STRUCTURAL STUDIES OF THE NORTHWEST IBERIAN CONTINENTAL MARGIN USING LONG-RANGE SIDE-SCAN SONAR

BY
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Structural studies of the northwest Iberian continental margin using long-range side-scan sonar

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ABSTRACT

The Atlantic margin of Iberia differs from typical 'Atlantic-type' passive margins in that its present-day morphology has been controlled by two major tectonic events: Mesozoic rifting, related to the opening of the Atlantic, and an Eocene compressive phase, related to the Pyrenean orogeny. This study discusses the structural framework of the Northwestern Iberian Margin in the light of recently-acquired seismic reflection profiles and GLORIA-II sidescan data and reviews the present knowledge of its structural evolution.

These new geophysical data have enabled us to construct an accurate basement outcrop map of the margin and have provided additional information on the tectonic lineaments. Further, the data have formed a basis for improved regional structure maps and are a refinement of those recently published by French workers.

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INTRODUCTION

In early 1978, as part of a wider study of the continental margin of Western Europe, some 2400 km of seismic reflection profiles, with simultaneous bathymetric, magnetic and gravity measurements, were shot by IOS on the Iberian margin, north of the Nazare Canyon. These observations were complemented by long-range side-scan sonar coverage using the GLORIA Mark II long-range sonar (Somers et al., 1978). Together, the seismic reflection profiles obtained and the GLORIA sonograph plan views have enabled us to produce the first basement outcrop map for the continental margin, north of Lisbon. This is presented with this report (Figure 7). In addition, this new range of geophysical data has also enabled us to produce new sediment thickness maps for the North West Iberian margin (also presented here).

This report has three primary objectives:

1. To provide a comprehensive review of the present knowledge of the structural evolution of the margin. Our understanding of this has increased rapidly in recent years due to numerous published studies. These are scattered throughout the literature and several important French studies are not yet available as English translations. Thus, in part, this report is an attempt to provide a summary of the published work under one cover.
2. To present new structural maps based on the GLORIA-II side-scan coverage and seismic reflection profiles obtained during RRS Discovery Cruise 90 and compiled published data.
3. To discuss the structural framework of the Iberian margin and its evolution through time in the light of recent surveys.

HISTORICAL ACCOUNT

Prior to 1960, the physiography of the Iberian margin was relatively unknown. The first detailed studies were made by RRS Discovery II in 1958 and 1960, using bathymetric, gravimetric, magnetic and seismic refraction methods, together with dredging. The results were published by Black et al. (1964) who showed that the non-magnetic marginal seamounts (Galicia Bank, Vigo and Porto seamounts) were probably collapsed blocks of continental crust. This was followed by several seismic surveys of the Galicia-Portugal continental margin with numerous cores and dredge hauls (Stride et al., 1969; Lamboy and Dupeuble, 1971; Boillot and Musellec, 1972; Boillot et al., 1972; Montadert et al., 1974; Dupeuble et al., 1976). These studies showed the offshore prolongation of the onshore Lusitanian basin and its local salt piercement. Further north,

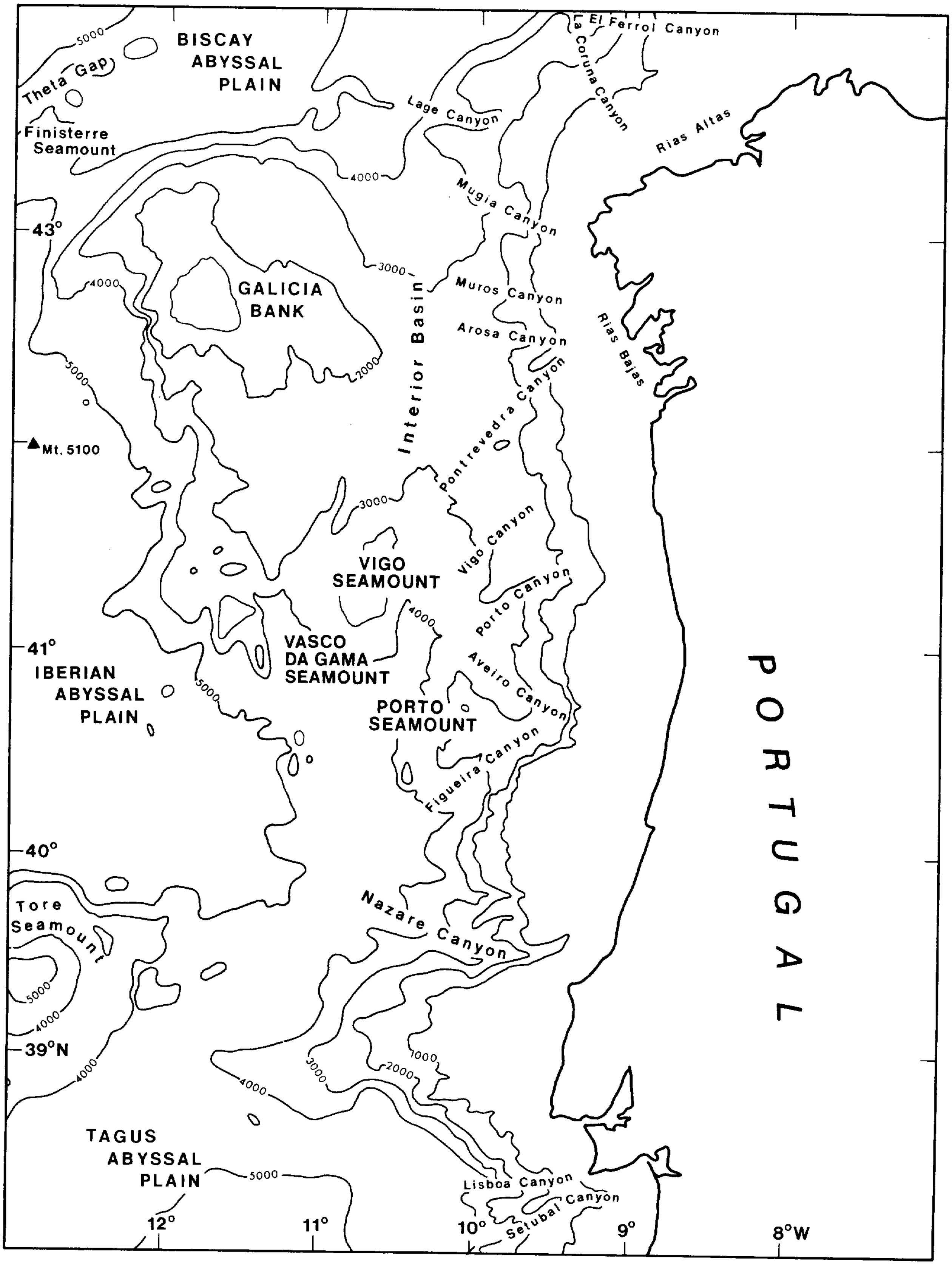


Figure 1. Northwestern Iberian margin: Location map. Contour interval: 1000 metres. Naming of features from Laughton et al. (1975) and Vanney et al. (1979).

