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Tectonics of the Continental Margin off Northwest Spain

D.G. Roberts and P.R. Miles

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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1. INTRODUCTION

The geological history of the Bay of Biscay and its role in the evolution of the North Atlantic Ocean first attracted interest when Carey (1958) and Bullard et al. (1965) proposed an anticlockwise rotation of Iberia away from Europe to account for the triangular opening of the Bay and the Pyrenean deformation.

Subsequent studies have confirmed the oceanic nature of at least the central part of the Bay and show that the Bay probably formed by spreading in Aptian time (Bacon et al., 1969; Montadert et al., 1971; Montadert et al., 1974, 1979). Deep seismic reflection profiles across the facing margins of Biscay have however demonstrated a very striking asymmetry. The northern or Armorican margin of the Bay and its prolongation in the Aquitaine Basin consists of a series of tilted and rotated fault blocks covered by Tertiary and Cretaceous sediments (Montadert et al., 1974, 1979). In marked contrast the southern or Iberian margin has been greatly affected by overthrusting along its entire length from the Pyrenees to northwest Spain and is flanked to the north by the deep marginal North Spanish Trough (Boillot et al., 1971; Montadert et al., 1974) (Fig. 1). The Iberian margin has been interpreted as a 'subduction' complex representing the western continuation of the collisional Pyrenean orogen (Boillot et al., 1971; Boillot and Capdevila, 1977; Le Pichon and Sibuet, 1971; Montadert et al., 1974).

In models of the evolution of the Bay of Biscay, these contrasts in structural style have been reconciled by an initial phase of rifting (Late Jurassic-Early Cretaceous) followed by Aptian spreading with a later phase of compression in Late Cretaceous to Eocene time (Le Pichon and Sibuet, 1971; Montadert et al., 1974; Boillot and Capdevila, 1977). However, the original position and the sense of movement during the later compression of Iberia relative to Europe and North America has remained uncertain although of obvious relevance to understanding the palaeogeographic framework of the Southwestern Approaches during the phases of rifting and early spreading. One important reason for the uncertainty has been that the history, nature and position of the westward continuation of the Pyrenean orogen toward the mid-Atlantic Ridge required by plate tectonic theory has remained largely unknown and speculative.

This report is principally concerned with the tectonics of the margin off northwest Spain (Fig. 2) considered by some to be a conjugate of the margin in the Southwestern Approaches. The study area includes the margin north and northwest of Spain, Galicia Bank and the adjacent parts of the floor of the Bay of Biscay. Seismic reflection profiles, gravity, magnetic and long-range sonar data are used to demonstrate the westward continuation of the Pyrenean compression zone.

2. METHODS OF STUDY

The first cruise to the area from R.R.S. Shackleton (Cruise 6/76) was made because FCO policy excluded work in the original working area of the Southwestern Approaches and a second cruise R.R.S. Discovery Cruise 90, was made in 1978. During these cruises seismic reflection profiles were occupied using a 300 cu inch airgun and 6-channel seismic array. Gravity and magnetic data were also acquired and sonobuoys were deployed at key points to determine interval velocities and sediment thicknesses. During R.R.S. Discovery Cruise 90 the long-range sonar GLORIA (Somers et al., 1978) was used extensively. The latter results are the subject of a separate report (Roberts and Kidd, 1980) but have been used herein to establish the continuity and trend of structures identified on the seismic reflection profiles. Operational details of these cruises can be found in the cruise reports (Roberts et al., 1976, 1978). Additional data sources are referred to in the relevant sections of this report.

3. BATHYMETRY (Fig. 2)

The physiography of the continental margin northwest of Spain has been previously outlined by Berthois et al. (1965), Black et al. (1964) and Laughton et al. (1975).

The linear margin north of Iberia trends WNW-ESE between 7^{o} and 9^{o}W and consists of a relatively narrow shelf and steep slope whose junction with the adjoining Biscay abyssal plain is sharp. The slope is cut by rare canyons whose course has been controlled by major left lateral transcurrent faults (Boillot et al., 1971; Lamboy and Dupeuble, 1975). The very narrow shelf off northern Spain compared to the broad shelf in the Southwestern Approaches here reflects the thin Late Tertiary sediments that have prograded over highly deformed sediments of Tertiary and Mesozoic age.

Near 9°W, the slope changes abruptly in trend to NE-SW. The upper part of the slope is in contrast gentler and is cut by two broad troughs originating in mid-slope and known as Coruna Canyon and Lage Canyon (Fig. 2). The latter feature is bounded to the south by a prominent steep sided ridge of WNW-ESE trend called the Pardo Bazan spur. West of this feature the slope changes trend to E-W and comprises the northern flank of Galicia Bank.

To the south a broad N-S trending trough, here called the interior basin, separates the shallow Galicia Bank from the shelf and slope off mainland Iberia. The interior basin continues northward as far as the base of E-W trending part of the slope proper and effectively breaks the continuity of the steeper slope developed north of Galicia Bank and northwest of Coruna.

East of the interior basin the Iberian shelf is narrow and only thin sediments are present (Boillot et al., 1971, 1979; Lamboy and Dupeuble, 1975; Groupe Galice, 1979). A few canyons and minor seamounts that may represent small horsts break the slope. The western side of the basin is the eastern slope of Galicia Bank defined in the north by a prominent NW-SE trending scarp that becomes increasingly subdued to the southeast. North of Galicia Bank the east-west slope is particularly steep and in its upper part is broken by several small, isolated ridges. West of 12°W, the slope curves to the southwest and then trends N-S.

No clear continental rise is present off northern Spain and the Biscay abyssal plain directly abuts the foot of the slope. The abyssal plain is constricted between the Iberian slope and the Biscay Seamounts but widens north of Galicia Bank. In this region, the abyssal plain (hereafter called the Galicia Abyssal Plain) has a barely perceptible slope to the southwest and funnels toward the Theta Gap (Laughton, 1960, 1968). The plain is cut by numerous distributary channels, that converge toward Theta Gap and are thought to have been cut by turbidity currents outflowing from the Biscay Abyssal Plain to the Iberian Abyssal Plain via the Theta Gap (Roberts and Kidd, 1980).

The northern edge of the Galicia abyssal plain is defined by the prominent east-west trending Biscay and Charcot Seamounts. Asymmetrically situated in the mouth of the Bay of Biscay, Williams (1975) postulated that these seamounts represented the extinct mid-ocean ridge axis of Biscay. However, Laughton et al. (1975) have noted that the seamounts are anomalously shallow compared to adjoining ocean basins of similar age. The Biscay seamounts are separated from the North Charcot Seamount by a prominent NW-SE trending scarp. The North and South Charcot Seamounts are divided by an E-W trending trough that is closed westward by the WNW curvature of the south side of Charcot Seamount. Coruna Seamount, located northwest of Theta Gap and on the west side of the Galicia Abyssal Plain has in comparison a subdued relief and an ill defined NW-SE trending northern edge. GLORIA traverses across Coruna Seamount show NNE-SSW topographic trends that parallel the oceanic magnetic lineations (Fig. 2).

To the west of Charcot and Coruna Seamounts, the topography is dominated by the elevated Azores-Biscay Rise. This feature trends NE-SW and links the Charcot Seamounts to the complex en echelon pattern of NW-SE trending ridges and troughs that comprise the King's Trough and Peake-Freen deeps. In its northern part, the Azores-Biscay Rise is linked to the Charcot Seamount by an east-west ridge that cuts across anomaly 31-32 (Fig. 2). Between the Azores-Biscay Rise and Coruna Seamount, the ocean floor is substantially depressed below the adjoining basins and depths are the greatest in the North East Atlantic outside the King's Trough complex (Laughton et al., 1975). This regional depression only occurs along the length of the Azores-Biscay Rise between the King's Trough complex in the south and the Charcot Seamounts in the north. Within the depression are a series of NE-SW trending linear ridges and troughs that include the Mirrol Trough (Laughton et al., 1975; Addy and Kagami, 1979) and lie oblique to the oceanic magnetic anomalies.

4. REGIONAL GEOLOGY AND SEISMIC STRATIGRAPHY

4.1 Regional Geology

The southern part of the study area embraces the northern edge of the

Lusitanian basin of onshore and offshore Portugal. The basin has an overall NNE-SSW trend that cuts across the tectonic grain of the Hercynian terrains of northwest Iberia (Wilson, 1975; Arthaud and Matte, 1975). Within the basin, the oldest Mesozoic beds are conglomerates, sandstones and evaporites of Triassic age. Evaporites and dolomites were deposited in Early Jurassic time but open marine conditions followed and prevailed until a regression in Oxfordian time. Marine deposition continued during the Late Jurassic and was succeeded in the Latest Jurassic and Early Cretaceous by a regional regression and associated clastic deposition possibly coeval with the important 'Cimmerian' epeirogenesis of western Europe that preceded the onset of spreading (Montadert, Roberts et al., 1979; Groupe Galice, 1979). After the mid-Cenomanian transgression, the basin was subjected to alternating transgressive-regressive episodes in Late Cretaceous and Tertiary time.

In northern Spain in contrast, the Mesozoic and Tertiary sediments are highly deformed and flanked northward by the thick and overthrust sediments of the North Spanish Marginal Trough (Boillot et al., 1971; Montadert et al., 1974). The deformed zone that characterises the margin corresponds to the north Pyrenean Frontal Zone and is continuous with the Pyrenees and southern Aquitaine Basin. The northern Iberian margin and the contiguous Pyrenees have been structured by both rifting and compression (Montadert et al., 1971; Winnock, 1971; Boillot et al., 1971; Montadert et al., 1974; Boillot and Capdevila, 1977; Boillot et al., 1979). Rifting may have begun as early as Late Stephanian-Early Permian time when Late Hercynian shear movements fractured the deformed Hercynian terrain (Arthaud and Matte, 1975). Regional extension took place in the Triassic but the major phase of rifting that structured the margins of Biscay was initiated in Oxfordian time and intensified during the Late Jurassic-Early Cretaceous to be followed by spreading in Aptian time (Montadert, Roberts et al., 1979). Possible initiation of the Pyrenean deformation in the Late Cretaceous may be recorded by the Late Cretaceous flysch (Mattauer and Henry, 1974). Partial 'subduction' or closure of the Bay of Biscay took place between Late Cretaceous and Eocene time culminating in late Eocene and Early Oligocene time although movement continued until Oligocene and perhaps as late as Miocene time in parts of the Pyrenees (Mattauer and Henry, 1975).

4.2 Seismic stratigraphy Data Sources

Seismic profiles occupied during RRS Shackleton 6/76 and RRS Discovery Cruise 90 form the major part of the data base. These profiles were planned to examine the structural relationships between the North Spanish Trough, Biscay Seamounts and the margin north of Galicia Bank. Previously published seismic profiles (Collette (1971); Talwani et al. (1974); Addy and Kagami (1979); Anonymous (1971); Groupe Galice, (1979)) have also been used in the regional seismic interpretation. In addition GLORIA sonographs obtained during RRS Discovery Cruise 90 have been used to establish the trend and continuity of structures identified on the seismic profiles.

