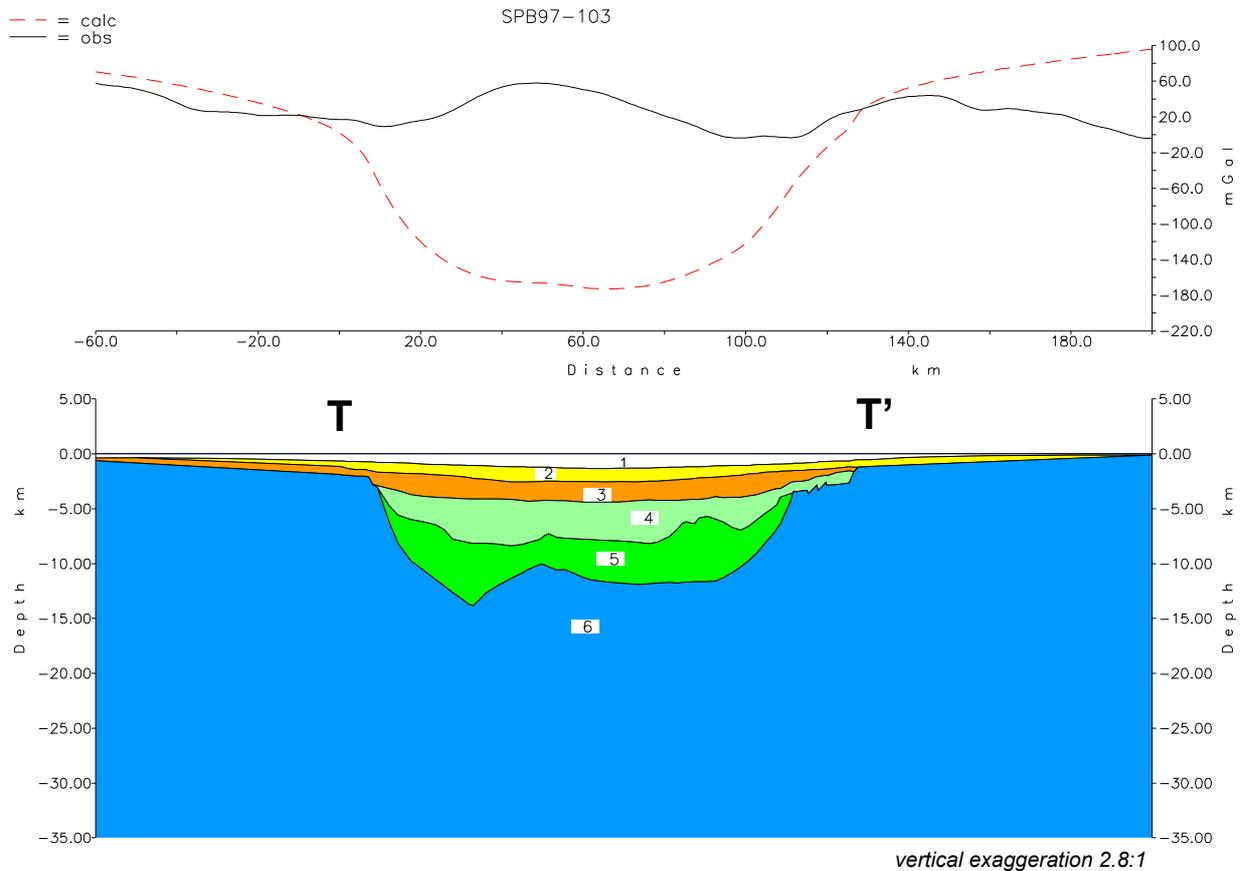


Figure 7 (a)

Transect T: Seismic profile SPB97-103 (T - T', 0 - 131 km)

The gravity effect of the seismic stratigraphic interpretation (Naylor *et al.* 2002) is shown by the dashed red line and compared with the observed gravity anomaly. The depth-to-basement between *ca* 65 and 110 km, where it is not defined by the seismic stratigraphic interpretation, has been estimated. In this initial model the crust has been given a uniform density of 2800 kg m^{-3} and there is no Moho (or flat Moho topography). Densities used for the post and syn-rift stratigraphy are as follows (polygon numbers are given in brackets): Neogene (2) 1900 kg m^{-3} , Paleogene (3) 2070 kg m^{-3} , Cretaceous (4) 2410 kg m^{-3} , pre-Cretaceous (5) 2550 kg m^{-3} ; Seawater (1) 1030 kg m^{-3} , Crust (6) 2800 kg m^{-3} .

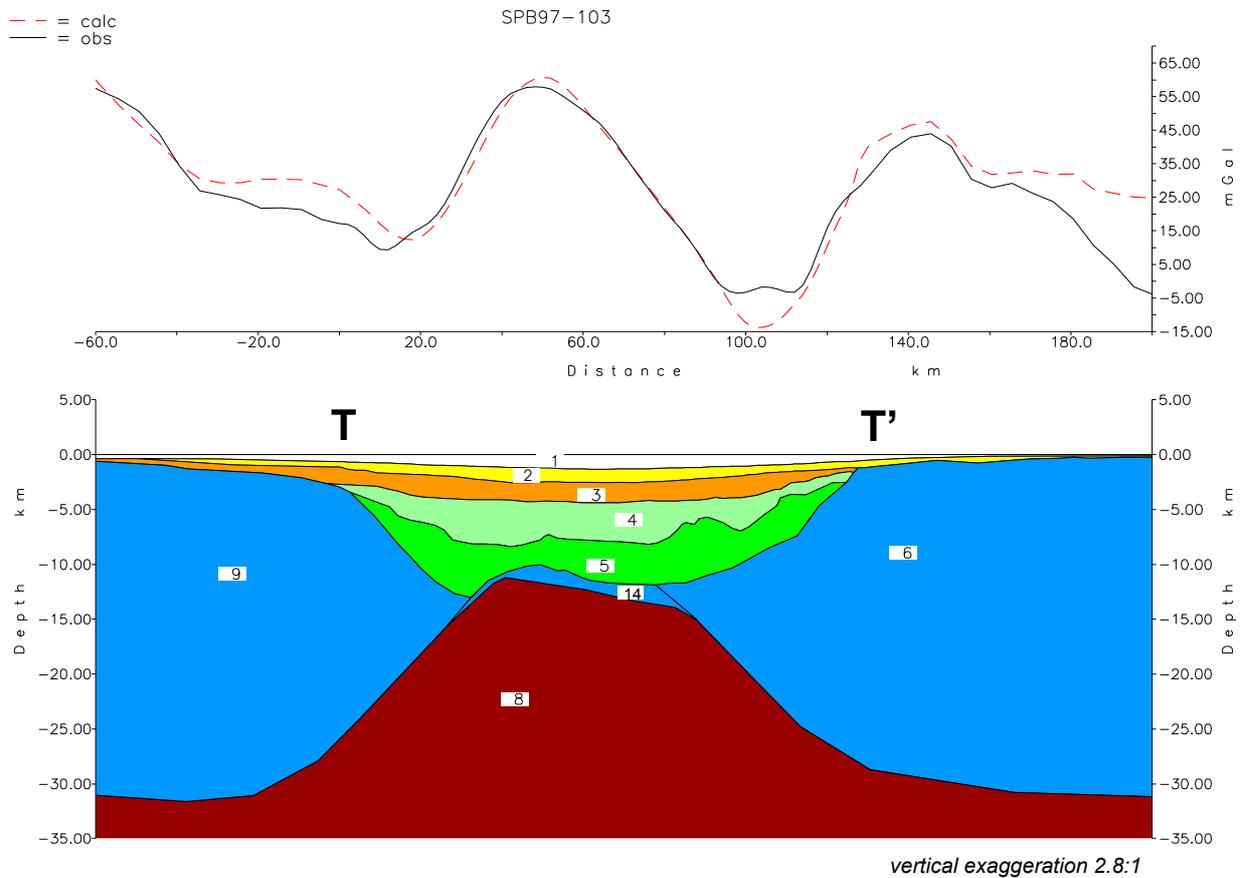


Figure 7 (b)

Transect T: Seismic profile SPB97-103 (T - T', 0 - 131 km)

In this model with a uniform density crust the depth to the Moho has been adjusted to fit the observed gravity anomaly. Densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (5) 2550 kg m^{-3} ; Crust (6, 9 and 14) 2800 kg m^{-3} ; Mantle (8) 3330 kg m^{-3} .

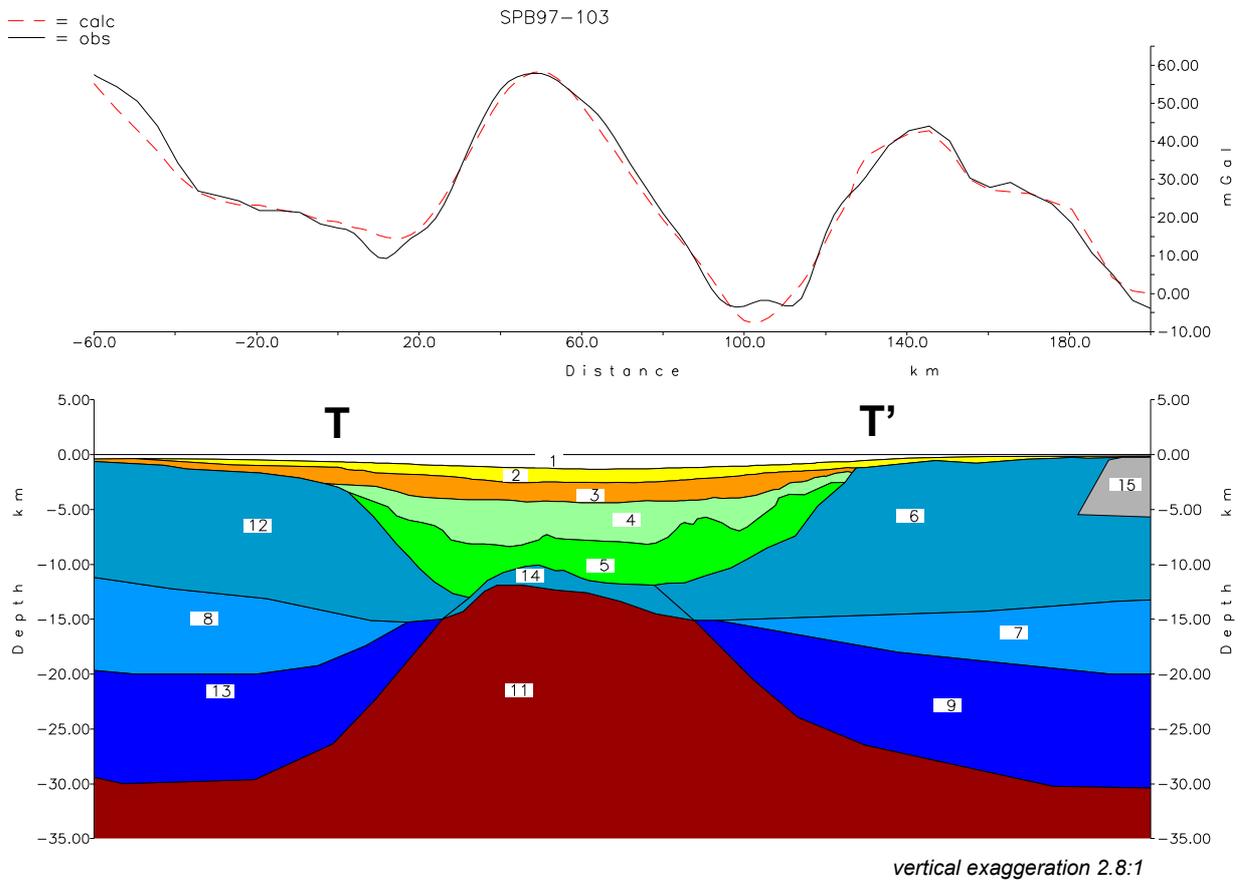


Figure 7 (c)

Transect T: Seismic profile SPB97-103 (T - T', 0 - 131 km)

This model is essentially similar to that in Fig. 7b except that a three-layer crust has been used and the gravity low at the eastern end of the profile (at *ca* 190 km) has been modelled by a low density body, assumed to be a granite. Densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m⁻³; Neogene (2) 1900 kg m⁻³; Paleogene (3) 2070 kg m⁻³; Cretaceous (4) 2410 kg m⁻³; pre-Cretaceous (5) 2550 kg m⁻³; Upper crust (6, 12 and 14) 2690 kg m⁻³; Mid-crust (7 and 8) 2800 kg m⁻³; Lower crust (9 and 13) 2900 kg m⁻³; Granite (15) 2600 kg m⁻³; Mantle (11) 3330 kg m⁻³.