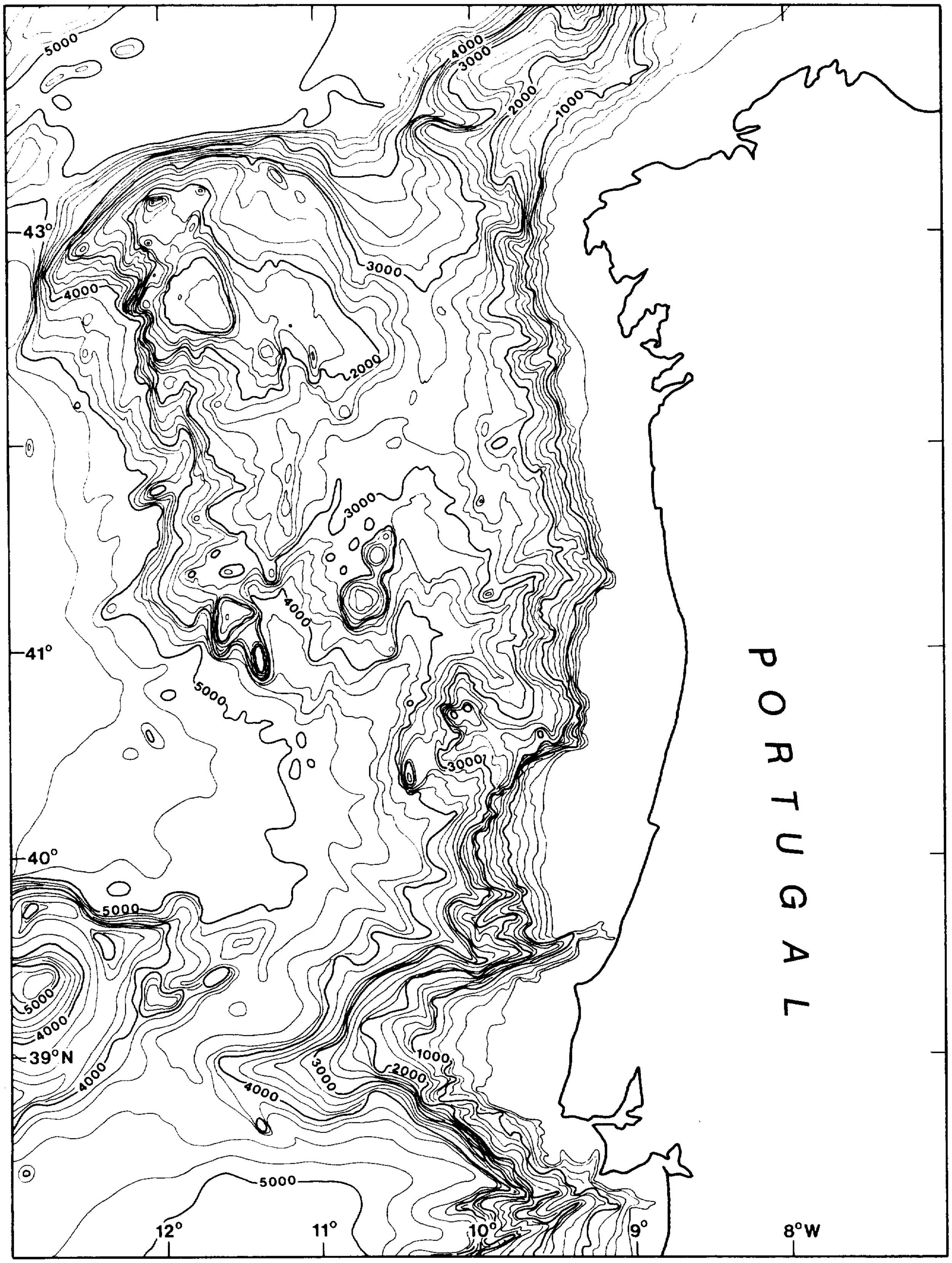


Figure 2. Northwestern Iberian margin: Bathymetric map. Contour interval: 200 metres. Contours north of 40°30'N from Vanney *et al.* (1979), south of 40°30'N from Laughton *et al.* (1975).

these studies provided the first description of the structural units composing the Galician marginal plateau. These early seismic reflection profiles showed the north western Iberian margin to be composed of a series of horst and graben structures, some of the horsts being capped by Jurassic reefs, formed during the crustal extension and rifting of the Mesozoic.

Since 1974, the Iberian Margin north of Nazare has been extensively studied by three French scientific teams that comprise the "Groupe Galice" (CNEXO, IFP and the Groupe d'Etude de la Marge Continentale, Universite de Pierre et Marie Curie). This research group was originally set up to provide a detailed geological and geophysical reconnaissance in preparation for IPOD drill site 398 (Figure 4). Their study was published collectively (Groupe Galice, 1979). They proposed a generalised stratigraphy and provided a comprehensive structural history which first documented the effects of the Pyrenean orogeny in the early Tertiary.

In 1976, IPOD drill site 398 (3910m water depth, 1740m total penetration) was drilled some 20 km to the south of Vigo seamount (Figure 4). This area has been much affected by rifting (Groupe Galice, 1979) and the 398 drillhole penetrated a tilted basement block (Sibuet et al., 1980). This study was followed by further seismic reflection profiling and dredging which provided improved correlations between the drilling results and the stratigraphy of the local sedimentary basins (Boillot et al., 1979). These results further documented the Eocene compressive phase and showed that during the Eocene, margin subsidence was interrupted by compression and related deformation caused by the subduction of oceanic crust from the Bay of Biscay beneath the Iberian peninsula. However, this subduction was short-lived and did not result in the associated volcanism and metamorphism, typical of active margins.

