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SEISMIC INTERPRETATION AND GRAVITY MODELLING OF BIRPS SWAT LINES 5 AND 6

by

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-bstract

Seismic interpretation of the British Institutes Reflection Profiling Syndicate (BIRPS) seismic reflection lines SWAT 5 and 6 was carried out and a time section showing the major reflective horizons drawn up. This section was depth converted and where possible geological ages given to the sedimentary reflectors and densities assigned to the geological bodies. Using a computer gravity modelling program the theoretical and observed gravity anomalies were compared and some slight modifications were made to the models to enhance agreement between the two.

The models indicate that the lower crust may have a higher density in the north, suggesting that there may be a boundary between two crustal blocks at the north end of the SWAT 6 profile. It is also tentatively suggested that the Haig Fras batholith was injected from below whereas the Cornubian Batholith may have been intruded from the south.

Seismic Interpretation and Gravity Modelling of BIRPS SWAT lines 5 & 6

Introduction

This report describes an attempt to model the whole of the earth's crust along sections delineated by SWAT lines 5 and 6 (South Western Approaches Traverse lines). Fig. 1 shows the location of these lines superimposed upon a Bouguer anomaly map of the region and also shows that the lines are approximately perpendicular to the anomalies. The BIRPS data extends to 15s TWT thus including reflections from the MOHO discontinuity which occurs at approximately 10s TWT. The modelling therefore attempted to incorporate an interpretation of the main seismic events above and including the Moho. After initial interpretation of the data a time section of each line containing the major reflective horizons was drawn and this was subsequently converted to a depth section by assigning appropriate interval velocities to the various bodies. These were chosen by an assessment of all the seismic refraction data available for the region (see separate section).

Densities were given to the bodies, and in the South Western Approaches relevant well data was also consulted. The gravity effect of the model thus arrived at was calculated and comparison with the observed anomaly was made. The models are, shown in Fig. 3. There is good general agreement between observed and calculated fields. However slight discrepancies do occur and these are discussed later.

Geological Description of the region

A map showing the major basins and granite outcrops is shown in Fig. 2. The major features are a series of WSW - ENE trending sedimentary basins with boundaries formed by basement highs and massifs. The basins were initiated by rifting in the Permo-Triassic and have been subsequently infilled with Mesozoic and Tertiary sediments. The opening of the North Atlantic has however exercised some control over basin development; particularly at the basin margins which are mainly fault controlled, consistent with the tensional tectonic regime to which the area has been subjected. The basement rocks range from Pre-Cambrian age on the southern margin of the South Western Approaches Basin (SWAB) to Devono-Carboniferous sediments and metasediments beneath the other basins, (Naylor & Shannon 1982).

The area traversed by SWAT 6

The SWAB is a deep, fault bounded structure. The northern and southern boundaries are formed by the Cornubian platform and Amorican basement massifs respectively. The northern margin has locally well developed faulting which is seen on the BIRPS data and the southern margin is strongly faulted against the Amorican massif. Eastwards it merges with the West English Channel Basin (WECB), the eastern boundary of which is formed by the Start-Cherbourg basement ridge. The western boundary of the SWAB is formed by a NW trending basement feature at the shelf edge.

To the north of the SWAB, gravity interpretation (Edwards 1984) indicates extension westwards of the Cornubian and Scilly Batholiths. However bottom sampling in the area by BGS has not proved granite outcrops west of the Scilly Isles. The granite is discussed in more detail later.

The area traversed by SWAT 5

The main features are the North and South Celtic Sea Basins, the Haig Fras granite, and the Haig Fras sub-basin. The North Celtic Sea Basin was not modelled and so will not be described here. The North and South basins are similar in character and history. The southern boundary of the South Celtic Sea Basin (SCSB) is formed by the Cornubian basement platform and it is bounded to the north by the Labadie bank basement high and the Pembrokeshire ridge. This ridge system is a long narrow WSW-ENE trending feature between SW England and Ireland, buried by a thin condensed sequence of Mesozoic sediments and forming a barrier between the north and south basins. Initial sedimentation probably occurred in minimal amounts in marine conditions in Upper Palaeozoic times, but this was terminated by the Hercynian orogeny. These Devono-Carboniferous sediments were folded and sometimes metamorphosed during the orogeny and now form the basement. In Permo-Triassic times an extensional regime was established and the processes of rifting and basin subsidence initiated. Permo-Triassic continental fluviatile sediments were succeeded in the Triassic by deposition of evaporites within a restricted lacustrine environment.