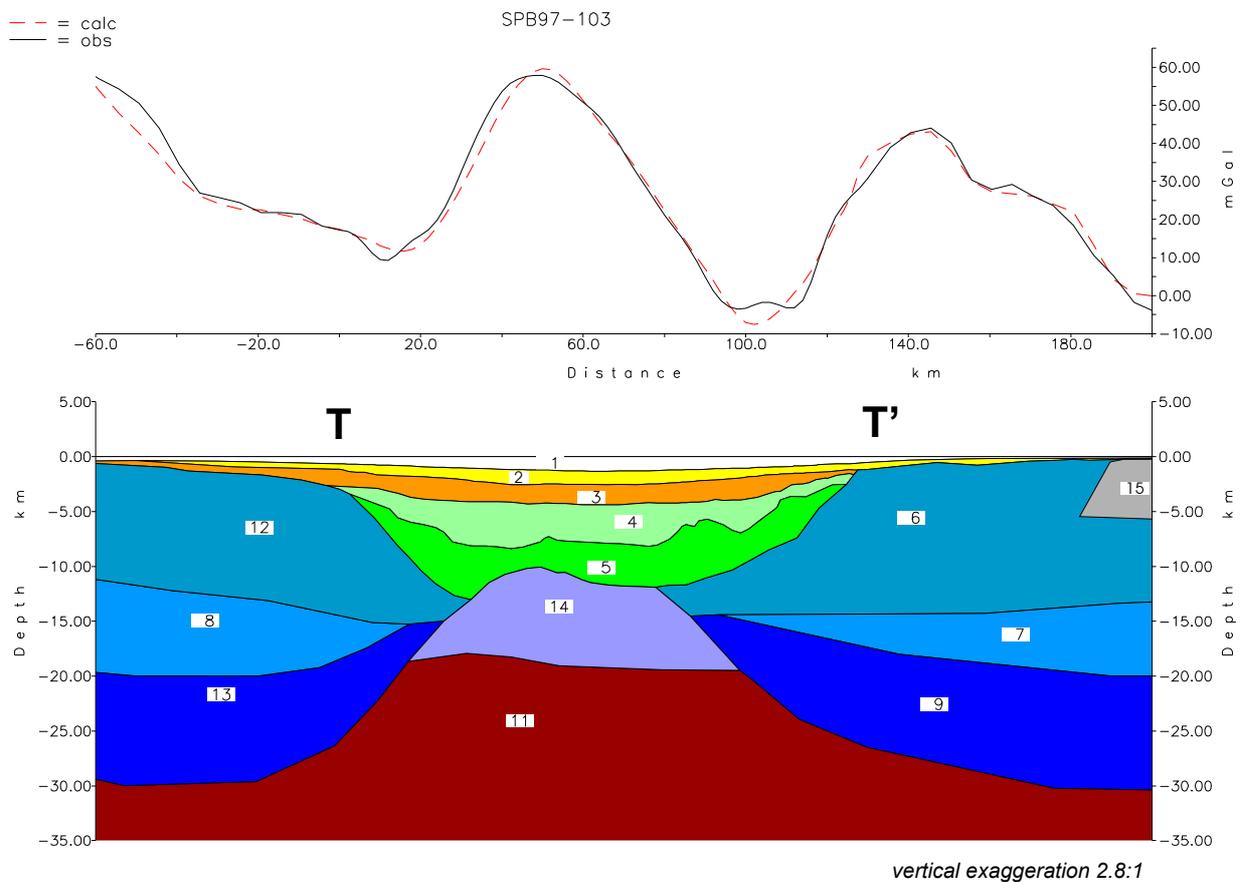


Figure 7 (d)

Transect T: Seismic profile SPB97-103 (T - T', 0 - 131 km)

This model is essentially similar to that in Fig. 7c, except that a dense body beneath the centre of the basin is used in place of the very thin crust in the previous models. Densities are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (5) 2550 kg m^{-3} ; Upper crust (6 and 12) 2690 kg m^{-3} ; Mid-crust (7 and 8) 2800 kg m^{-3} ; Lower crust (9 and 13) 2900 kg m^{-3} ; Granite (15) 2600 kg m^{-3} ; Dense crust? (14) 3200 kg m^{-3} ; Mantle (11) 3330 kg m^{-3} .

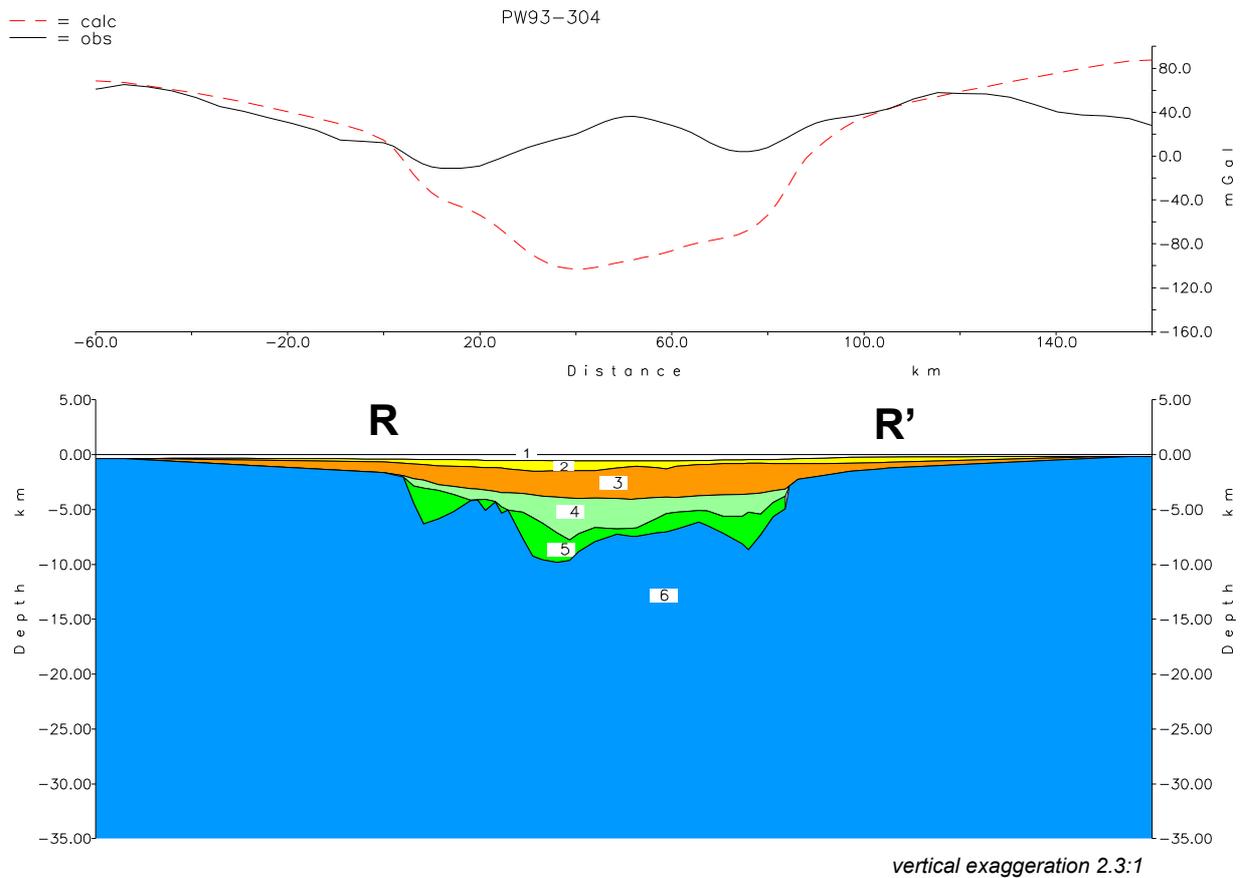


Figure 8 (a)

Transect R: Seismic profile PW93-304 (**R - R'**, 0 - 105 km)

The gravity effect of the seismic stratigraphic interpretation (Naylor *et al.* 2002) is shown by the dashed red line and compared with the observed gravity anomaly. The depth-to-basement between *ca* 65 and 85 km where it is not defined the seismic stratigraphic interpretation has been estimated. In this initial model the crust has been given a uniform density of 2800 kg m^{-3} and there is no Moho (or a flat Moho). Densities used for the post and syn-rift stratigraphy are as follows (polygon numbers are given in brackets): Neogene (2) 1900 kg m^{-3} , Paleogene (3) 2070 kg m^{-3} , Cretaceous (4) 2410 kg m^{-3} , pre-Cretaceous (5) 2550 kg m^{-3} ; Seawater (1) 1030 kg m^{-3} ; Crust (6) 2800 kg m^{-3} .

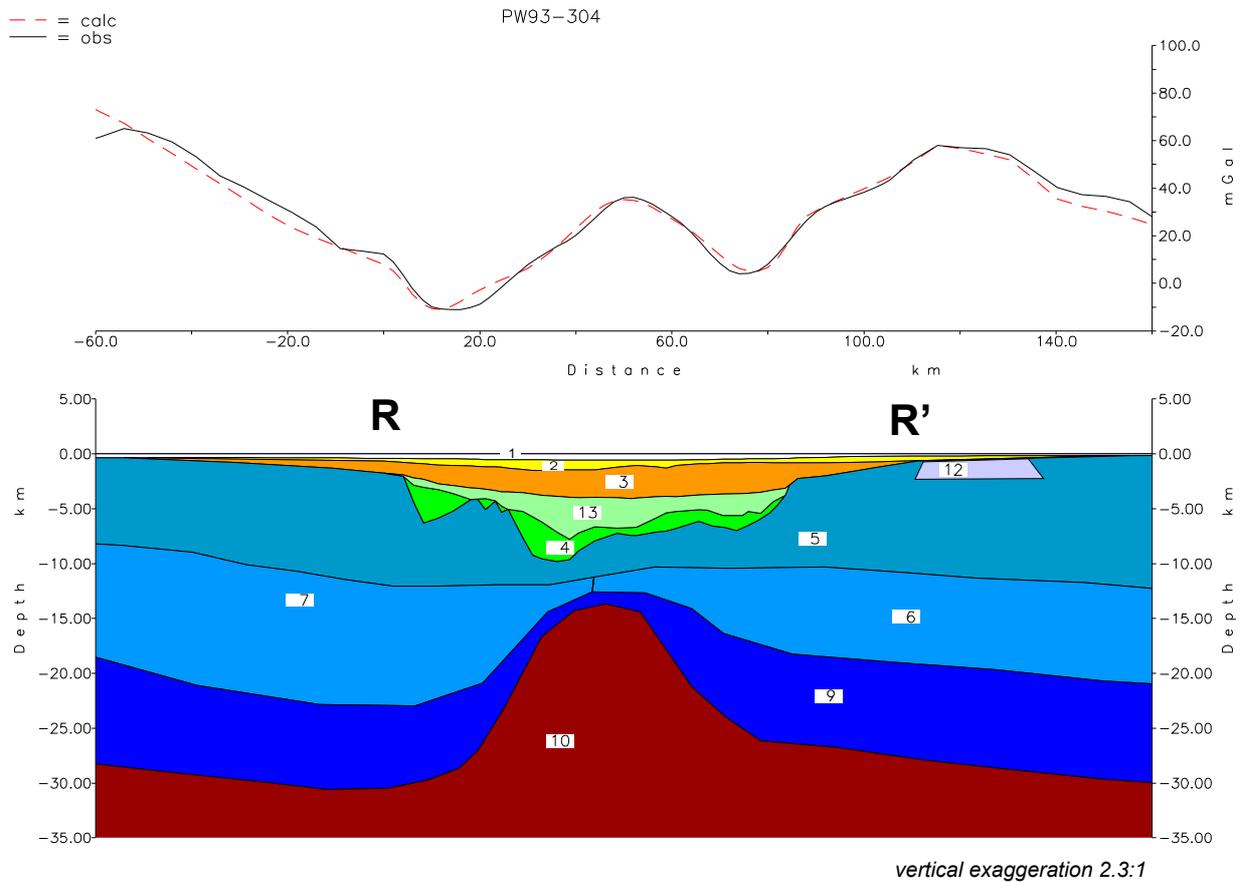


Figure 8 (b)

Transect R: Seismic profile PW93-304 (**R - R'**, 0 - 105 km)

In this model the depth to the Moho has been adjusted to fit the observed gravity anomaly with a three-layer crust used. A high density body (12) has been introduced at the eastern end of the profile (at *ca* 110 - 130 km). Densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 Kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (13) 2410 kg m^{-3} ; pre-Cretaceous (4) 2500 kg m^{-3} ; Upper crust (5) 2600 kg m^{-3} ; High density body (12) 2900 kg m^{-3} ; Mid-crust (6 and 7) 2700 kg m^{-3} ; Lower crust (9) 2900 kg m^{-3} ; Mantle (10) 3350 kg m^{-3} .

