AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

PETREL SUB-BASIN STUDY 1995-1996

2-D GRAVITY MODELLING

by

J.B. Willcox

AGSO RECORD 1996/41

R9604101

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

Minister for Primary Industries and Energy: Hon. J. Anderson, M.P.
Minister for Resources: Senator the Hon. W.R. Parer
Secretary: Paul Barratt

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Neil Williams

© Commonwealth of Australia 1996

ISSN 1039 - 0073
ISBN 0 642 24974 1

This work is copyright. Apart from any fair dealings for the purposes of study, research, criticism or review, as permitted under the *Copyright Act 1968*, no part may be reproduced by any process without the written permission of the Executive Director, Australian Geological Survey Organisation. Inquiries should be directed to the Principal Information Officer, Australian Geological Survey Organisation, GPO Box 378, Canberra, ACT 2601, Australia.

Contents

Figures

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Summary

Gravity modelling and fabric-analysis studies have been carried out for the Kimberley/Bonaparte Gulf region. It is considered that this has led to a realistic crustal model of the Petrel Sub-basin that is consistent on three tied lines. The model honours the deep-seismic reflection interpretation to the base of the sub-basin and provides good indications of the crustal structure beneath it.

The model supports the concept of the Petrel Sub-basin being part of a Late Devonian-Early Carboniferous, broadly NNE- to NE-directed extensional system. Rifting of the Kimberley craton may have been about 120 km in a left-lateral sense. Extension in the brittle upper crust is interpreted to be about 200+ percent, and in the ductile lower crust in the range 300-400 percent. The crust thins from about 40 km beneath the craton (based on seismic Moho) to 26-28 km beneath the sub-basin.

The lower crust beneath the Petrel Sub-basin appears to have been heavily intruded by high-density material. The age of this igneous intrusion is uncertain and could be Proterozoic, Early Cambrian, or a product of the Late Devonian-Early Carboniferous rifting which gave rise to the Petrel Sub-basin itself. As there are indications that the high-density zone extends beyond the southeastern edge of the Petrel Sub-basin, and seems to be related to the band of gravity anomalies associated with the Halls Creek Mobile Zone, it may well have its origins as part of that mobile zone.

A sub-Moho zone lying directly beneath the Petrel Sub-basin, appears to be composed of rocks that have a density somewhat less than that of the mantle itself, and could be interpreted as a zone of underplating.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

PREFACE

AGSO's 1995-96 Petrel Sub-basin Study was undertaken within AGSO's Marine, Petroleum and Sedimentary Resources Division (MPSR) as part of MPSR's North West Shelf Project. The study was aimed at understanding the stratigraphic and structural development of the basin as a basis for more effective and efficient resource exploration. Specifically, the study aimed to:

- define the nature of the major basement elements and structures underlying the Petrel Sub-basin and their influence on the development of the basin through time,
- determine the events that have controlled the initiation, distribution and tectonic evolution of the basin;
- define the nature of the basin fill, and the processes that have controlled its deposition and deformation; and, importantly,
- establish the controls on the development and distribution of the basin's petroleum systems and occurrences.

This record outlines the results of a gravity modelling study on three key profiles within the Petrel Sub-basin. The models largely honour the interpretation of the reflection seismic data and allow the nature of the deep crustal structure to be deduced. Some speculative models of basin evolution are shown.

Preferred citation:
Willcox, J.B., 1996 - AGSO Petrel Sub-basin Study 1995-1996, 2-D Gravity Modelling. *AGSO Record*, 1996/41.

OTHER PRODUCTS AVAILABLE FROM THE PETREL STUDY

Summary Report *(AGSO Record 1996/40, compiled by J.B. Colwell & J.M. Kennard).*
Summarises major results of the project

Well Folio *(by J.M. Kennard).*
Provides well composites for 31 key wells in the basin, as well as 6 well-well cross-sections.

Map & Seismic Folio *(by J.B. Colwell, D.J. Wilson & J.E. Blevin).*
Includes 25 time-structure and time isopach maps as well as select interpreted seismic lines.

Digital Database of Seismic Interpretations.
Covers ~ 8200 line km of AGSO deep- and conventional industry seismic data.

Petrel Stratigraphic Time Chart *(by P.J. Jones et al.).*
Shows latest understanding of the Petrel stratigraphy against biozonations and the AGSO timescale.

Organic Geochemistry Report *(AGSO Record 1996/42, by D. S. & R. E. Summons). Includes digital file of geochem data (spreadsheets)*

Geohistory Modelling Report *(AGSO Record 1996/43 , by J.M. Kennard).*
Details geohistory subsidence and thermal maturation modelling of 20 wells and 6 pseudo-wells and hydrocarbon generation and expulsion models.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Introduction

The Petrel Sub-basin underlies the Joseph Bonaparte Gulf in the north of Western Australia (Fig. 1). In outline, it is broadly 'fan-shaped', opening to the northwest.

The Petrel Sub-basin is an element of a Late Devonian-Early Carboniferous northeast-southwest-opening extensional system that probably also included the Fitzroy Trough to the southwest. It is characterised by an unusually thick, sag-dominated section of Carboniferous-Tertiary age (Gunn, 1988; AGSO North West Shelf Study Group, 1994; Colwell & Kennard, 1996). It is flanked to the southwest, southeast and northeast sides by Precambrian cratonic sequences (Kimberley Block/Kimberley Basin, Victoria River basin, Darwin Shelf etc.), and along its northwest margin by the Malita Graben and Sahul Platform (Fig. 1). The sub-basin may have been compartmentalised by accommodation zones controlled by 'hard-link' fractures within the craton (O'Brien et al., 1996).

As first noted by Caye (1968), the southern offshore part of the Petrel Sub-basin is characterised by a prominent gravity high which broadens and decreases in amplitude along the axis of the basin to the northwest (Figs 2 & 3). This high, which has an amplitude about 50 mGal greater than the surrounding gravity field, is similar to a gravity high occurring within Proterozoic basic intrusives and metamorphics of the Halls Creek Mobile Zone to the south (Anfiloff, 1988; Plumb, 1990).

The gravity high within the Petrel Sub-basin was attributed by Gunn (1988) to crustal thinning associated with Palaeozoic rift development leading to the intrusion of a broad axial dyke, with the dyke splitting to the northwest due to the emplacement of oceanic crust. Alternatively, O'Brien et al. (1996) suggested that, although the gravity signature over the Petrel Sub-basin is related to deep thinning and associated partial melting and magmatism, its manifestation varies throughout the basin depending upon the degree of thinning (and probably other factors such as variations in the thermal state of the lithosphere), and the way in which the magmatic products are distributed through the lithosphere.

This report outlines the results of a detailed gravity modelling study based on three key profiles within the Petrel Sub-basin; two cross-basin profiles and one along the basinal axis. The modelling largely honours the interpretation of AGSO deep-seismic reflection data (Colwell et al., 1996) and utilises some density data derived from initial ray-trace modelling in the Petrel Sub-basin (Goncharov et al., in prep.) and from a refraction survey in the adjacent Browse Basin (Symonds et al., 1994). It provides a model for the crustal structure of the region and a possible scenario for basin evolution. Previous gravity models (e.g. Mory, 1991) have been more specific, being largely aimed at testing for the presence of oceanic crust in the centre of the sub-basin, and evaluating whether the sub-basin was the failed arm of a Carboniferous rift or an active spreading centre.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Gravity Models of Mory (1991)

Mory's (1991) models are based on a northeasterly-trending profile passing through the Sandpiper-1, Tern-1, Petrel-1 and Flat Top-1 exploration wells. The modelling was relatively simplistic, in that it treated the Phanerozoic basin-fill sediments of the Petrel Sub-basin as a single body of density 2.6 tm^{-3} and considered the crust as made up of two basic layers. The high-density oceanic crust that was postulated to underlie the basin's axial zone, was found to give rise to a computed gravity high far in excess of the observed field. To compensate for this effect, the model incorporated relatively low-density bodies within the centre of the rift; these were assumed to be Silurian evaporites (ρ=2.4 tm^{-3}) or halite (ρ=2.2 tm^{-3}).

Mory (1991) concluded that:

(1) models in which oceanic basalt is present in the centre of the Petrel Sub-basin require a significant thickness of low-density material (eg. salt) which would be unstable beneath the overburden. Hence, oceanic crust is unlikely to be present.

(2) the gravity high in the southern part of the basin confirms the presence of deep intrusions, probably emplaced during late Proterozoic or early Phanerozoic crustal thinning.

Petrel Sub-basin Gravity Study

The gravity models described in this report are based on Free-air Anomalies (FAA) computed from ship-board profile data.. Theoretically, the FAA may be expected to average zero over regions that are in isostatic equilibrium; however, the minimum size of features that are compensated is usually 200+ km across, while more local structures are supported by the crust, thereby producing gravity anomalies.

Three lines were modelled in the present study: two northeasterly-trending 'dip' lines (AGSO lines 100/2 and 100/3), and a north-northwesterly-trending tie-line (AGSO line 100/5 (part); Fig. 4). All lines are in less than 100 m of water.

Approach Used

The deep-seismic profiles were interpreted in terms of megasequences, and deep reflections which were believed to result from intra-crustal interfaces (see Colwell et al., 1996). In most instances, these megasequences are associated with substantial changes in seismic reflection velocity, and thus correspond to significant variations in density.

The input geometry of the gravity model was derived by approximating the shape of the megasequences by polygonal bodies. The depths of the polygon apices were

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

computed from reflection times and smoothed stacking velocities (line 100/2) or by direct measurement from depth-converted sections (lines 100/5 & 100/3).

Most of the densities employed for the basin sediments were derived from the reflection stacking velocities using the Nafe-Drake velocity/density relationship modified for the Australian region (Dooley, 1976). However, the densities of the Kimberley Block and the lower crust were based on a refraction survey in the adjacent Browse Basin (Symonds et al., 1994). The mantle density was assumed to be 3.30 tm^3. A deep band of reflections in the seismic records at about 40 km beneath the cratons at the ends of lines 100/2 and 100/3 was interpreted to be reflection Moho, and consequently the regional crustal thickness was taken as 40 km. In summary, the input densities are as shown below:

Body Type (Input)	Average Velocity (ms^{-1})	Density (tm^{-3})
Water	1500	1.03
Sag Phase (E.Cret.-Cenozoic)	2000	2.19
Sag Phase (L.Triassic-E.Cret.)	3250	2.32
Sag Phase (L.Carb.-L.Triassic)	4250	2.44
Sag Phase (E.Carb.)	5500	2.61
Synrift (L.Dev.-E.Carb.)	5750	2.65
Kimberley Basin/Darwin Shelf	5900	2.67
Kimberley Block/Darwin Shelf	6200*	2.74
Lower Crust	6800*	2.80
Mantle	8000*	3.30

* Velocity derived from Symonds et al. (1994).

The modelling led to the inclusion of two further density layers/bodies:

Body Type (Interpretation)	Average Velocity	Density
Intruded Lower Crust	(~7000)	3.00
Zone of possible Underplating	(~7800)	3.20-3.25

Petrel Sub-basin Refraction Data

In order to identify major intra-crustal boundaries and to determine the velocity structure of the crust beneath the Petrel Sub-basin and the depth to Moho, a program of seismic refraction data acquisition was undertaken along AGSO deep-seismic reflection line 100/3. This work, which formed part of a North West Shelf-wide study (AGSO Survey 168; Lee et al., 1996), involved the placement of 15 ocean-bottom seismometer (OBS) stations along the line, as well as land stations on the Kimberley coast and Bathurst Island. The total profile length was approximately 500 km.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Although refraction data in the Petrel region are of variable quality, a preliminary interpretation of the first arrivals of the vertical component, and selected reflections, has been produced (Petkovic et al. *in* Colwell & Kennard, 1996; Goncharov et al., in prep). This refraction model, in which six velocity layers have been distinguished, provides a further check on the seismic velocities:

Body Type (Refraction Model)	Average Velocity (ms^{-1})	Density (tm^{-3})
Tertiary+ (Layer 1)	1900-2400	1.05-2.23
Sag Phase (Layer 2)	2900-3400	2.28-2.33
Sag Phase (Layer 3)	4900-5400	2.53-2.59
Synrift/Rift-fill (Layer 4)	5400-5900	2.59-2.67
Basement/Crust	5900-6400	2.67-2.80
Mantle	8000	3.30

In general, it appears that the velocities (and their derived densities) used for the gravity modelling agree with the density ranges deduced from the preliminary refraction results.

Modelling Procedure
Line 100/2

Line 100/2 is a 'dip' profile across the southern Petrel Sub-basin, extending SW-NE for about 270 km from the Kimberley coast to the Darwin Shelf area (Fig. 4).

The modelling procedure involved a series of logical steps to get to the end product - a realistic structural cross-section of the sub-basin. Minimal adjustment was made to the seismic reflection interpretation, although some shaping of the deeper layers was undertaken in the final stages to provide an improved fit.

The modelling steps were as follows:

(1) Figure 5.
A basic model was constructed which honoured the reflection seismic data. Reflection times were converted to depths using smoothed stacking velocities. Densities were derived from the seismic reflection data, except for the Kimberley Block density (2.74 tm^{-3}) which was based on the Browse Basin refraction study (Symonds et al., 1994).

(2) Figure 6.
The above model was directly underlain by a mantle layer (ρ=3.30 tm^{-3}), effectively placing the Moho at about 28 km at the ends of the line. The calculated gravity contribution of the Petrel Sub-basin and the flanking Precambrian rocks, as interpreted from the seismic reflection profile, produced a broad negative anomaly of about 50 mGal, an effect that is of opposite polarity to the observations.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

(3) Figure 7/8.

The Moho was deepened to a level of ~40km by introducing a lower crustal layer of density 2.80 tm^{-3}. The Moho depth corresponded to a zone of reflectors on the deep seismic profile, and is reasonably standard for crust of Precambrian age.

In order to increase the density beneath the centre of the basin to produce the observed positive gravity anomaly, it was assumed that the lower crustal layer has been intruded by high-density material, to create an overall density of approximately 3.00 tm^{-3}. This corresponded to the zone of intruded lower crust interpreted by Gunn (1988). The mantle was also upwelled into this zone by ~5 km, with a slightly reduced density (3.25 tm^{-3}), effectively creating a zone of underplating.

The gravity effect of this model (Fig. 8) has a shape that is broadly in accord with the observations, though with about half the required amplitude.

(4) Figure 9.

The amplitude and shape of the computed profile with respect to the gravity observations was greatly improved by making the following variations to the model:

- The Kimberley Basin and Kimberley Block were adjusted to maintain their thicknesses at about 8-10 km and 15-16 km respectively, throughout the area. This involved the incorporation of Kimberley Basin section into the basin-bounding fault-block on the SW flank, and also into the smaller fault-block on the NE flank. This modification did not conflict with the seismic interpretation which was unclear in this area.

- The top of the body representing intruded lower crust was controlled by the seismic profile, however, the gradient of its flanks could be adjusted to improve the computed anomaly shape. The same also applied to the high-density body overlying the mantle.

- Thickening and shallowing of the high-density body overlying the mantle brought the amplitude of the observed and computed values into near coincidence.

The overall impression created by this model, is of a basin that has been extended along a detachment surface 'D' within the Kimberley Block. It appears to be underlain by a zone of almost basinal width, comprising heavily intruded and densified Lower Crust (ρ=3.00 tm^{-3}), and underlying it an even denser body (ρ=3.25 tm^{-3}) above the mantle, possibly representing an area of underplating.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

(5) Figure 10/11.
Further adjustments were made to the boundaries of the Precambrian and deep crustal layers to produce an enhanced gravity fit. However, as there is little real evidence for such modifications on the deep seismic profile, they should be regarded as largely cosmetic. Such changes do not change the geological conclusions.

Figure 11 shows further modification to the Kimberley Block and Lower Crust on the SW flank of the sub-basin, which provides a good fit to the SW negative gravity lobe. This is regarded as the most-realistic final model on the basis of the information available.

(6) Figure 12.
Following from the model shown in Figure 10, a test was made on the structure of the NE flank of the sub-basin. There was some uncertainty in the seismic interpretation as to the position of the hinge at which the basement deepens substantially into the sub-basin, and there was a possibility that the NE margin was simply a low-angle ramp structure. A reasonable fit was obtained with this variant of the model.

Line 100-03

The model for the more seaward of the modelled dip lines, line 100/3, was input directly from an interpretation of a depth-converted seismic profile.

(1) Figure 13.
The basic model for line 100/3 employs the same densities as for line 100/2 (Fig. 7). Subtle changes in the seismic character observed below the deepest reflection horizon were assumed to be caused by individual lower crustal bodies of different densities. From the apices of the deepest horizon where these character changes are observed, five lower crustal polygonal bodies were constructed by projecting lines vertically downwards to a Moho at about 40 km. This Moho depth was consistent with a diffuse band of deep-seismic events. The densities chosen for the lower crustal bodies were based on the preliminary results of the OBS refraction survey of the Petrel Sub-basin (Fig. 15; Petkovic et al. *in* Colwell & Kennard, 1996). The refraction model shows two lobes where material of mantle velocity (~8.0 km/s or ρ=3.30 tm^{-3}) appears to have intruded into the lower crust, but only the upper surfaces of these lobes are evident on the reflection seismic profile.

The starting model has many of the characteristics of line 100/2 but is structurally more complex.