4.3 Seismic stratigraphic nomenclature

For convenience and ease of description we have followed the seismic stratigraphic nomenclature developed by Montadert et al., (1974, 1979) for the Bay of Biscay and adopted by Groupe Galice (1979) for the margin west of Iberia.

In the margin off Portugal the seismic reflection profiles typically show a layered sedimentary sequence resting on acoustic basement. Four seismic formations numbered 1 to 4 in downward succession comprise the sedimentary cover. Of these formations 1 to 3 correspond to those previously identified in the Bay of Biscay (Montadert et al., 1979). Information on the age stratigraphy and lithology is based on the calibration given by the section cored at DSDP site 398 and on the results of dredgings in the Galicia Bank area (Black et al., 1964; Dupeuble et al., 1976; Mauffret et al., 1978; Ryan, Sibuet et al., 1979; Groupe Galice, 1979).

4.4 Seismic stratigraphy and structure west of Iberia

To the south, west and east of Galicia Bank, the basement exhibits considerable relief and is considered to consist of a series of tilted and rotated fault blocks (Fig. 3). In the deeper part of the basins the original asymmetry of the tilted blocks has been preserved but the flat tops of Galicia Bank and small seamounts adjacent to the west Iberian shelf may indicate truncation by sub-aerial erosion (Montadert et al., 1974; Mauffret et al., 1978; Groupe Galice, 1979). The tilted blocks can be followed close to the continent-ocean boundary west of Galicia Bank where Lherzolites of continental affinity have been dredged (Boillot et al., 1980). Plutonic and metamorphic rocks have also been dredged from basement outcrops as well as neritic limestones of late Jurassic and early Cretaceous age although these may not represent part of the basement (Group Galice, 1979).

Formation 4 is apparently restricted to the margin since it cannot be followed out into the oceanic crust west of Iberia (Groupe Galice, 1979). It infills narrow troughs between tilted blocks or horsts and the reflectors exhibit upward flattening dips indicative of syn-tectonic deposition. Formation 4 was partly penetrated at site 398 (Sibuet & Ryan, 1979) and at T.D. consisted of Hautervian limestones and marls that graded upward into Aptian turbiditic non-calcareous sandstones and siltstones. The top of formation 4 thus corresponds to the lower part of formation 3 of Biscay (Montadert et al., 1979; Roberts et al., 1980). The oldest Mesozoic beds dredged in the area are of Late Jurassic-Early Cretaceous age and in contrast comprise shallow water bioclastic limestones and Calpionellid pelagic micrites indicative of open sea shelf conditions (Boillot et al., 1971; Groupe Galice, 1979). These beds may correspond to the base of formation 4.

Formation 3 is in contrast transparent exhibiting only minor layering. The site 398 data indicates that it represents the Albian-Cenomanian black shale interval (Sibuet, Ryan et al., 1979).

Formation 2 rests with erosional and perhaps minor tectonic unconformity on top of formation 3 and is of Campanian to Eocene age. As in the Bay of Biscay much of the Late Cretaceous section is absent. Well developed reflectors within formation 2 are attributed to variations in $CaCO_3$ content (Sibuet, Ryan et al., 1979; Groupe Galice, 1979).

Formation 1 consists of an upper member 1a and a lower member 1b. The latter member rests on the deformed surface of formation 2 with clear angular unconformity revealed by onlap of the well developed reflectors in the lower part of the unit. Correlation with site 398 shows that the basal part of Formation 1 is of Oligocene age and therefore that the deformation affecting formation 2 is contemporaneous with that observed in Biscay and is thus related to the Pyrenean deformation (Sibuet, Ryan et al., 1979; Groupe Galice, 1979). The upper part of formation 1b is of Miocene age. Formation 1a is of Late Miocene to Recent age. Beneath the slope, mud waves observed in formation 1a indicate differential deposition by bottom currents but beneath the Iberian abyssal plain it is well layered.

4.5 Seismic stratigraphy and structure north of Iberia

Correlation of the seismic stratigraphic sequences observed south and east of Galicia Bank with those observed to the north is difficult. This is because the deformation extending up to the top of formation 2 increases northward and becomes most intense in a narrow zone of overthrusting that extends the length of the margin from Finisterre Seamount to the North Spanish Trough (Fig. 4, 7, 8). The existence of this zone precludes a direct correlation between the sequences observed on and around Galicia Bank and those present north of and within the deformed zone. Contemporaneous tectonism also extends from the Azores Biscay rise, north of the Biscay-Charcot Seamounts and through the Biscay Abyssal Plain (Fig. 5). In these areas correlation is further complicated by the change from the well layered seismic facies characteristic of the abyssal plain areas to the acoustically transparent facies draped on the crests of seamounts and buried abyssal hills. Nonetheless throughout this region two seismic formations divided by a clear unconformity that marks the end of a period of regional tectonism are present (Fig. 5, 7, 8). In the abyssal plain areas the upper seismic unit extending to the present sea-floor is not deformed and is characterised throughout by numerous strong reflectors interpreted as turbidites although a number of sequences may also be present within the unit. Correlation with DSDP holes 118, 119 and 400A (Laughton, Berggren et al., 1972; Montadert et al., 1974; Montadert, Roberts et al., 1979) shows that the base of this unit is of Oligocene age in good agreement with the correlation established south of Galicia Bank. The seismic formation above the unconformity corresponds to formations 1a and 1b identified to the west of Galicia Bank and is probably equivalent to the undeformed and acoustically transparent formation that drapes the Biscay and other seamounts. The stratigraphic equivalence of the underlying deformed formation is however much more questionable. It is clear that the top is of Eocene age but the age of its base is uncertain because a clear basement surface cannot always be seen partly because of the quality of the seismic data but also because of subsequent tectonism. For example, formation 3 can be followed south and across Biscay to the Biscay Seamounts but there disappears completely in the tectonised zone bordering these seamounts (Fig. 5). Impersistent but coherent reflections within the seamounts may indicate that they consist of uplifted and tectonised Biscay ocean crust and sediments. Between the Biscay Seamount and Galicia Bank there are hints of deeper reflections within the basement. In this area the nature of the transition between continental and ocean crust and its position is obviously relevant to the presence or absence of formations 3 and 4. The magnetic and gravity data discussed later impose some constraint on this problem but an unambiguous division of basement into crustal types within this tectonised zone is clearly impossible from the seismic reflection data alone and there are no refraction data. For the purposes of this report, the basement has been mapped as the deepest clear reflector (Fig. 4).

5. STRUCTURE OF THE MARGIN AND THE ADJACENT DEEP SEA-FLOOR (Fig. 4)

The structure of the margin west and northwest of Spain can be divided into two provinces of contrasting structural style and age that are reflected in the physiography (Fig. 2, 4).

The slope and adjacent sea-floor north of Spain have been tectonised by transcurrent and thrust faulting that ended in Eocene-Oligocene time (Fig. 4, 5, 7, 8). Those movements created the complex topography between the Azores-Biscay Rise, Biscay Seamounts and Galicia Bank as well as the steep slope off western and northern Spain.

In contrast, the region to the south of and including Galicia Bank was largley shaped by rifting during Late Jurassic-Early Cretaceous time. The shallow banks and deep troughs developed in the area represent the original relief of horsts and grabens developed during rifting and modified by subsequent sedimentation (Fig. 3). In this region, the principal faults have been mapped from seismic reflection profiles and GLORIA data. Three different fault trends are apparent on Galicia Bank (Fig. 4). Major faults of NW-SE trend that control the east margin of Galicia Bank probably also structured the interior basin between Galicia Bank and the Iberian margin. Faults of this trend are hinted at by steeper gradients in the isopachs of the Iberian slope but their identity is less clear. On the west margin of Galicia Bank NW-SE trending faults influence the major relief but are themselves cut by a system of NE-SW trending faults producing a complex region of horst and graben. N-S trending faults are apparent near 42°N in the west margin of Galicia Bank but are generally rare. These fault trends are closely similar to the trends of the principal structural lineaments observed in the Hercynian terrains of Iberia (Berthois and Sibuet, 1979). These lineaments are of Permo-Stephanian age and originated in the Late Hercynian shear movements (Arthaud and Matte, 1975). Rifting between Iberia, Europe and the Grand Banks may have rejuvenated and followed these older lineaments.

North of Spain, in contrast, folded and faulted sediments of Mesozoic and Palaeogene age underlie the shelf (Boillot et al., 1971; Lamboy and Dupeuble, 1975). Folds are cut by prominent NW-SE trending transcurrent faults that may also be rejuvenated Late Hercynian shears. Beyond the base of the slope, at least 4 seconds of sediment underlie the North Spanish Trough, which is flanked to the north by the South Gascony Ridge. Within the trough, close to the base of the slope, the flat lying sediments below formation 2 are overthrust by a series of thrust faults (Fig. 4, 8). Horizontal displacement on the outer thrust fault may be about 20km but the cumulative shortening cannot be estimated from our data. These faults can be followed on both seismic profiles and GLORIA sonographs as a characteristic zone of rough topography along the base of the slope as far as its change in trend near 9°W. Although the seismic profiles do not provide any information on the deformation beneath the steep slope, the GLORIA sonographs show a very clear WNW-ESE trending lineament that obliquely crosses the contours up slope and can be linked to one of the thrusts observed at the base of the slope (Roberts and Kidd, 1980). A particularly striking feature is the westward decrease in width and depth of the North Spanish Trough also revealed by the convergence of the thrusts within the trough toward 9°W (Fig. 4).

Between 9°W and 12°13'W the slope is also tectonised and is similarly flanked to the north by a deep trough here called the

Galicia Trough (Fig. 4). The Galicia Trough joins the North Spanish Trough at its constriction near 9^{O}W and is thus its westward continuation. However, in contrast to the WNW-ESE trend of the latter, the axis of the Galicia Trough trends NE-SW. Within the trough and towards the slope, sediments below formation 2 are cut by thrust faults, that are clearly revealed in the topography and on GLORIA sonographs as curvilinear features extending along the base of the slope. North of Pardo Bazan Spur, thrusts on the slope curve to the south and are truncated against this prominent NW-SE trending spur. To the west, the zone of thrusting is confined to the region of the slope and has not apparently affected the normal faults on Galicia Bank (Fig. 4). The thrusting cannot be traced with confidence beyond 12^{O}30'W where the isopachs show that the deep basement underlying the North Spanish Trough and associated with the deformation has shoaled to depths more typical of the adjoining oceanic basement (Fig. 4). West of Galicia Bank, faults continue up to the top of formation 2 but the spectacular compression observed to the north is no longer apparent.

Deformation has also affected much of the sea-floor north and north-west of the Iberian margin. The deformation can be traced as far north as the Trevelyan escarpment but it becomes most significant at the northern edge of the Biscay and Charcot Seamounts. In this area (Fig. 4, 5, 8) transcurrent and thrust faults affect about 2.0 seconds of sediment above the underlying oceanic crust, which is then cut out on the seamounts where less than 0.5 seconds of sediment rest on the 'basement' of the Biscay Seamounts. The seamounts plunge eastward beneath the younger Oligocene to Recent turbidities of the Biscay Abyssal Plain to merge with the South Gascony Ridge (Fig. 4). Uplifted fault blocks developed along the South Gascony Ridge include Cantabria Seamount (Laughton, Berggren et al., 1972; Montadert et al., 1974) (Fig. 7).