Thus, by 1978, the structure, stratigraphy, and physiography of the Atlantic margin of Iberia were thought to be well-known. However, it was not until Discovery Cruise 90 that the importance of large sediment drifts deposited by slope-following contour currents was recognised on this margin (Roberts and Kidd, in press).

THE CRUISE 90 STUDY

The Cruise 90 study was conceived in the context of a wider study of the Western European continental margin, using the technique of producing sonograph mosaics of substantial areas with simultaneously collected bathymetric, magnetic, seismic reflection and gravity measurements (Figure 5). These data were

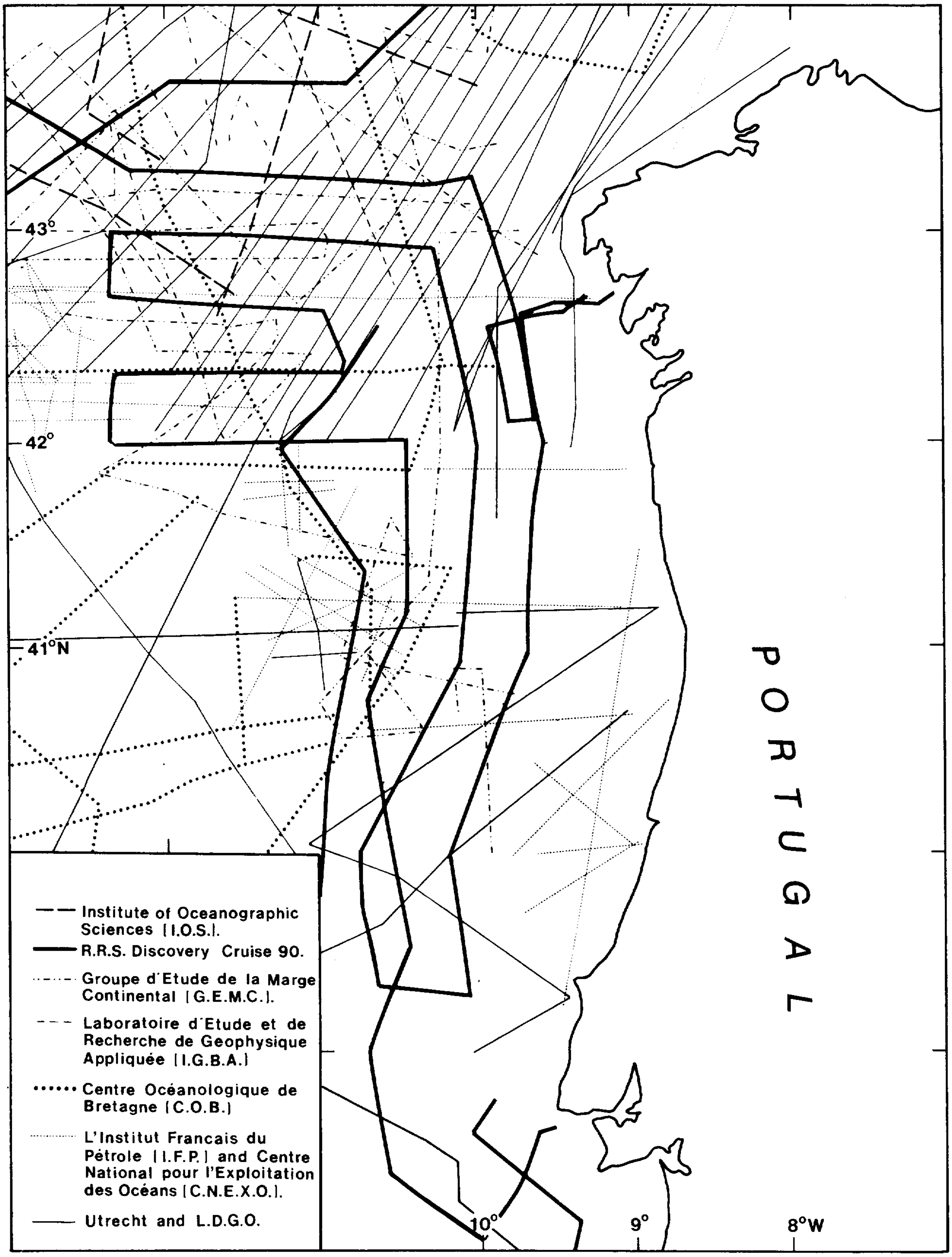


Figure 3. Northwestern Iberian margin: Location map of the seismic profiles used in producing the structural maps. Non-IOS data compiled from Auxietre and Dunand (1978) and Grimaud (1981).