At the end of the Triassic there was a rapid transgression to marine conditions which have remained, though varying in nature, through to the present. Tertiary sediments exist, and are thought to have been more widespread before glacial erosion which was followed by deposition of a thin layer of Quaternary sediments.

To the south of the SCSB the Haig Fras granite (of Hercynian age) is intruded into the basement and crops out in the sea bed. Gravity interpretation (Edwards 1984) suggests this could be part of a granite batholith running parallel and similar to the Cornubian batholith.

South of this is the Haig Fras Sub Basin which is thought to contain Permo-Triassic and possibly Jurassic sediments, overlain by a thin layer of Cretaceous chalk.

Seismic Interpretation

In the interpretation lines 5 and 6 were considered as a single section. Although SWAT 5 is offset to the west of SWAT 6, it is still reasonable to consider lines 5 and 6 together because the strike of the geological features is ENE-WSW and the BIRPS lines were run perpendicular to this direction. SWAT line 7, although not modelled was considered where aspects of the deeper geology related to features seen on SWAT 6.

SWAT lines 5,6, and 7, in common with other BIRPS lines, can be broadly divided into four main zones on the basis of seismic character. The Mesozoic and younger sedimentary basins are easily recognisable as sets of closely spaced coherent reflectors. The upper crust has relatively few reflectors down to 6 or 7 seconds where there is a distinct change to a highly reflective lower crust with a series of near horizontal discontinuous reflectors. This zone terminates at a fairly constant TWT of 10s and below this the records show few coherent reflectors.

SWAT 6

On line 6 the Moho discontinuity was picked at the bottom of the highly reflective zone where this exists between shot points (SPs) 102 and 10800 in agreement with evidence from refraction and reflection experiments (Barton et al., 1984, Matthews, 1986). Where a highly reflective zone is absent from S.P. 11180 onwards there are nevertheless a few strong reflections varying between 9½s and 10½s and the lowest of these was taken as the Moho.

The character of the Moho in other BIRPS experiments around the British Isles has been found to vary from a particularly sharp reflector at the base, indicative of a high acoustic impedance contrast, to a more gentle transition with fewer strong reflectors.

Between SPs 10990 and 11180 the Moho reflection becomes ambiguous and there are a number of diffractions associated with this part of the record. This has been modelled as a small step in the Moho which is suggested by the diffraction patterns on the record. Diffractive events were identified by placing hyperbolic diffraction curves of appropriate RMS velocities, drawn on transparencies, on top of the record. The tails of events that matched the curves were ignored.

To the north of SP 10990 the lower crust has the characteristic highly reflective appearance already described which continues northwards into SWAT 5 and remains unbroken until SP 800 of SWAT 5 which lies below the North Celtic Sea Basin. To the south of SP 11180 on SWAT 6 the highly reflective zone is not seen until SP 2070 on SWAT 7 where a zone of high reflectivity reappears. This suggests a change in the composition and history of lower crustal material at these points. The diffractive events at SP 10990 also suggest a discontinuity. The region and events being considered here lie within the Hercynian orogenic belt. The changes in seismic character of the crust may reflect the juxtaposition of different terranes brought together by the collision tectonics of the Hercynian orogeny. The term 'terrane' is here used to designate a crustal block, not necessarily of uniform composition, bounded by faults.

The possible change in lower crustal material at SP 10990 occurs in approximately the same position as the boundary between the Rhenohercynian zone and the Saxothurigian zone of the Hercynian belt suggested by Rast (1983).

In the southern section of SWAT 6 there are a number of southerly dipping events around 3 to 4 seconds TWT that continue into SWAT 7 which have been interpreted as Variscan thrust planes. Although there are some diffractive events associated with this part of the record (around SP 12000) there is little doubt that there are some strong real dipping events. The events have been modelled as a body thrusting from the south along the thrust plane shown in Fig. 3. At SP 12050 a large well developed fault has been modelled. The event can be traced down to the Devono-Carboniferous basement and possibly further, though somewhat uncertainly due to the fact that faulting in the sediments probably interferes acoustically with events at greater depth. This represents a possible site of post-Hercynian relaxation of a thrust associated with the Permo-Triassic rifting that initiated the basin. An account of thrusting in the South Western Approaches is given by Day and Edwards (1985) where the question of the validity and origin of the events is also examined.