To the west the Biscay Seamounts are separated from the North and South Charcot Seamounts by a prominent NW-SE trending fault. These seamounts are thinly covered in sediments and themselves divided by an east-west trending trough that is closed near 14^{O}W by the north-west curvature of South Charcot Seamount (Fig. 4). In this area, the western edge of both North and South Charcot Seamounts is marked by a NE-SW trend that defines an abrupt change in the depth and nature of the relief. To the west, the sea-floor is deeper (Fig. 2, 4) and characterised by extremely irregular topography of short wavelength in which no trends can be mapped convincingly. The zone, which is crossed by anomaly 31-32 (Fig. 2) rises westward to form the northeastern limit of the Azores-Biscay Rise. The fault zone associated with the northern edge of the Biscay and Charcot Seamounts may persist westward along the northern edge of the Azores-Biscay Rise but its continuation beyond 15°W is doubtful.

To the south, the Galicia Trough comprises the region between the Biscay and Charcot Seamounts, Coruna Seamount and Galicia Bank. The north side of the trough is defined by a prominent fault zone that marks the southern edge of the Biscay and Charcot Seamounts (Fig. 4). The fault zone gradually changes trend westward from ENE to WNW and in the east is continuous with the north flank of the North Spanish Trough or faulted flank of the South Gascony Ridge. The fault has a throw of between 1 and 2 seconds near 10°W but increases in throw westward to about 3 seconds adjacent to the more elevated point of South Charcot Seamount. The fault cannot be traced west of 14°W with confidence. However the clear east-west gradient marking the boundary between the Azores-Biscay Rise and adjacent rough zone to the south may mark its continuation. Within the Galicia Trough the basement shoals westward toward Coruna Seamount. There is some evidence (Fig. 4, 8) of a buried sub-surface E-W trending high that plunges eastward dividing the western Galicia Trough into two sub-basins but the structural relationship between the Coruna Seamount and the Galicia Trough is not clear. NNE-SSW structural trends on Coruna Seamount parallel the magnetic anomalies but terminate against the inferred NW-SE trending fault defining the north edge of the seamount near 44°30'N 14°W. Further south however, these trends bear to the NE, parallel to the tilted blocks off West Galicia Bank and apparently merge with the sub-surface high.

Northwest of Coruna Seamount, there is a radical change in the topography and tectonic trends of the basement. The northwestern side of the seamount is defined in part by a prominent NE-SW scarp with downthrow to the northwest (Fig. 4). Within the intervening basin between Coruna Seamount and the shallower Azores-Biscay Rise, are several deep troughs whose trends lie oblique to the Azores-Biscay Rise and the Coruna Seamount fault (Addy and Kagami, 1979). These troughs end northward against the shallower and generally east-west trending topography of the northern Azores-Biscay Rise and Charcot Seamounts. To the south, they become parallel to the steep east flank of the Azores-Biscay Rise. These troughs, of which the most prominent is the Mirrol Trough (Addy and Kagami, 1979) are substantially deeper than the adjoining ocean floor and at least partly cut across the trend of the oceanic magnetic anomalies here of anomaly 31-32 age. Seismic profiles across the troughs show a deformed pelagic sequence of presumed pre-Oligocene age infilled by turbidites. The anomalous depth of these troughs and their cross cutting relationship to the magnetic anomalies suggests that they have been affected by tectonism that post-dated the formation of the ocean crust and may have continued up till Oligocene time.

Topographic and structural trends on the adjacent Azores-Biscay Rise are E-W in the north but NE-SW in the south. The trends established from GLORIA surveys cut across the magnetic anomalies that characterises the underlying crust.

6. FREE-AIR GRAVITY ANOMALIES

6.1 Data Sources

The free-air gravity anomaly map (Fig. 6) has been compiled from data collected by the Institute of Oceanographic Sciences, the Department of Geodesy and Geophysics, University of Cambridge, the Centre Oceanologique de Bretagne (Anonymous, 1971), the Hydrographic Department (MoD) of the United Kingdom and Lamont-Doherty Geological Observatory. Cross-over errors between tracks positioned using satellite navigation were less than 5 m gal and the contours have been weighted toward these better quality gravity data.

6.2 Free-air gravity anomalies

The free-air gravity anomaly clearly reflects the major topographic elements of the study area but shows three obvious and important features. To the north of Iberia, a WNW-ESE trending zone of strongly negative anomalies coincides with the thick sedimentary section of the overthrust

North Spanish Trough (Fig. 6). Towards the continent, the anomaly has an amplitude of about 250 m gal. The northern edge of the anomaly is defined by a strong ENE-WSW trending gradient coincident with the flank of the South Gascony Ridge. The negative anomaly narrows westward reflecting the partial closure in the sub-surface of the North Spanish Trough and has a value of -60 m gal at the most constricted point near 9^{O}W. In the Galicia Trough the anomaly broadens and deepens southwestward but closely parallels the trend of the slope. The axis of minimum gravity values coincides with the maximum sediment depths in the Galicia Trough. The negative anomaly is smaller than that associated with the North Spanish Trough although the amplitude of the anomaly reaches 270 m gal near 9^{O}W. The anomaly is closed to the southwest near Finisterre Seamount by the zero contour. The sub-surface high within the Galicia Trough is revealed as an east-west trend of more positive values in the negative zone.

To the north, the steep gravity gradient and positive anomalies are associated with the Charcot and Biscay Seamounts. The anomaly contour map clearly shows the continuity between the Biscay-Charcot Seamount and the South Gascony Ridge.

In the western part of the area, the gravity field is dominated by topographic effects associated with the Azores-Biscay Rise and Coruna Seamount. The positive anomalies associated with the latter feature define the western edge of the broad negative anomaly associated with the Galicia Trough. The northeastern edge of Coruna Seamount is defined by a fairly linear NW-SE gradient suggesting a clearer structural break than is immediately obvious from the structure map. Between the Coruna Seamount and Mirrol Trough there is a total change in gravity of 130 m gal. The Mirrol Trough region is associated with negative anomalies of about -50 m gal that close southward in the region where linear structural trends become important. The total gravity change between the Mirrol Trough and the Azores-Biscay Rise is 200 m gal and is comparable in value with the change between the Galicia Trough and the margin off Galicia Bank and northwest Spain.

Galicia Bank is associated with a positive anomaly that locally exceeds 120 m gal. Prominent NE-SW trending gradients and anomalies reflect both topographic effects and the influence of buried NW-SE trending fault blocks. Off west Iberia, the more complex anomaly pattern may arise from the effect of buried fault blocks of uncertain trend superimposed on regional topographic effect of the slope.

6.3 Gravity models

To further investigate the relationship between the deep structure and negative gravity anomalies associated with the overthrust Galicia and North Spanish marginal troughs, profiles oriented perpendicular to the slope of Galicia Bank and Coruna were selected for quantitative model studies (Fig. 7, 8). A third NW-SE profile from the Azores-Biscay Rise to Galicia Bank was also modelled to investigate the Mirrol Trough and the slope region west of Galicia Bank apparently unaffected by overthrusting (Fig. 9). A specific objective of the study was to determine the position and nature of the continent-ocean boundary within the overthrust marginal troughs.

Seismic refraction velocity control on the depths and densities is limited to early refraction profiles on Galicia Bank reported by Black et al. (1964) and more recent refraction profiles in Biscay (Bacon et al., 1969). Interval velocities in the sedimentary section are better known from sonobuoy velocity measurements (Sichler et al., 1971; Miles, 1979). Two-dimensional gravity models were computed using a program developed to compute and plot sea level gravity and mass anomalies.

The choice of densities of the sediment and underlying crystalline basement was made using the Nafe-Drake curve (Ludwig et al., 1970) and the limited refraction data. An average density of 2.0 Mg m^{-3} was used for the upper sediments. Higher densities within these sediments indicated by interval velocities of over 2.5 km sec^{-1} did not significantly improve the fit between the calculated and observed anomalies. Deeper sedimentary layers were assigned densities of 2.2 - 2.4 Mg m^{-3} according to the Nafe-Drake relationship and further adjusted to allow for depth of burial. Average crustal densities of 2.6 and 2.9 Mg m^{-3} were assumed for the crystalline basement and a density of 3.4 Mg m^{-3} for the upper mantle. Lateral variations in mantle density were simulated by a small density gradient.

Profile 3 (Fig. 7) is a nearly N-S profile that crosses Cantabria Seamount atop the South Gascony Ridge and the North Spanish Trough, and lies close to profiles previously modelled by Bacon et al. (1969) and Sibuet and Le Pichon (1971). Control on the position of the interfaces in the upper part of the section is based on the overthrusting observed on the seismic profile above and profiles reported by Montadert et al. (1974). The agreement between the observed and calculated anomalies is very good. The model does however have a number of unusual features. The depression of the surface of the crystalline basement toward the base of the slope is particularly clear but it does not begin to thicken appreciably until a point about half-way across the marginal trough. To satisfactorily model the anomaly, it was found necessary to include a sharp density discontinuity beneath the lower slope between low density material oceanward and a high density landward. The existence of such a discontinuity was previously recognised by Sibuet and Le Pichon (1971) who concluded that it was not produced by relative changes in the depth and gradient of the Moho relative to the slope, and they considered that the lateral variation in density might be caused by the presence of intrusive bodies such as are known at DSDP site 118, or by the presence of imbricated sheets of ocean crust incorporated in the thrust zone along the northern margin of Iberia. The position of the continent-ocean boundary is not obvious from the model and it is quite possible that the original boundary may have been totally obscured by the overthrusting. There are nonetheless two possibilities. The steep discontinuity in density may correspond to the boundary modified by oceanward thrusting that has incorporated the oceanic basement. Alternatively, a zone of thinned continental crust (c.f. Avedik & Howard, 1979; Montadert et al., 1979) may underlie the inner part of the North Spanish Trough.

Profile 1 (Fig. 8) crosses the Biscay Seamounts, Galicia Trough and Galicia Bank. The interpretation is constrained by sonobuoy data in the Galicia Trough and by refraction data on Galicia Bank and in central Biscay. The agreement between the calculated and observed profiles is good. The most striking feature of the profile is the very gradual increase in thickness from north to south and the very small difference in depth of the Moho beneath the Biscay Seamounts and Galicia Trough. The profile across the Biscay Seamount has been satisfactorily modelled using a high density basement thus precluding the existence of a low density sedimentary section perhaps incorporated in the seamount by the thrusting along its northern edge. Within the Galicia Trough only 3km of sediments are present compared to 5km beneath the North Spanish Trough although the two troughs are comparable in width. In contrast to the profile across the North Spanish Trough (Fig. 7), the landward edge of the Trough has been modelled by a vertical boundary suggesting that here the boundary may consist of high angle thrust faults as opposed to low angle thrusts. Further the observed anomaly has been satisfactorily modelled without postulating the large density discontinuity required in the lower crust in profile 3, suggesting its absence. The position of the continent-ocean boundary is again not obvious on the model and, on the basis of the gravity profile alone, it would be perfectly reasonable to postulate thinned continental crust beneath the Galicia Trough that thickens southward beneath Galicia Bank. The seismic evidence however shows that the Late Eocene-Oligocene deformation affecting formation 2 extends the length of this profile in contrast to the restricted but more intense deformation observed in the North Spanish Trough. The greater width of the tectonised zone in this area may here reflect the presence of a wider zone of thinned continental crust beyond the base of the slope in contrast to a narrower zone off Northern Spain.