(2) Figure 14.
The gravity effect of the starting model shows the same overall characteristics as the observed gravity profile. The computed gravity values comprise a broad positive anomaly with a central low, but the central low has an amplitude far

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

greater than the observed values. The effect is similar to that seen in the modelling line 100/2, in that compensation of the gravity contribution of the sub-basin is not obviously reflected in the deep-seismic data.

(3) Figures 16-19 show the results from a series of modelling tests in which the configuration and character of bodies in the lower crust were varied, while honouring the seismic data which imaged the upper crustal layers.

Figure 16.
In order to reduce the central gravity low, all the central lower crustal bodies were given a mantle density (3.30 tm^{-3}). The gravity effect of this model still produced flanking anomalies which were much too large.

Figure 17.
All the central lower crustal bodies were given a density of 3.00 tm^{-3}, thus creating a model similar to that for Line 100-02 in which the lower crust was intruded with a commensurate increase in density.

Figure 18.
In this variant of the previous model, the central lower crustal bodies and the rocks flooring the sub-basin were all given a density of 3.00 tm^{-3}, creating a broad zone of lower crustal intrusion beneath the entire basin. The effect was to produce good correspondence of both the shape and amplitude of the computed profile.

Figure 19.
The fit was improved still further by creating a model which combined the effects of lower crustal intrusion and crustal thinning.

(4) Figure 20.
A 'best fit model' was obtained by combining the effects of lower crustal intrusion and thinning, together with a layer of density 3.20-3.25 between the lower crust and mantle. Such a layer could be interpreted as a zone of sub-basinal underplating. The resulting fit of the computed and observed profiles is convincing both in terms of the gravity anomaly shape and its amplitude. This model is considered to be the most-realistic representation of the structure of the region.

Line 100-05

The NNW-SSE 'strike' line 100/5 was tied to lines 100/2 & 100/3 as shown in Figures 4, 21 & 22. While the modelling is based on the tied 2-D seismic interpretation, it should be noted that the observed gravity field incorporates 3-D effects, particularly those from offside features such as the sub-basin boundary faults and ramp, and the complex upwelling of high density (ρ=3.3 tm^{-3}) ?mantle material into the lower crustal layers.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

(1) Figure 21.
This model honours all basic seismic reflection data to the base of the Kimberley Block, with the deeper layers being tied to the line 100/2 & 100/3 gravity models (Figs 11 & 20). The Kimberley Basin section which was interpreted on the flanks of both 'dip' lines, is considered to be present only at the SSE-end of line 100/5, and terminates short of the tie with line 100/2. Its thickness is unknown, but has been set at an arbitrary 10 km as on the other lines. Similarly, the Kimberley Block section terminates short of the tie with line 100/3. It was also assumed that intrusion of the lower crust (ρ= 2.80 tm^{-3}) to give a high density zone (ρ=3.00 tm^{-3}) occurs only under the basin, and is hence a product of basin development.

Considering the nature of the assumptions that had to be made and the likely gravity contribution from offside features, the correspondence of the observed and computed gravity profiles is excellent.

(2) Figure 22.
This provides for a further refinement of the deep crustal layers at the SSE-end of the model, and allows for the intruded zone of lower crust to extend SSE of the basin boundary.

The resulting fit of the computed and observed profiles is extremely good and probably marginally better than that shown in the previous model.

Fabric Analysis & Gravity Provinces

Some further insight into the development of the Petrel Sub-basin can be deduced from gravity-field maps and images.

The gravity anomaly field of the North West Shelf region can be divided into several regional gravity provinces, each of which is characterised by uniformity of trend, anomaly intensity, or degree of disturbance. In general, the gravity signature of a province is considered to correspond to major crustal elements; however, a common gravity response does not necessarily imply a common source. Gravity fabric analysis has been carried out using both the Free-air and Bouguer anomaly images, and also images of the maximum horizontal gradient (Elliott et al., 1996). The gradient images more clearly define the block and basin boundaries, and accentuate the mobile belts and other regional linear structures.

The gravity provinces are best defined on the image of Bouguer anomaly maximum horizontal gradient, with a northwest illumination and 45° 'sun-angle' (Petkovic et al., 1996; Elliott et al., 1996, plate 33; Fig. 23). Six categories of anomaly amplitude and alignment were recognised, of which Types 2 and 4 characterise the Petrel Sub-basin region:

Type 2 - a low amplitude/low alignment signature, which appears to be generated by a variety of sources, but in general corresponds to basinal areas

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

overlying the more stable platforms. This province clearly shows the extent of the Proterozoic Kimberley Basin.

Type 4 - a medium amplitude/high alignment anomaly signature, related to the basinal areas, including the Petrel Sub-basin. On the horizontal gradient images of the Petrel Sub-basin, this province incorporates three northwest-trending arcuate lineaments (B1 - B3 of Elliott et al., 1996, plate 34) which correspond broadly to the boundaries of the elevated areas and sub-basinal troughs, and a possible offshore extension of the Halls Creek Mobile Zone, aligned approximately orthogonal to the extensional direction.

The AGSO North West Shelf Study Group (1994, figure 6) suggested that the northeast-southwest extension that gave rise to the Petrel Sub-basin and Fitzroy Trough in the Late Devonian-Early Carboniferous was accommodated by two regional shear zones: the Lasseter Shear Zone to the east-southeast (Braun & others, 1991), which in the Petrel Sub-basin region is the Halls Creek Mobile Zone; and a postulated 'North West Shelf Megashear', offshore and to the northwest. A reconstruction of the Petrel/Kimberley region to a pre-extension configuration, using gravity images, lends support to this concept. Figure 24 shows a second horizontal derivative image on which the Petrel Sub-basin has been closed, on a NNE-SSW azimuth, by approximately 120 km. The continuity of the gravity fabric in this reconstruction is striking.

Results

A good fit of the observed and calculated gravity profiles was obtained for models based on all three seismic lines (Figs 11, 20 & 22). Considering the constraints applied in the modelling process, in which the models were set up to largely honour the seismic interpretation, the results show convincing consistency, particularly for the two 'dip' lines (Figs 11 & 20). Further, the seismic/gravity tie-line (Fig. 22) provided a realistic result with minimal adjustment to the model.

An near-perfect fit on all three profiles can, of course, be obtained through minor adjustments to the shape of the crust/mantle interface (Moho). The high sensitivity of the model to the Moho configuration (owing to the large density contrast across it) is, of course, a limiting factor when it comes to determining the geometry of the overlying section. Thus, the aim of this modelling process was not to obtain perfect fits, but to test various general possibilities related to basin geometry and formation.

The principal results of the gravity modelling study are considered to be:

Petrel Sub-basin Gravity High

The geometry of the Petrel Sub-basin as interpreted from the seismic reflection profiles makes little contribution to the broad gravity high and flanking negative lobes that occupy the region.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Zone of High-Density Lower Crust

The broad gravity high must result from a high-density zone (about 3.00 tm^{-3}) within the lower crust underlying the sub-basin, and this zone is relatively steep-sided. The upper surface of bodies corresponding to this zone are visible on parts of the seismic profiles (particularly line 100/3) and such bodies are also suggested by the preliminary results of the refraction survey (Fig. 15).

The crustal geometry suggests that the high-density zone may result from the intrusion of dense material into rocks that originally made up part of the Precambrian Kimberley Block and the lower crust. However, there is some uncertainty as to whether this intrusion predates formation of the Petrel Sub-basin or is an integral part of basin formation. In as much as there are indications that the high density zone extends beyond the southeastern edge of the Petrel Sub-basin, it may result from bodies within the Halls Creek Mobile Zone. Its correspondence to the width of the Petrel rift may then have been a controlling factor on the rifting geometry, rather than a direct result of the rifting process. On the axial tie-line (Fig. 22), the lower crustal body at the SE end, which has a density of 2.80 tm^{-3}, is effectively replaced by the higher density material (3.00 tm^{-3}). It may also partially replace or intrude into the Kimberley Block basement, which thins northwestwards and terminates midway between the two dip lines. The high-density material forms a wedge that thins to the northwest and eventually directly underlies the synrift sediments of the Petrel Sub-basin on line 100/3.

Crustal Thickness

The crust thins significantly beneath the Petrel Sub-basin, with Moho shallowing from about 40 km to 28 km on the inboard line (100/2) and to 26 km on the outboard line (100/3). The crustal thinning appears to be confined approximately to the width of the sub-basin. The axial line shows that the Moho shallows north-northwestwards from about 40 km to about 26 km and that the Petrel sag-phase sediments thicken in the same direction.

'Underplating'

The 'best fit' of the observed and calculated gravity profiles is obtained if the material immediately underlying the thinned crust and the Moho comprises a lens of material with a density in the range 3.20 - 3.25 tm^{-3}. On the axial line, this sub-Moho body is seen as a northwest-thickening wedge. This could be interpreted as underplating of the sub-basin.

Extent of Kimberley Basin and Kimberley Block

The modelling suggests that the Kimberley Basin section probably underlies both sides of the Petrel Sub-basin and is consistently about 10 km thick. It appears to have been downfaulted, particularly along the southwestern high-displacement

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

southwestern side of the Sub-basin, and forms a ramp on the low-gradient northeastern flank. The Kimberley Basin section is probably not present within a broad (100 km wide) zone along the sub-basin axis. However, the modelling of line 100/5 indicates that Kimberley Basin sediments (or a body of similar density) are probably present to the southeast.

A similar situation seems to occur with the Kimberley Block, although it extends further into the sub-basin. On the inboard line (100/2, Fig. 11) the Kimberley Block tapers to zero thickness at the basinal axis, whereas on the outboard line (100/3, Fig.20) it appears to be entirely absent.

Northeast Ramp

The geometry of the northeastern flank of the sub-basin is difficult to determine from the seismic data. Unfortunately, gravity modelling designed to differentiate between a normally-faulted style of margin and a low-angle ramp margin was inconclusive.

Conclusions

The gravity fabric analysis and gravity modelling support the concept of the Petrel Sub-basin being a NNE- to NE-directed extensional basin, created by rifting within rocks of the Precambrian Kimberley Block and Kimberley Basin. The extensional process, shown from seismic and other data to be of Late Devonian-Early Carboniferous age (Colwell & Kennard, 1996), appears to have been contemporaneous with that of the Fitzroy Trough to the southwest. These basins are thought to have developed from relative movements between Precambrian basement blocks, and were probably accommodated by major shear zones in the manner described by the AGSO North West Shelf Study Group (1994; Fig. 25). Reconstruction from the gravity gradient images suggests that the lithospheric extension may have been accommodated by left-lateral shearing along the line of the Halls Creek Mobile Zone with about 120 km of displacement (Fig. 24). The basin formation may have been slightly rotational (creating a fan-shaped geometry in the Petrel Sub-basin), allowing intrusion of high-density material into the axial zone of the sub-basin.

An approximate estimate of the degree of extension along the azimuth of the 'dip' lines can be deduced from Figures 11 & 20. If it is assumed that most of the extension within the brittle upper crust took place above a low-angle detachment within the Kimberley Block and at the major basin-boundary faults (as shown in Fig. 9), then the extension is of the order of 200+ percent. Extension within the ductile lower crust appears to have occurred immediately beneath the Petrel Sub-basin, but is variable and more difficult to determine. It is in the range of 300-400 percent, and has probably reduced the crustal thickness to a degree where seafloor spreading was about to take place.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

The Kimberley Basin and Block (or rocks of similar densities) appear to flank the NE, SE and SW sides of the Petrel Sub-basin (see block diagram, Fig. 26). On the modelled 'dip' lines, the Kimberley rocks have been downfaulted to form a high-displacement, southwestern margin. On the northeastern flank of the sub-basin, the rocks show a lesser displacement or possibly form a low-angle ramp. Along the Petrel Sub-basin axial zone, the Kimberley Basin section seems to terminate at about 13°40'S, just to the north of the Bougainville-1 exploration well. This termination may relate to the location of an accommodation zone controlled by an underlying 'hard-link' boundary (HL1), separating extensional compartments of the basin, as postulated by O'Brien & others (1996). Also, about 100 km further to the northwest, the Kimberley Block itself appears to wedge out.

The seismic data and gravity modelling suggests that the crust is probably about 40 km thick beneath the sub-basin flanks, thinning fairly abruptly to about 26-28 km beneath the basin axis. Minor thinning also occurs to the north-northwest. The crustal thinning has largely been concentrated in rocks of the Kimberley Block and lower crust. Beneath the sub-basin, these rocks seem to be replaced by high-density bodies, which may be the result of intrusion of mafic mantle material into the crust, in the form of dykes etc. The high-density zone forms a northwest-thinning wedge. There are a number of possibilities for the age and origin of this zone: it could be Proterozoic, associated with melts which produced features such as the Hart Dolerite; or Early Cambrian and related to the Antrim Plateau Volcanics; or a product of the Late Devonian-Early Carboniferous rifting which gave rise to the Petrel Sub-basin itself. In as much as there are indications that the high-density zone extends beyond the southeastern edge of the Petrel Sub-basin, and seems to be related to the band of gravity anomalies associated with the Halls Creek Mobile Zone, it may well have its origins as part of that Proterozoic mobile belt.

A sub-Moho zone lying directly beneath the Petrel Sub-basin, appears to be composed of rocks that have a density somewhat less than that of the mantle. This is interpreted as a zone of possible underplating. The presence of underplating has probably had profound effects on the space available for deposition of the immense thickness of 'sag- phase' sediments (up to 20 km) that make up the bulk of the Petrel Sub-basin section. It is generally considered that such a thick accumulation cannot be attributed to thermal cooling alone, but the buoyancy effects of underplating require further investigation.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

References

AGSO North West Shelf Study Group, 1994 - Deep reflections on the North West Shelf: changing perceptions of basin formation. *In* Purcell, P.G. & Purcell, R.R. (Editors), *The Sedimentary Basins of Western Australia,* Proceedings West Australian Basins Symposium, Perth, 1994, 63-76.

Anfiloff, V., 1988 - Polycyclic rifting - an interpretation of gravity and magnetics in the North West Shelf. *In* Purcell, P.G. & Purcell, R.R. (Editors), *The North West Shelf, Australia,* Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1988, 443-455.

Braun, J., McQueen, H., & Etheridge, M., 1991 - A fresh look at the Late Palaeozoic tectonic history of western-central Australia. *Exploration Geophysics*, 22, 49-54.

Caye J.P., 1968 - The Timor Sea - Sahul Shelf area. *APEA Journal*, 8(2), 35-41.

Colwell, J.B., Blevin, J.E., & Wilson, D.J., 1996 - *AGSO Petrel Sub-basin Study 1995-1996 Map & Seismic Folio,* Australian Geological Survey Organisation, Canberra.

Colwell, J.B., & Kennard, J.M., 1996 - Petrel Sub-basin Study 1995-1996 Summary Report. *Australian Geological Survey Organisation Record*, 1996/40.

Dooley, J.C., 1976 - Variation of crustal mass over the Australian region. *BMR Journal of Australian Geology & Geophysics*, 1, 291-296.

Elliott, C.I., Liu, S., Willcox, J.B., & Petkovic, P., 1996 - A lineament tectonic study of the basement architecture of northwestern Australia. *Australian Geological Survey Organisation Record*, 1996/50.

Goncharov, A., Petkovic, P., Collins, C., Colwell, J., Fomin, T., & Lee, C-S, in prep. - Deep structure of the crust and crust-mantle transition zone in Petrel Sub-basin, Northwest Australia, from ocean-bottom refraction and wide-angle data. *Australian Geological Survey Organisation Record.*

Gunn, P.J., 1988 - Bonaparte Basin: evolution and structural framework. . *In* Purcell, P.G. & Purcell, R.R. (Editors), *The North West Shelf, Australia,* Proceedings of the Petroleum Exploration Society of Australia Symposium, Perth, 1988, 275-285.

Lee, C-S, Collins, C., Goncharov, A., Petkovic, P., & Nakamura, Y., 1996 - Ocean-bottom and land seismometer survey of the Australian North West Shelf. *EOS Transactions AGU*, 77(22), Western Pacific Geophysics Meeting Supplement, W1, 1996.

Mory, A.J., 1991 - Geology of the offshore Bonaparte Basin northwestern Australia. *Geological Survey of Western Australia Report*, 29.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

O'Brien, G.W., Higgins, R., Symonds, P., Quaife, P., Colwell, J., & Blevin, J., 1996 - Basement control on the development of extensional systems in Australia's Timor Sea: an example of hybrid hard linked/soft linked faulting? *APPEA Journal*, 36, 161-200.

Petkovic, P., Stagg, H.M.J., & Willcox, J.B., 1996 - *Northwest Australia Gravity Montage - Bouguer Anomaly, 1:5 000 000 scale*, Australian Geological Survey Organisation, Canberra.

Plumb, K.A., 1990 - Halls Creek Province and the Granites-Tanami inlier - regional geology and mineralisation. *In* Hughes, F.E. (Ed.), *Geology of the Mineral Deposits of Australia and Papua New Guinea*, Australasian Institute of Mining and Metallurgy, Melbourne, 681-695.

Roach, M., 1993 - *MODEL 2D version 3.1 Interactive: interactive 2D gravity and magnetic modelling*. Centre for Ore Deposit and Exploration Studies, Uinversity of Tasmania (unpublished).