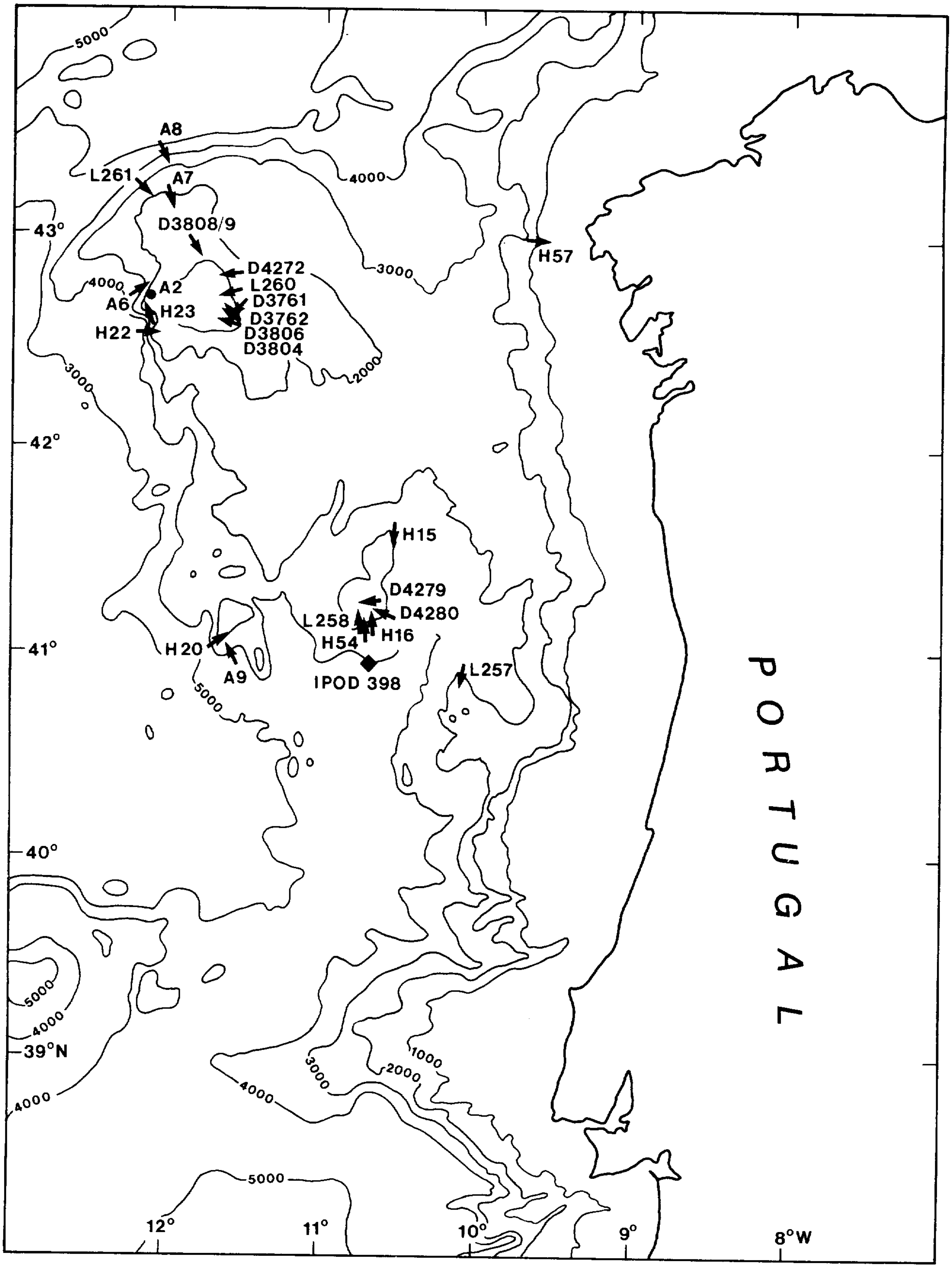


Figure 4. Northwestern Iberian margin: Dredge samples. Four-figure numbers prefixed by the letter D refer to those described by Black *et al*. (1964). Numbers preceded by the letters A and L refer to samples studied by Dupeuble *et al*. (1976). Samples preceded by the letter H are described by Boillot *et al*. (1979).

envisaged as providing, firstly, the basis of complementary sedimentological and structural studies of the Iberian Margin and, secondly, a wider evaluation of the early history of the Atlantic Ocean. Related studies using the same techniques were subsequently made on the East Greenland margin and on the Grand Banks off Newfoundland; the results of those surveys are to be published elsewhere.

The GLORIA (Geological LOng-Range Inclined Asdic) Mark II of the Institute of Oceangraphic Sciences is a dual-scan sonar towed at shallow depths with a maximum range of 30 km, each side of the ship's track. Sound pulses during the cruise were transmitted every 40 sec with a pulse length of 20 or 40 msec at frequencies of 6.5 and 6.7 kHz. The beam's width is 2.7° in azimuth and 10° in the vertical. The sonographs produced are photographically anamorphosed to produce sonographs correctly scaled in the horizontal range, except in the near field.

The ship's track was chosen to run parallel to the margin for much of its length and east-west in the vicinity of Galicia Bank. Thus the seismic reflection profiles would cross existing profiles and provide a rudimentary 'grid' on which future structural interpretation could be based (Figure 3). The survey was made at speeds of 7-9 knots and was controlled by satellite navigation.

This report is restricted to the Northwestern Iberian margin (north of the Nazare Canyon - Figure 1) and is part of a bipartite study at the Institute of Oceanographic Sciences. Complementary sedimentary studies of the same area using the GLORIA II data have been made by Gardner and Kidd (in preparation).

THE SEISMIC STRATIGRAPHY

The stratigraphy of the Atlantic margin of Iberia has been extensively studied through seismic profiling (Figure 3), drilling at IPOD site 398 and numerous dredgings (Figure 4, Table II). The seismic profiles show a well-defined seismic stratigraphy with up to five main units, each having a distinct acoustic character and often separated by unconformities (Figures 6, 11; Table I). The IPOD drilling results and dredge hauls provide the basis for correlation between the seismostratigraphic units and the lithology. In the present study, the correlation with the drilling results from site 398 (Sibuet et al., 1980) has been slightly modified after Gardner and Kidd's suggestion (in preparation) of the Late Miocene hiatus in Unit 1 (Table 1).

On the margin off Portugal and Galicia, the seismic reflection profiles typically show a layered sedimentary sequence resting on an irregular diffractive