The part of the SWAB crossed by SWAT 6 shows five major reflective horizons; the first of these was taken to be the base of the Tertiary sequence (ie the top of the Upper Cretaceous). The remaining four events were identified as top Lower Cretaceous, top Permo-Triassic, top and base intra Permotriassic (top of the basement/metasediments). The picking of these horizons was compared and correlated to seismic interpretation from a previous survey in the area commissioned by BGS in 1973 (see reference section), and good agreement in TWT for these horizons was found. Well data in the area were also examined, in particular from wells 83/24-1 and 86/18-1: the former showed Tertiary, Upper and Lower Cretaceous, Permo-Triassic sediments, and also metamorphosed Devono-Carboniferous sediments; the latter showed Tertiary, Upper and Lower Cretaceous, possible Upper Triassic, Permo-Triassic, possible Upper Permian sediments and late Devono-Carboniferous sediments.

From these two wells the geological ages assigned to the horizons picked are reasonably well confirmed (and the exclusion of a Jurassic sequence in this part of the basin justified). The BGS 1:250 000 solid geology map of the region was also used to identify seabed sediments. The extension of the Cornubian batholith, indicated by the elongated shape of the gravity anomaly over the area extending SW from the Scilly Isles, is not clearly seen on the seismic record. The main reason for this may be that much of the body of the batholith probably has very steeply sloping sides. Current acquisition and processing techniques used to obtain seismic profiles are designed to resolve horizontal or shallow dipping reflectors, so it is not surprising that the granite is not well resolved. However an indication of its position is given by a subtle change in seismic character of the record around SPs 10700 to 10900 which suggests the possibility of a change in rock type ie from metasediments to granite. The observed gravity field has an indented "shoulder" in the southern half of line, see Fig. 3, and a simple wall-like body does not model the anomaly well. Between SP 10980 at approximately 3s and SP 11130 at approximately 1.8 secons there is a dipping reflector which has been interpreted as shown in Fig. 3 as the sloping roof of an extension to the granite body and this markedly improves the agreement between observed and calculated anomalies. The acoustic impedance contrast between basement rock and the granite is expected to be great enough to produce such a reflection event on the seismic record. The general shape of the granite as shown in Fig. 3 is such that it gives the best fit of the calculated anomaly to the observed anomaly that could be achieved during the modelling, taking into account the seismic evidence for its shape.

SWAT 5

The seismic interpretation of SWAT line 5 was carried out by G Day of BGS and so is not discussed in detail by this author. The important features are the South Celtic Sea Basin, the Haig Fras granite batholith, and the Haig Fras Sub-Basin.

Models

The models are presented in Fig. 3. They are shown mounted end to end for ease of presentation, but there is in reality a slight overlap which can be seen by referring to Fig. 1.

The basement has been modelled in three layers: upper crust, an intermediate layer, and lower crust. The dashed lines represent boundaries chosen between layers where there is no observed seismic event of any significance. The lines of transition have been chosen to follow the general trend of either the Moho or lower crust and to allow the best fit between observed and calculated anomalies. The modelling of the sedimentary basins on SWAT 5 is more simple than on SWAT 6 but good agreement between observed and calculated anomalies is achieved.

At the ends of the models the sedimentary layers and basement layers were continued horizontally for 50 km to provide a representative mass so that the calculated anomalies would not drop to zero at the end of the modelled sections. This is not entirely satisfactory since in reality the geology will not conveniently continue uniformly at the end of each line. The discrepancies between observed and calculated anomalies would not drop to zero at the end of the modelled sections. The discrepancies between observed and calculated anomalies are fairly small and tend to occur at the ends of the model sections. These discrepancies could therefore partly be due to "end effects" because of the over simple assumption mentioned above, but on the southern end of SWAT 6 there is disagreement between observed and calculated anomalies which starts some distance before the end of the line. It is possible that the sediments were incorrectly modelled or that rock densities chosen for this section of the model are incorrect or the effect could be due to a slightly deeper feature not imaged on the seismic record or erroneous interpretation. However the discrepancy almost certainly arises from a shallow feature(s) because the general shape of the calculated anomaly is correct.

The thickness of each model was extended beyond the Moho to a depth of 31.2km below mean sea level. The reason for choosing this thickness is that uniform crust of average crustal density and thickness 31.2km with its surface at mean sea level will produce a zero Free Air Anomaly (Dewey 1982).