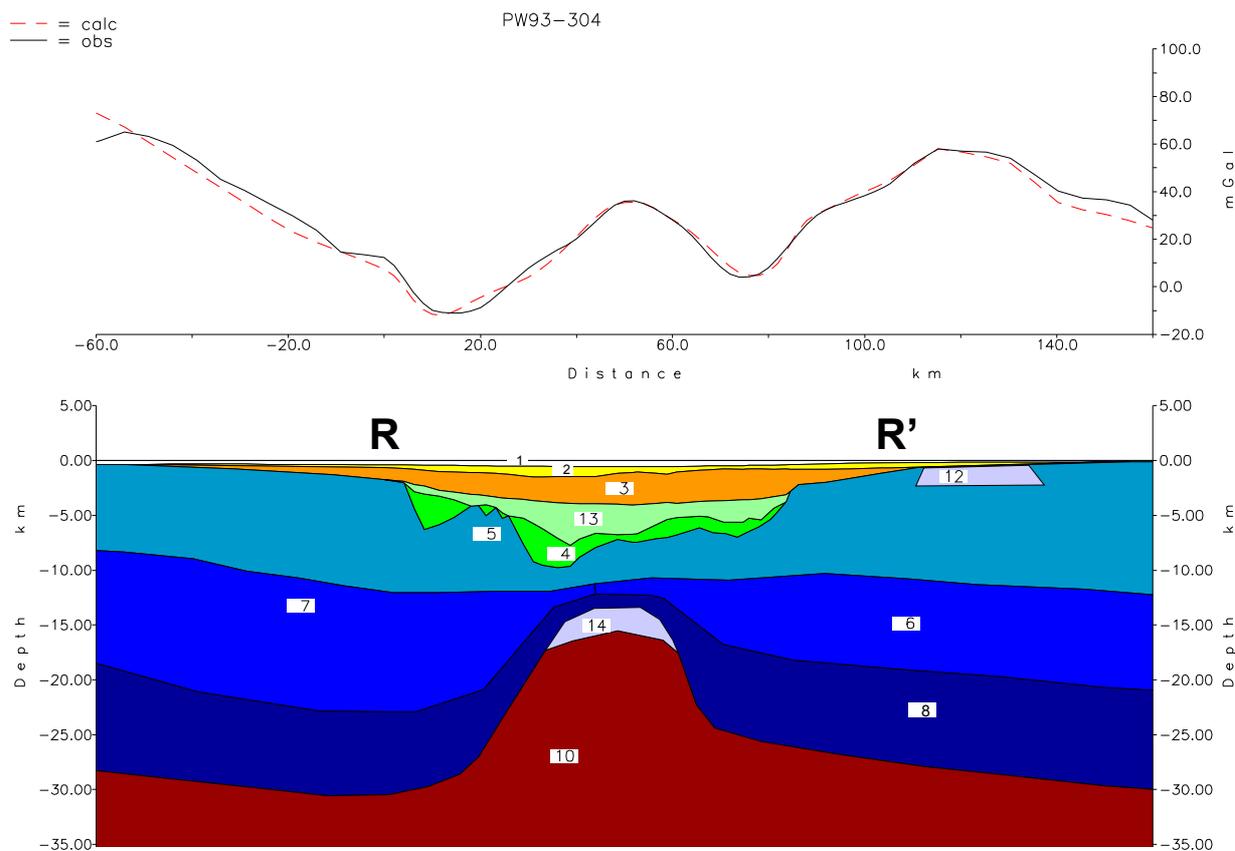


Figure 8 (c)

Transect R: Seismic profile PW93-304 (R - R', 0 - 105 km)

This model is essentially similar to that in Fig. 8b except that high density body (14, 3200 kg m^{-3}) has been introduced at the base of the lower crust beneath the centre of the basin. Densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (13) 2410 kg m^{-3} ; pre-Cretaceous (4) 2500 kg m^{-3} ; Upper crust (5) 2600 kg m^{-3} ; High density body (12) 2900 kg m^{-3} ; Mid-crust (6 and 7) 2700 kg m^{-3} ; Lower crust (9) 2900 kg m^{-3} ; High density body (14) 3200 kg m^{-3} ; Mantle (10) 3350 kg m^{-3} .

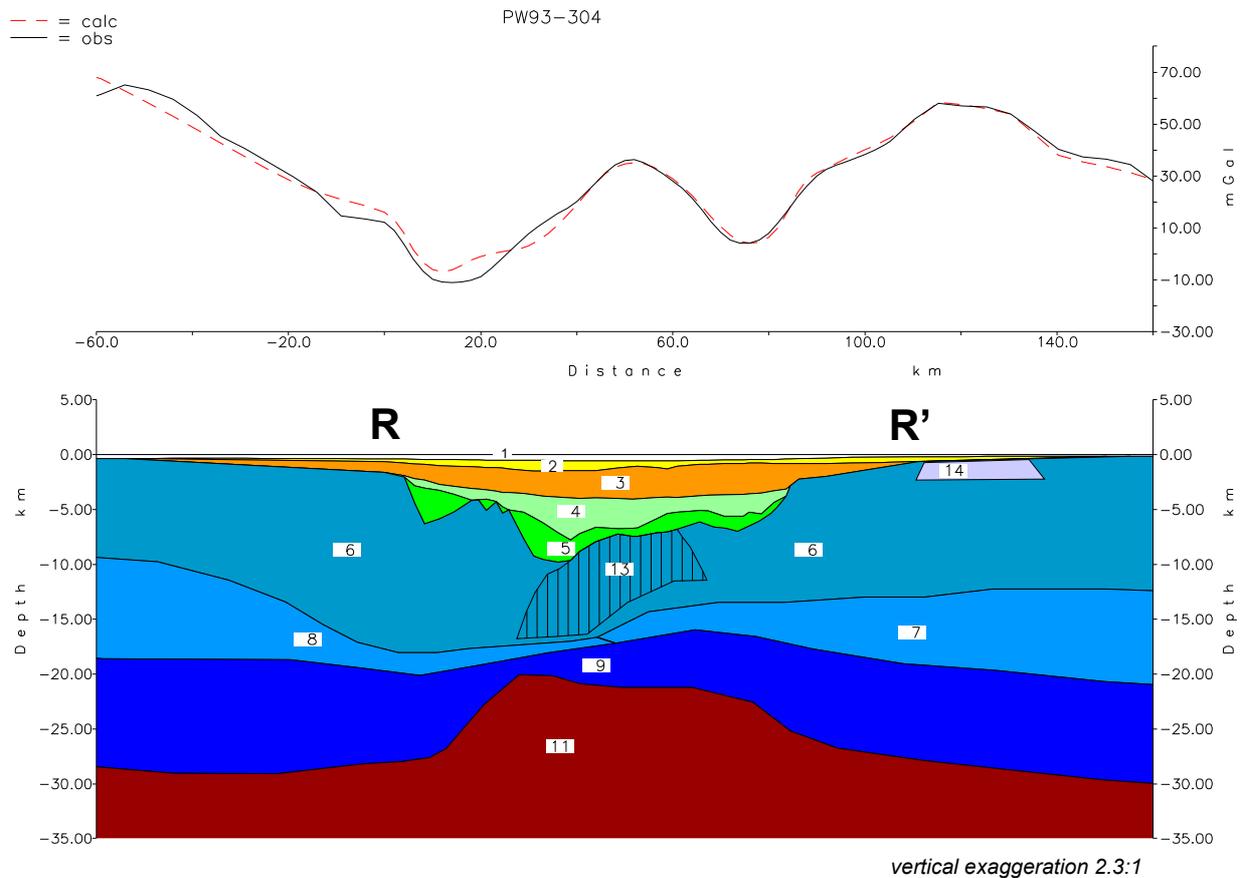


Figure 8 (d)

Transect R: Seismic profile PW93-304 (R - R', 0 - 105 km)

In this model a thicker crust beneath the basin is used and the central anomaly high explained by introducing a high density body (13) within the upper crust. Densities are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (5) 2500 kg m^{-3} ; Upper crust (6) 2600 kg m^{-3} ; High density body (13) 3050 kg m^{-3} ; High density body (14) 2900 kg m^{-3} ; Mid-crust (7 and 8) 2700 kg m^{-3} ; Lower crust (9) 2900 kg m^{-3} ; Mantle (11) 3350 kg m^{-3} .

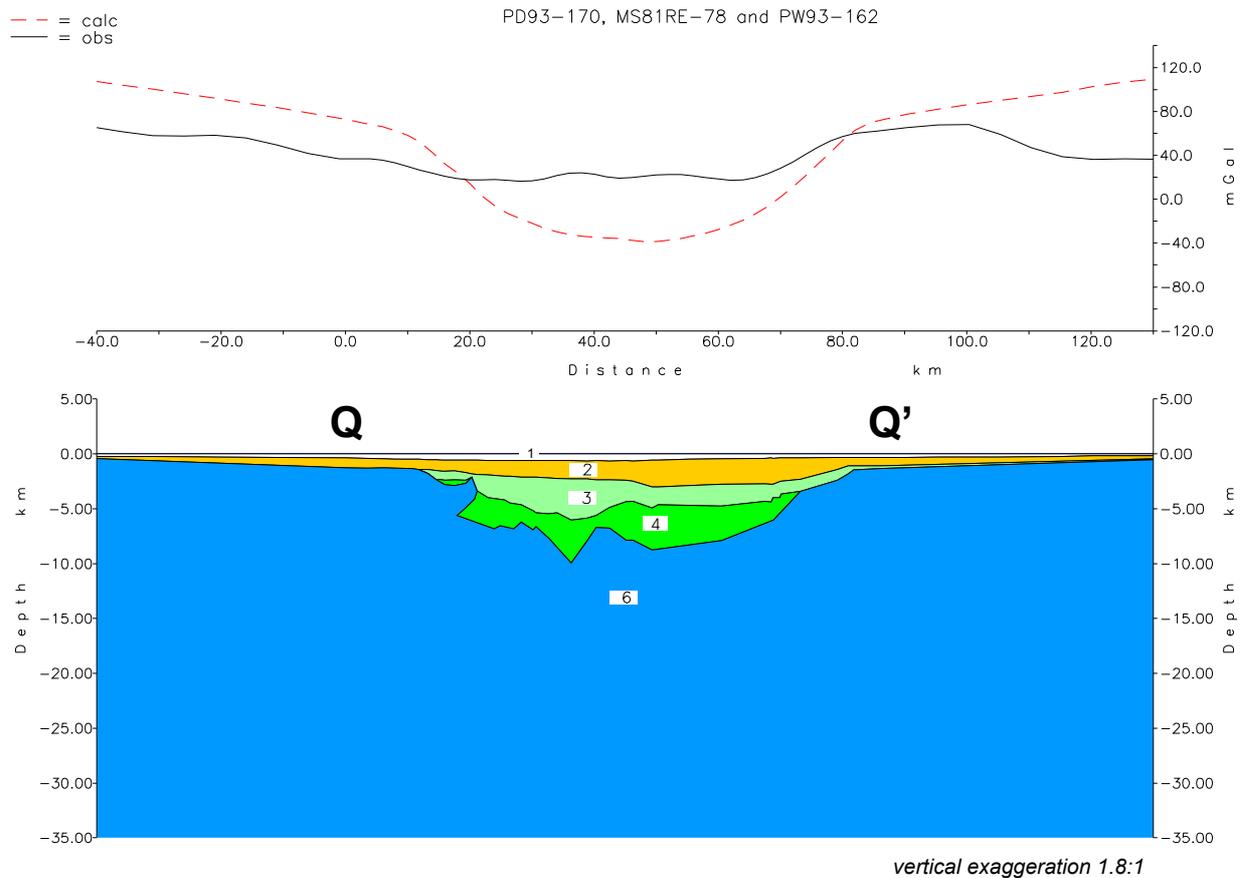


Figure 9 (a)

Transect Q:

Seismic profiles PD93-170, MS81-RE78 and PW93-162 (Q - Q', 0 - 86 km)

The gravity effect of the seismic stratigraphic interpretation (Naylor *et al.* 2002) is shown by the dashed red line and compared with the observed gravity anomaly. The top-of-basement between *ca* 45 and 75 km where it is not defined by the seismic stratigraphic interpretation has been estimated. In this initial model the crust has been given a uniform density of 2800 kg m^{-3} and there is no Moho (or a flat Moho). Densities used for the post and syn-rift stratigraphy are as follows (polygon numbers are given in brackets): Neogene/Paleogene (2) 2050 kg m^{-3} ; Cretaceous (3) 2410 kg m^{-3} ; pre-Cretaceous (4) 2550 kg m^{-3} ; Seawater (1) 1030 kg m^{-3} ; Crust (6) 2800 kg m^{-3} .