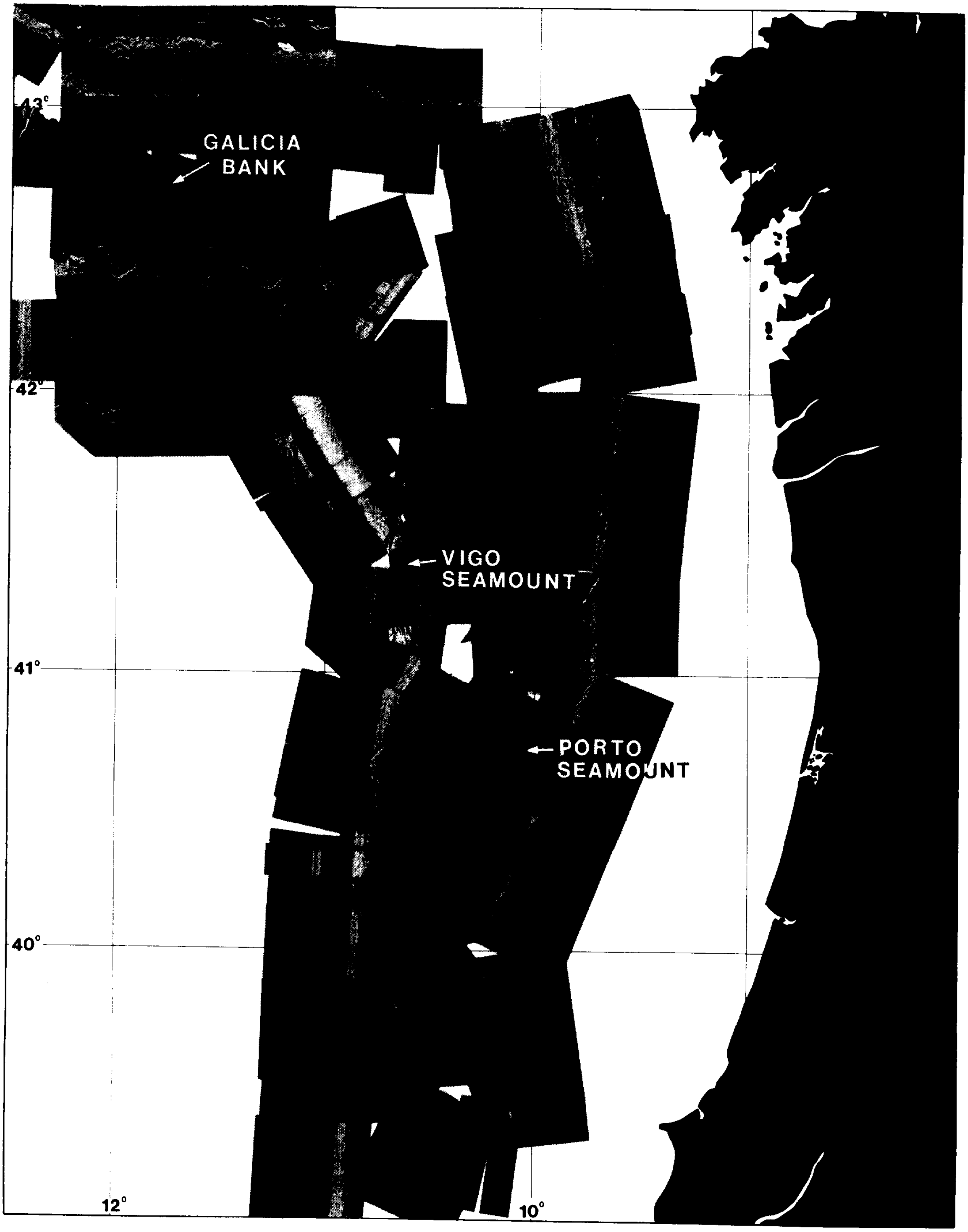


Figure 5. Northwestern Iberian Margin: GLORIA-II coverage.

acoustic basement (Figures 6, 11). The seismostratigraphic units 1-4 comprise the sedimentary cover and unit 5, the acoustic basement. Of these, units 1-3 correspond to those previously identified in the Bay of Biscay (Montadert et al., 1979).

Unit 5 (Acoustic Basement)

The diffractive, irregular acoustic basement represents the rifted margin of the proto-Atlantic ocean. At site 398, the deepest 75m out of a total penetration of 1740m were drilled into the acoustic basement (Sibuet, Ryan et al., 1979) (Figure 6). The sediments recovered were calcareous mudstone, siltstone and limestone of Late Hauterivan to Early Barremian age (Early Cretaceous). The acoustic basement appears in places to be layered and where this is so, the layering is unconformable with the faulted upper surface. In some areas, internal basement reflectors can be distinguished and appear to be folded into anticlines and synclines. This acoustic basement outcrops along fault escarpments from which several samples have been dredged (Boillot et al., 1979). Samples dredged from west of Galicia Bank have consisted of metamorphic and plutonic rocks similar to those of the Hercynian Basement of the Iberian meseta. However, where acoustic basement outcrops on the flanks of Vigo, Porto and Vasco da Gama seamounts, dredge hauls recovered Late Jurassic to Early Cretaceous limestones (Boillot et al., 1979).

Generally, the acoustic basement shows considerable relief and is considered to consist of a series of tilted and rotated fault blocks or horsts. Such a structure is typical of Biscay-type, passive continental margins (cf. de Charpal et al., 1978) and it is believed to form in response to crustal tension. This interpretation follows the model for crustal attenuation and rifting as postulated by Bott (1971) and others.

Unit 4

The first sequence overlying the diffractive acoustic basement is a moderately to strongly-layered formation. Seismostratigraphic unit 4 fills the troughs between the horst structures of the acoustic basement. The dip of the layering decreases upwards through layer 4 and may be nearly flat towards the top of the unit. This indicates that deposition occurred during the tilting of the basement blocks. However, where it is thin, unit 4 may be difficult to distinguish from the top of the acoustic basement.