The assignment of rock density for the geological bodies in the models and the seismic velocities that were chosen when converting the models from time to depth sections is discussed in Appendix B and given in tabular form in Appendix C.

The reliability of the gravity anomaly values for the observed fields is discussed in Appendix A and further considerations of possible sources of error in the models are also given in Appendix B.

Discussion

Comparing the two models the Moho in SWAT 5 is flatter and at slightly greater depth (around 28km) than in SWAT 6 where the Moho undultes and in some areas rises to almost 25km. The lower crustal material in SWAT 5 is of greater density than in SWAT 6. This suggests confirmation of the interpretation of a change in crustal material at around SP 10990 of SWAT 6 as mentioned previously. SWAT 6 could be modelled with slightly denser lower crust to the north of SP 10990 than to the south (vertical dotted line on Fig. 3) and good agreement of observed and calculated fields could be made. In the model presented however the lower crust is of uniform density. An explanation of this (as described briefly in the "Seismic Interpretation" section) may be that the area marks the transition zone between two continental plates or terranes which would have been subject to collision at some stage of their history. If subduction occurred during collision the geometry of the profiles, such as the orientation of the thrusts, would suggest that the northern plate would have been subducted under the southern plate. However there is no evidence from the seismic records to suggest this and it is equally possible that the collision zone was subject to shearing. Other evidence to support either of these suggestions has not yet been examined.

The origin and emplacement of the granite batholiths cannot be determined with certainty. The shape of the granite modelled in SWAT 5 suggests vertical intrusion. Some authors have argued a thin skinned origin for the batholiths, that is that they have been channelled along shallow boundaries between thrust nappes but this would have meant that a great enough temperature would not have existed for the granite to have formed at this location and this applies equally to the batholith of SWAT 6. However this can be countered by reasoning that due to a greatly increased overburden, the temperatures required would have been reached and water within these metasediments may have caused a geochemical reaction lowering the temperature required to initiate partial melting thus forming a granite.

Shackleton et al (1982) proposed that the batholiths originated SSE of their present positions at depth and were intruded northwards in the form of a sheet.

There is some evidence from the model presented for SWAT 6 which to some extent supports the view that the batholith formed some way to the south of its present position. On the seismic record there is an event, below the thrusting, which is similar in character to the thrust events. This is shown on the model. This possibly represents a line of fracture along which the granite may have migrated to intrude in its present position, but this event does not go as far south as Shackleton suggests for the area of origin of the granite. An explanation for the bulbous nature of the granite in SWAT 6 is that it came about by part of beginning to rise as a separate "finger", or incipient intrusion, but for some reason being halted leaving the remainder to be intruded as shown.

An increase in rock density has been modelled across the thrust plane in SWAT 6 and would be expected as the material thrusting from the south would have originated at depth and hence be denser than the crust which it over-rides. The modelling, if correct, confirms the interpretation of a thrust at this location.

Conclusions

Generally good agreement between observed and calculated anomalies was achieved. The depth of the Moho in the models is in agreement with the results of other work. The change in lower crustal density between the two models suggests the location of a transition between two continental plates or terraines in this area with the possibility of either shearing or subduction in the collision zone which is placed approximately in the region of overlap between the two lines.

South dipping events in the southern end of SWAT 6 have been interpreted as thrusts and the modelling confirms a body thrusting from the south and over-riding a less dense body to the north.

It is tentatively concluded that the Haig Fras Batholith probably intruded in its present position whereas there is some evidence that the westwards extension of the Cornubian and Scilly Batholith originated some way to the SSE of its present position.

Acknowledgements

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Many thanks to John Edwards and Geoff Day for helpful discussion, suggestions, and help with the text.

Appendix A

Reliability of the gravity survey

The models were tested by comparing the observed gravity anomaly with the calculated effect of the model. It is obviously important that the observed data are accurate and errors within reasonable limits.

For the gravity survey along all the SWAT lines carried out by BGS a Lacoste-Romberg air-sea meter S75 was used. This is of the zero-length spring type. It was noticed during the survey that the total correction to the spring tension was being applied incorrectly and giving an erroneous value of the total gravity. This fault occurred on an isolated group of lines only, but included in these were SWAT lines 5, 6 and 7. The data tapes containing the gravity meter output (total gravity, spring tension, total correction) were examined and re-processed and corrections applied to the final values calculated for the Free Air Anomaly. These corrections improved the error distribution from a bimodal distribution with a mean of 1.8mgal to a monomodal distribution with a mean of 0.9mgal. A detailed account of the processing and corrections applied to the gravity data is given in BGS Offshore Computer Data report no. 18.