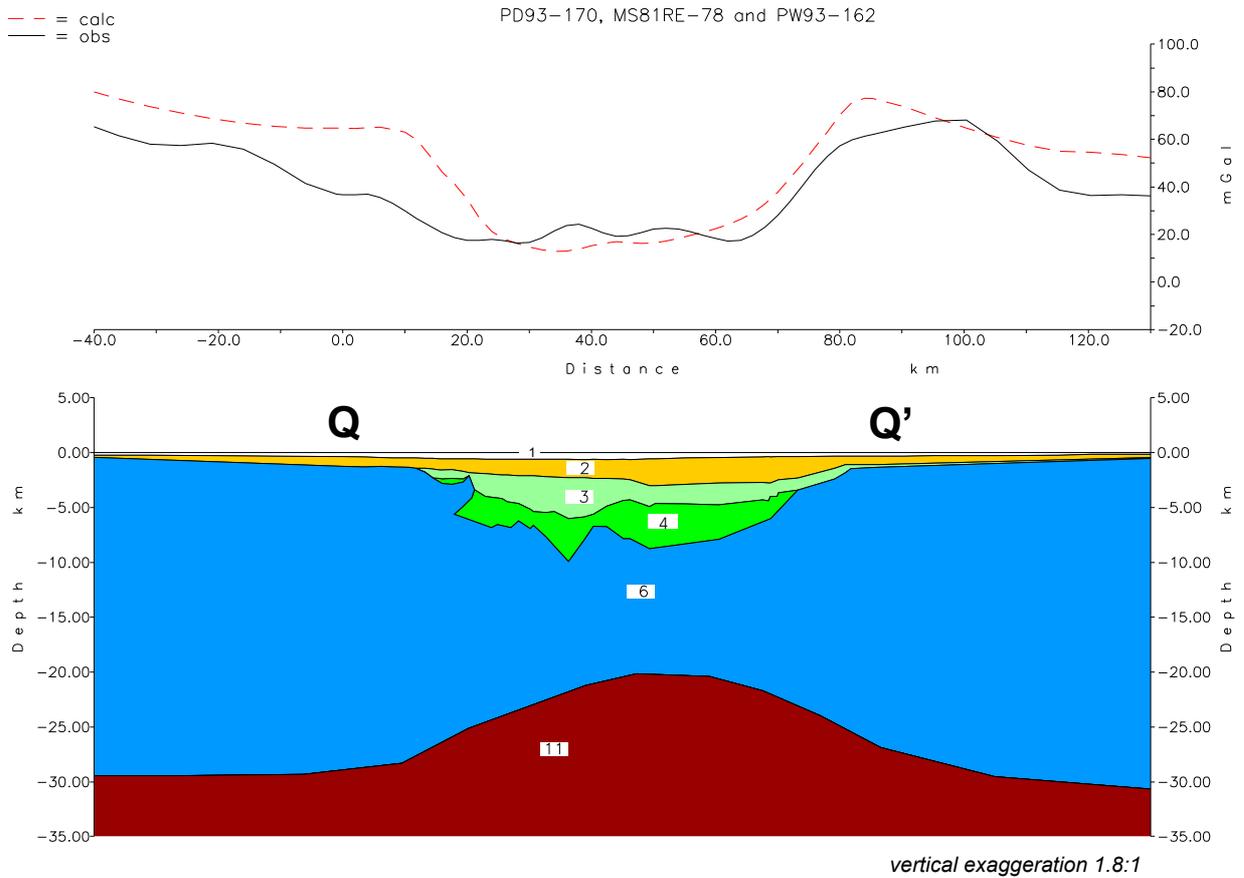


Figure 9 (b)

Transect Q:

Seismic profiles PD93-170, MS81-RE78 and PW93-162 (Q - Q', 0 - 86 km)

Here an attempt is made to fit the observed anomaly by introducing topography onto the Moho. The densities are as in Fig. 9a with the densities of the crust (6) and mantle (11) as 2800 kg m^{-3} and 3350 kg m^{-3} , respectively.

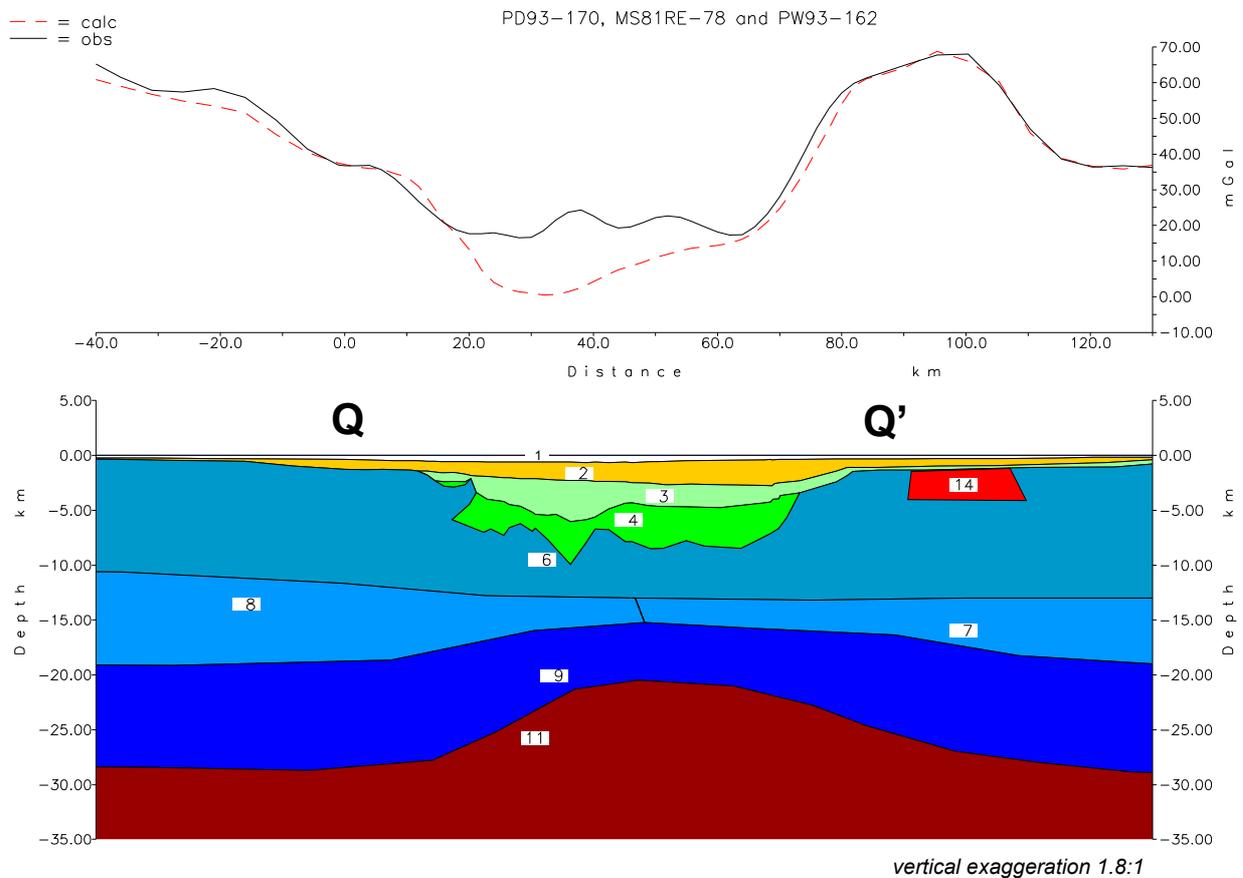


Figure 9 (c)

Transect Q:

Seismic profiles PD93-170, MS81-RE78 and PW93-162 (Q - Q', 0 - 86 km)

The use of a three-layer crust for this profile has improved the fit at the ends of the profile but cannot at the same time explain the magnitude of the gravity low between 20 - 60 km. A high density body (14) representing the edge of the Brendan Igneous Centre has been included at *ca* 90 - 110 km. The densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene/Paleogene (2) 2050 kg m^{-3} ; Cretaceous (3) 2410 kg m^{-3} ; pre-Cretaceous (4) 2550 kg m^{-3} ; Upper crust (6) 2700 kg m^{-3} ; Mid-crust (7 and 8) 2780 kg m^{-3} ; Lower crust (9) 2900 kg m^{-3} ; Igneous body (14) 2900 kg m^{-3} ; Mantle (11) 3350 kg m^{-3} .

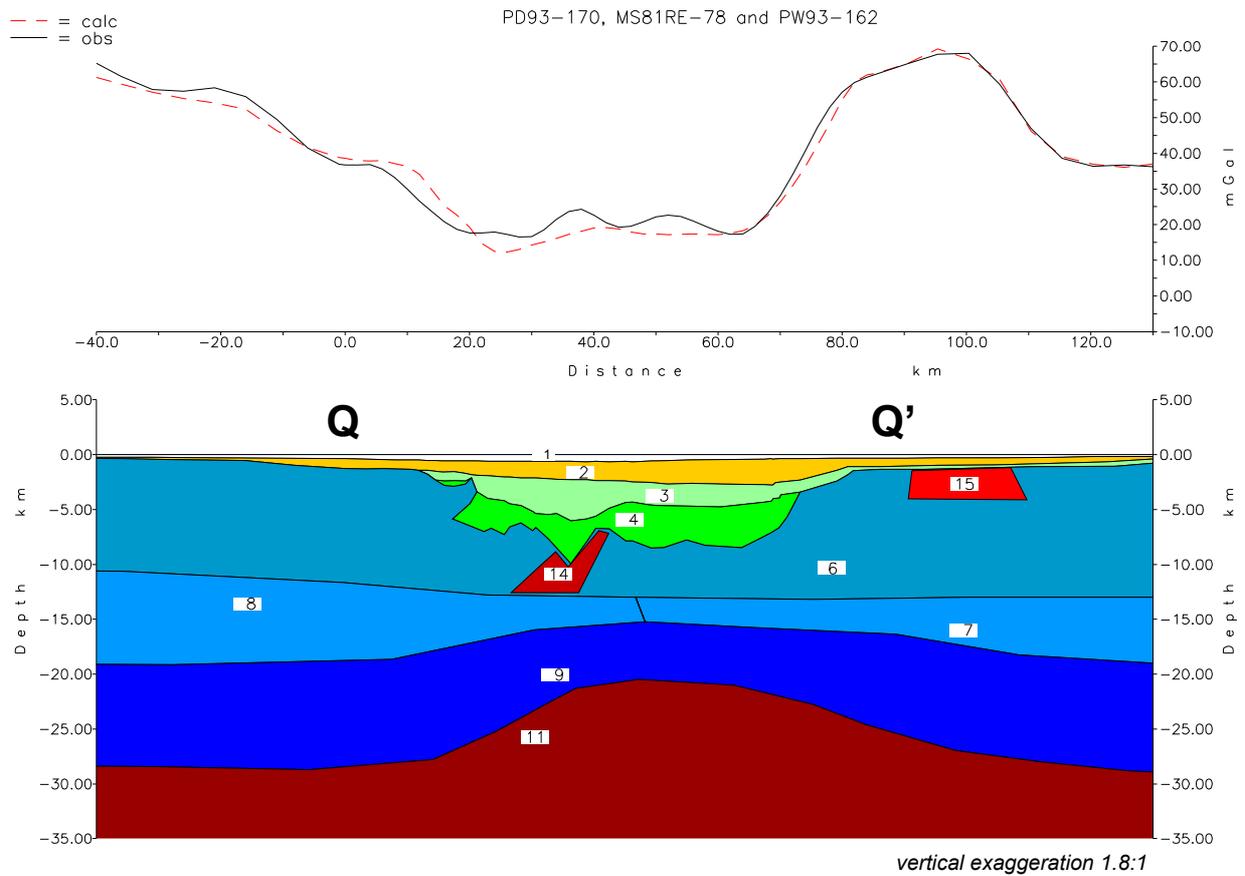


Figure 9 (d)

Transect Q:

Seismic profiles PD93-170, MS81-RE78 and PW93-162 (Q - Q', 0 - 86 km)

Less steep topography on the Moho is used to increase the magnitude of the negative gravity anomaly in the centre of the profile, but this is found to require the inclusion of a high density crustal body at *ca* 40 km distance. Densities are as in Fig. 9c with the addition of the body (labelled 14) of density 3100 kg m^{-3} .