Profile 2 (Fig. 9) extends from the Azores-Biscay Rise to Galicia Bank. The profile is arguably not two-dimensional but is approximately perpendicular to the NE-SW trending fault blocks of northwest Galicia Bank. The profile is not constrained by any refraction data except on Galicia Bank. Sediment depths have been taken from the accompanying reflection profile and the deeper crustal layers simply adjusted to give the best fit. The crust thins northwestward from Galicia Bank to about 17km in the vicinity of Finisterre Seamount. The change in magnetic anomaly character at this point and the presence of continental Lherzolites along the strike to the south (Boillot et al., 1980) suggests the continental-ocean boundary may lie in this area. The Moho shoals westward beneath the Coruna Seamount to a point near 300km. West of this point and beneath the complex area of the Mirrol Trough the Moho deepens to rise again beneath the Azores-Biscay Rise. Coincidence of the changes in Moho depth with the tectonized zone at the foot of the Azores-Biscay Rise suggests that these may be real although the sense of change is the reverse of that which might be anticipated from the topography alone. More refraction data are clearly needed but we speculate that one cause of the crustal thickening might be due to compression related to that observed off Northern Spain.

7. MAGNETIC ANOMALIES

The magnetic anomaly contour map (Fig. 10) is based princiaplly on the compilation by Roberts and Jones (1975) of data from a variety of sources including the aeromagnetic survey of the Bay of Biscay (Le Mouel et al., 1971).

There are three distinct magnetic anomaly provinces in the area. The shelf and slope are characterised by low amplitude predominantly negative anomalies whose trend broadly reflects the underlying topography. Beyond this region, the anomalies have substantially greater amplitude and two distinct sets of lineations are present. One set that characterises much of the Bay of Biscay, trends WNW-ESE to E-W and terminates near 45°N 14°W. North of this point the prominent lineations sub-parallel the axis of the Mid-Atlantic Ridge and curve from NNW to NNE. The change in trend of these anomalies and their junction with the Biscay anomalies closely coincides with the tectonised area at the junction of the Azores-Biscay Rise and Charcot Seamounts.

The pattern of anomalies within the Bay of Biscay is complex and not easily understood in terms of a simple spreading model (Le Mouel et al., 1971). In the northern and eastern parts of Biscay, the rather weak anomalies trend NW-SE parallel to the North Gascony Ridge. These anomalies are superimposed on the broad positive anomaly assotiated with the Biscay Seamounts and terminate against the prominent east-west trending negative anomaly that continues westward across the Charcot Seamounts. South of this negative anomaly an ENE-WSW trending positive anomaly coincides with the outer flank of the North Spanish Trough (the South Gascony Ridge) and continues southwestward across the foot of the slope and into the Galicia Trough. Displacements in the axis of this anomaly coincide with major thrust faults identified from seismic records and the GLORIA sonographs (Fig. 4). North of the seamounts and west of 9°W, the suite of WNW trending anomalies continues as far west as the prominent NNW trending anomalies of Late Cretaceous age lying to the west of the Goban Spur (Williams, 1975; Kristoffersen, 1978; Roberts et al., 1980). The marked discontinuity between the two trends may indicate a buried fracture zone but the seismic coverage in the area is presently inadequate to test this. The central part of the Bay is in contrast dominated by a pair of positive and negative anomalies whose axes trend east-west. In detail the northernmost positive is a complex anomaly that consists of a number of WNW-ESE trending anomalies superimposed on an east-west axis. These anomalies and the positive as a whole cut across both topographic and structural trends e.g. the anomaly continues from the Biscay Seamounts to the abyssal plain and cuts across the tectonised zone bordering the northern edge of the Seamount. The prominent east-west negative to the south shows rather less convincing evidence of superimposed WNW trends but equally bears no clear relationship to topography or structure. Indeed, the southern part of the Charcot Seamount is characterised by a positive magnetic anomaly.

The region of Galicia Trough is characterised by broad low amplitude positive and negative anomalies that are related to the buried structure. The sub-surface high within the Trough is identified as a series of negative anomalies but the WNW-ESE trends observed to the north, are not apparent. The anomalies associated with the Galicia Trough are terminated near 13^{o}W by a series of NW-SE trending anomalies that may be related to the fault inferred to the north of Coruna Seamount. These anomalies apparently cut across the structural trends identified on thenorthern part of Coruna Seamount but further south, the structural and magnetic anomaly trends on the seamount are subparallel. Between Coruna Seamount and Galicia Bank broad low amplitude anomalies are present. The change in magnetic anomaly character occurs in the vicinity of Theta Gap which with the gravity and seismic evidence is tentatively considered to represent the ocean continent transition.

The junction of the Biscay anomalies with the NNW and SSW trending anomalies characteristic of the Mid-Atlantic Ridge flank occurs in the vicinity of 45^{o}N 14^{o}30'W. West of this point, the magnetic anomalies are curvilinear and continuous. Their pronounced curvature decreases westward toward the axis of the Mid-Atlantic Ridge. The supposed contiguity of the three sets of anomalies in the junction area has been previously cited as evidence for a former triple ridge junction in the Bay of Biscay (Williams, 1973, 1975). It should be noted however that the supposed junction occurs in the highly tectonised zone at the junction of the Charcot Seamount and Azores-Biscay Rise (c.f. Fig. 4, 10).

The oldest anomaly of the suite of Mid-Atlantic Ridge lineations has been identified as anomaly 31-32 by Williams (1975) and Pitman and Talwani (1972) (Fig. 2, 10). Cande & Kristoffersen (1978) have presented an alternative interpretation that the anomaly is 33-34. North of 45°N 14°30'W the anomaly trends north-south and is greatest in amplidue just north of the junction. GLORIA and seismic observations (R.C. Searle - pers. comm.) indicate structural trends are parallel to the axis of this anomaly and show no convincing evidence of major tectonism of Late Eocene-Oligocene age. South of 45°N 14°30'W, the anomaly trends SSW approximately sub-parallel to the Azores-Biscay Rise but in the vicinity of the deep Mirrol Trough structural trends cut across the axis of the anomaly. The anomaly is also cut by the major east-west trending structures at the northern end of the Azores-Biscay Rise. Anomalies to the east of anomaly 31-32 are linear but markedly less so than the equivalent set north of 45°N 14°30'W.

The negative anomaly 31-32 merges without major interruption with the prominent east-west negative of Biscay near 45°N 14°30'W, immediately west of Charcot Seamount. In contrast the adjoining positive anomalies are discontinuous and their junction to both north and south of the supposed triple point is complex. North of the 'triple point' the discontinuity occurs at the end of the NE trending break between the WNW trending negative anomalies of Biscay and the NNW trending anomalies. To the south the pattern is complex and coincident with the fault zone along the South Charcot Seamount.

The magnetic anomalies associated with the Biscay and Charcot Seamounts have been modelled by Williams (1973, 1975) and Kristoffersen (1978) to test the hypothesis of an extinct spreading ridge and triple junction. Williams (1975) considered that for east-west blocks the axis of magnetic symmetry did not lie along a particualr lineation but lay between a positive and negative lineation. The youngest anomaly was identified as anomaly 31-32 and the axis of symmetry was found to lie along the southern flank of the prominent positive anomaly associated with the Biscay Seamounts. The oldest anomaly was identified as anomaly -34 in the vicinity of the 2500km contour of North Biscay. In an alternative interpretation Kristoffersen (1978) modelled the axial anomaly in the same position but identified it as anomaly -34. At best, both models crudely approximate the shape of the anomalies and require an asymmetrically situated spreading axis. In the former case, the oldest anomaly overlaps the continent-ocean boundary of north Biscay and is inconsistent with the evidence of continental crust in this area and with the evidence for Aptian ocean crust in Biscay given by Leg 48 results (Montadert, Roberts et al., 1979; De Charpal et al., 1978). These show that Aptian-Albian sediments rest on the oceanic basement and continue across Biscay to the northern edge of the Biscay Seamounts, without apparent onlap. However, the existence of pre-anomaly -34 crust proposed by Kristoffersen (1978) is consistent with the Leg 48 results. Magnetic modelling of the basement topography identified from seismic profiles has clearly shown (IOS - unpublished results) that the southern part of the Biscay Seamount is reversely magnetised. Because of the age constrain provided by the seismic data and the absence of any reversal during the long Cretaceous normal polarity interval, (Larsen and Hilde, 1975) a late Cretaceous age is implied for part of the Seamount. This negative magnetic anomaly can be followed as far east as 6^{o}W and the adjoining WNW trending lineations are truncated against it.

To the west of Biscay, anomaly 31-32 curves north-eastward at the junction between the tectonised zone of the Charcot Seamounts and the Azores-Biscay Rise. The trend of the anomaly is also discordant with the structural fabric of the Mirrol Trough and the adjacent Azores-Biscay Rise (Fig. 2, 4). Kristoffersen (1978) has demonstrated that reconstruction of the North East Atlantic to anomaly 31-32 results in an overlap of about 100km. The overlap is greatest along the Azores-Biscay Rise but is less south of its junction with the King's Trough lineament and is absent to the north of the Rise. The overlap of this anomaly indicates post-Late Cretaceous compression along the rise that is supported by the gravity model (Fig. 9) and may be contemporaneous with the Pyrenean deformation. West of the Azores-Biscay Rise, the anomalies are consistently displaced on either side of King's Trough (Roberts and Jones, 1975). The displacement evidently ended by anomaly -13 (Oligocene time) (Grimaud et al, in press), because this anomaly passes the western end of King's Trough without interruption. The displacements of the anomalies indicate the presence of a plate boundary active between Late Cretaceous and Early Oligocene time associated with convergence along the Azores-Biscay Rise and shear (or oblique extension) along the King's Trough.

8. STRUCTURE OF NORTHWEST IBERIA

The seismic, gravity and magnetic data presented in this report show that the continental margin off northwestern Iberia has been affected by extensional and compressional tectonics in two distinct episodes.

South of Galicia Bank and off western Iberia the structure consists of tilted and rotated fault blocks, horsts and grabens of predominant NNW-SSE trend although other trends are also present. These fault blocks developed in response to the major rifting between Iberia, Europe and North America during Late Jurassic-Early Cretaceous time. The major NNW-SSE trends contrast with the predominant WNW-ESE fault trends observed on the conjugate margin off North Biscay where the fault blocks are draped in varying thickness by a largely undeformed sequence of Cretaceous and Tertiary sediments.