The improvement in the cross-over errors after reprocessing gives reasonable confidence that the reprocessed data are quite accurate enough for the type of modelling attempted here.

Appendix B

Depth Conversion, Assignment of Rock densities, and Error considerations

The time sections containing the major reflectors and postulated geological bodies were drawn following the interpretation of the sections. Interval velocities were chosen after an overall assessment of the available seismic refraction data relating to the region. This is summarised in BGS Marine Geophysics report 144. The crust was modelled in four velocity layers. The sediments (with separate velocities assigned to each geological age), upper crust basement material, an intermediate crustal layer, and the lower crust down to the Moho. The velocity of sound within the granite of the region has been the subject of many refraction surveys and can be confidently assigned. Refraction evidence suggest a velocity layer of 5.9 kms^{-1} below the granite and this was assumed in the models. After interval velocities had been assigned the sections were depth converted.

The seismic records upon which the interpretations are based are unmigrated sections. Quantitative migration of dipping events was not carried out and therefore errors in the depth conversion (and hence the models) may have been introduced at this stage. Migration was considered in a qualitative way during the interactive stage of the computer modelling which allowed small changes in the positions of reflective horizons to be made; but the fact that the models are based on unmigrated sections is a possible source of some of the disagreement between the observed and model anomalies.

Appendix A discussed the reliability of the observed gravity values and stated that for the modelling attempted here the confidence in the values and their limits of error were satisfactory; the justification of this statement lies in the fact that the modelling program assumed a 2-D structure. The SWAT lines are approximately perpendicular to the trend of the anomalies but the assumption is nevertheless an over-simplification since bodies of different densities offset from the lines could affect the observed anomaly along a line. This effect is significant at distances of up to 50 km, particularly if buried at depth. Therefore the uncertainty in the calculated anomaly arising from the assumption of a 2-D structure is likely to be of much greater significance than the limits of error in the actual observed values.

The densities for the bodies of rock in the models were chosen in a number of ways. In the South Western Approaches Basin Compensated Neutron Formation Density data was examined from wells 86-18-1 and 87-12-1A. These data give some predictions of the densities that might be expected in the sediments; but slight increases were made to the densities obtained from the well data because the sediments in the part of the basin profiled by SWAT 6 lie at greater depths than where they occur in the wells.

Measurements of the granite density have been made in the SW of England where the Cornubian granite batholith outcrops and these were taken into account to assign a density to the granites modelled, but these measurements must be treated with caution since they have been made on the cupolas of the granite outcrops and the composition and hence density of the granite may well vary at depth.

Densities for the basement layers of the models were chosen by converting the seismic velocity for each layer to its related density using a combination of various empirically derived relationships between density and seismic velocity.

The assumption that layers of rock of uniform density extend along the lengths of the lines is probably an over-simplification and a further possible source of disagreement between the observed and model anomalies. At the scale of the modelling however the assumption is valid and not enough evidence is available to justify modelling the variations in rock density in greater detail.

Appendix C

The values of seismic velocity and rock density used in the models are given in tabulated form. Each body of rock in each model is given a number (refer to Fig. 3) and seismic velocity and density are shown against this.

SWAT 5

Body No.	Seismic Veolocity/kms^{-1}	Rock density/g cm^{-3}
1	3.4	2.3
2	3.6	2.45
3	4.4	2.5
4	4.8	2.55
5	6.2	2.83
6	6.7	2.91
7	5.2	2.67
8	5.8	2.55
9	5.2	2.69
10	3.6	2.45
11	4.3	2.57
12	-	3.35
SWAT 6		
1	3.6	2.45
2	5.3	2.69
3	3.4	2.4
4	5.8	2.55
5	6.2	2.8
6	6.7	2.85
7	-	3.35
8	5.3	2.69
9	5.3	2.73
10	5.2	2.67
11	4.35	2.65
12	3.4	2.4
13	2.8	2.25
14	2.3	2.2