Symonds, P.A., Collins, C.D.N., & Bradshaw, J., 1994 - Deep structure of the Browse Basin: implications for basin development and petroleum exploration. *In* Purcell, P.G. & Purcell, R.R. (Editors), *The Sedimentary Basins of Western Australia,* Proceedings West Australian Basins Symposium, Perth, 1994, 315-331.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

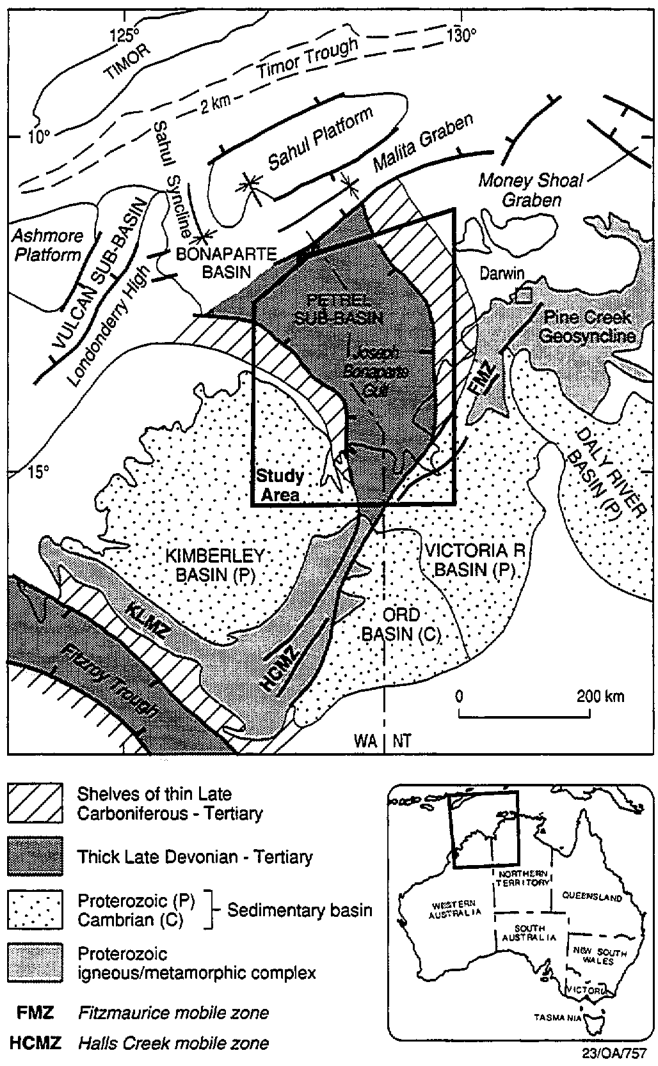

Figure 1. Petrel Sub-basin region locality map (based on Gunn, 1988).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604102

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

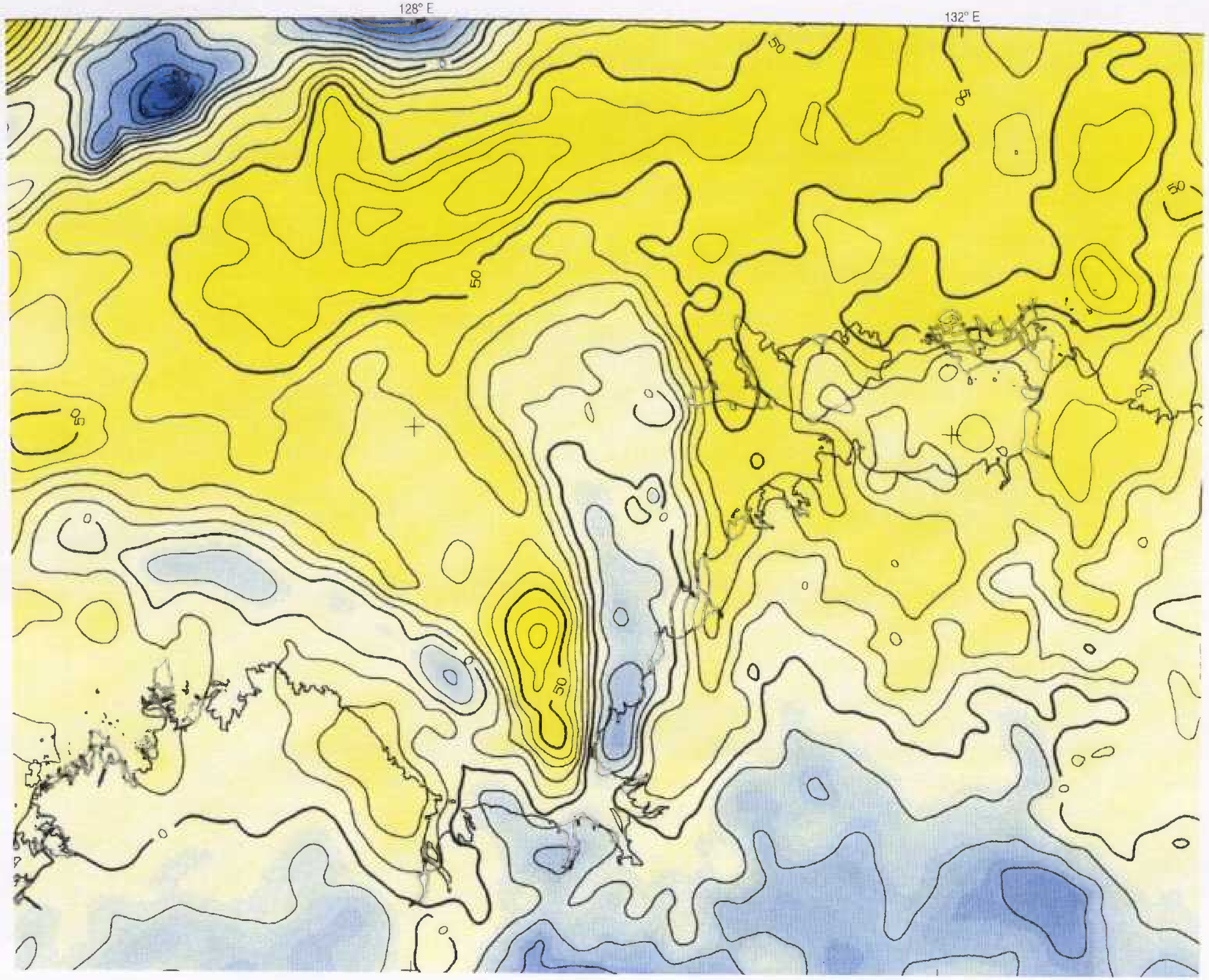

Figure 2. Bouguer Anomaly map of the Petrel Sub-basin region. Note the prominant gravity 'high' along the basinal axis.

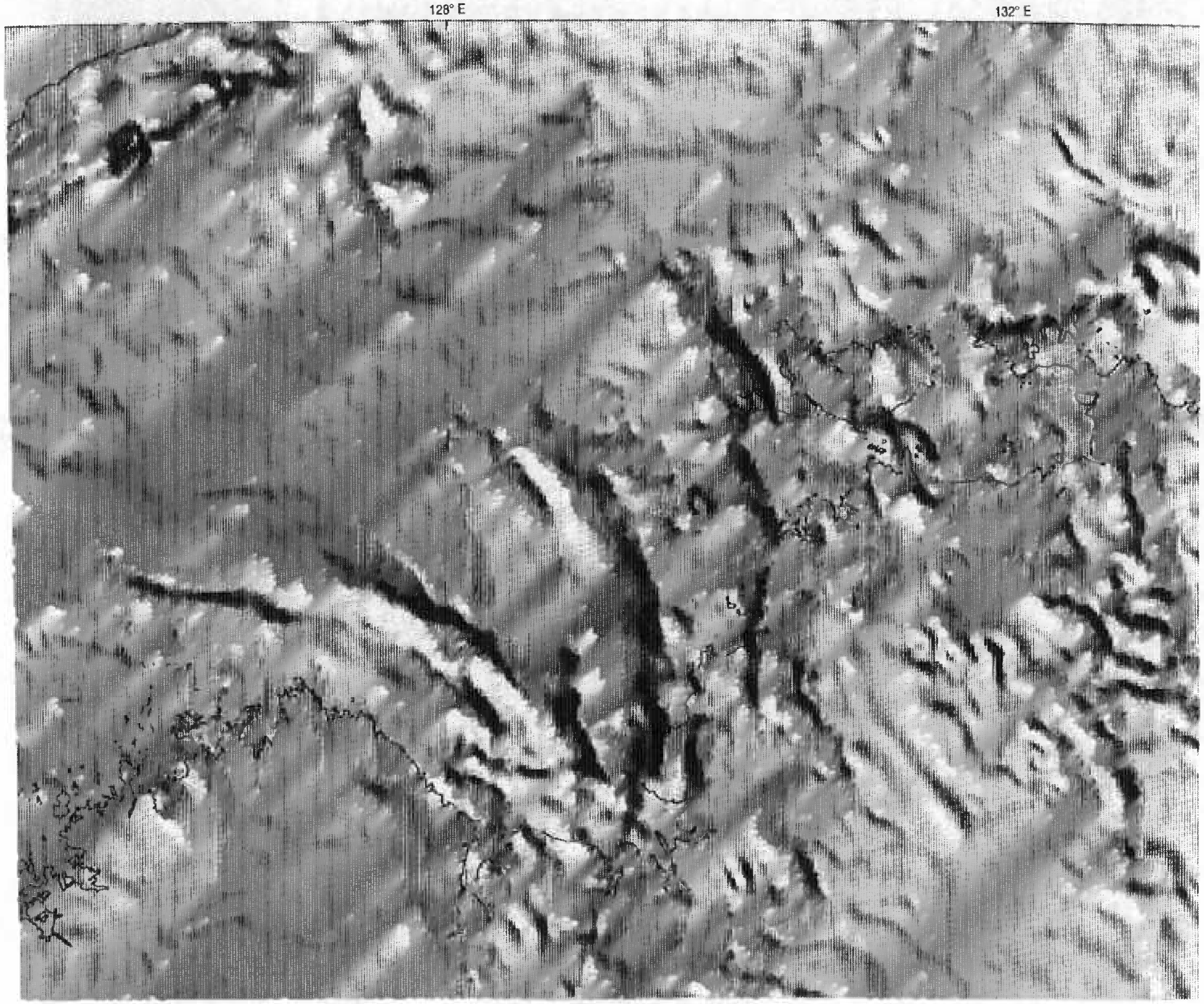

Figure 3. Absolute value of maximum horizontal gradient of Bouguer Anomaly in Petrel Sub-basin region, with sun-shaded relief (sun elevation 45° and azimuth 45°).

R9604103
© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

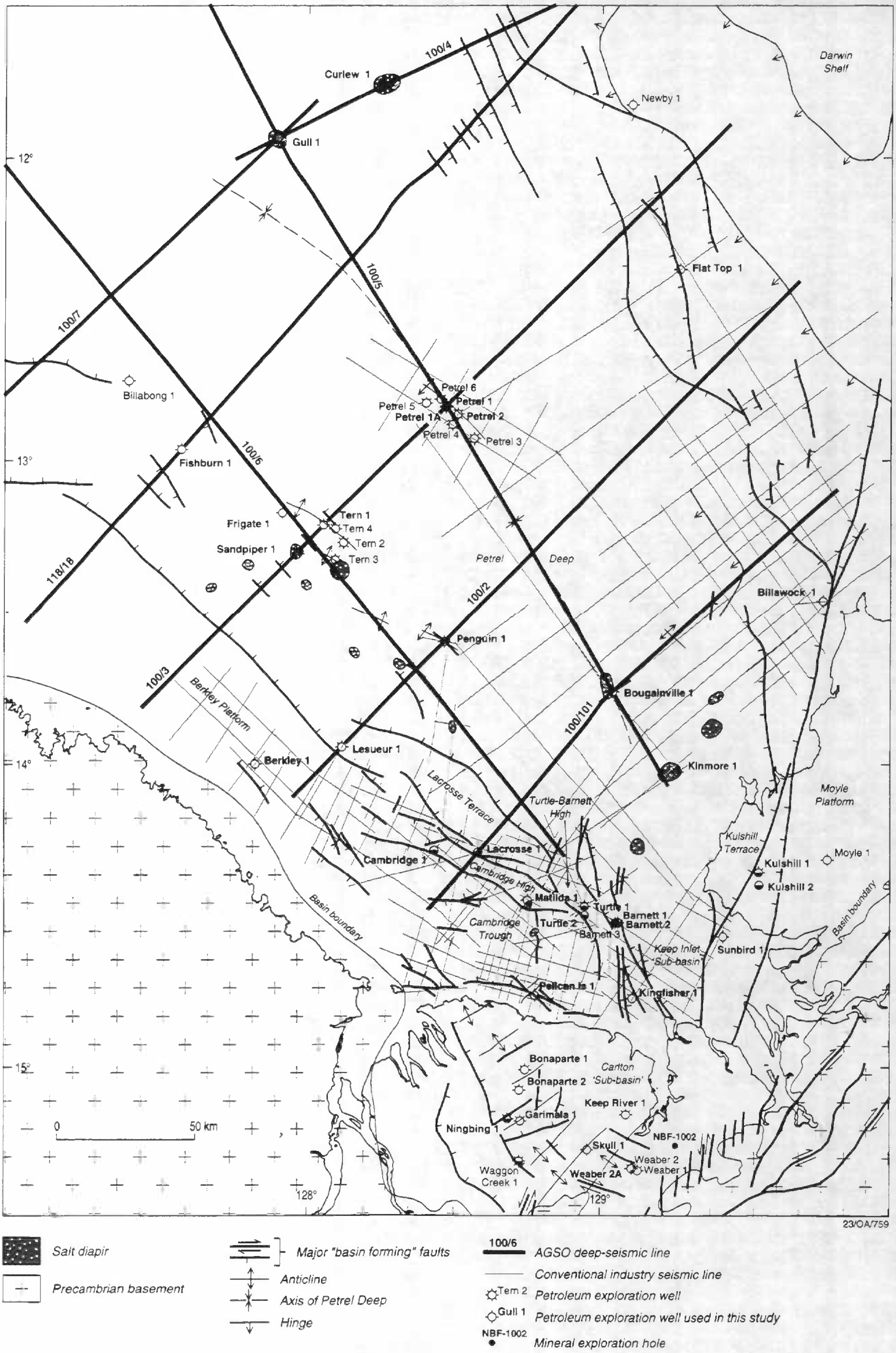

Figure 4. AGSO regional seismic lines in the Petrel Sub-basin. Gravity models were based on an interpretation of Lines 100/2, 100/3 & 100/5.

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604104

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

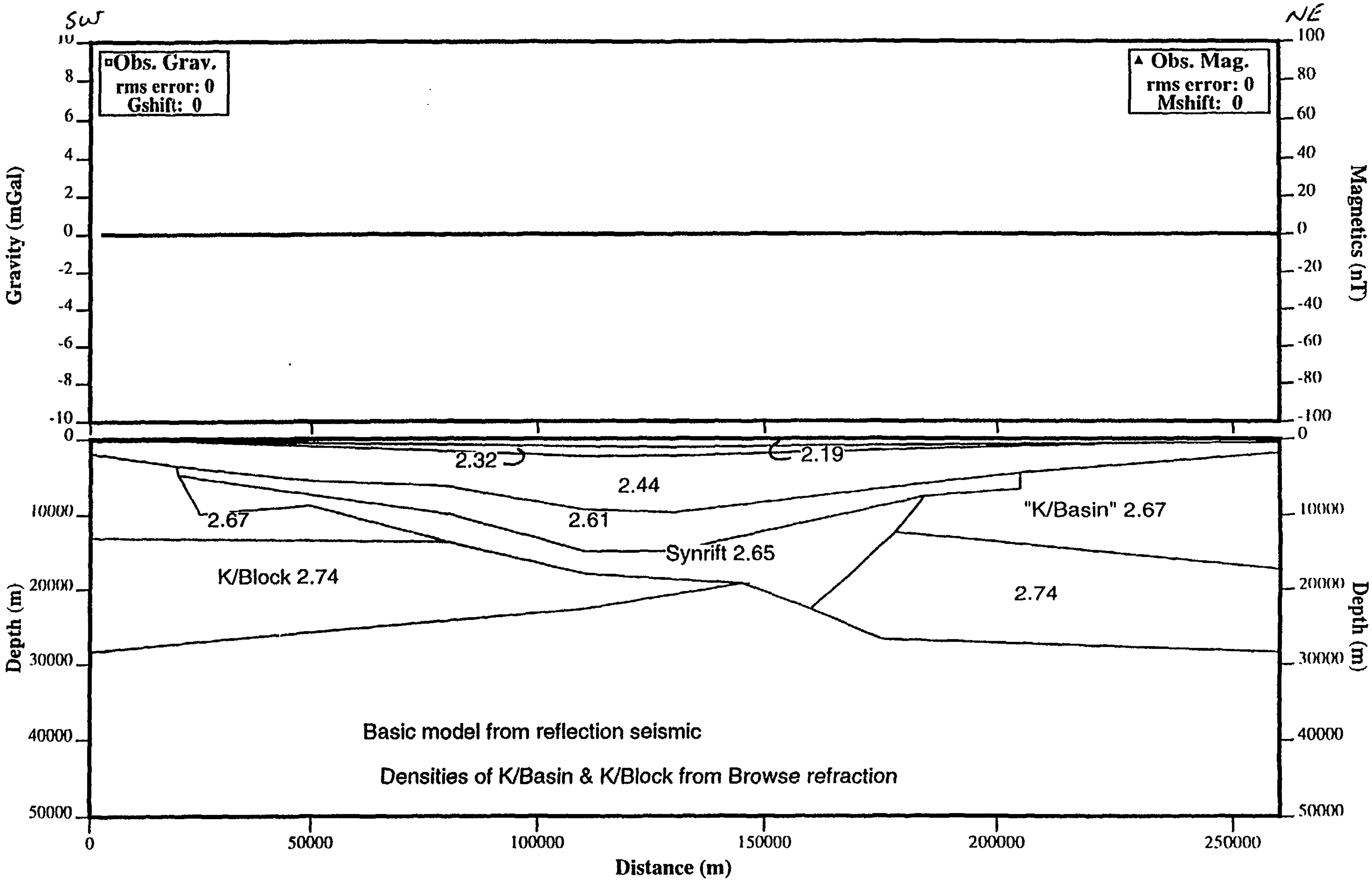

Figure 5. Basic model derived from the seismic reflection interpretation for Line 100-02, using MODEL2D (Roach, 1993). Note: program used in gravity modelling mode only. Densities from Nafe-Drake conversion of the stacking velocities, except for the Kimberley Basin and Block which were taken from the Browse Basin refraction survey. (File 100-2HH.