In marked contrast, the slope off Northern and northwestern Spain and the adjacent deep floor of Biscay has undergone compression that ended in Eocene-Oligocene time. Thrusting has affected the slope north of Galicia Bank and north of Spain and several thrusts affect the thick sediments of the North Spanish Trough. Thrusting is also observed in the Galicia Trough but is not observed west of Galicia Bank. In the vicinity of the Ortegal Spur, the North Spanish Trough is constricted and the zone of major thrusting changes trend from WNW-ESE to NW-SW. The northern edge of the North Spanish Trough is defined by the flank of the South Gascony Ridge. Mapping shows that this feature is the sub-surface continuation of the South Charcot and Biscay Seamounts. These seamounts are reversely magnetised in part and abnormally shallow. Their southern edge is faulted and there is a change in basement depth of 1.5 seconds. Northwest-southeast trending faults also cross the seamounts. The tectonised area embraces the entire Biscay-Charcot Seamount group but is most intense between their northern edge and Galicia Bank. Thrusting and transcurrent faulting can be followed across the entire Bay to the Trevelyan uplift on the Armorican margin. To the west the tectonised zone continues to the Azores-Biscay Rise. Evidence of a southwestward continuation is shown by the recently tectonised deep troughs that are aligned along the eastern base of the rise and possibly by the King's Trough-Peake Deep lineament whose activity apparently ceased in Oligocene time. Eastward, the zone of deformation encompassing the North Spanish Slope and marginal trough continues into the Pyrenean orogenic belt. The tectonised zone extending the length of the north Spanish margin and west of Iberia into the King's Trough thus represents the submarine extension of the emerged Pyrenean plate boundary.

9. CONCLUSIONS

The geological development of northwestern Iberia has resulted from the opening of the Bay of Biscay by rifting and spreading followed by partial closure due to the Pyrenean compression.

After the Hercynian orogeny Late Hercynian shear movements extensively fractured and displaced the highly deformed Hercynian terrain. Important examples of such faults include the South Armorican Shear Zone of Brittany and the North Pyrenean Fault. These late Hercynian shears may have profoundly influenced the fabric of rifting around Iberia. Sedimentary basin development was first initiated in Permo-Stephanian time but these movements had largely ceased by the Triassic. During Triassic and Liassic time, further distension took place and thick evaporites were deposited in the Aquitaine Basin and Grand Banks basin. A parallel sequence of events is known in the Lusitanian Basin but the absence of diapirs north of 42°N suggests that the evaporite basin was closed to the south. There is some evidence of minor volcanism which took place in the Triassic (190-225 m.y.) and during the Lias (172-190 m.y.). Epicontinental conditions persisted throughout the area however until Late Jurassic time when a regional regression occurred possibly in association with the initial phases of rifting. In the Aquitaine Basin rifting may have begun as early as Oxfordian time but there is little doubt that there was major rifting throughout the region in Early Cretaceous time. In the Aquitaine Basin, thick contemporaneous sedimentation took place in fault bounded troughs accompanied by local submarine eruptions. In northern Spain, 'Wealden' sediments overstep the Kimmeridgian and older Jurassic beds and a closely similar pattern is apparent both west of Spain and on the conjugate margin now represented by the Grand Banks. Palaeomagnetic data indicate that spreading between Europe and Iberia began in Barrennian-Aptian time. The Aptian date for the end of rifting is independently confirmed by results from Leg 48 and Leg 47B. On the Grand Banks, the end of rifting may be marked by a major angular unconformity close to the base of the Cretaceous that truncates fault blocks containing Jurassic and older sediments. Following the rifting, the Bay of Biscay opened by sea-floor spreading initiated in Aptian time. The duration and direction of this spreading are not known but it seems reasonable to suppose accretion in a NNE-SSW direction perpendicular to the trend of the weak anomalies that characterise the Cretaceous ocean crust of Biscay. This episode ended by Late Cretaceous time when convergence began along the northern margin of Iberia, initiating the Pyrenean plate boundary and its westward extension into the Atlantic. The nature of the early movements along this boundary and the role of the Biscay Seamounts cannot be determined from our data. The Biscay-Charcot Seamounts hitherto interpreted as the extinct spreading axis of Biscay lie within the tectonised zone and their origin is thus enigmatic. There was quite clearly a major reorganisation in plate movements during the Late Cretaceous that could have involved uplift and extension so producing the seamounts, although later movements could have been responsible. By Eocene time, the compressional boundary extended the length of the Iberian margin to continue out into the Atlantic where it is marked by the Biscay-Charcot Seamounts, the Azores-Biscay Rise and the King's Trough lineament (Fig. 11). The compression affected north Biscay and caused the development of the North Spanish and Galician Troughs. NW-SE faults that offset these troughs and the Biscay-Charcot Seamounts, and significantly terminate the compressional zone north-west of Galicia Bank are interpreted as transform faults. The possible configuration of the plate boundary is shown in Figure 11. The model suggests that the Pyrenean deformation was produced by WNW-ESE oblique convergence and shear rather than orthogonal NE-SW motion as has been previously supposed.

FIGURE CAPTIONS

FIG. 1. Principal structural elements of the Bay of Biscay: Survey area is indicated by box off North West Spain.

FIG. 2. Bathymetry (in fathoms) and principal magnetic anomalies (after Laughton et al., 1975; Roberts and Jones, 1980). Seismic control coverage is shown with positions of profiles illustrated in Figs. 3, 5, 7, 8, 9.

FIG. 3. Seismic section across Galicia Bank. (Profile is located on Figs. 2 and 4).

FIG. 4. Tectonic map indicating thrusts, major faults basement structural highs and sediment isopachs contoured at 0.5 sec. reflection travel time. Profiles illustrated in Figs. 3, 7, 8, 9 are shown.

FIG. 5. Seismic section north of the Biscay seamounts. Profile is located in Figs. 2 and 4.

FIG. 6. Gravity - free air anomaly with tracks and 2-D model locations. Contour interval 10 mgal. Principal bathymetric contours are also shown.

FIG. 7. Model profile 3. Cantabria Knoll to north Spanish shelf. (Profile is located in Figs. 2, 4, 6).

FIG. 8. Model profile 1. Central Biscay to Galicia Bank: Biscay Seamount at left. (Profile is located on Figs. 2, 4, 6).

FIG. 9. Model profile 2. Galicia Bank (left) to Azores-Biscay Rise: G (gravity), M (magnetic). (Profile is located on Figs. 2, 4, 6).

FIG. 10. Magnetic anomaly chart: contour interval 50 and 100 nT (from Roberts and Jones 1975, 1980).

FIG. 11. Schematic configuration of Pyrenean plate boundaries in Late Eocene-Oligocene time.

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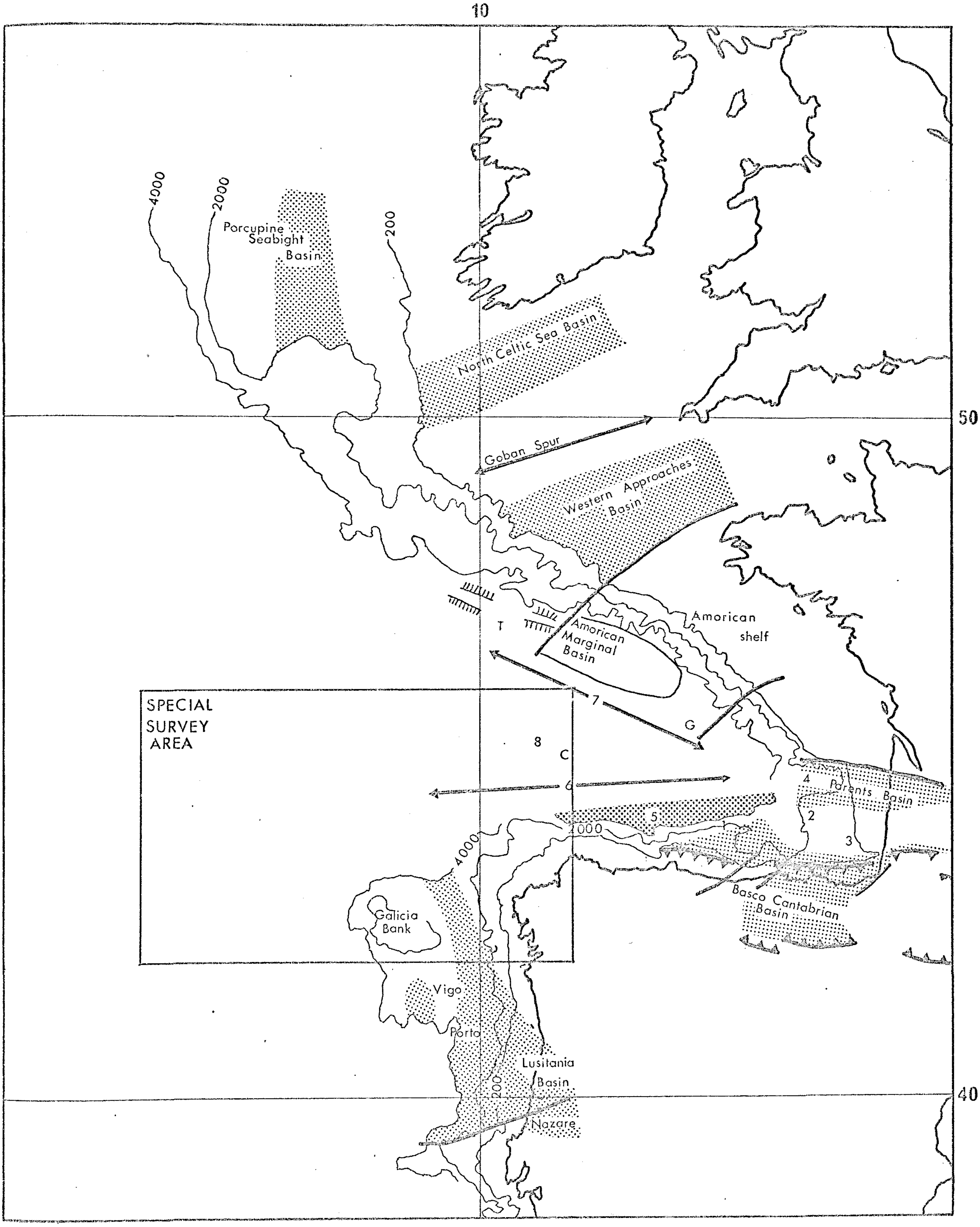
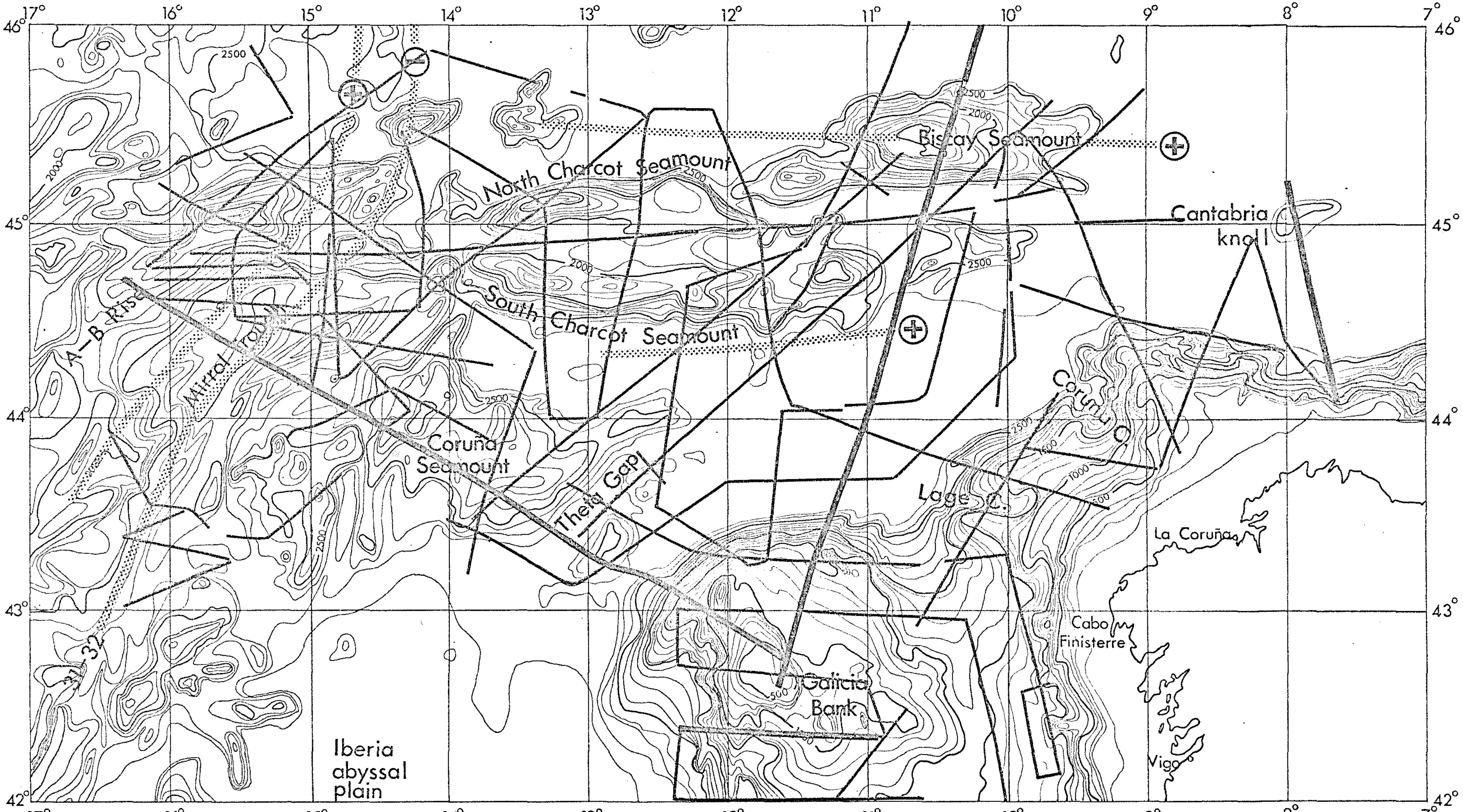
FIG 1