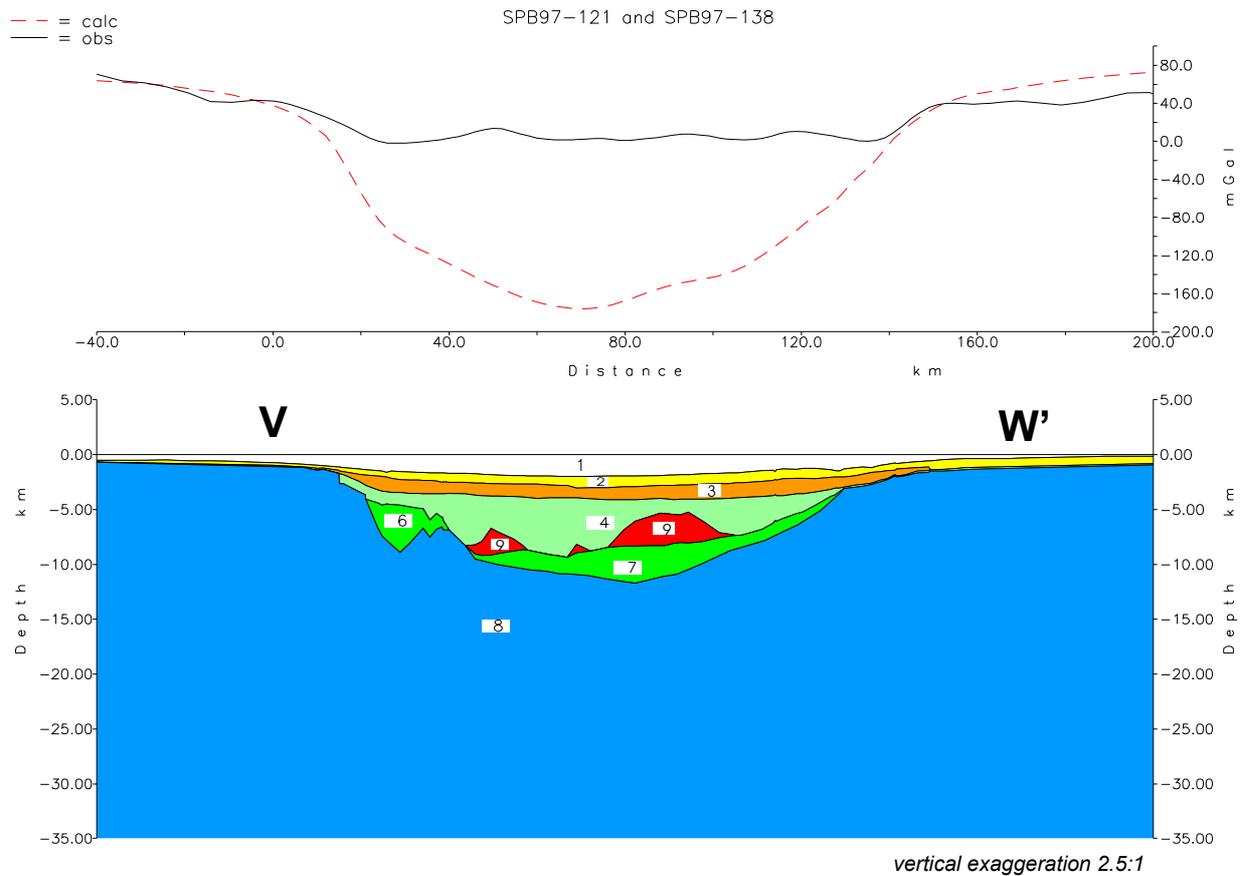


Figure 10 (a)

Transect VW:

Seismic profiles SPB97-121 and SPB97-138 (V - W', 169 km)

The gravity effect of the seismic stratigraphic interpretation (Naylor *et al.* 2002) is shown by the dashed red line and compared with the observed gravity anomaly. The top-of-basement between *ca* 45 and 130 km where it is not defined the seismic stratigraphic interpretation has been estimated. In this initial model the crust (8) has been given a uniform density of 2800 kg m^{-3} and there is no Moho (or a flat Moho). A density of 2700 kg m^{-3} has been used for the bodies associated with the Porcupine Volcanic Ridge System (9). Densities used are as follows (polygon numbers are given in brackets): Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (6 and 7) 2550 kg m^{-3} .

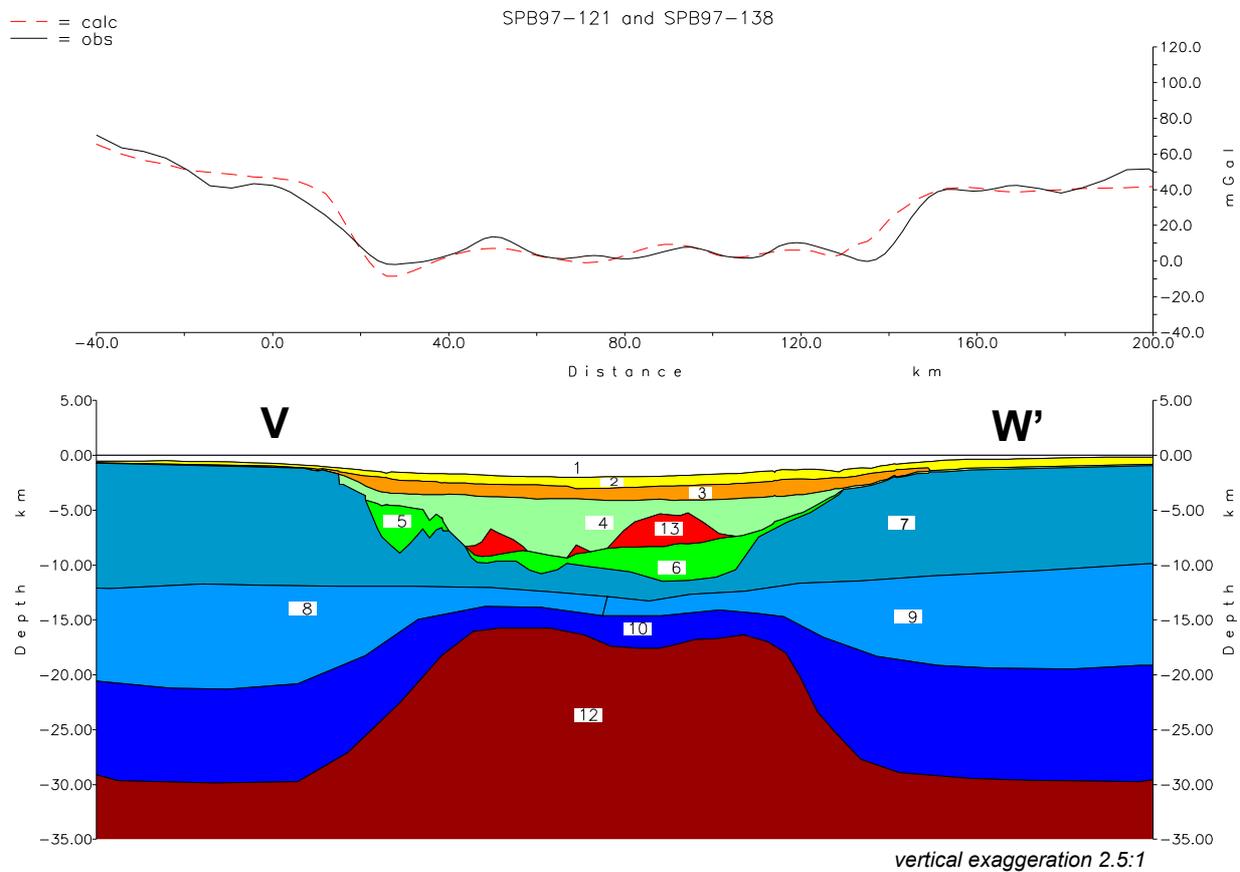


Figure 10 (b)

Transect VW:

Seismic profiles SPB97-121 and SPB97-138 (V - W', 169 km)

Thinning the crust below the basin is seen to explain most of the observed gravity variation but it was not found possible to satisfactorily reproduce the anomaly pattern at the basin edges. Densities used in this model were:
 Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ;
 Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (5 and 6) 2550 kg m^{-3} ; upper crust (7);
 Volcanic Ridge System bodies (13) 2700 kg m^{-3} ; Upper crust 2700 kg m^{-3} ;
 Mid-crust (8 and 9) 2800 kg m^{-3} ; Lower crust (10) 2900 kg m^{-3} ; Mantle (12) 3350 kg m^{-3} .

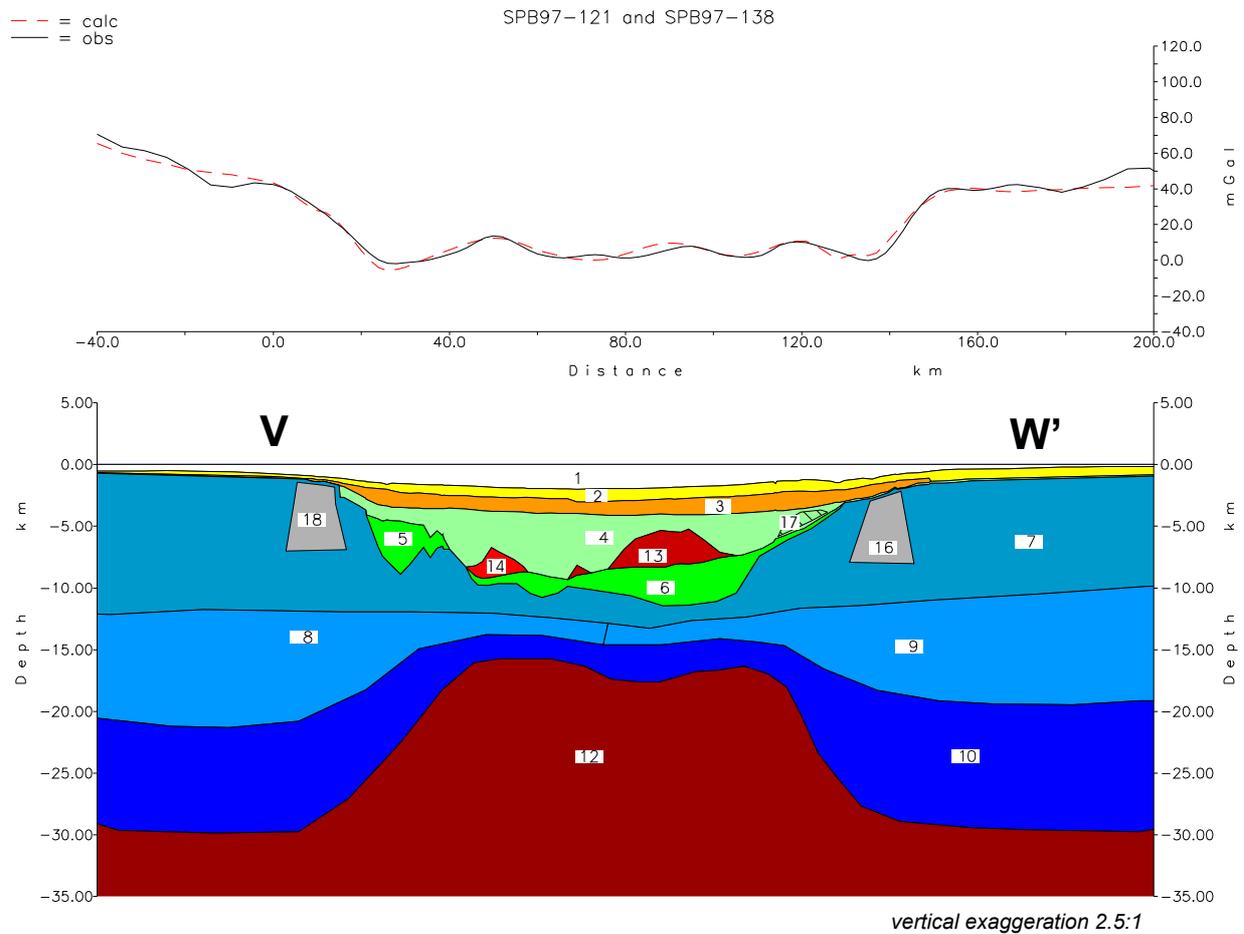


Figure 10 (c)

Transect VW:

Seismic profiles SPB97-121 and SPB97-138 (V - W', 169 km)

Refinement of the model depicted in Fig. 10b has been made by including low density bodies (granites?) on the margins of the basin (labelled 16 and 18 with density 2600 kg m^{-3}) and an upper-crustal dense body (17, density 2700 kg m^{-3}) within the Cretaceous. Otherwise densities are as in Fig. 10b, i.e., Seawater (1) 1030 kg m^{-3} ; Neogene (2) 1900 kg m^{-3} ; Paleogene (3) 2070 kg m^{-3} ; Cretaceous (4) 2410 kg m^{-3} ; pre-Cretaceous (5 and 6) 2550 kg m^{-3} ; Volcanic Ridge System bodies (13) 2700 kg m^{-3} and (14) 2900 kg m^{-3} ; Upper crust (7) 2700 kg m^{-3} ; Granites? (16 and 18) 2600 kg m^{-3} ; Mid-crust (8 and 9) 2800 kg m^{-3} ; Lower crust (10) 2900 kg m^{-3} ; Mantle (12) 3350 kg m^{-3} .