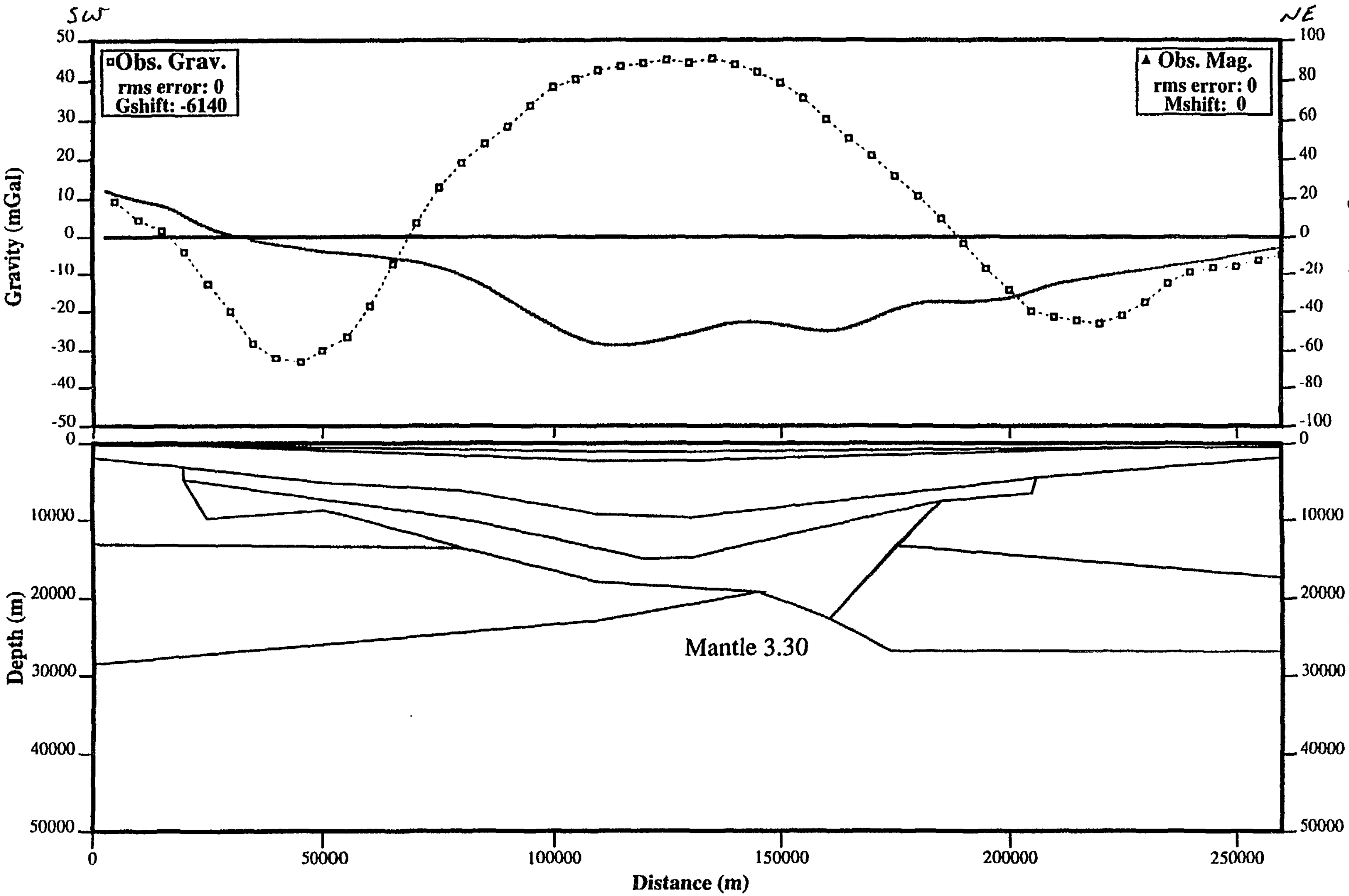

Figure 6. Gravity effect (continuous line) calculated for the basic model when underlain by a Mantle layer of density 3.30 tm^{-3}. Also shows the observed profile at 5000 metre intervals. (File 100-2S).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

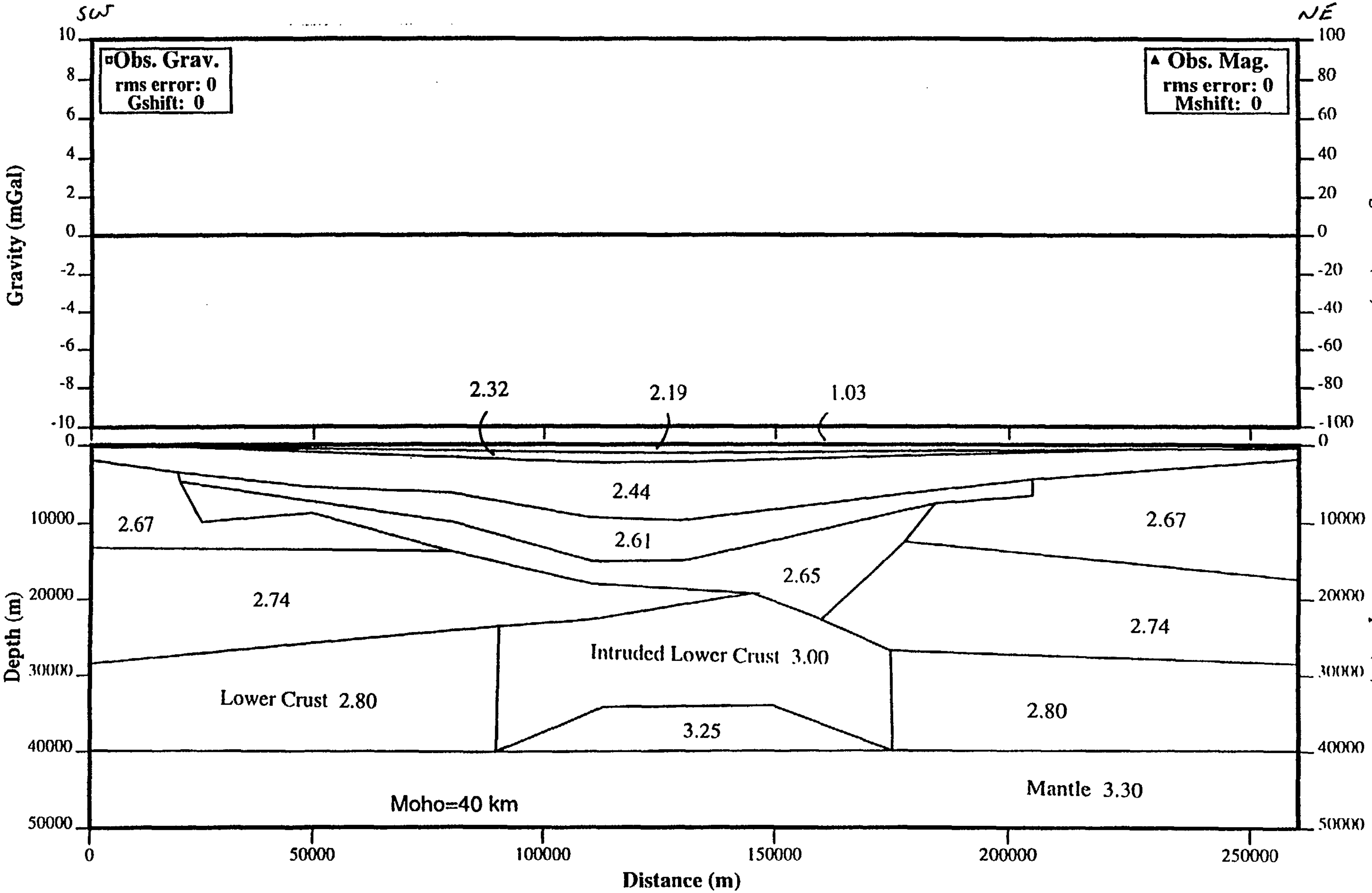

Figure 7. Basic model from seismic data, but with the addition of Lower Crust (2.80 tm^{-3}) and Moho at 40 km. A zone of intruded and densified Lower Crust (3.00 tm^{-3}) is added to the centre of the basin in an attempt to model the large positive gravity anomaly. (File 100-2II).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

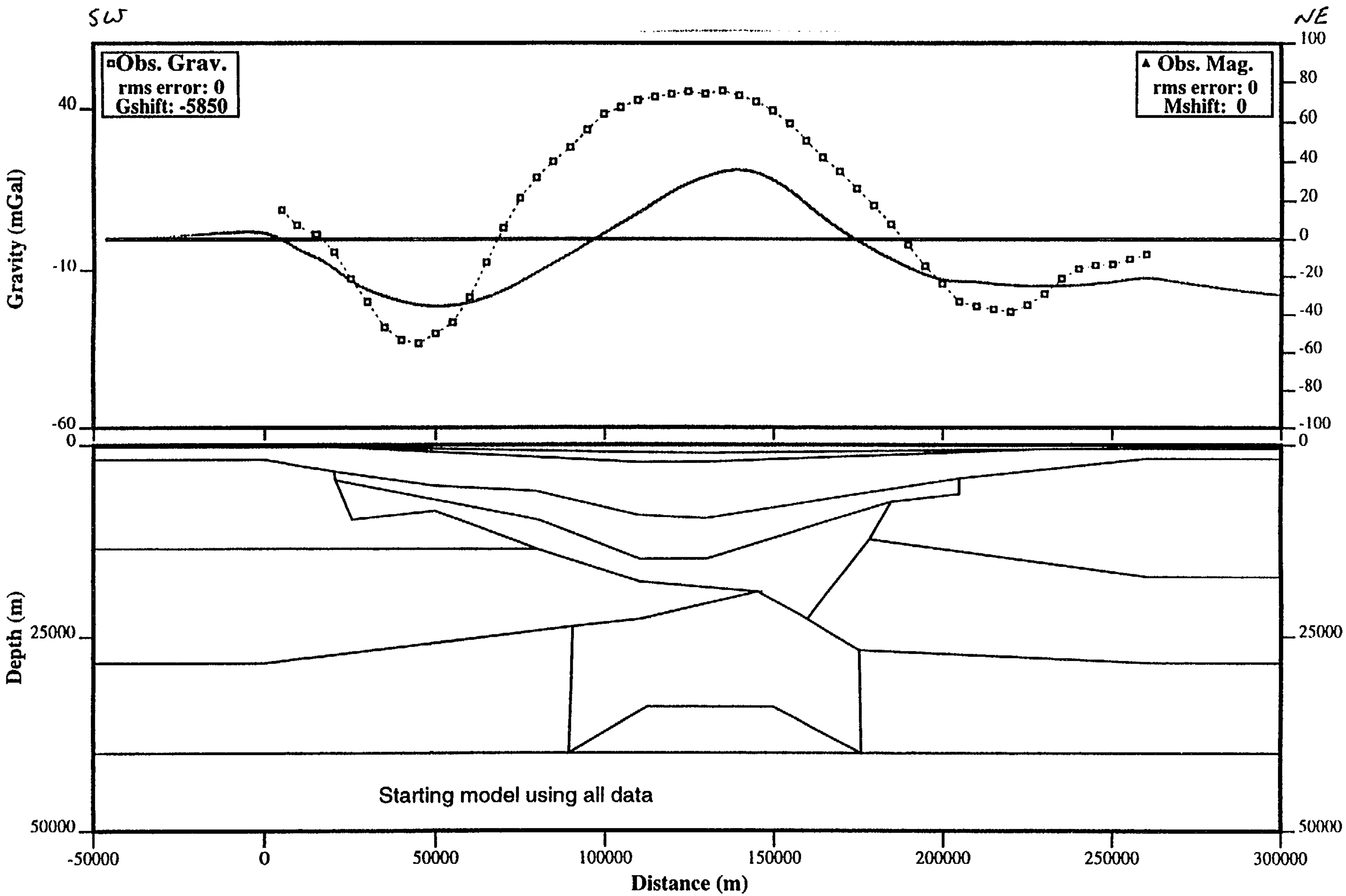

Figure 8. Gravity effect (continuous line) for model using all data as shown in Figure 7. Also shows the observed profile at 5000 metre intervals. (File 100-02KK).

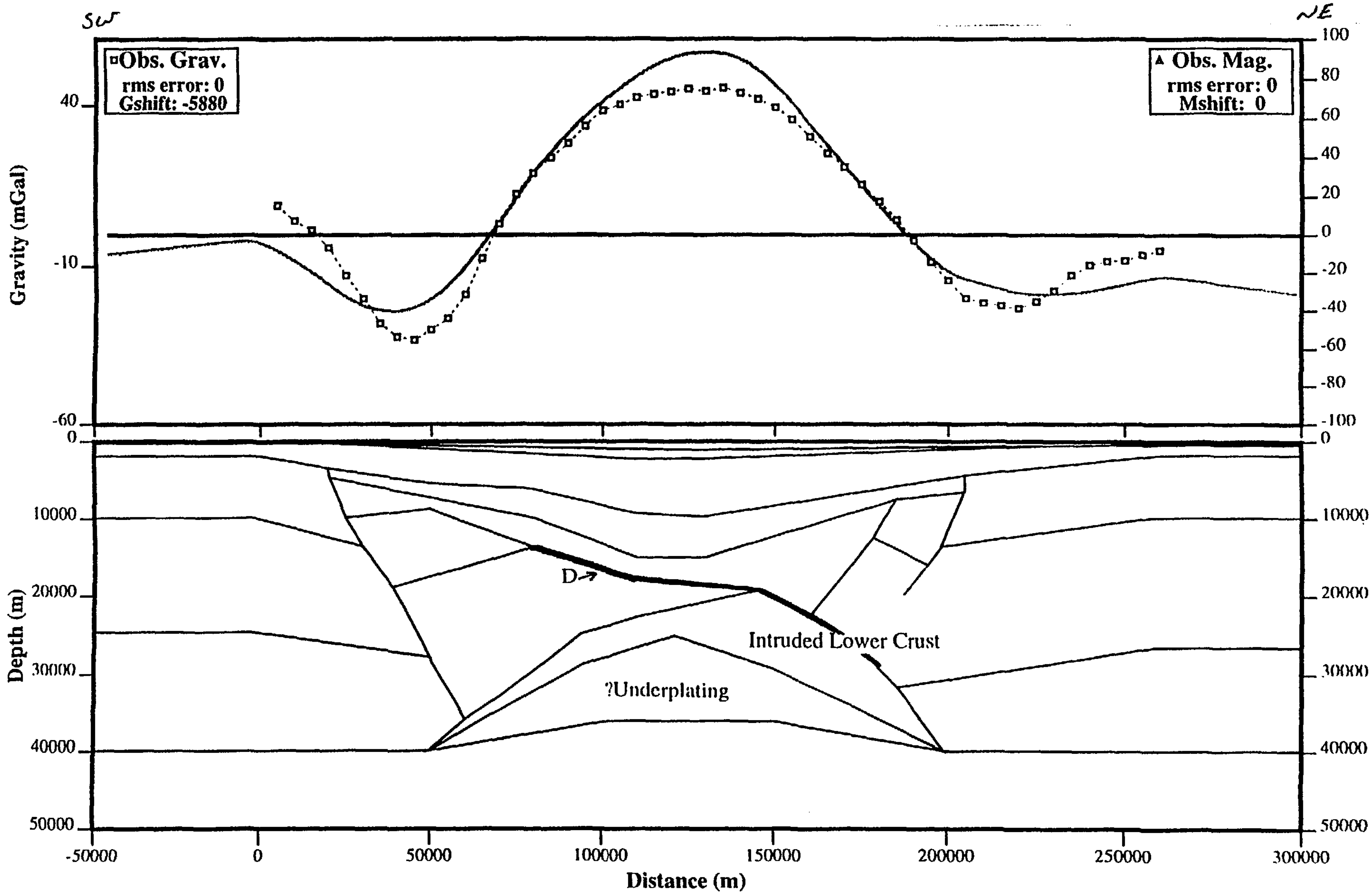

Figure 9. Gravity effect created by adjusting the thicknesses of Kimberley Basin and Block, modifying the boundary fault-blocks, and the shape of the flanks of the deep-seated high-density bodies. Model may represent extension on detachment 'D', intrusion of Lower Crust, and ?underplating. (File 100-2O).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