Continental Mesozoic & Cenozoic basins

Pyrenean folds limit	1 Asturian marginal plateau	5 Tectonised area	
T Trevelyan	2 Landes marginal plateau	6 S.Gascony Ridge	
G Gascony	3 Cap Breton Canyon	7 N.Gascony Ridge	
C Cantabria	4 Cap Ferret Graben	8 Central area with irregular basaltic basement magnetic anomalies	
200 Isobaths (mtrs)			



Magnetic Anomalies — FIG 2 — Figure profiles

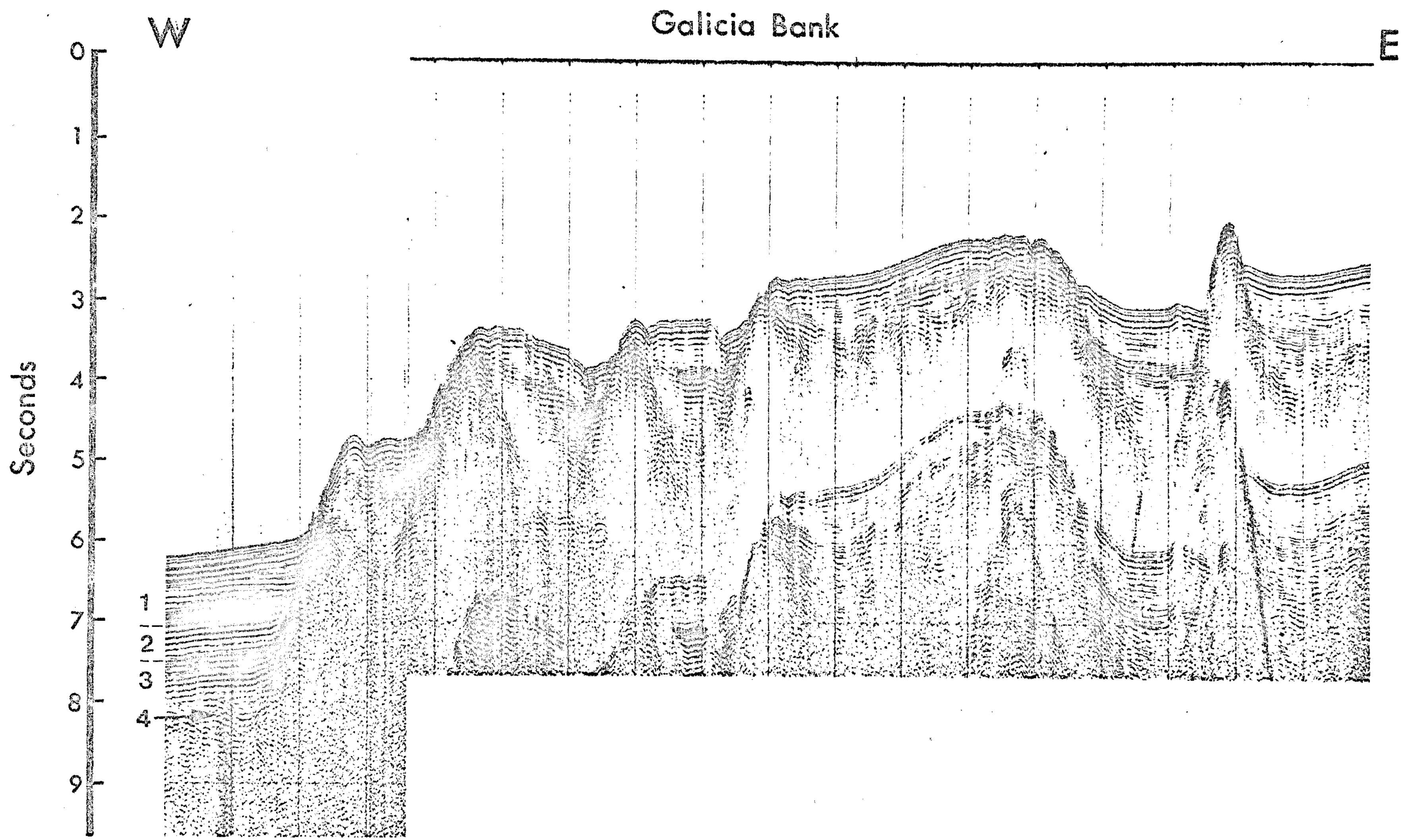


FIG 3

FIG 4

FIG 5

INSTITUTE OF OCEANOGRAPHIC SCIENCES

PROSPECT: S.W. APPROACHES

BLOCK: NORTH BISCAY

LINE SHACK 1

SP's 6222–9200

SECURITY No. 111003 / 4481

PARTY I.O.S. 6/76

DATE RECORDED OCTOBER 1976

DATE PROCESSED APRIL 1977

FILTERED STACK

PROCESSED THROUGH SEISYSTEM 370

SEISMOGRAPH SERVICE (ENGLAND) LIMITED

LONDON ENGLAND

RECORDING PARAMETERS

CONTRACTOR INSTITUTE OF OCEANOGRAPHIC SCIENCES
CREW PARTY 6 76
VESSEL SHACKLETON

RECORDING
ANALOGUE RECORDING
INSTRUMENTS BELL & HOWELL CPR 4010
FORMAT FM 7-CHANNEL

ENERGY SOURCE
SOURCE SINGLE AIRGUN
CAPACITY 300 cu ins.
GUN DEPTH 10m

CABLE
TYPE GEOMELCANIQUE
GROUP INTERVAL 100m

CENTRE OF GUN ARRAY

PROCESSING SEQUENCE

1. ANALOGUE TO DIGITAL CONVERSION
2. DEBUBBLE
3. DIVERGENCE CORRECTION (T^2)
4. D.C. BIAS CORRECTION
5. MULTI-VELOCITY STACKS (EVERY 10KM)
6. DECONVOLUTION : S.P. 6222
   OPERATOR TOTAL LENGTH 300ms. GAP 12ms
   DESIGN WINDOW 6000-9000
7. BASE LEVEL SCALING
8. NMO. MUTE & STACK (300%)
9. T.V. FILTERS