At site 398, acoustic unit 4 was found to be Late Barremian to Uppermost

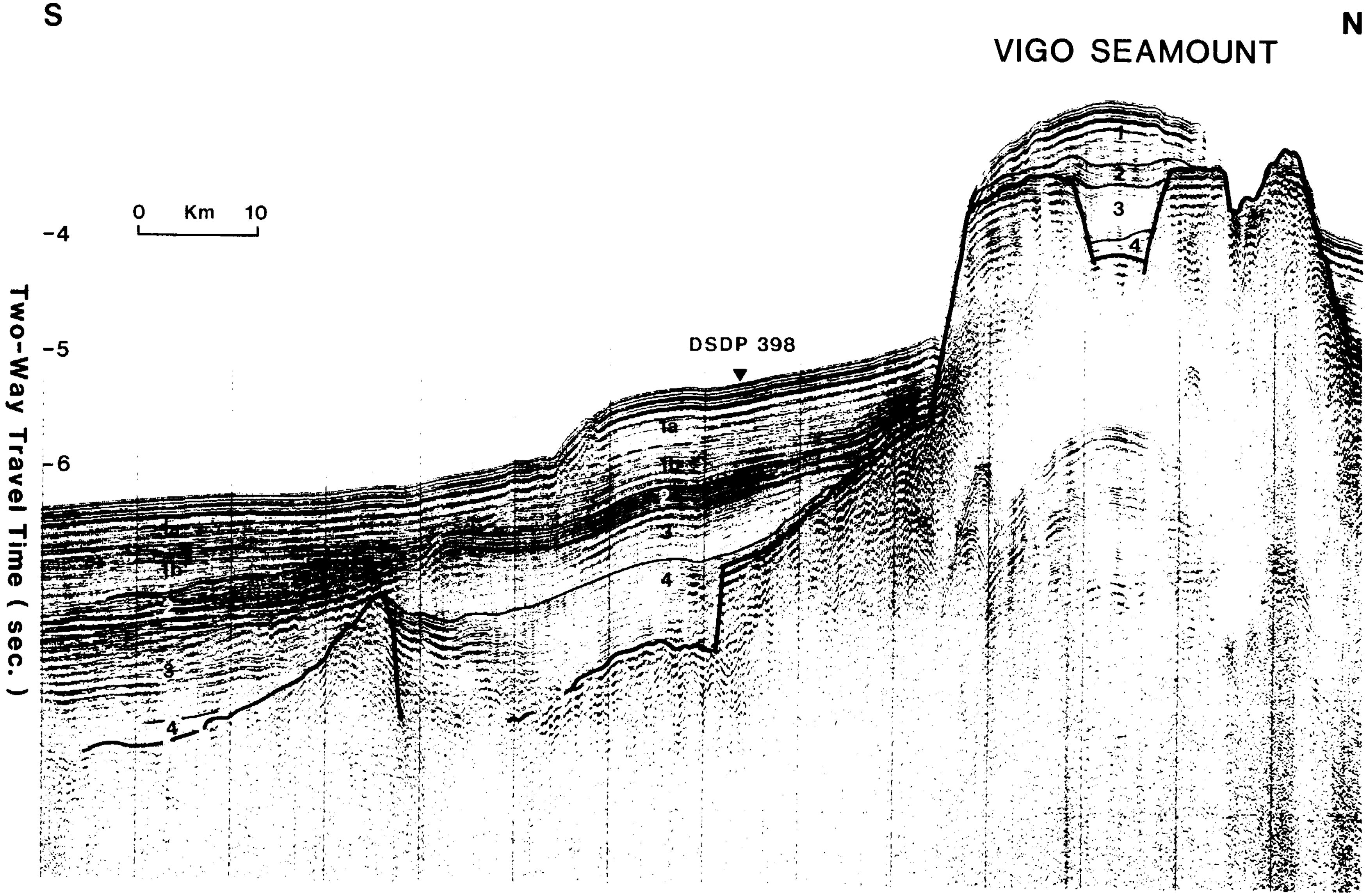


Figure 6. Seismic reflection profile across Vigo Tablemount and DSDP drillsite 398, located in Figure 10, showing the clearly-defined seismic units 1-4 and the irregular diffractive acoustic basement.

Aptian age and to consist of sand-silt-clay graded sequences, interbedded with turbidites (Sibuet et al., 1980). The top of formation 4 is thought to correspond to the lower part of formation 3 of Biscay (Montadert et al., 1979; Roberts et al., 1980). Unit 4 is apparently restricted to the margin as it cannot be followed out into the oceanic crust west of the margin (Groupe Galice, 1979).

Unit 3

Above unit 4 is an acoustically transparent series, unit 3, the two units being separated by a strong reflector. At IPOD drillsite 398, unit 3 was found to be Lower Albian to Middle Cenomanian in age and to consist of laminated dark shales of continental provenance passing upwards into redeposited marl and chalk of pelagic origin (Sibuet et al., 1980). Formation 3 infills the troughs between the horsts and tilted blocks and its deposition has resulted in the almost complete levelling of the topography. Many highs are completely buried, although unit 3 may be missing on some structural crests.

Unit 2

Overlying the acoustically transparent series and separated from it by a small unconformity is a distinctive layered sequence - acoustic unit 2. At drillsite 398, the unconformity at the base of unit 2 corresponds to a hiatus encompassing the entire Turonian, a gap of some 4 m.y. This formation seems to have been deposited on an almost flat topography and may blanket basement areas which have previously received little sediment. The bedding is typically conformable with the base of the formation. Correlation with IPOD drillsite 398 shows formation 2 to be of Senonian to Palaeocene age and to consist of pelagic carbonates and zeolitic red claystones with thin silt and sand bands (Rehault and Mauffret, 1979; reinterpreted by Gardner and Kidd, in preparation). The prominent reflectors within acoustic unit 2 are attributed to variations in calcium carbonate content (Sibuet, Ryan et al., 1979; Groupe Galice, 1979). Prior to the deposition of the overlying unit 1, unit 2 has been deformed. This deformation affecting unit 2 is contemporaneous with that observed in Biscay and is related to the Pyrenean orogeny (Sibuet, Ryan et al., 1979; Groupe Galice, 1979).

Unit 1

Unit 1 consists primarily of a sediment drift cover deposited by presumed northward-flowing bottom currents that may be related to a combined eastern boundary current and the extension of the Mediterranean outflow (Gardner and Kidd, in preparation). It comprises an upper Member 1a, which is widespread over the entire area, and a lower Member 1b of more limited extent. Gardner and Kidd (in preparation) have suggested that this hiatus between Members 1a and 1b reflects the Messinian dessication event in the Mediterranean.

THE NEW STRUCTURAL MAPS

Seismic profiles and GLORIA-II coverage obtained during RRS Discovery Cruise 90 form the basis of the structural maps presented in this report. Previously published studies (Auxietre and Dunand, 1978; Groupe Galice, 1979; Grimaud, 1981) have also been used in the regional structural interpretation.

Examination of the long-range sidescan sonographs, even at a small scale, shows two principal types of acoustic character, here termed acoustic facies: a diffuse backscattering which covers much of the margin (acoustic facies 1) and contrasting areas of stronger backscattering of more limited extent (acoustic facies 2) (Figure 5, Table III). The backscattering of sound from the ocean bottom will be dependent on the parameters of the sound source, sediment type and surface relief. The simultaneous seismic reflection and echo-sounder profiles provide information on sediment type and surface relief for the areas traversed by the ship's track and allows correlation with the acoustic facies mapped away from the track by GLORIA.