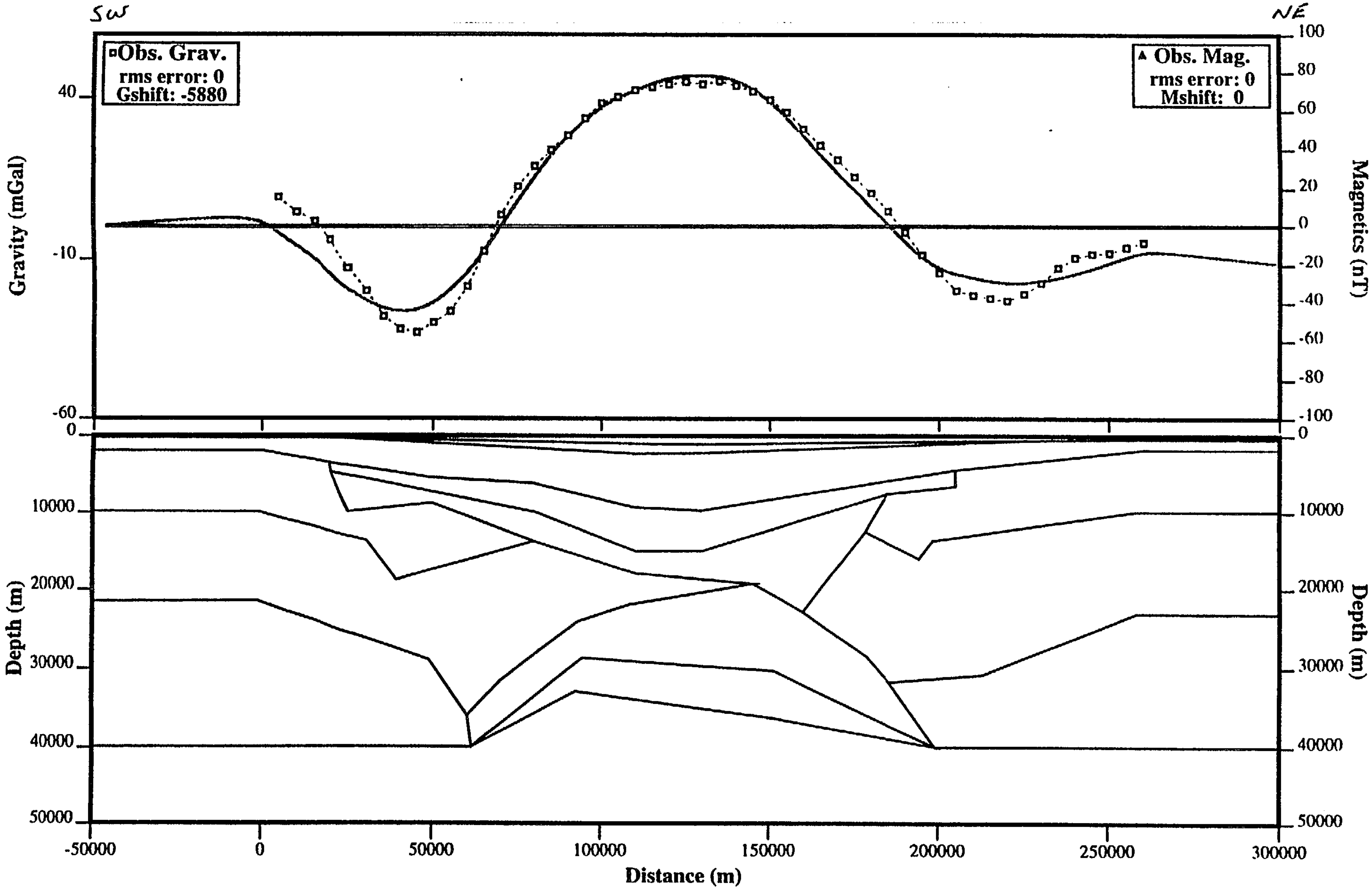

Figure 10. Adjustments made to the boundaries of the Precambrian and deep crustal layers to produce an enhanced gravity fit. (File 100-2P).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

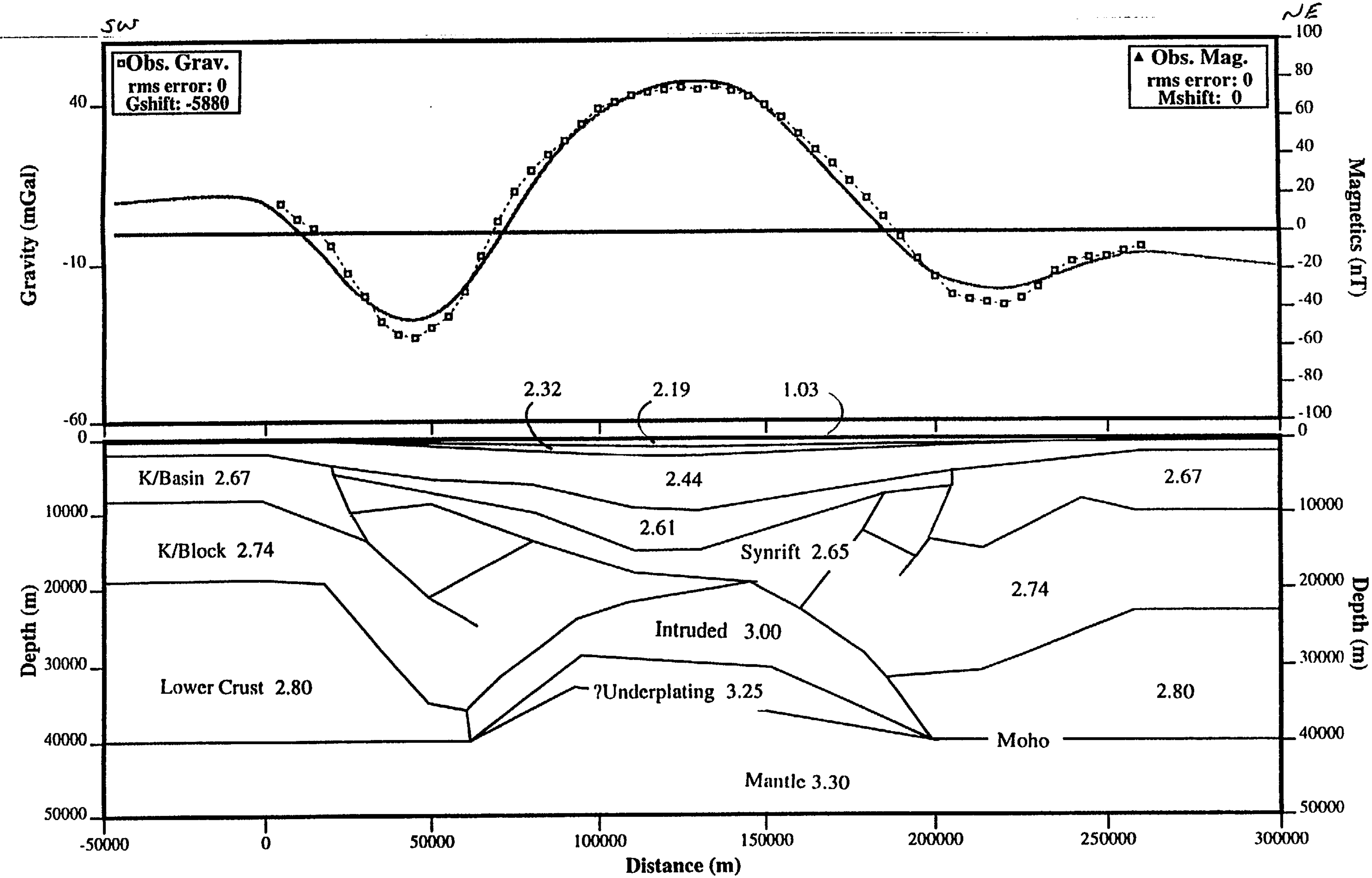

Figure 11. Final modification to the Kimberley Block and Lower Crust on the SW flank of the sub-basin, to provide a good fit to the SW negative gravity lobe. This is regarded as the most plausible **final model** on the basis of the information available. (File 100-2Q).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

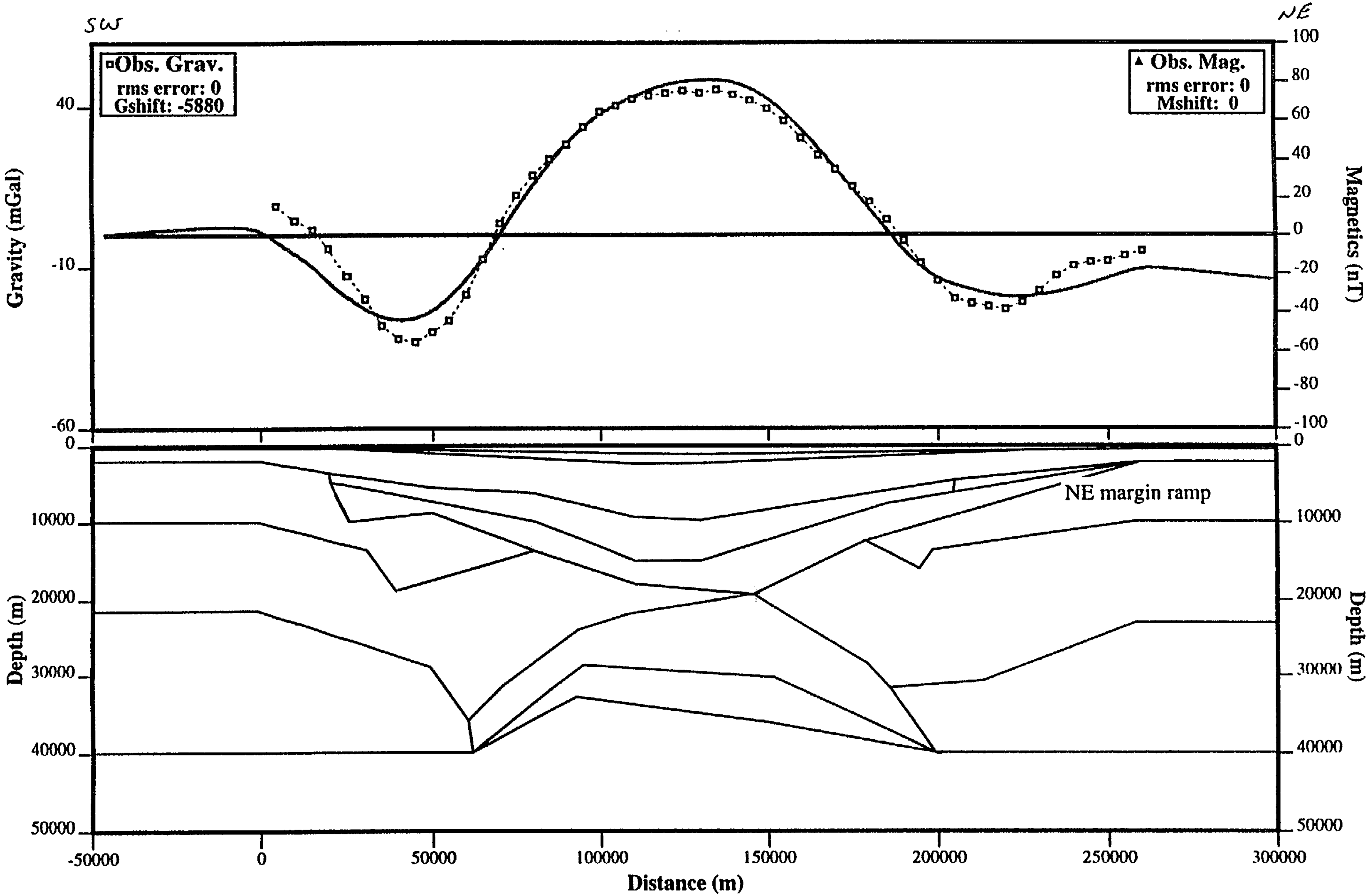

Figure 12. This model is a variant based on Figure 10. It was designed to test the geometry of the NE flank of the Petrel Sub-basin which was poorly defined on the seismic interpretation. This model assumes the NE flank to be a low-angle ramp. The fit is reasonable but the result is considered inconclusive. (File 100-2R).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

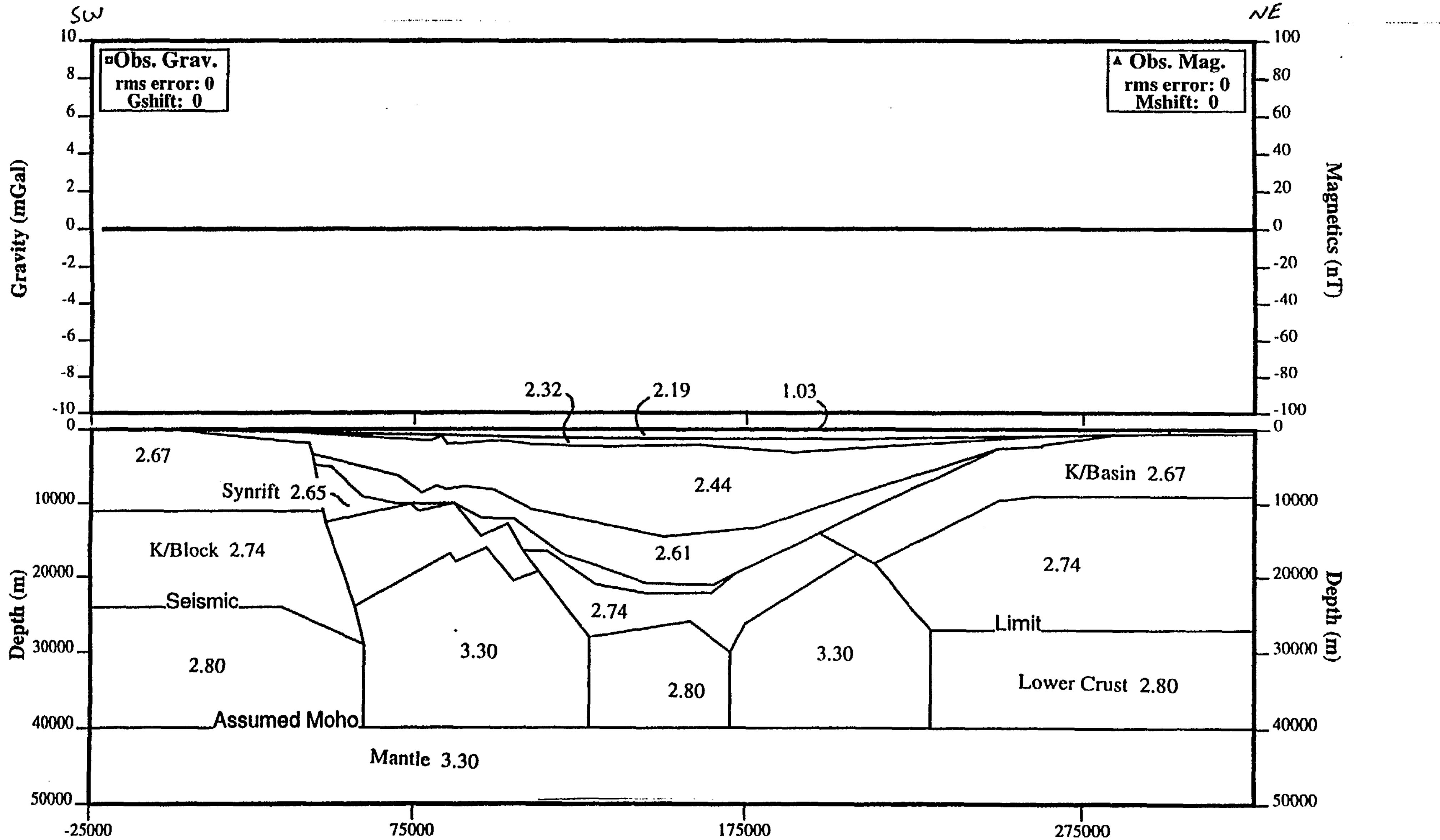

Figure 13. The basic model employs the same densities as for Line 100-02 (Figure 7). Changes in the seismic character at some of the apices of the deepest observable seismic horizon were assumed to mark the corners of individual bodies of different density. These apices were projected vertically downwards to a Moho at 40 km, as indicated by a vague band of deep seismic reflections, thus defining five lower crustal polygonal bodies. The layers were again extended to +/- 1000 km to eliminate edge effects.