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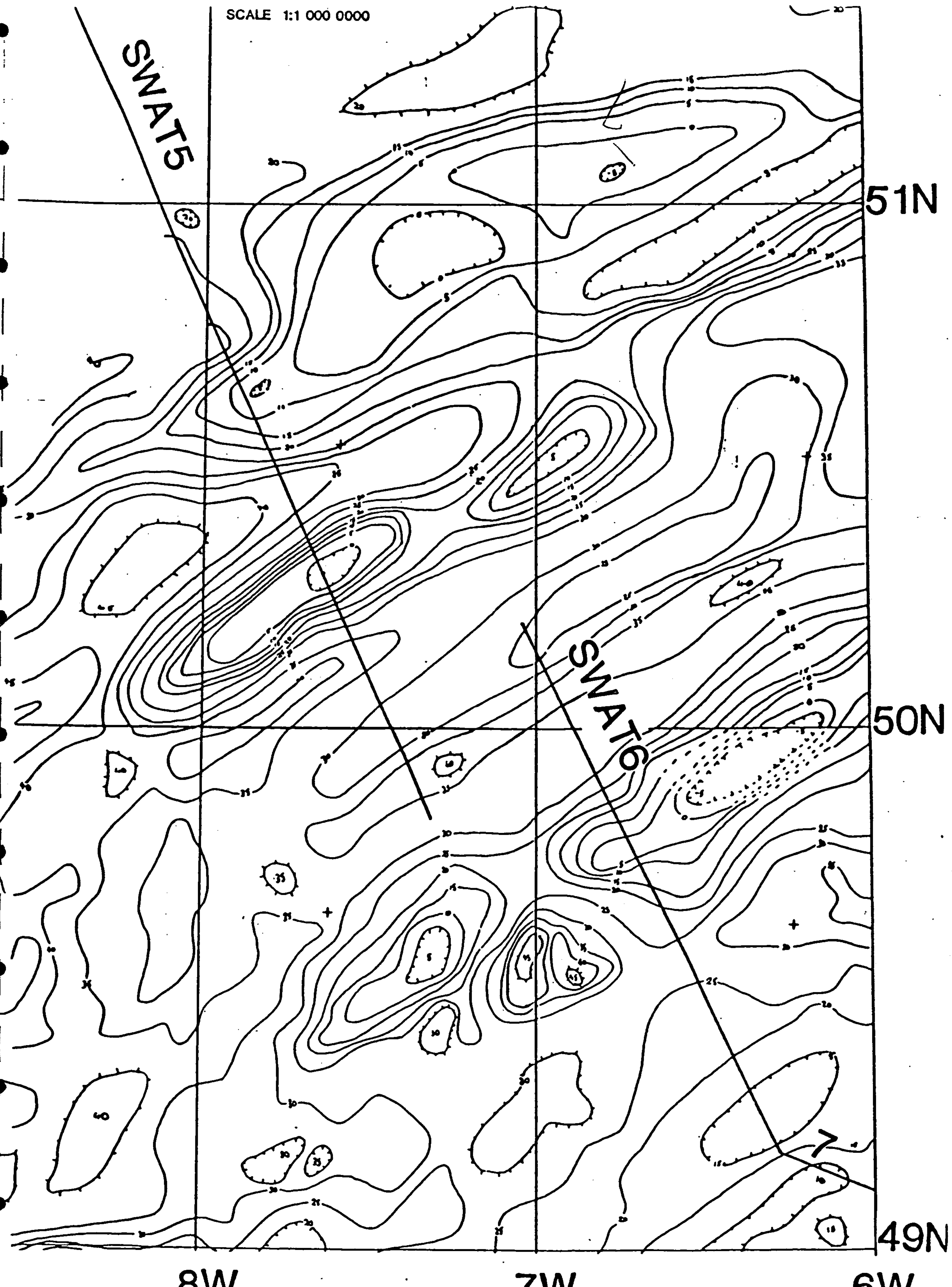


FIG.1 Bouguer anomaly map with the location of SWAT lines shown.

Fig. 2   CAPTION

Fig. 2. Regional Map Showing the main basins and granite outcrops —— x —— marks the approximate boundary between the Rhenohercynian and Saxothuriglan zones. NCSB, North Celtic Sea Basin; SCSB, South Celtic Sea Basin; VF, Variscan Front; BCB, Bristol Channel Basin, HF, Haig Fras granite outcrop; HFSB, Haig Fras Sub-basin; CP, Cornubian Platform; SI, Scilly Isles; GS, Goban Spur; CBB, Cardigan Bay Basin; FB, Fastnet Basin; SWAB, South Western Approaches Basin; WECB, West English Channel Basin. Black areas mark granite outcrops. The 2000m bathymetry contour is shown.