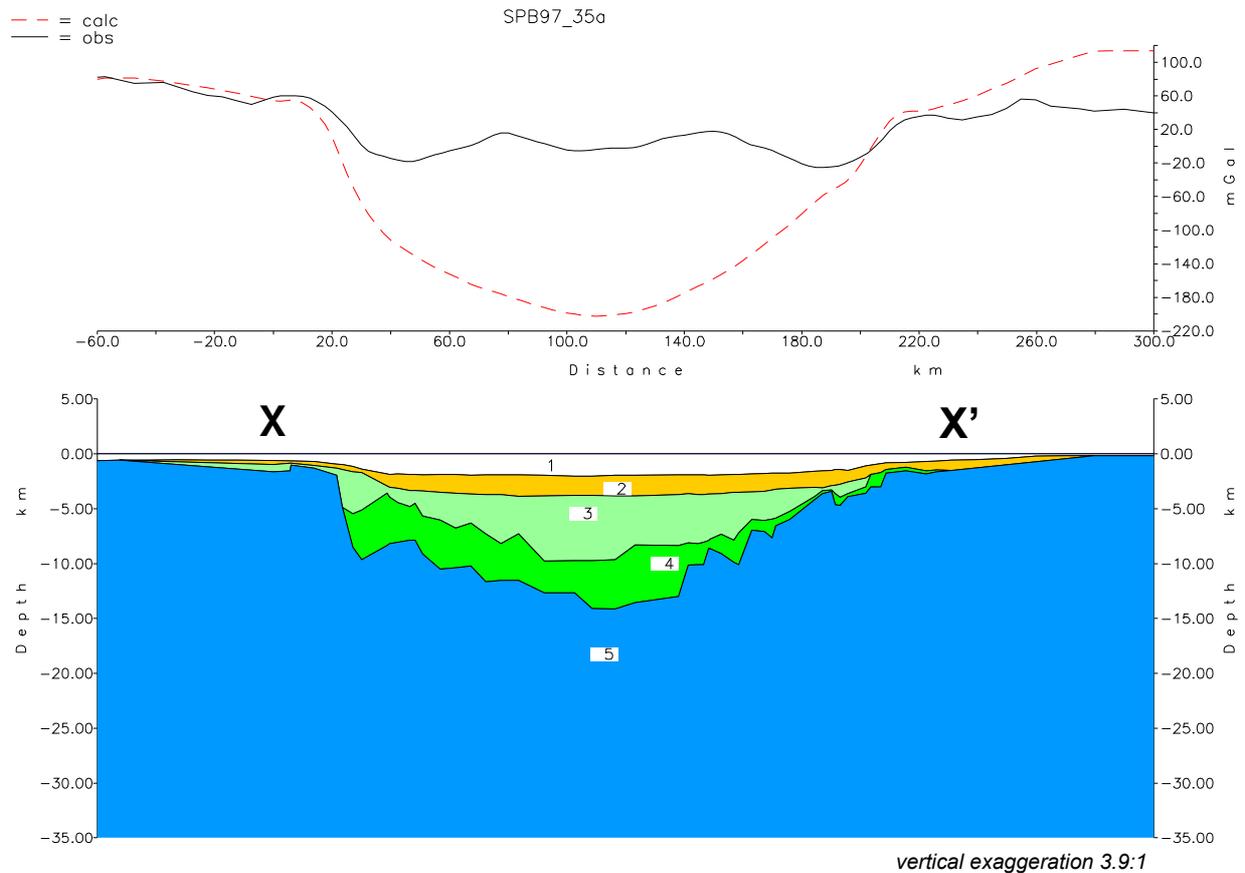


Figure 11 (a)

Transect X: Seismic profile SPB97-35a (X - X', 0 - 232 km)

The gravity effect of the seismic stratigraphic interpretation (Naylor *et al.* 2002) has been calculated assuming no Moho topography and a crustal density of 2800 kg m^{-3} . The depth-to-basement has been assumed between distances 20 - 140 km along the profile where there is no seismically defined stratigraphy. Densities for the post and syn-rift sequences are as follows (polygon numbers are given in brackets): Neogene/Paleogene (2) 1950 kg m^{-3} , Cretaceous (3) 2410 kg m^{-3} , pre-Cretaceous (4) 2510 kg m^{-3} ; Seawater (1) 1030 kg m^{-3} ; Crust (5) 2800 kg m^{-3} .

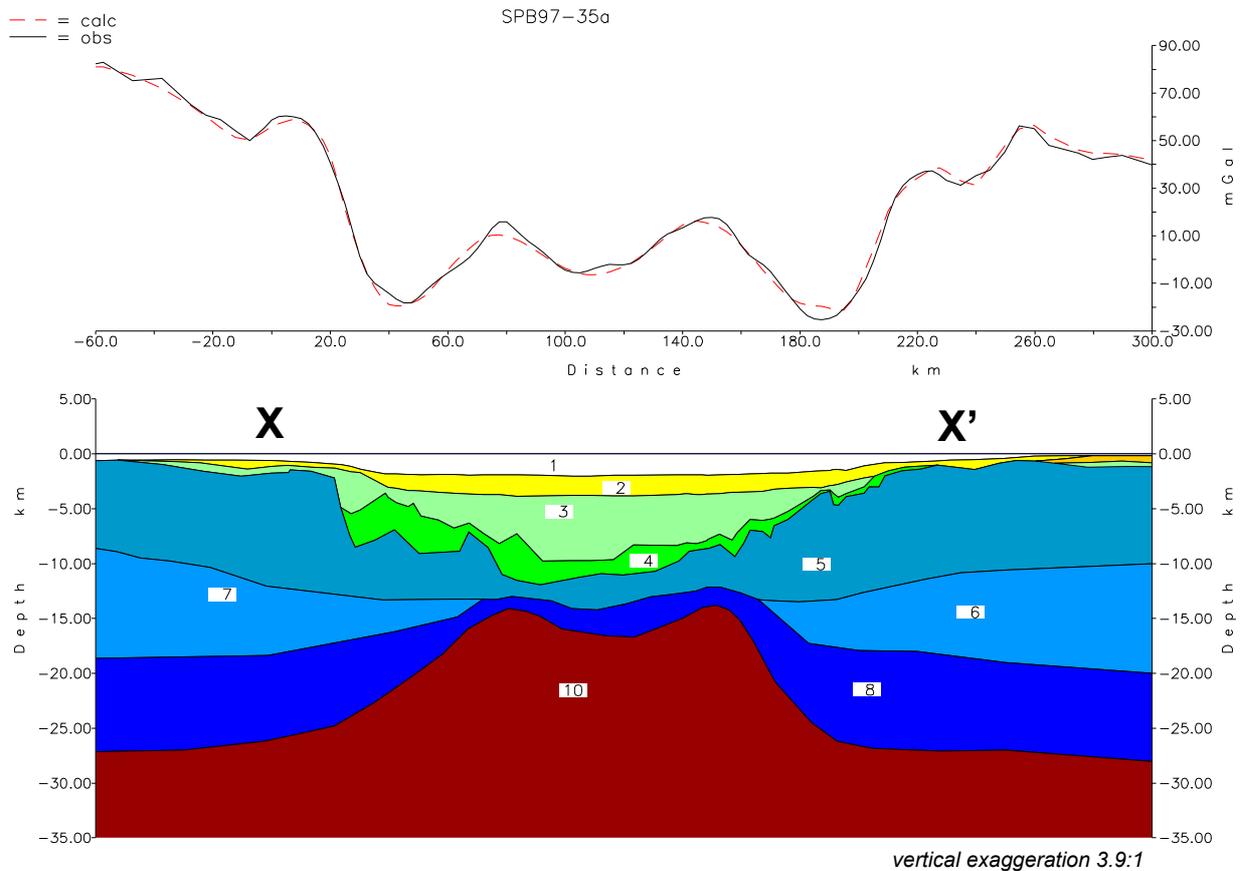


Figure 11 (b)

Transect X: Seismic profile SPB97-35a (X - X', 0 - 232 km)

In this model the observed anomaly pattern is well reproduced by a high crustal stretching factor (*ca* 4.5 - 9). A three-layer crust has also been used but the main factor is the decrease in depth to the Moho. Note that a considerable crustal thickening is required to satisfactorily explain the undulating anomaly pattern observed across the basin. It is difficult to replicate the observed anomaly pattern without this, as shown by Fig. 11c. Densities used in this model are as follows: Seawater (1) 1030 kg m^{-3} ; Neogene/Paleogene (2) 1950 kg m^{-3} ; Cretaceous (3) 2410 kg m^{-3} ; pre-Cretaceous (4) 2510 kg m^{-3} ; Upper crust (5) 2690 kg m^{-3} ; Mid-crust (6 and 7) kg m^{-3} ; Lower crust (8) kg m^{-3} ; Mantle (10) 3340 kg m^{-3} .

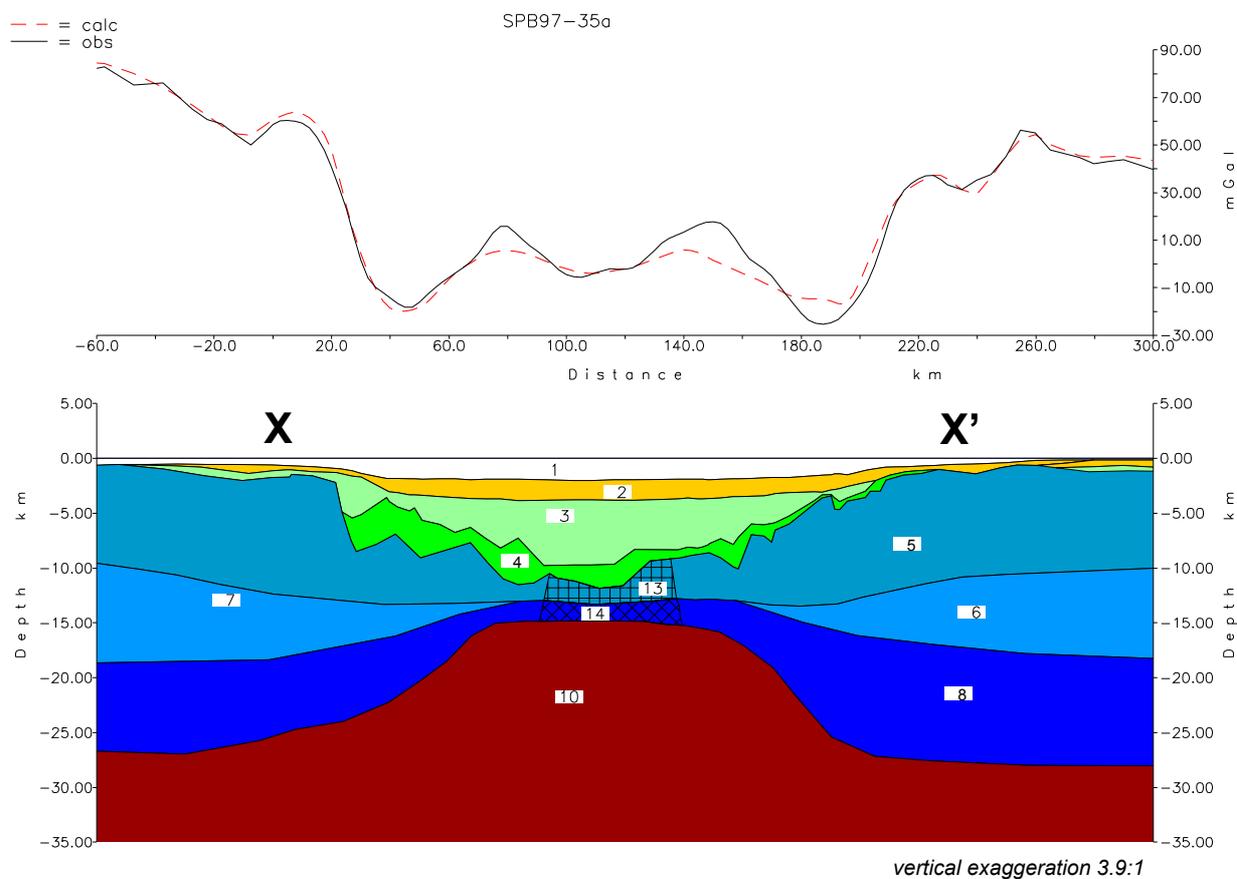


Figure 11 (c)

Transect X: Seismic profile SPB97-35a (X - X', 0 - 232 km)

In this model an attempt has been made to model the anomaly pattern without the necessity of the crustal thickening in the centre of the profile. Changes in the depth-to-basement in the region where it is not seismically defined cannot produce the observed pattern. Decreasing the crustal densities beneath the basin to 2600 kg m^{-3} for the upper crust and 2700 kg m^{-3} for the lower/mid-crust goes some way towards this but cannot replicate the pattern as well as with a thickened centre region of crust as in Fig. 11b. Densities used are as in Fig. 11b with the addition of lower density crust (labelled 13 and 14, densities 2600 and 2700 kg m^{-3} , respectively) beneath the centre of the basin (*ca* 90 - 130 km).