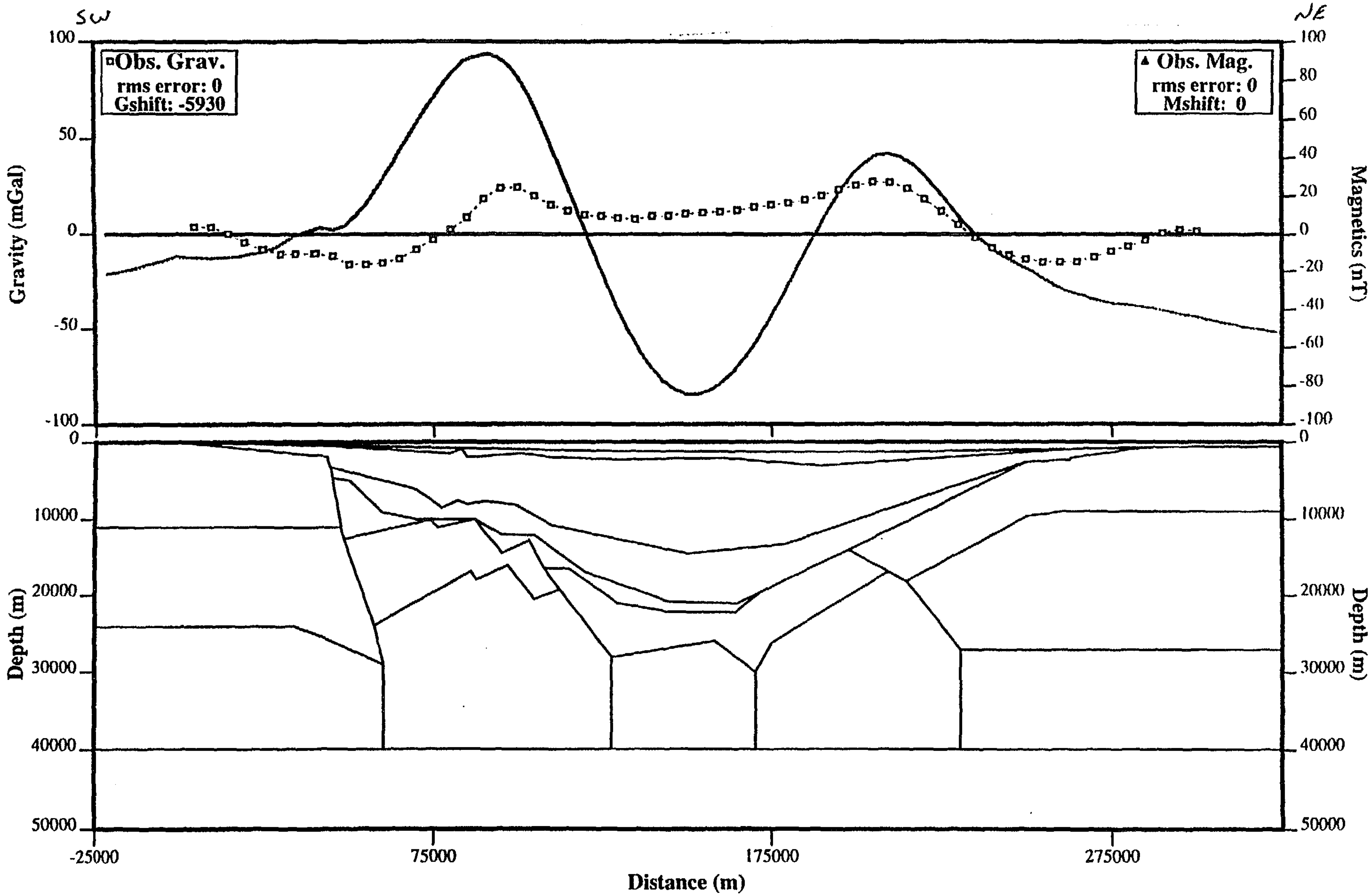

Figure 14. Gravity effect (continuous line) of the starting model for Line 100-03. (File 1003A).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604105

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

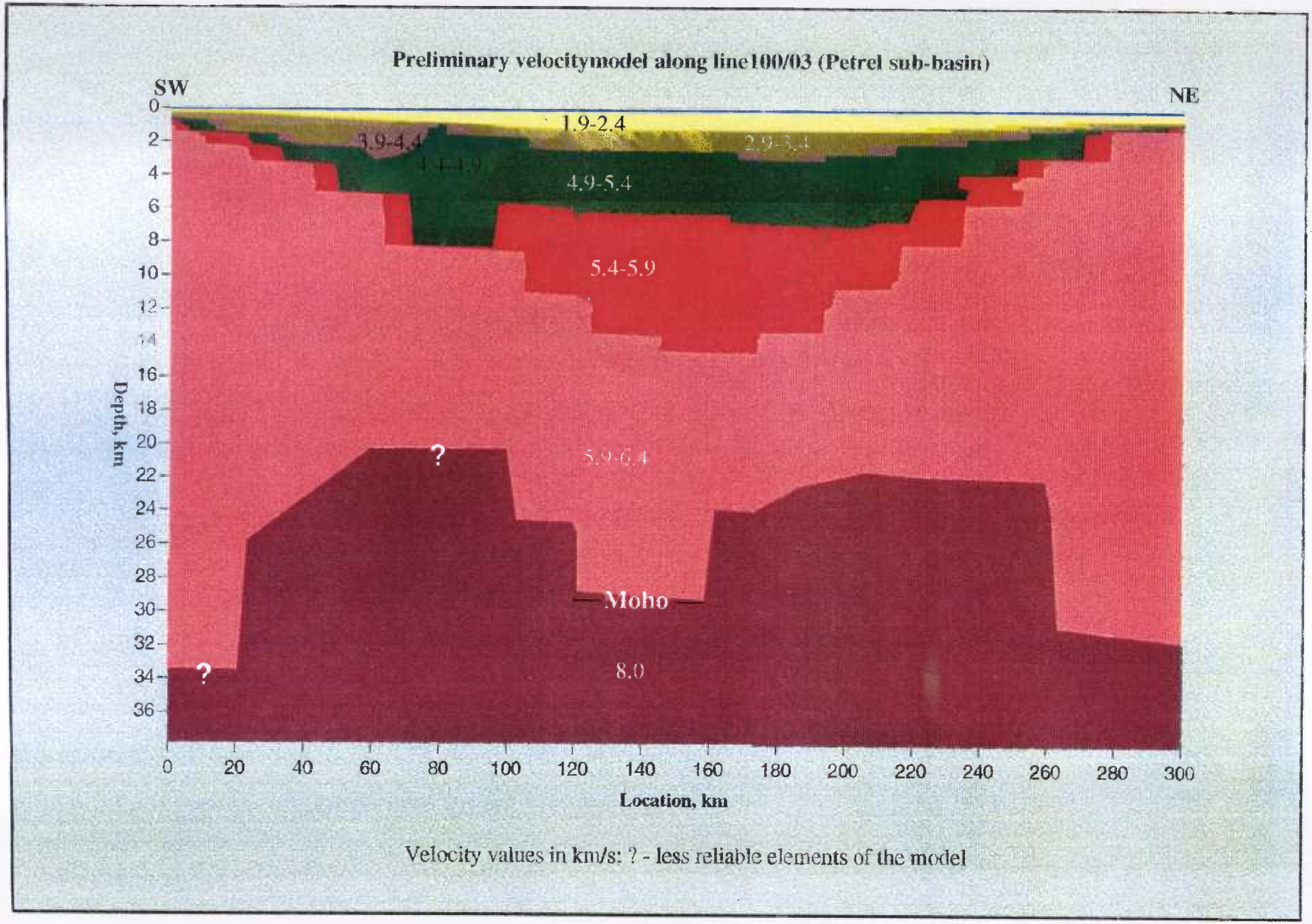

Figure 15. Petrel Sub-basin refraction study: preliminary velocity model along Line 100-03 (after Petkovic et al. in Colwell & Kennard, 1996).

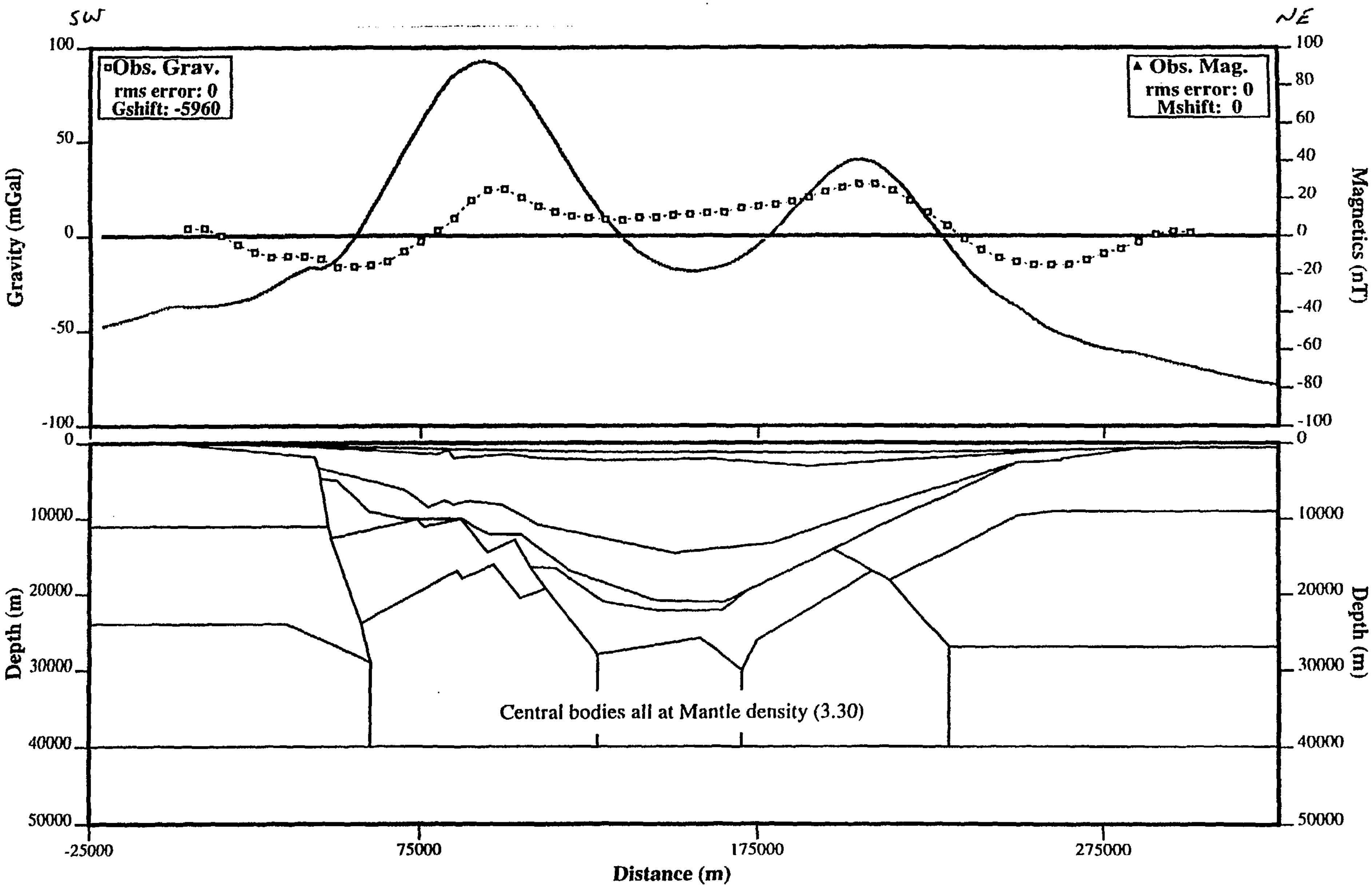

Figure 16. Density of the central lower crustal body increased to that of mantle ($3.3\ tm^{-3}$). (File 1003C).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604106

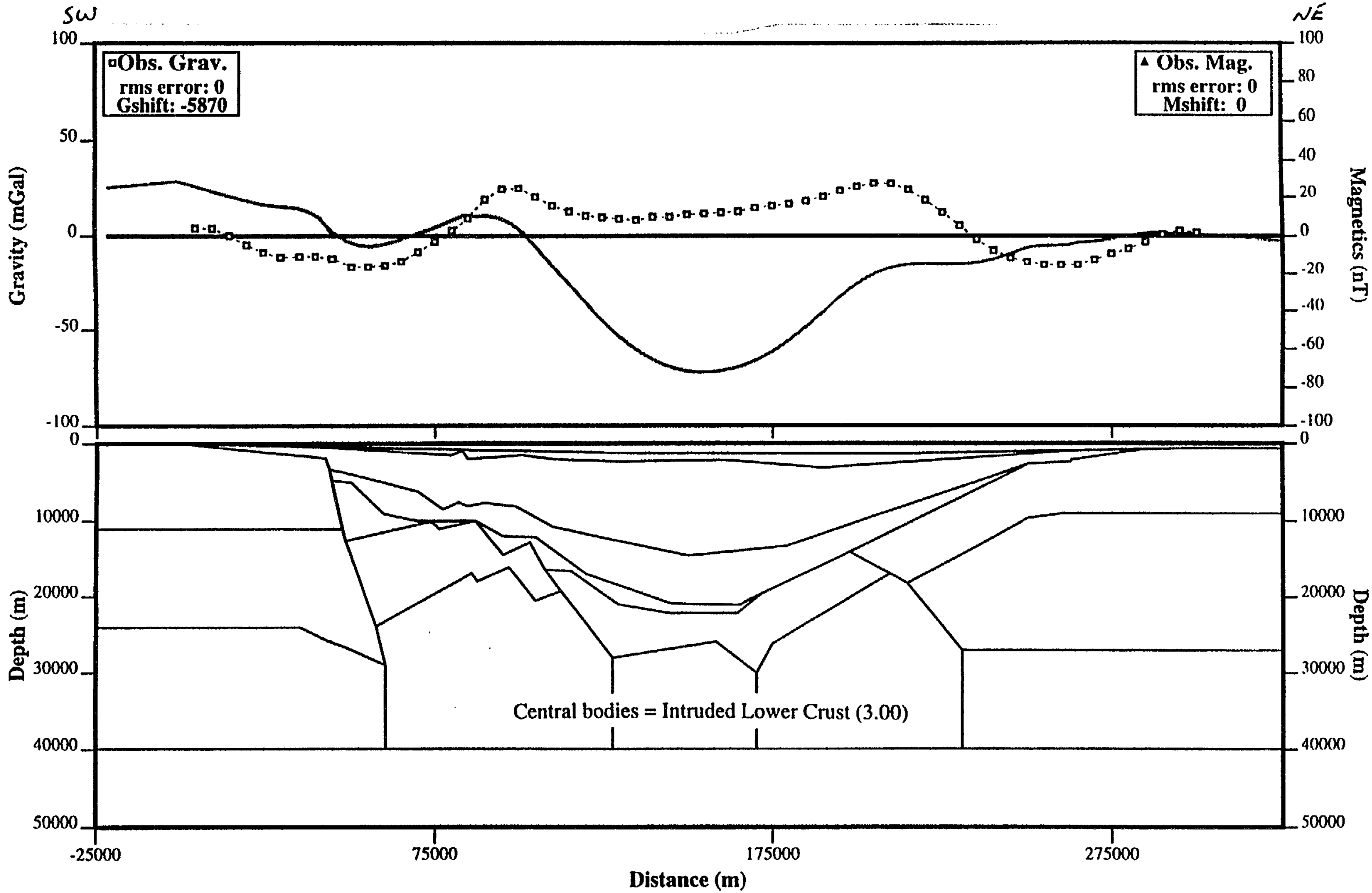

Figure 17. Gravity effect when all three central lower crustal bodies are assumed to be intruded lower crust (3.00 tm^{-3}). (File 1003D).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

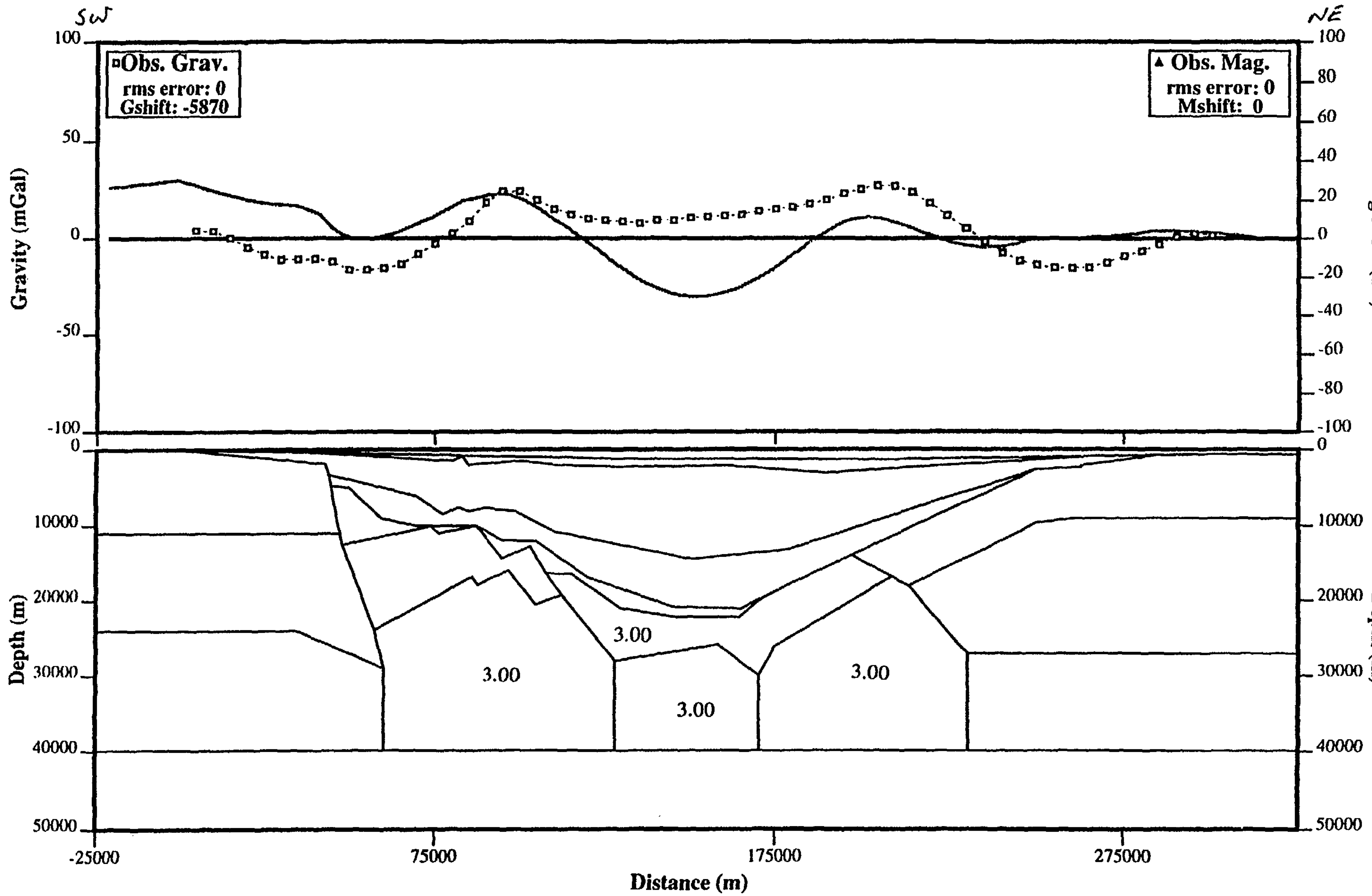

Figure 18. Gravity effect when the three central lower crustal bodies and the basin-floor are all assumed to be intruded lower crust (3.00 tm^{-3}). (File 1003E).