S.P. 6222	CUT-OFF Hz	BAND-PASS Hz	CUT-OFF Hz
0-7300	5	8 - 40	44
6900-7700	5	8 - 30	33
7300-11300	3	5 - 25	28

10. TRACE EQUALISATION (1000ms WINDOW)

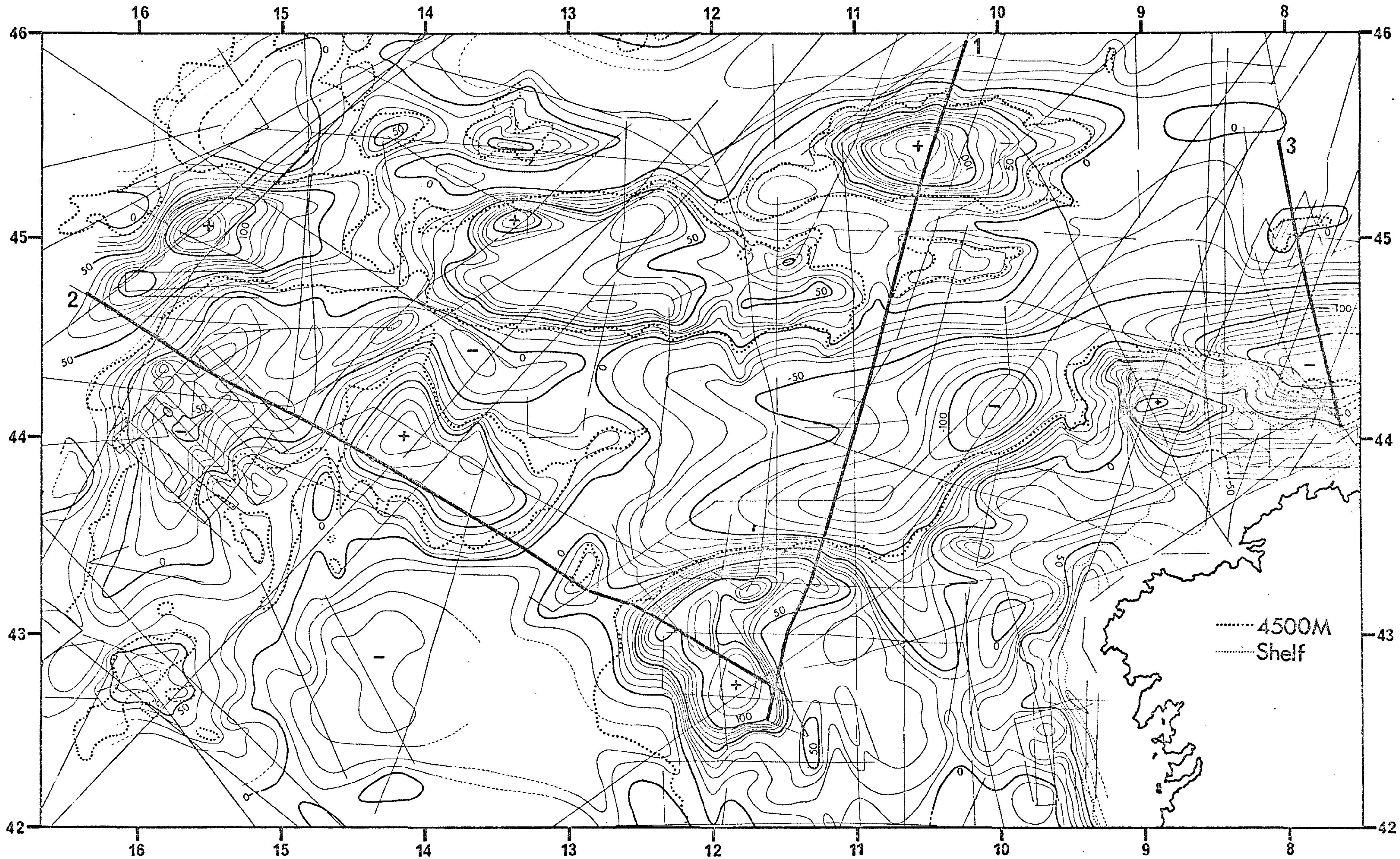


FIG 6

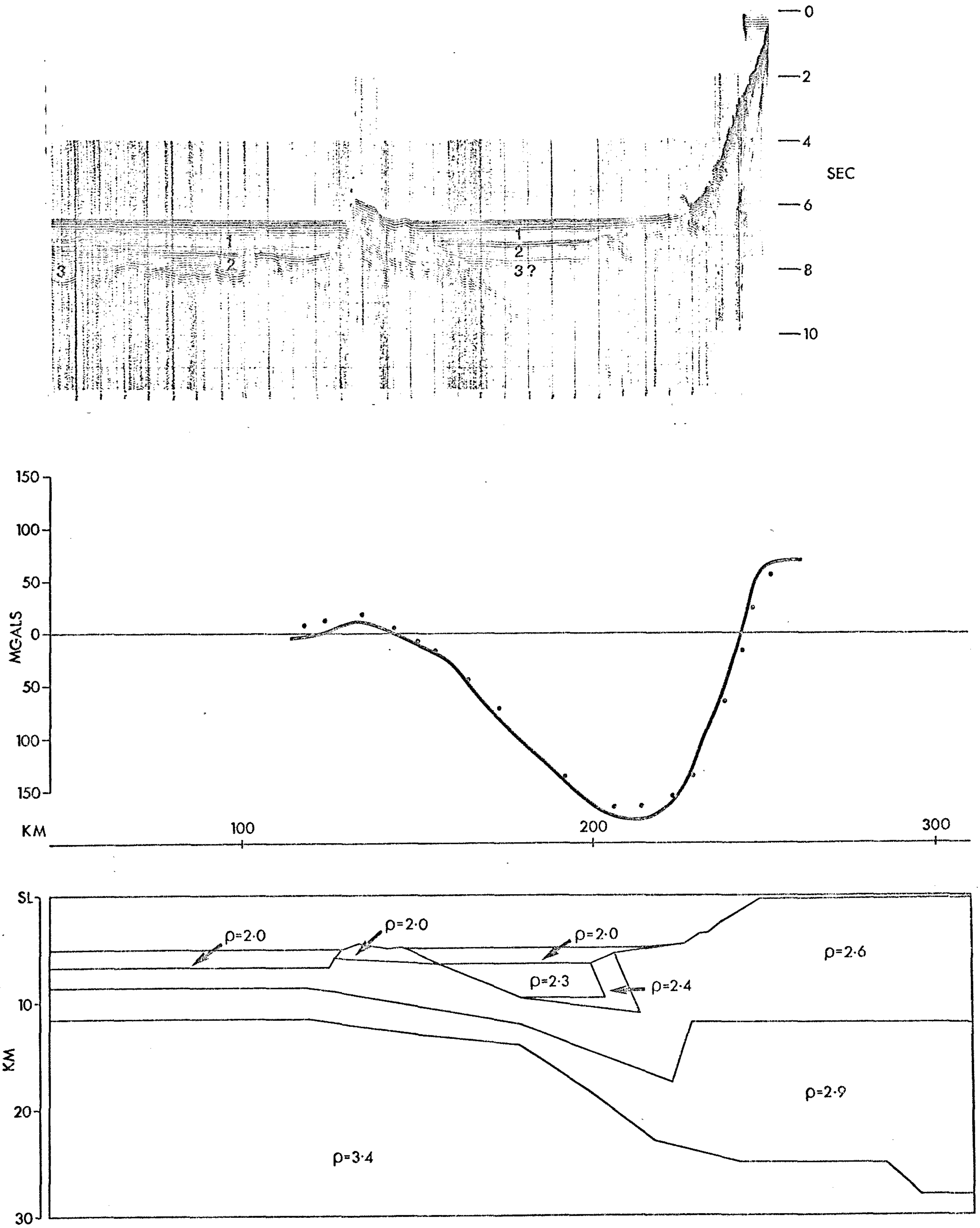
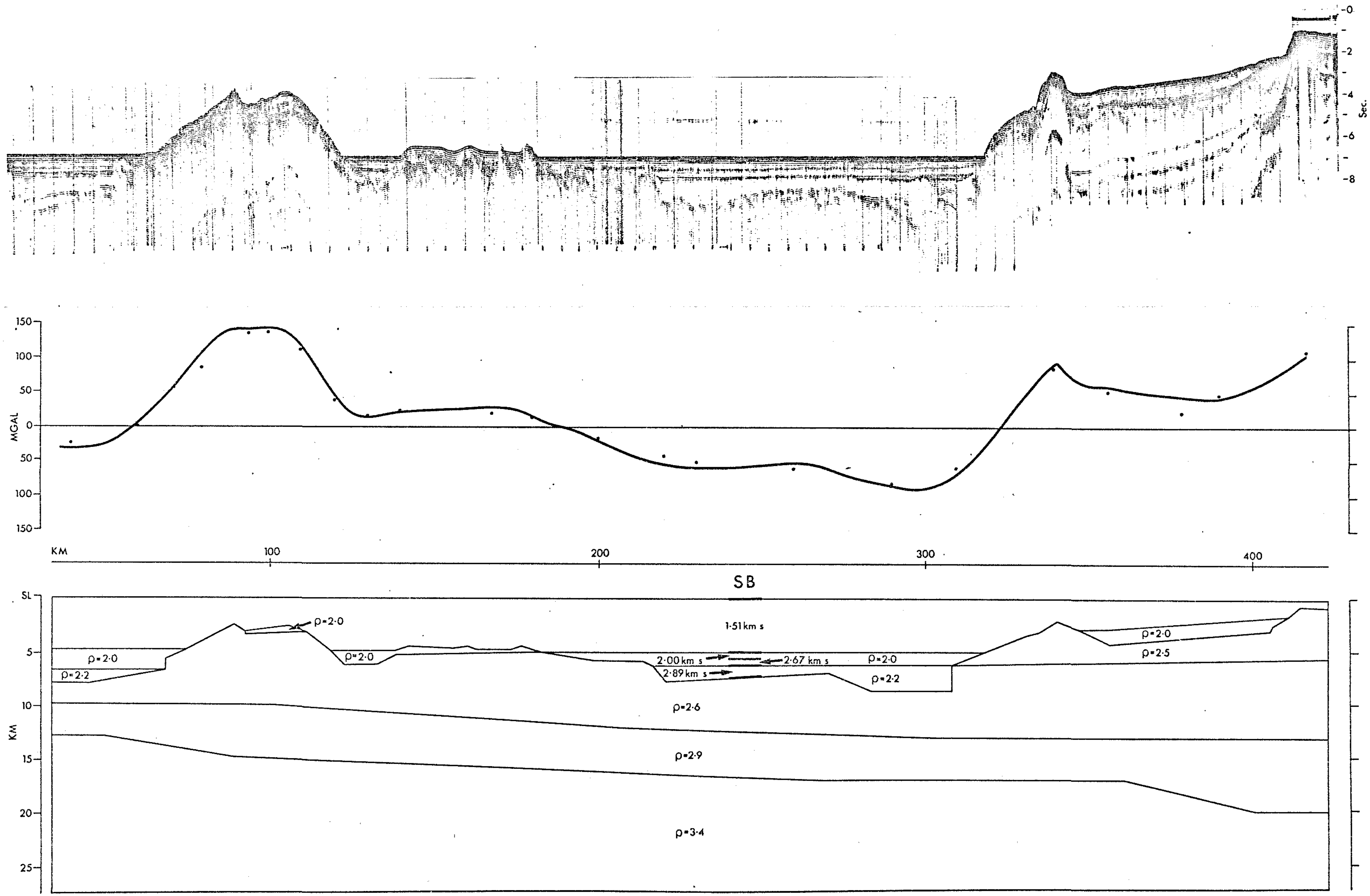

0
2
4
SEC
6
8
10
1
2
3
1
2
3?
150
100
50
0
MGALS
50
100
150
KM
100
200
300
SL
10
KM
20
30
ρ=2·0
ρ=2·0
ρ=2·0
ρ=2·6
ρ=2·3
ρ=2·4
ρ=2·9
ρ=3·4

FIG 7



Sec.
0
2
4
6
8
MGAL
150
100
50
0
50
100
150
KM
100
200
300
400
SB
SL
5
10
15
20
25
KM
ρ=2·0
1·51 km s
ρ=2·0
ρ=2·2
ρ=2·0
2·00 km s
2·67 km s
2·89 km s
ρ=2·0
ρ=2·2
ρ=2·0
ρ=2·5
ρ=2·6
ρ=2·9
ρ=3·4