Fig. 9(d)

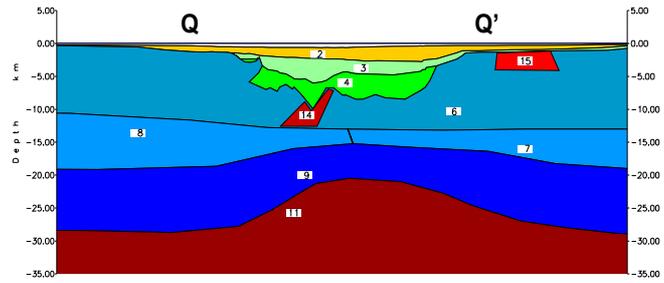


Fig. 8(d)

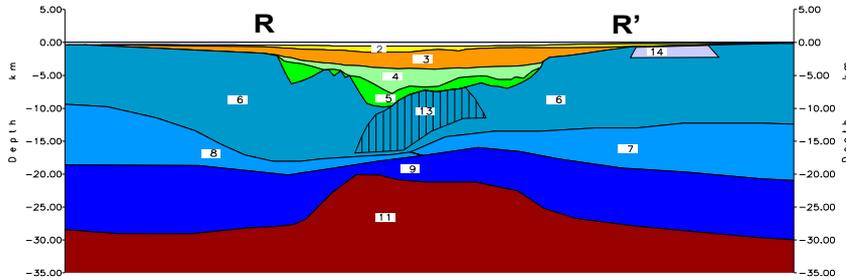


Fig. 7(d)

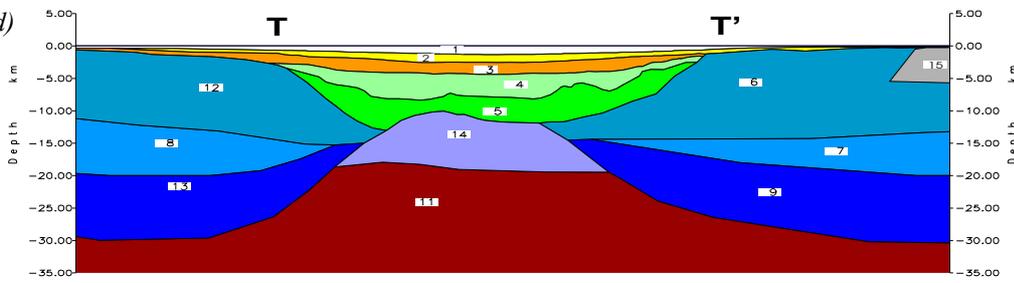


Fig. 10(c)

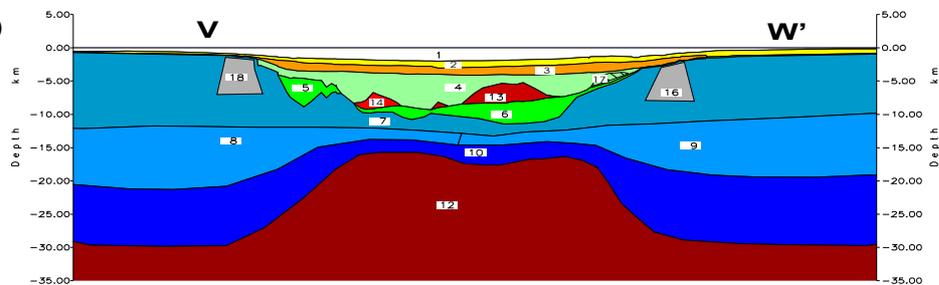


Fig. 11(b)

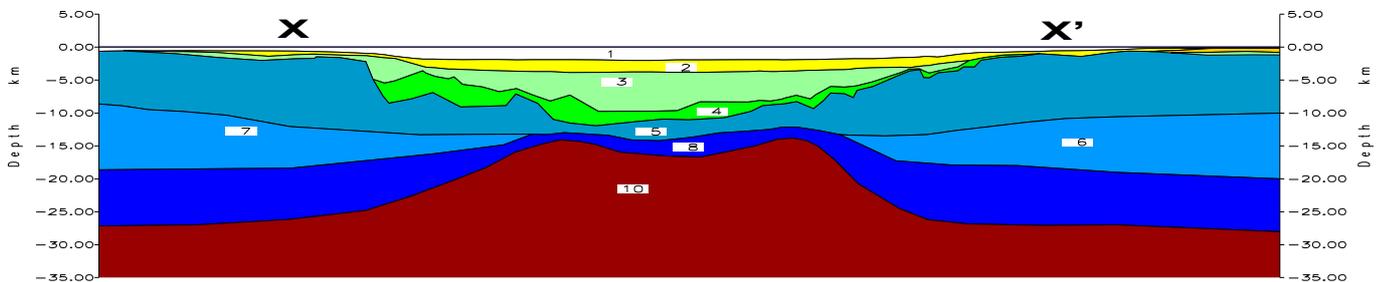


Figure 12

Summary of the preferred gravity models plotted with the same vertical exaggeration of approximately 2. From top to bottom (north to south): **Transect Q** (Seismic profiles PD93-170, MS81-RE78 and PW93-162), **Transect R** (PW93-304), **Transect T** (SPB97-103), **Transect VW** (SPB97-121 and SPB97-138), and **Transect X** (SPB97-35a).

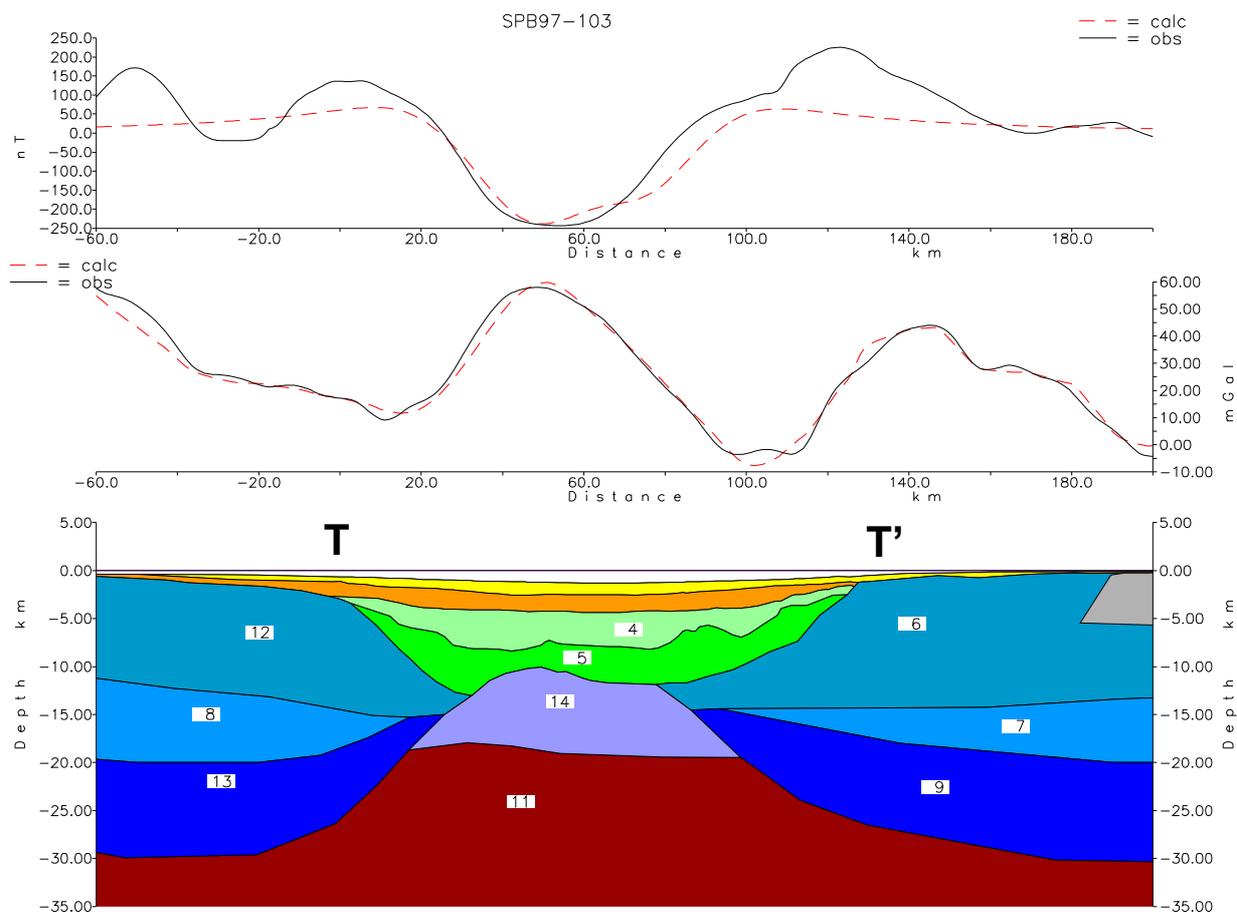


Figure 13

Transect T: Seismic profile SPB97-103 (T - T', 0 - 131 km)

Simple magnetic model based on the gravity model of Fig. 7(d). The upper curve shows the calculated and observed magnetic anomaly (calculated - dashed red line, observed - black continuous line). The lower curve shows the corresponding gravity anomaly. For the magnetic modelling, the high density body (labelled 14) beneath the centre of the basin has been assigned a negative magnetisation value of 2.4 A m^{-1} . Magnetisation of sedimentary and crustal layers has been neglected. For details of the gravity model, see Fig. 7(d).

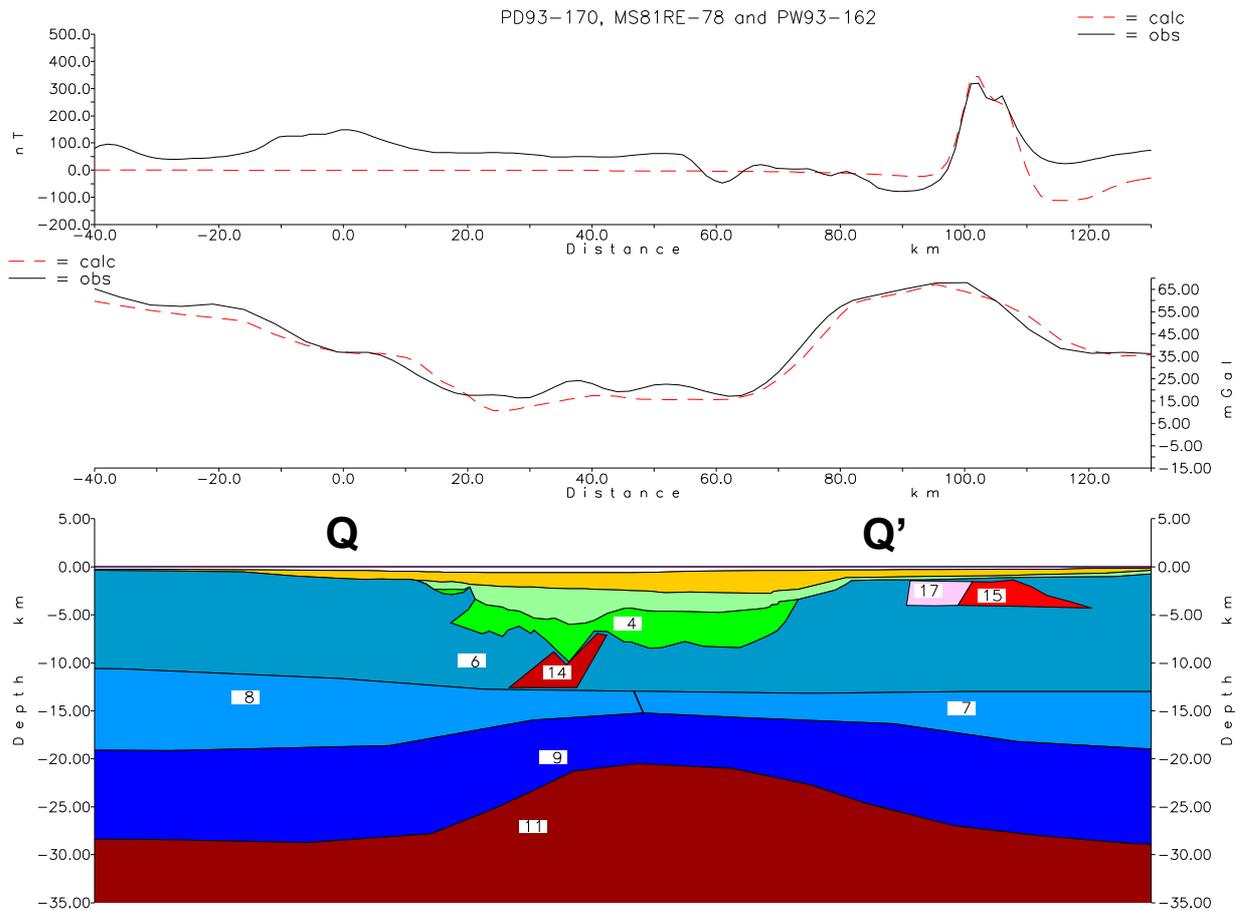


Figure 14

Transect Q:

Seismic profiles PD93-170, MS81-RE78 and PW93-162 (Q - Q', 0 - 86 km)

Simple magnetic model based on the gravity model of Fig. 9(d). The upper curve shows the calculated and observed magnetic anomaly (calculated - dashed red line, observed - black continuous line). The lower curve shows the corresponding gravity anomaly. For the magnetic modelling, part of the the high density body on the eastern flank of the basin (labelled 15) has been assigned a magnetisation value of 2.0 A m^{-1} . Magnetisation of sedimentary and crustal layers has been neglected. For details of the gravity model, see Fig. 9(d).