The seismic data shows a correlation between the low backscattering and the softer sediments which mantle the structural framework. Variations in backscattering strength within this facies have been attributed to canyons, channels and other sedimentary features (Roberts and Kidd, in press).

The distribution of acoustic facies 2 relates to areas of high relief or where areas of hard rock crops out on the seabed (i.e. seismostratigraphic units 2-5). Examination of the seismic reflection profiles show that these two backscattering controls, surface relief and rock hardness, often reinforce one another. For example, acoustic facies 2 is especially evident around the periphery of Galicia, Vigo and Porto seamounts. The seismic profiles show that these areas correspond to fault scarps where acoustic basement (seismic unit 5) crops out at the surface or is only covered by thin sediments. In other areas, especially west of Galicia Bank, areas of acoustic facies 2 correspond to where the crests of rotated fault blocks pierce the sedimentary cover. A major finding in this study was that in all cases where areas of acoustic facies 2

TABLE I - Summary of the seismic stratigraphy of the northwestern Iberian Margin from DSDP site 398 and Seismic Reflection Profiles

SEISMIC UNIT		AGE*	ACOUSTIC CHARACTER	LITHOLOGY*
1	1a	Late Miocene to Recent	Moderately well-stratified layers with evidence of some reworking by bottom currents	Sediment drifts - contourites, turbidites and carbonate poor hemipelagic sediments
	1b	Oligocene - Late Miocene		
2		Senonian to Upper Eocene	Well-stratified sequence with several strong reflectors	Siliceous marly nanno chalk with turbidites.
3		Lower Albian to Middle Cenomanian	Acoustically transparent series	Dark, laminated shales, rich in organic matter passing upwards into redeposited marl and chalk of pelagic origin
4		Late Barremian to Upper Aptian	Moderately well-stratified sequence	Sand-silt-clay graded sequences with turbidites
5 ACOUSTIC BASEMENT		Hercynian basement overlain by pre-Barremian Mesozoic sediments	Diffractive with irregular surface - horst graben and half graben internal basement reflectors	Metamorphic and plutonic rocks overlain by Jurassic to early Cretaceous limestones

* Correlation with DSDP Site 398 (from Sibuet et al., 1980). Additional data from Boillot et al. (1979).

TABLE II - Summary of dredge hauls obtained from Galicia Plateau and Vigo, Vasco da Gama and Porto Seamounts (after Boillot et al., 1979). Location of samples is shown on Figure 4.

SAMPLE	LOCALITY	DESCRIPTION	AGE AND PALAEOENVIRONMENT	ACOUSTIC STRAT.	REFERENCE
A06	Western Flank Galicia Bank	Marls with *Globorotalia truncatulinoides* with some reworked Palaeocene and Upper Cretaceous foraminifera.	Pleistocene, bathyal	1a	Boillot et al., 1979 Dupeuble et al., 1976
		Marl with planktonic assemblage: *Globigerinita dissimilis* and *Globigerina ciperoensis*.	Late Oligocene, bathyal	1b	
A07	Northern Flank Galicia Bank	Marly limestone with planktonic assemblage (*Globorotalia truncatulinoides*)	Pleistocene, probably bathyal	1a	Boillot et al., 1979 Dupeuble et al., 1976
A08	Northern slope Galicia Bank	Andesite	Hercynian basement	5	Grimaud, 1981.
A09	Vasco da Gama	Micritic limestones with calpionellids	Late Tithonian Pelagic assemblage	5	Boillot et al., 1979 Dupeuble et al., 1976
A02 H22 H23	Western flank of Galicia	Metamorphic and igneous rocks	Hercynian basement	5	Boillot et al., 1979
A09 H20 H57	Vasco da Gama	Fine grained to pellitoidal limestone with upper Jurassic to Lower Cretaceous microfauna	Kimmeridgian to Berriasian or lower Valanginian. Shallow shelf waters.	5	Boillot et al., 1979

TABLE II - continued 1

SAMPLE	LOCALITY	DESCRIPTION	AGE AND PALAEOENVIRONMENT	ACOUSTIC STRAT.	REFERENCE
D3762	Southwestern flank, Galicia Bank	Detrital limestones with broken foraminifera, molluscs and calcareous algae	Lower Cretaceous shelf facies	4	Black et al., 1964
D3804	Southern Flank Galicia Bank	Chalk with planktonic assemblage	Upper Maestrichtian Bathyal	2	Black et al., 1964 Funnell et al., 1969
D3806	Southern Flank Galicia Bank	Coarse detrital limestone with reworked fragments of rudist and Halimeda (Black et al., 1964)	Lower Palaeocene (Danian ?) Shallow water	2	Black et al., 1964
D3808	Northern flank Galicia Bank	Porous and chalky limestone.	Middle Eocene Shallow water	2	Black et al., 1964
D3809	Northern flank Galicia Bank	Chalk with planktonic assemblage	Upper Maestrichtian Bathyal	2	Black et al., 1964 Funnell et al., 1969
D4272	Eastern flank Galicia Bank	Detrital limestones with broken foraminifera, molluscs and calcareous algae	Lower Cretaceous Shelf facies	4	Black et al., 1964

TABLE II - continued 2

SAMPLE	LOCALITY	DESCRIPTION	AGE AND PALAEOENVIRONMENT	ACOUSTIC STRAT.	REFERENCE
D4279	Vigo	Foraminiferal limestone and ooze	Mid-Tertiary Bathyal	1	Black et al., 1964
D3804	Southern Flank Galicia Bank	Chalk with planktonic assemblage	Upper Maestrichtian Bathyal	2	Black et al., 1964 Funnell et al., 1969
D4280 L258 H15 H16 H54	Vigo	Fine-grained to pelletoidal limestones with Upper Jurassic to lower Cretaceous microfauna.	Kimmeridgian to Berriasian or lower Valanginian Shallow shelf waters	5	Boillot et al., 1979 Black et al., 1964
L257	Porto	Micritic limestones with Upper Jurassic to lower Cretaceous microfauna	Berriasian Pelagic assemblage	5	Boillot et al., 1979 Black et al., 1964
L258	Vigo	Marls with *Globorotalia truncatulinoides* and *reworked Palaeocene* and Upper Cretaceous planktonic foraminifera.	Pleistocene Bathyal	1a	Boillot et al., 1979 Dupeuble et al., 1976
		Marl with planktonic assemblage: *Globorotalia aequa*, *G. velascoensis*.	Late Palaeocene Bathyal	2	