Fig. 3   CAPTION

The models of SWAT 5 & 6 are shown mounted end to end, note however there is in fact an overlap between the two (see fig. 1). SCSB, South Celtic Sea Basin; HFSB, Haig Fras Sub-basin; HFB, Haig Fras Batholith; CB, Cornubian Batholith; SWAB, South Western Approaches Basin. The calculated anomaly for each model is shown by the unbroken line the observed anomaly is shown by a dashed line. The dashed lines in the models represent boundaries where there is no seismic event on the record. —— x —— marks a possible boundary between lower crust bodies of different densities. Selected Shot Points are shown for SWAT 6.

FIG. 2

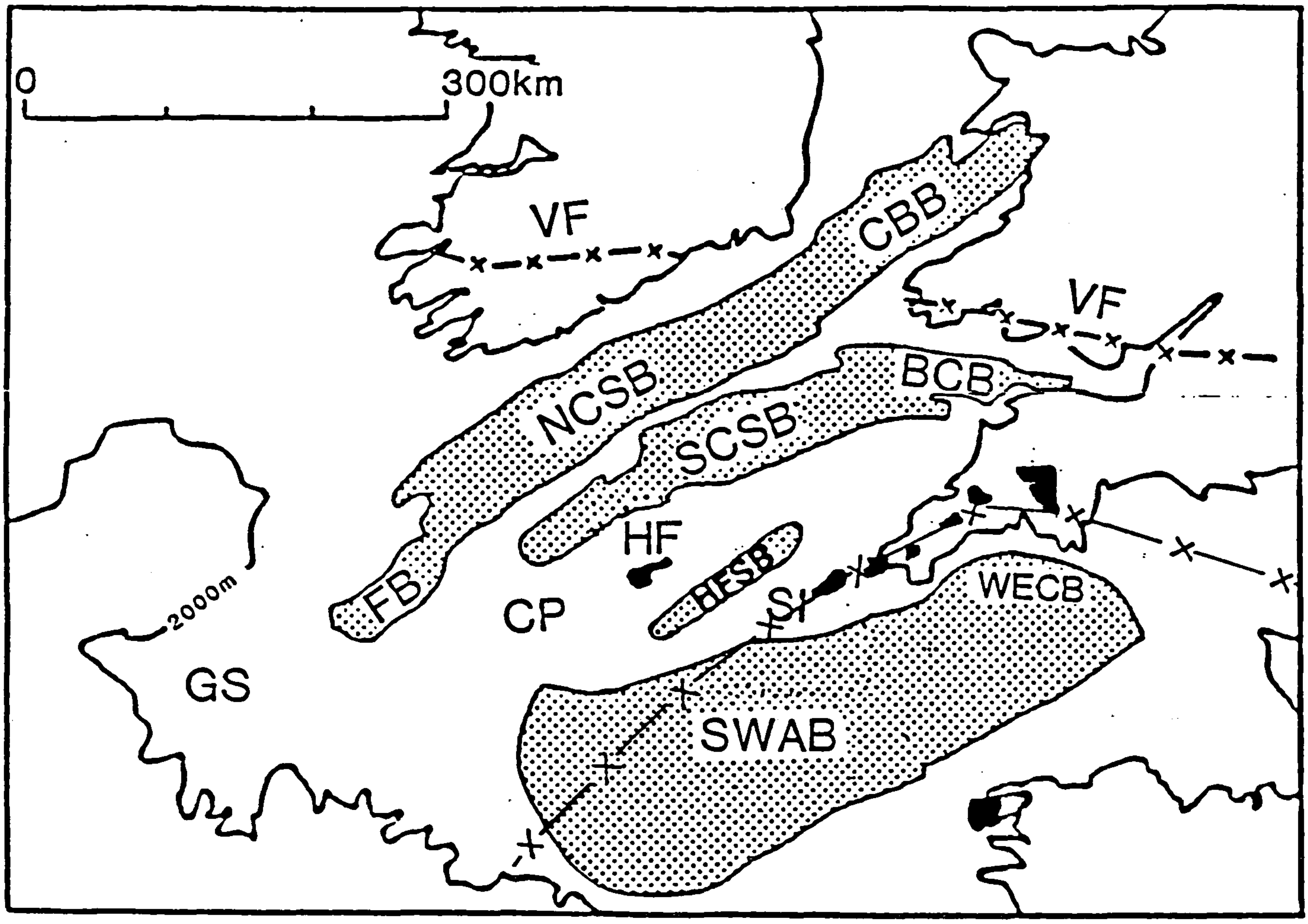
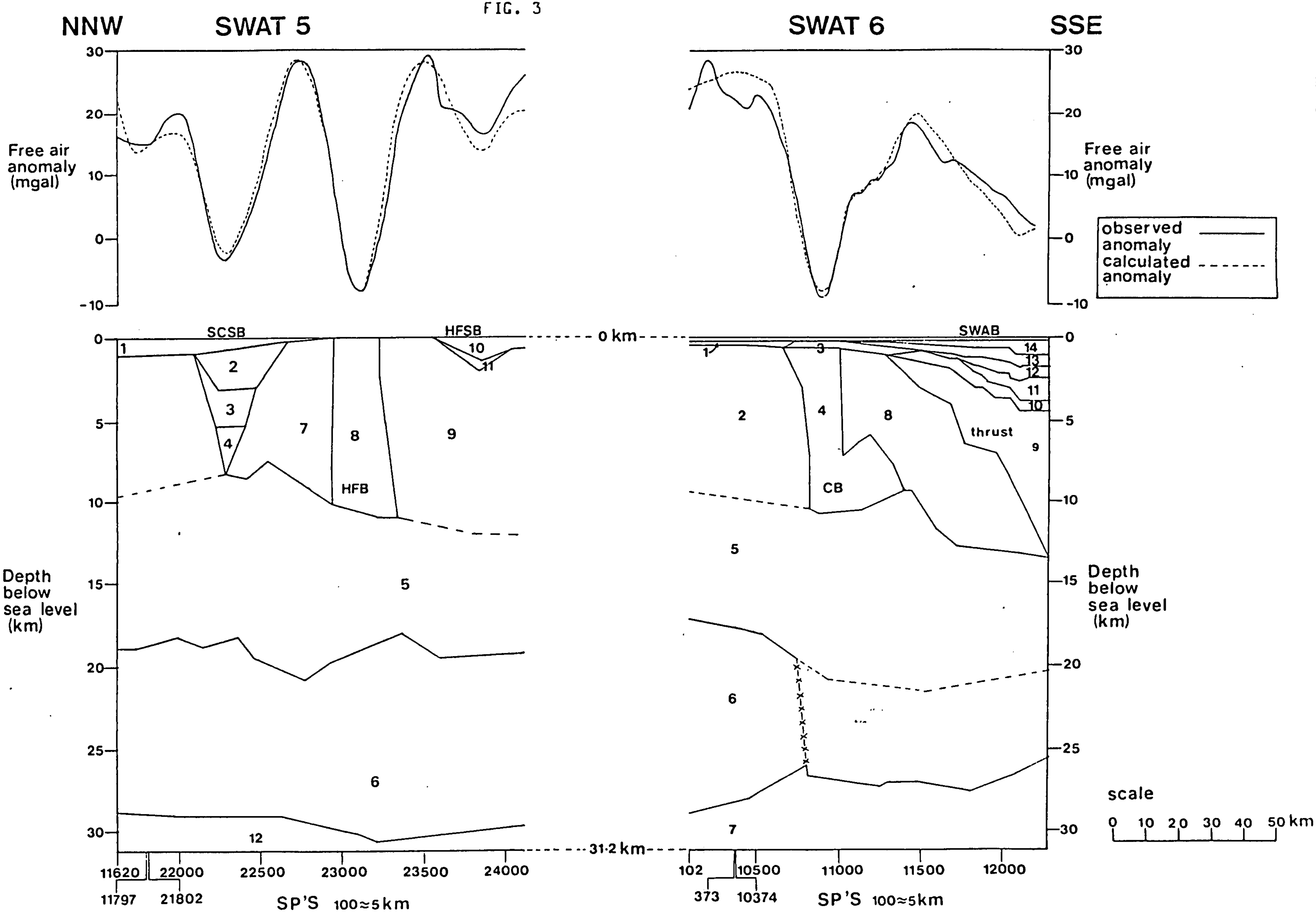


FIG. 3


NNW
SWAT 5
SWAT 6
SSE
Free air anomaly (mgal)
observed anomaly
calculated anomaly
SCSB
HFSB
SWAB
0 km
31·2 km
HFB
CB
thrust
Depth below sea level (km)
scale
0 10 20 30 40 50 km
SP'S 100≈5km
11620 22000 22500 23000 23500 24000
11797 21802
102 10500 11000 11500 12000
373 10374