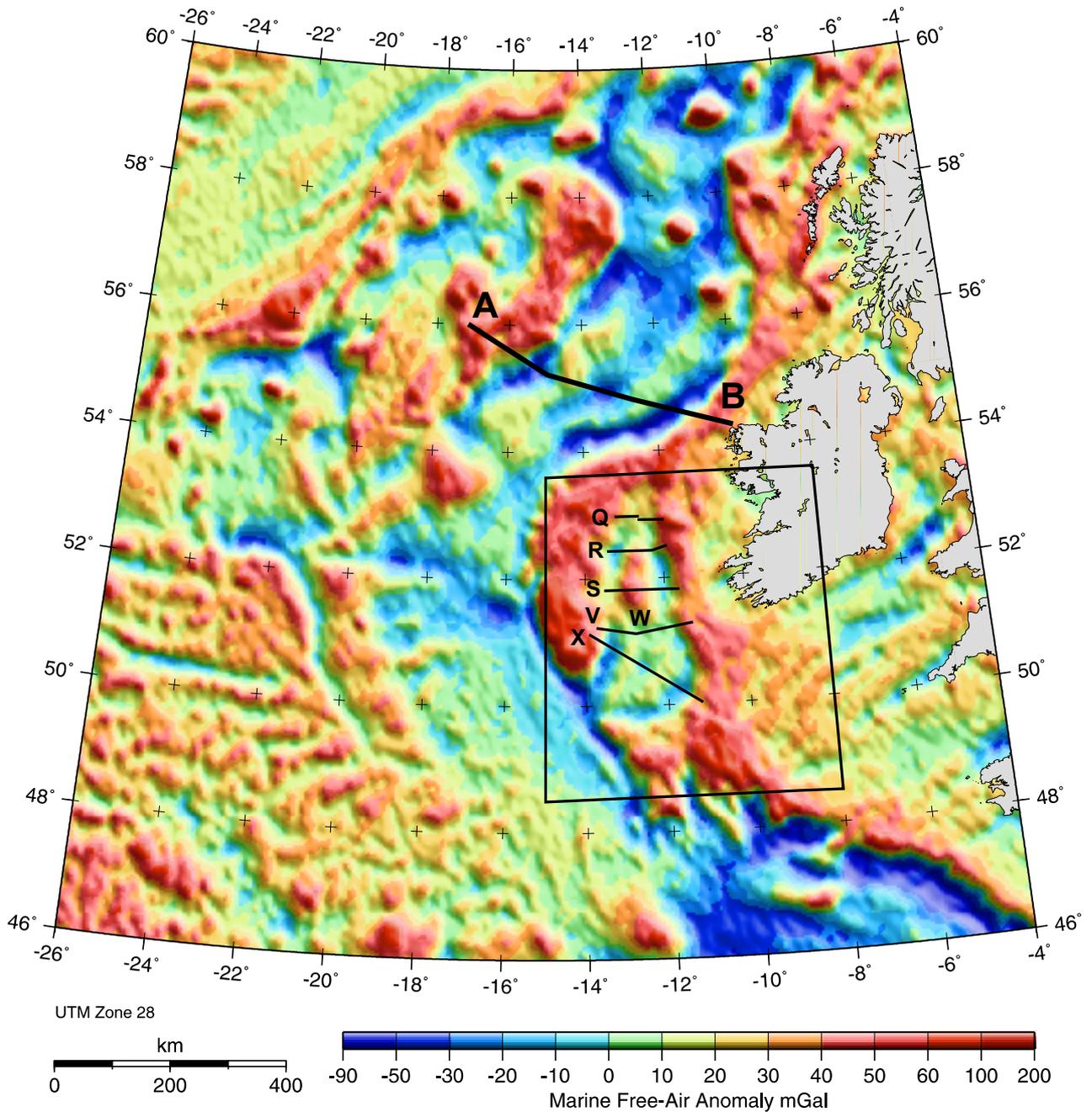


Figure 15

Regional free-air gravity map for the NE Atlantic. The location of the transverse RAPIDS1 profile (A - B) spanning the Rockall Trough (see Fig. 17) is shown. The Porcupine profiles modelled in this report and the Porcupine Studies Group project area (black outline) are also indicated. The map is plotted using a 5-minute grid based on 2-minute gridded satellite data (Sandwell & Smith 1997) with pseudo-illumination from the northeast.

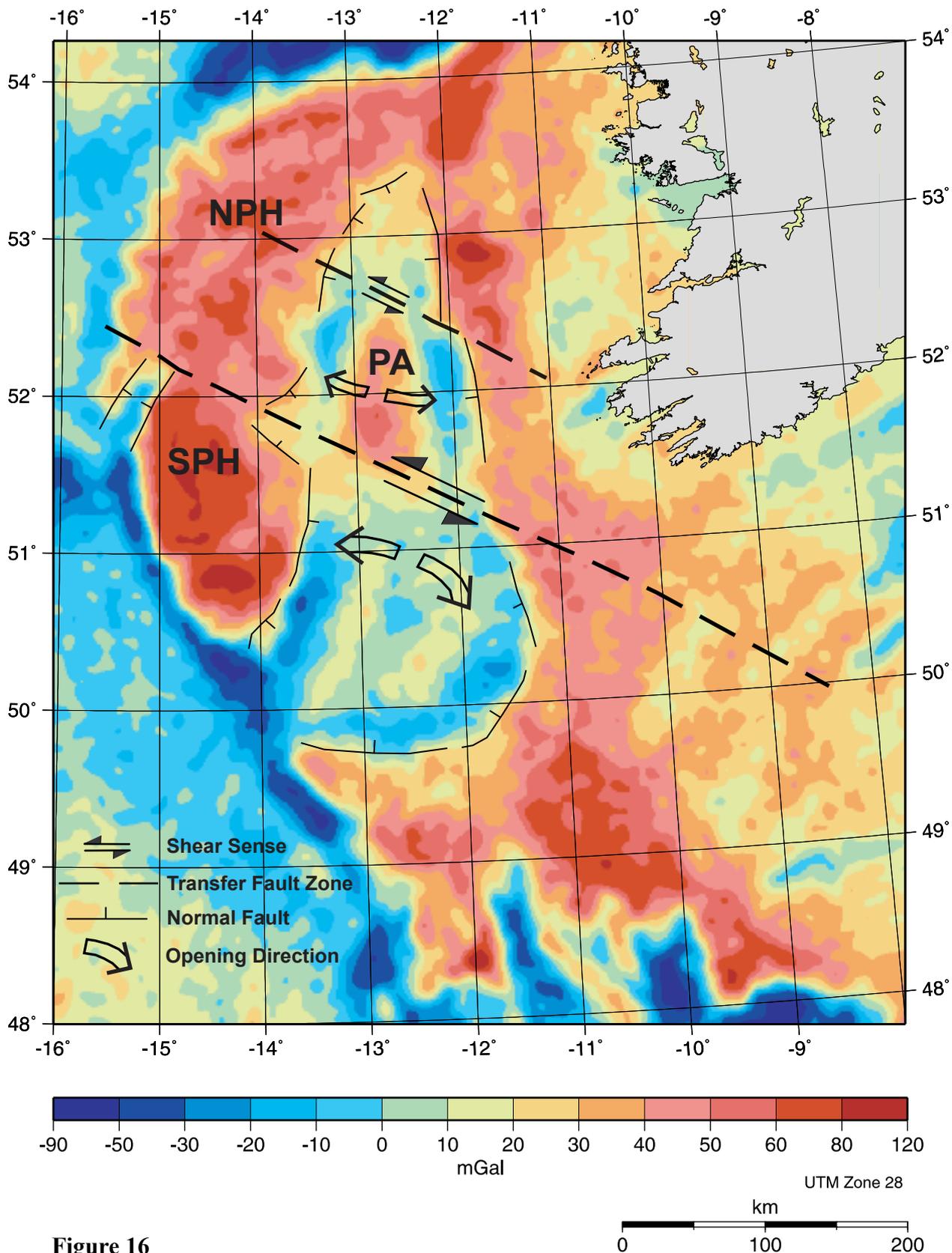


Figure 16

Summary of the preliminary structure development model for the Porcupine Basin region, depicting the main structural elements involved. PA - Porcupine Arch (Naylor *et al.* 2002); NPH - Northern Porcupine High; SPH - Southern Porcupine High. The major structural elements interpreted from the gravity are indicated. These include major normal fault systems and a zone of NW transfer faulting. This zone divides the basin into two domains of different crustal structure. Arrows indicate the sense of micro-plate rotation and sinistral transtension (?) during basin opening. In this model the antipathetic opening of the Porcupine Basin and Porcupine Seabight Basin occur simultaneously and is accompanied by several 10s of km of sinistral movement on the main NW transfer fault system.

Rockall Trough, offshore Ireland: Seismic + Gravity Model

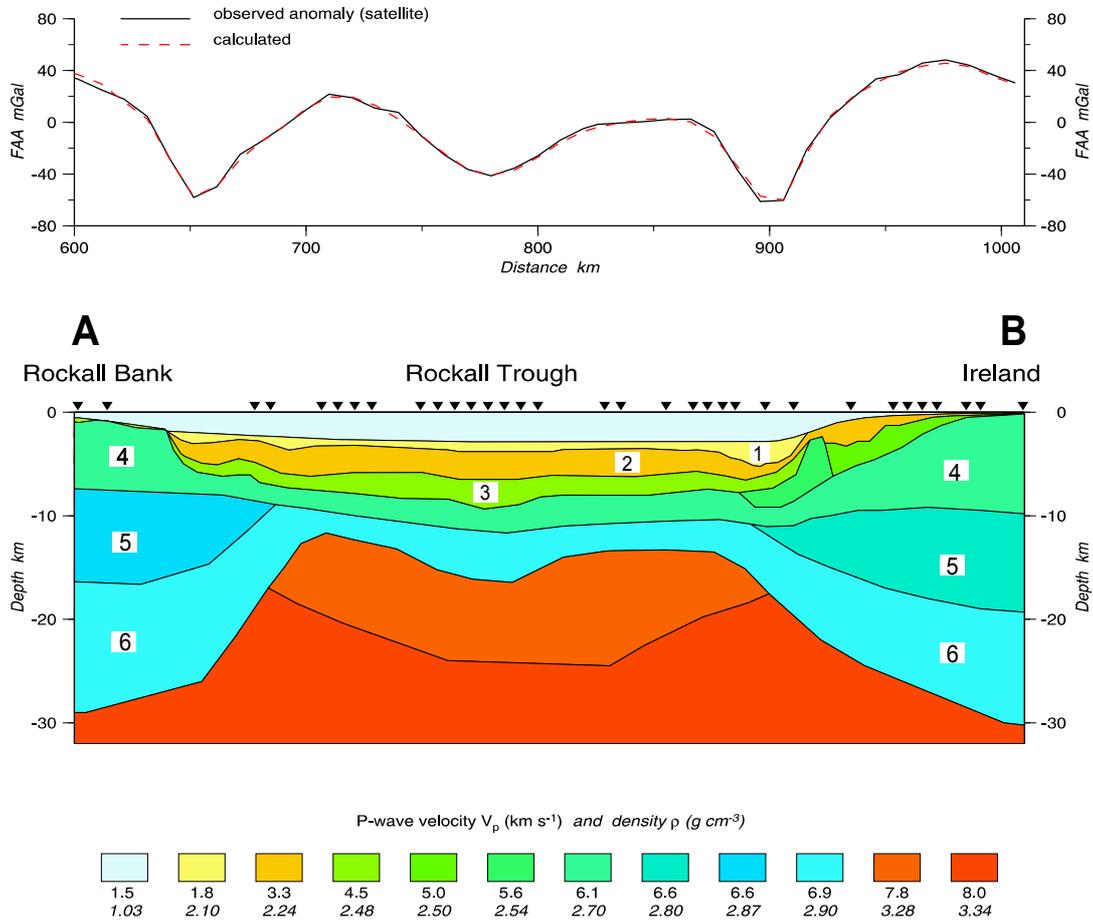


Figure 17

Gravity model across the Rockall Trough (see profile **A - B** in Fig. 15). The model is based on the RAPIDS 1 (Rockall and Porcupine Irish Deep Seismics) wide-angle seismic model (O'Reilly *et al.* 1998). Yellow and light green (labelled 1 - 3) are basin-fill sediments, green (4) is upper crust, green/blue (5) is mid-crust and blue (6) is lower crust. Triangles represent OBS (Ocean Bottom Seismometers) positions used to derive the seismic model. Note the similarity between this model and that for the profile XX' and VW' in the Porcupine Basin (Fig. 10c and 11b).