FIG 8

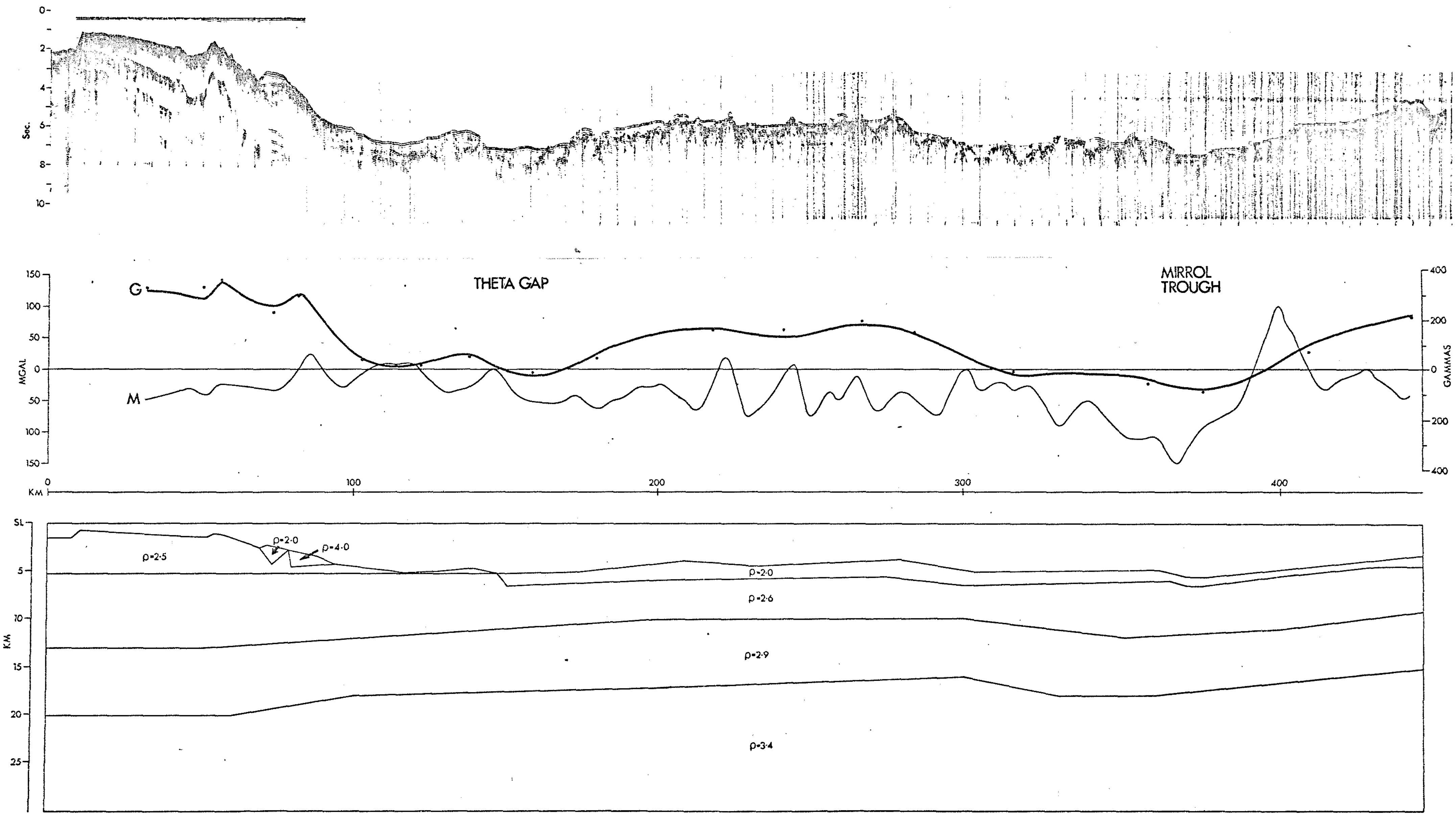
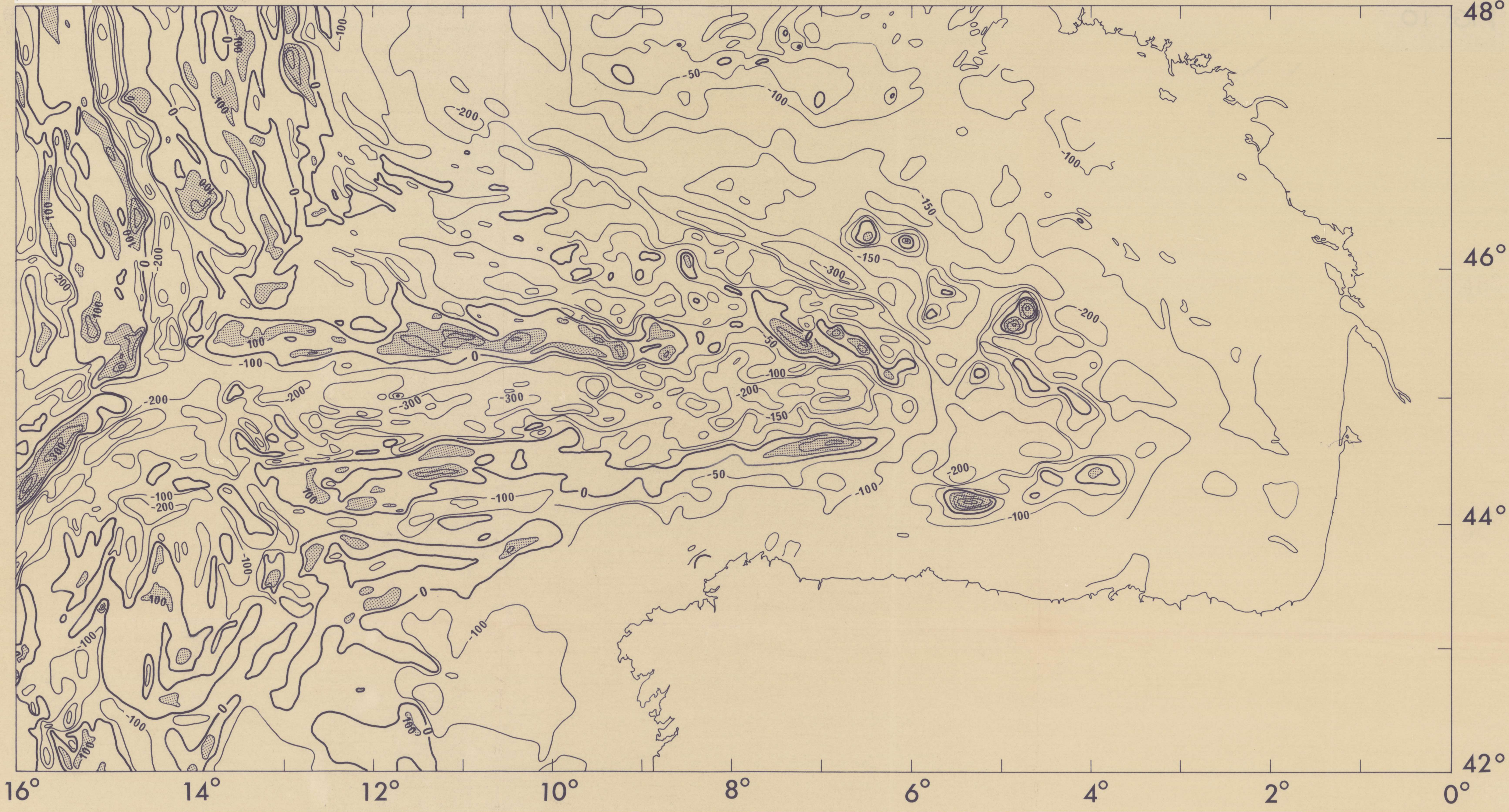
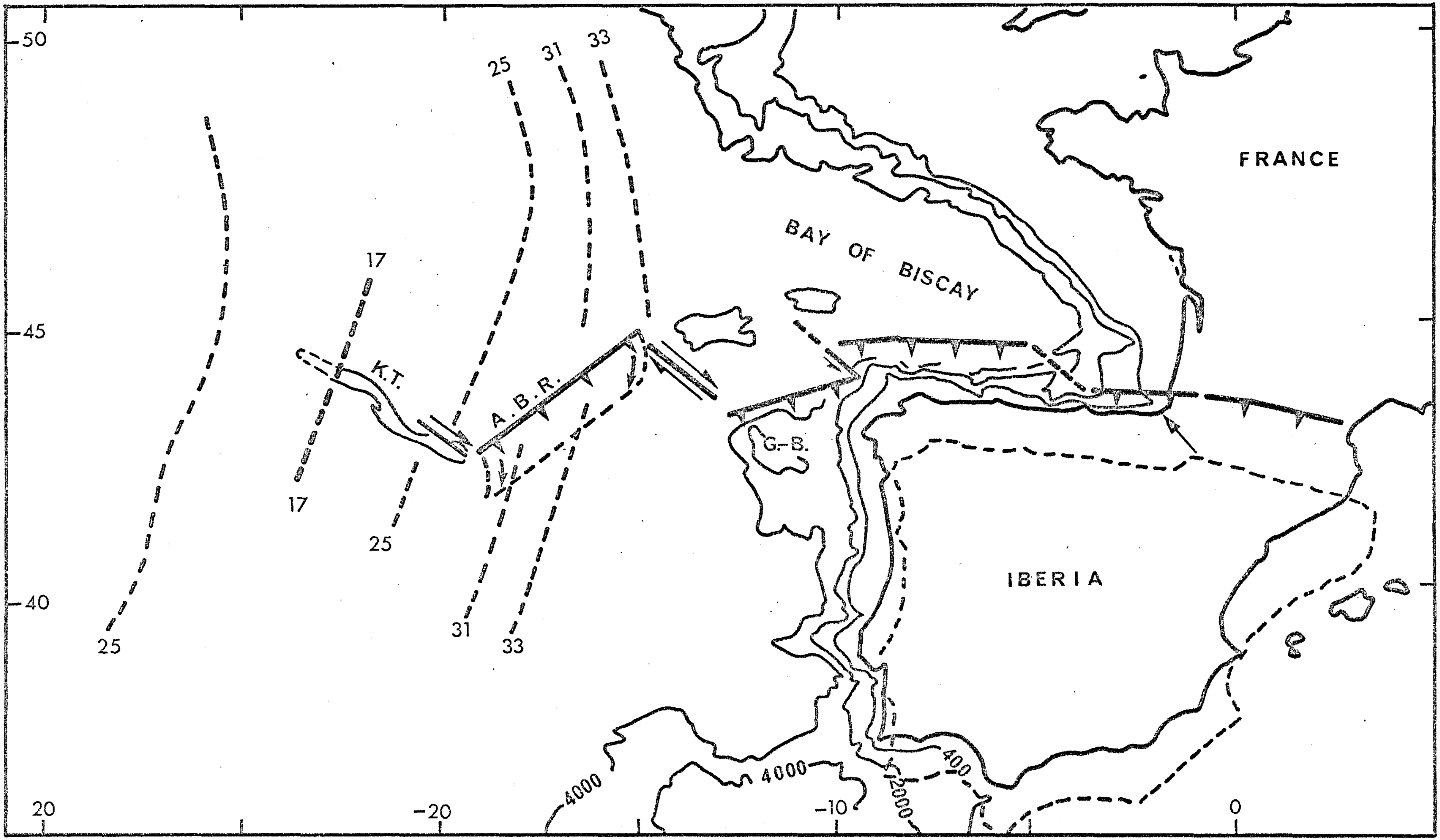

Sec.
THETA GAP
MIRROL
TROUGH
MGAL
GAMMAS
G
M
KM
SL
ρ=2·5
ρ=2·0
ρ=4·0
ρ=2·0
ρ=2·6
ρ=2·9
ρ=3·4

FIG 9

FIG 10





50
45
40
FRANCE
BAY OF BISCAY
IBERIA
K.T.
A.B.R.
G.-B.
17
25
31
33
4000
2000
400
20
-20
-10
0

FIG 11