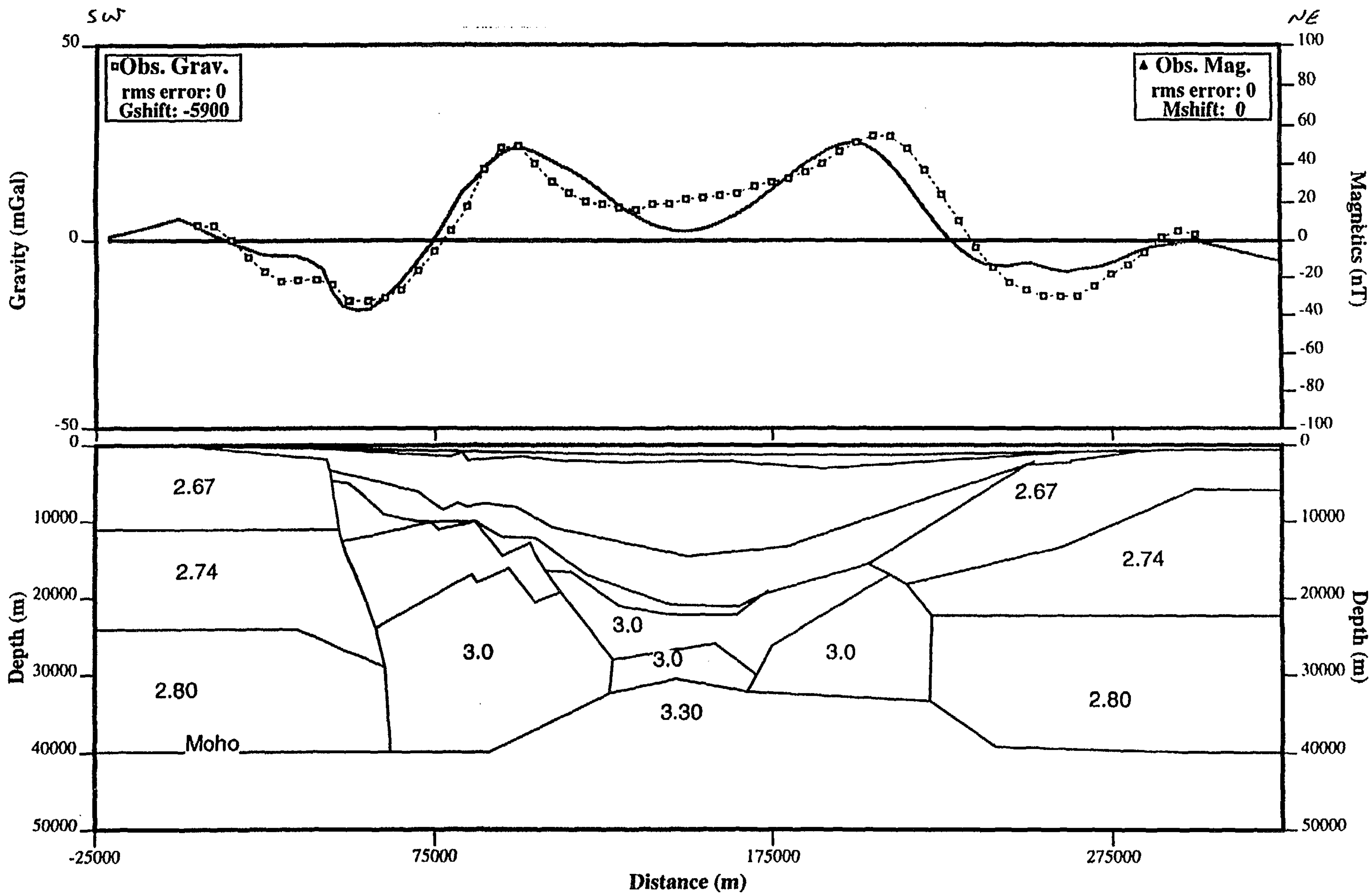

Figure 19. Gravity effect showing improved fit created by a combination of lower crustal intrusion and crustal thinning. (File 100-03R).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

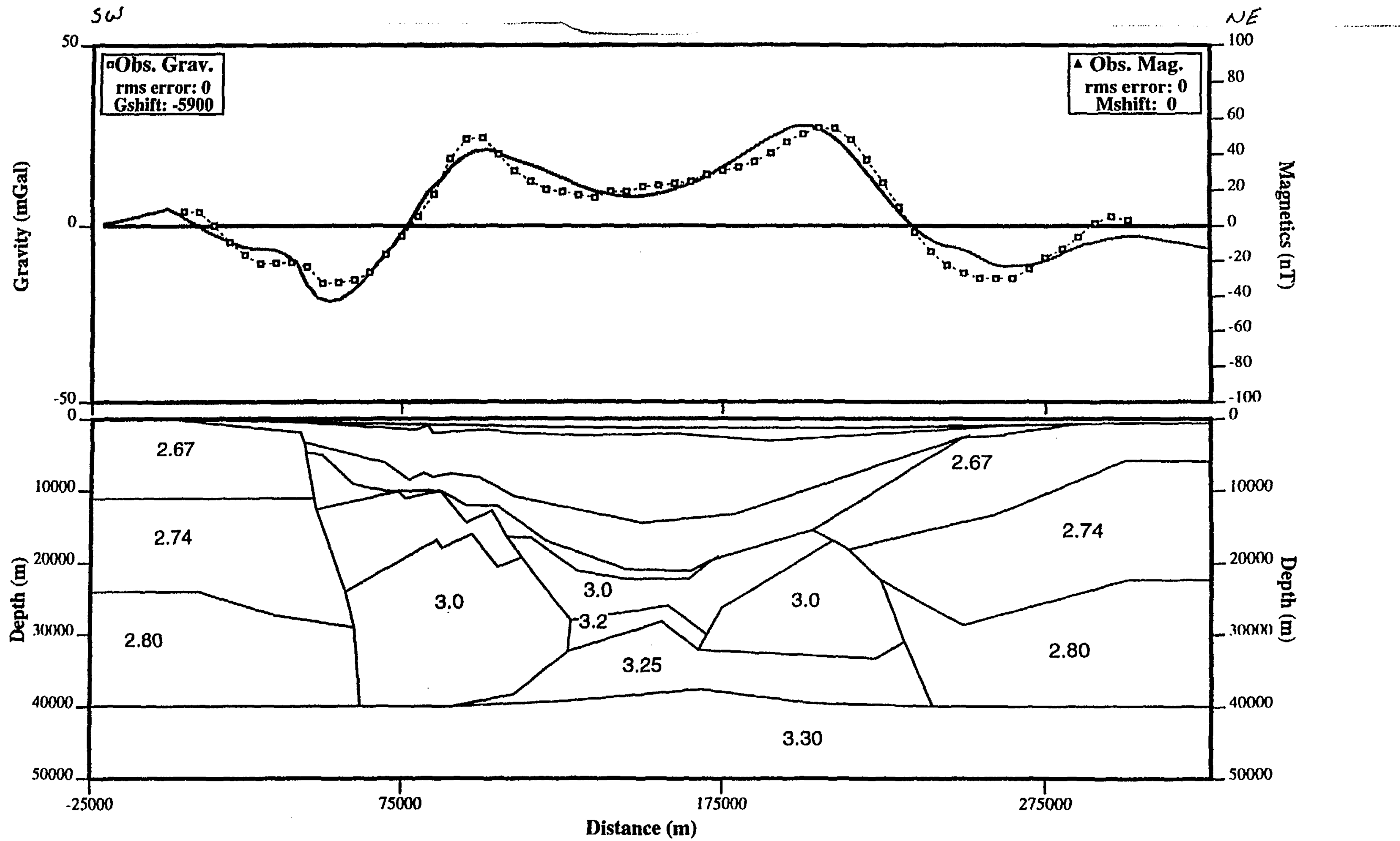

Figure 20. Gravity effect of 'best fit model' showing lower crustal intrusion and thinning, together with a layer of ρ= 3.20-3.25 possibly representing 'underplating'. (File 100-03T).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

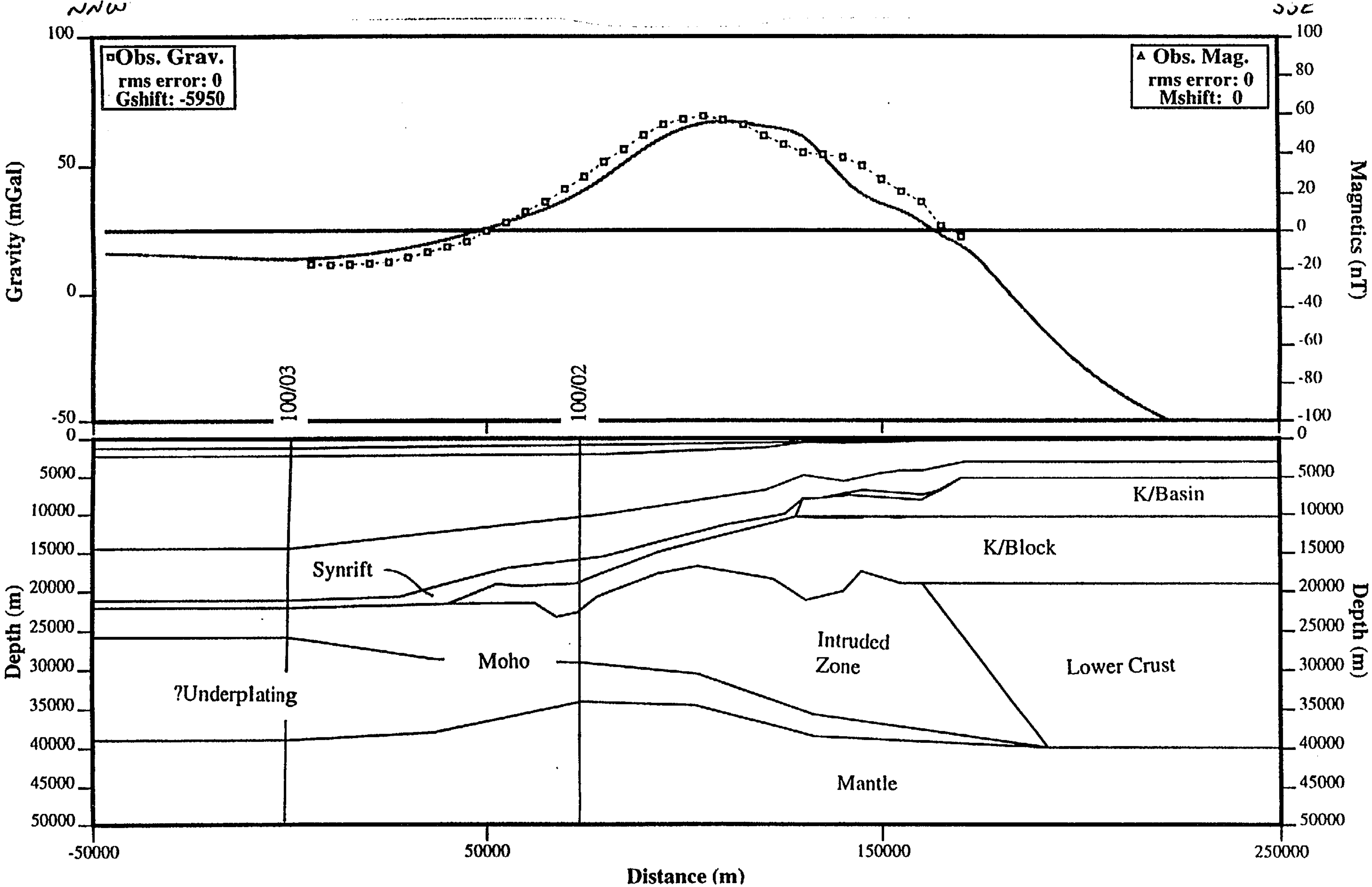

Figure 21. Gravity effect of model based on axial (NNW-SSE) tie-line 100-05. Note ties to Lines 100-02 & 100-03. Honours basic seismic reflection data to base of the Kimberley Block. The model assumes that intrusion of the Lower Crust ($\rho=2.80\ tm^{-3}$) to provide a high density zone ($\rho=3.00\ tm^{-3}$) occurs only beneath the Petrel Sub-basin, and is hence a product of basin development. (File 100-05XX).

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

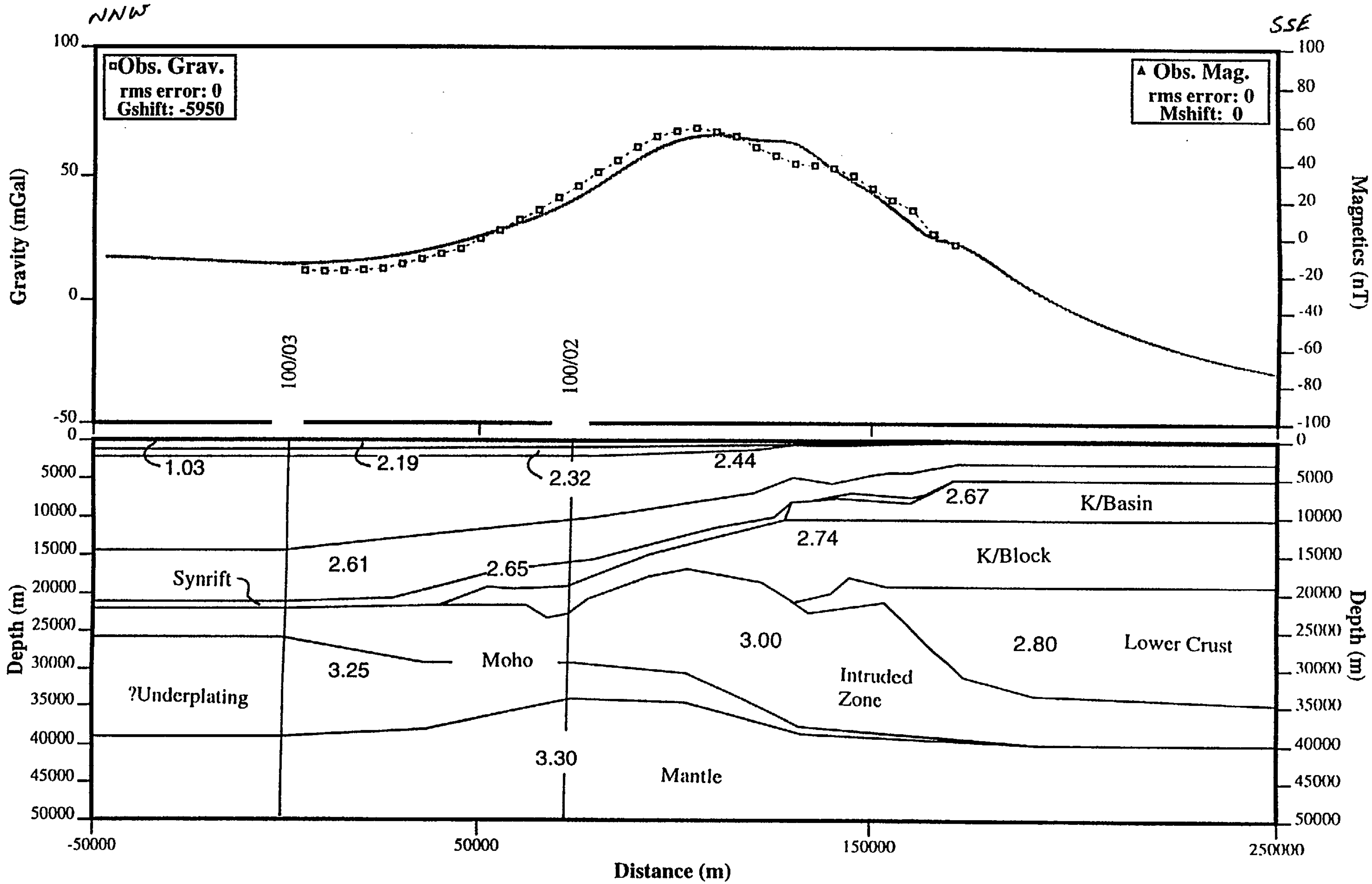

Figure 22. Gravity effect of further model based on axial (NNW-SSE) tie-line 100-05. Note ties to Lines 100-02 & 100-03. Honours basic seismic reflection data to base of the Kimberley Block. This model assumes that the high density zone in the Lower Crust extends beyond the SE boundary of the Petrel Sub-basin, and could be caused by a pre-existing feature such as intrusions within a mobile belt. (File 100-05WW).

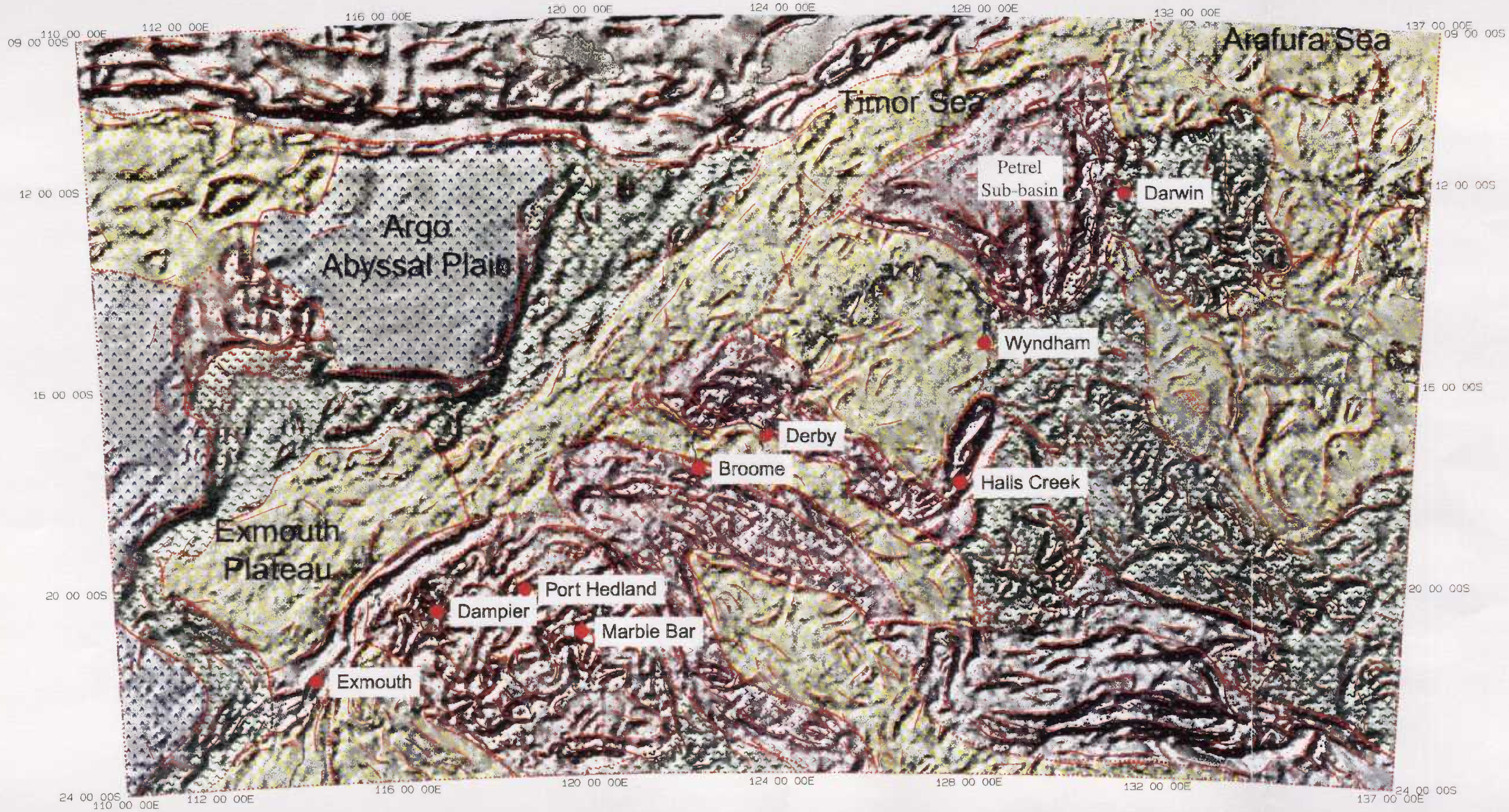

Figure 23. Gravity provinces based on the Bouguer gravity anomaly, northwest illumination.

The absolute value of the maximum horizontal gradient of Bouguer anomaly was classified according to the amplitude and alignment of trends.

The colours show this classification, using the following scheme:

Colour	amplitude	alignment
^ blue	zero	none
x yellow	low	low (Type 2)
~ green	medium	low
> purple	medium	high (Type 4)
+ orange	high	low
. magenta	high	high

1: 10000000

0 200 400 600 800 1000

KILOMETRES

SIMPLE CONICAL PROJECTION
AUSTRALIAN NATIONAL SPHEROID
PARALLELS 12 00 00S AND 21 00 00S, CENTRAL MERIDIAN 123 00 00E

The trend lines represent alignments of maximum horizontal gradient, which may be interpreted to be structural boundaries or lines along which subsurface density changes occur.

R9604107

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604108

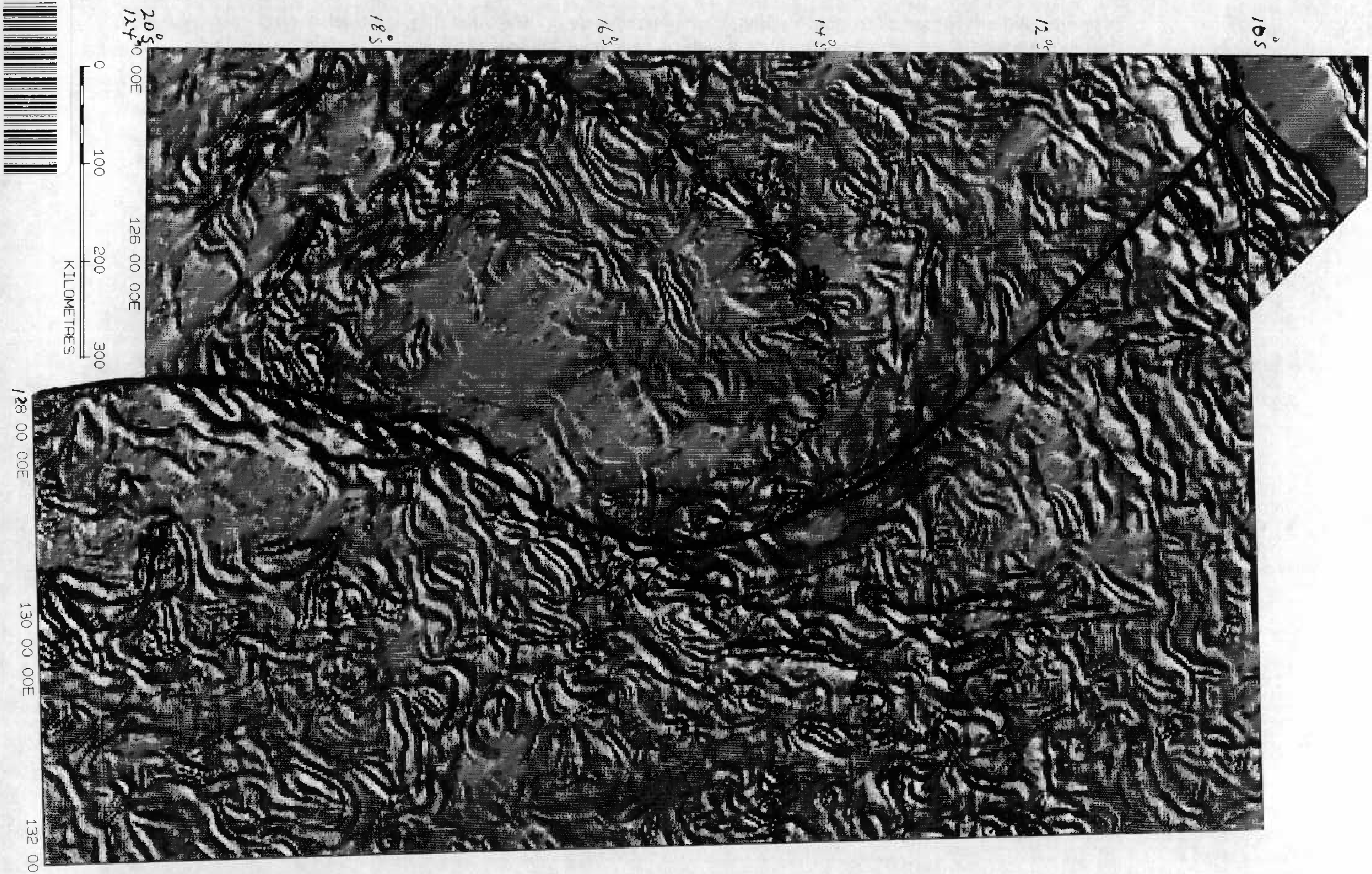

Figure 24. Restoration of the second derivative gravity image to a postulated pre-Petrel rift position. Petrel rift has been closed by approximately 120 km.

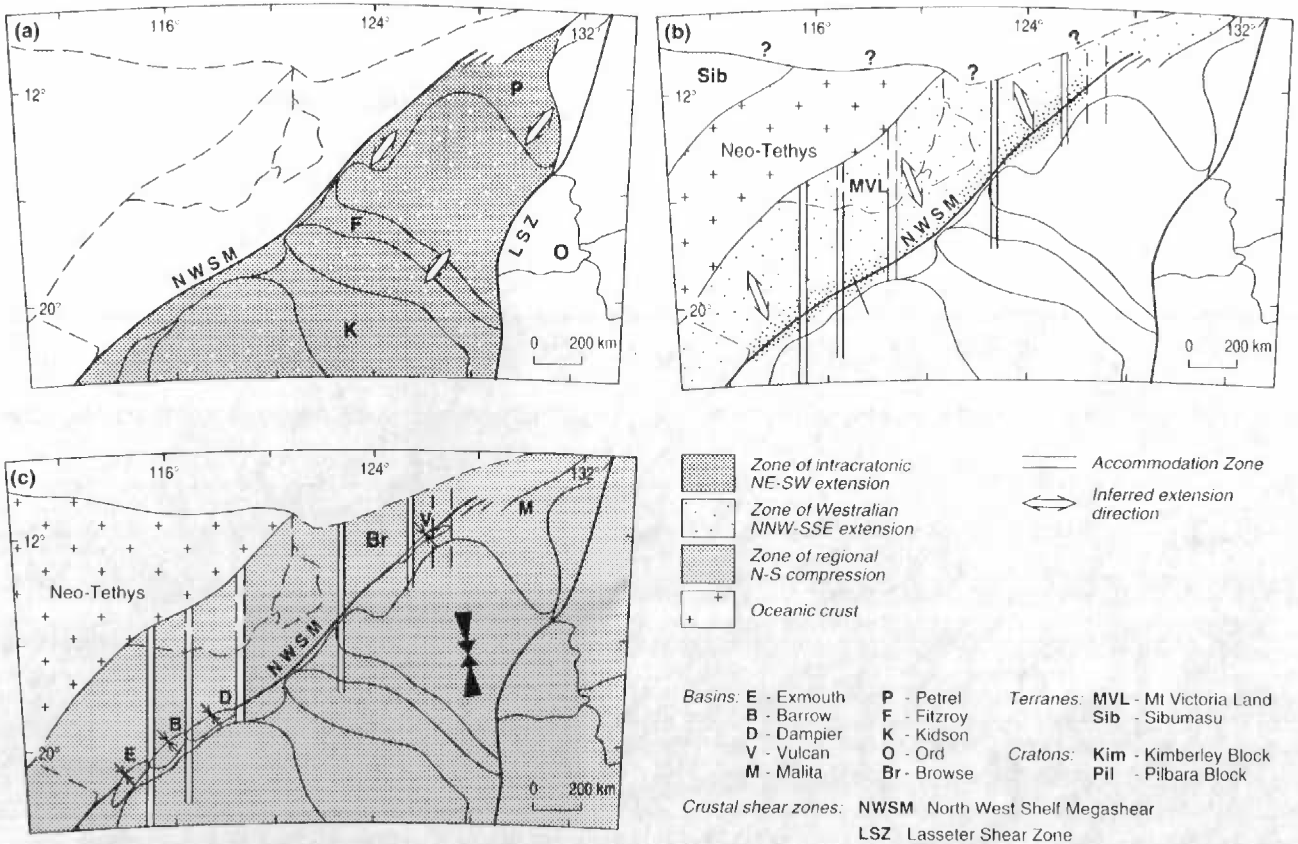

Figure 25. Conceptual evolution of the North West Shelf basin system (after AGSO North West Shelf Group, 1994). (a) Late Devonian-Early Carboniferous (b) Mid Carboniferous-Early Permian (c) Late Triassic-Early Jurassic

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

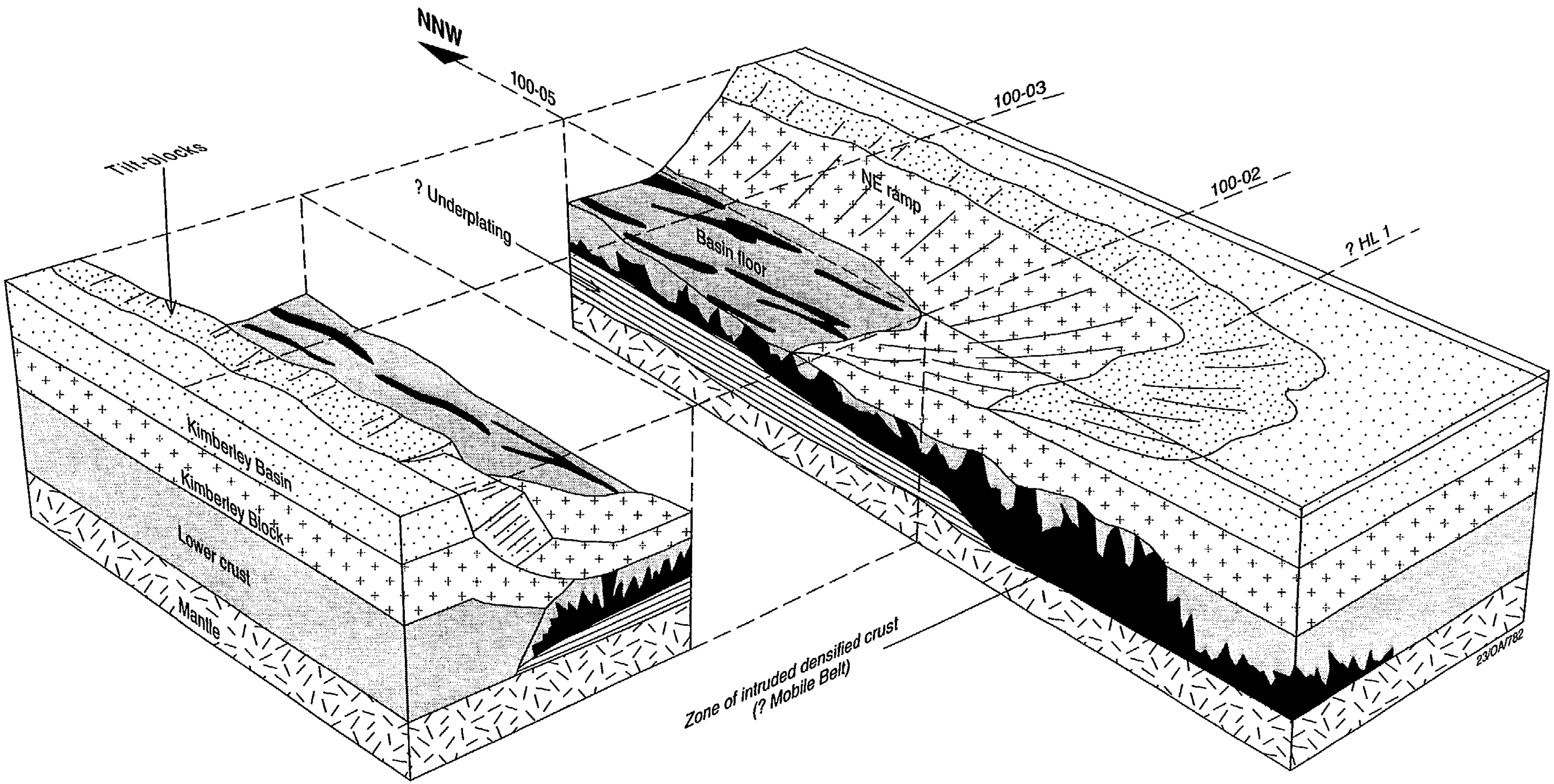

Figure 26. Petrel Sub-basin: conceptual block diagram deduced from the seismic and gravity interpretation

© AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

R9604109