TABLE II - continued 3

SAMPLE	LOCALITY	DESCRIPTION	AGE AND PALAEOENVIRONMENT	ACOUSTIC STRAT.	REFERENCE
L258	Vigo	Reworked *Globorotalia pusilla* and *G. angulata* in marls.	Middle Palaeocene Bathyal		
		Reworked *Globotruncana* and Heterohelicidae in marls.	Maestrichtian, probably bathyal	2	
		Indurated marls with *Globotruncana arca*, *G. falsostuarti*, *Racemigumbelina fructiosa*	Maestrichtian bathyal	2	
L260	Eastern flank Galicia Bank	Marly limestone with corals. Planktonic foraminifera *Globorotalia truncatulinoides*.	Pleistocene, probably bathyal	1a	Boillot et al., 1979 Dupeuble et al., 1976
		Marly limestones with *Globotruncana* sp.	Senonian, bathyal	2	
L261	North flank Galicia Bank	Marl with planktonic assemblage	Lower Middle Miocene	1	Boillot et al., 1979 Dupeuble et al., 1976

Key: D = RRS Discovery II
A = Albatlante 74
L = Lusitanie 74
H = Hesperides 76

straddled the ship's track, it correlated precisely with outcrop of seismic unit 5 (acoustic basement). Rocks derived from seismostratigraphic units 2-4 have been dredged (Table II), showing that they also outcrop on the seabed. It is possible, therefore, that outcrops of these unit 2-4 rocks also contribute to areas of brighter backscattering. However, the distance run of the dredge hauls at the seabed mean it is difficult to know the exact location from which these rocks were dredged. The GLORIA sonographs were then used to follow the outcrops of acoustic basement away from the ship's track into the insonified area. Strongly reflective features lying off the ship's track were matched with areas of known basement outcrop on the basis of other cross profiles and sampling. In this way, a map showing the outcrop of acoustic basement on the Iberian Margin has been compiled (Figure 7). It provides a substantial modification to the results of previous studies. An accurate picture of areas of nil or very thin sediment cover built up in this way enables a closer control to be presented in mapping isochrons on basement, as in Figure 8, and total sediment thickness, as in Figure 9, than has been possible in previously published maps (Auxietre and Dunand, 1978; Groupe Galice, 1979; Grimaud, 1981). Some areas of known basement outcrop fell outside the insonified area and the extent of these is taken from previously published work.

Dredging across some of the areas of acoustic basement outcrop has resulted in the recovery of a variety of rocks (Black et al., 1964; Dupeuble et al., 1976; Boillot et al., 1979; Boillot et al., 1980). From the fault scarps west of Galicia Bank, metamorphic and plutonic rocks, similar to those of the Iberian meseta have been dredged (A02, H22, H23, Table II). From the fault scarps of Vigo, Porto and Vasco da Gama seamounts, dredge hauls have recovered Late Jurassic to Early Cretaceous limestones - a reefal facies which capped the tilted blocks during rifting. Dredging at Mt. 5100 (Figure 1) by Boillot et al. (1980) recovered abundant serpentinised ultrabasic rocks. Mt. 5100 is an abyssal hill, west of Galicia Bank, close to the continental rise. Seismic profiling has shown that a peripheral basement ridge pierces through Cretaceous and Tertiary sediment cover and reaches a height of 200m above the surrounding abyssal plain (Boillot et al., 1980). The dredge haul across Mt. 5100 indicates that a serpentinite intrusion of altered plagioclase-bearing herzolite has been emplaced, probably along the normal fault system produced by the initial rift.

THE STRUCTURAL FRAMEWORK

Figures 2, 8 and 9 demonstrate the close structural control on the

TABLE III - GLORIA acoustic facies

GLORIA ACOUSTIC FACIES	ACOUSTIC CHARACTER	INTERPRETATION (from seismic reflection profiles)
1	Wide areas of diffuse, low intensity, back-scattering containing subtle variations in intensity which correlate with sedimentary features.	Sedimentary cover
2	Sharp, high contrast coherent bands and discrete features of high-intensity back-scattering.	Acoustic basement outcrop (seismic unit 5)

bathymetry of the Iberian margin. In broad terms, the structural highs correspond to bathymetric highs while the sedimentary basins with their thick infills correspond to the deeper parts of the margin (Figures 2, 8 and 9).

The regional bathymetry is relatively well known (Figure 2) and regional bathymetric maps have been produced by Laughton et al.(1975) and Vanney et al.(1979). Laughton et al. was based largely on soundings supplied by the Hydrographic Department (U.K.) with additional material supplied by the GEBCO collections of Deutsches Hydrographisches Institüt, Service Hydrographique et Oceanographique de la Marine Française and the U.S. Naval Oceanographic Office. Several institutions also contributed unpublished data (Laughton, et al., 1975). The map of Vanney et al. although based on that of Laughton et al. also includes data from the more recent French surveys which provided much of the background reconnaissance for IPOD drill site 398. The map of Vanney et al., being a more recent compilation, is considered to be more accurate than Laughton et al. The complex topography of Porto seamount, very apparent from the GLORIA sonographs (Figure 14), is clearly shown. The bifid nature and the southern prolongation of Vasco da Gama seamount, not shown on the map of Laughton et al., is recorded. However, as Vasco da Gama seamount lay beyond the insonified region, this could not be verified in the Cruise 90 study. There is further modification in the shelf and slope zones. Even so, on the map of Vanney et al., the bathymetric contours reflect considerable interpolation because of uneven distribution of ship tracks and differences in navigational position fixing between the surveys.

For ease of description, the following discussion of the structural framework of the Iberian Margin has been divided into three sections, each corresponding to major morphological units: (1) The Interior Basin (41°30'-43°30'N, 9°-11°W); (2) The Galician Marginal Plateau (41°30'-43°30'N, 11°-13°W); and (3) Vigo to Nazare (39°30'-41°30'N, 9°-12°W) (Figure 10).

The morphological features are systematically described with regard to their bathymetric expression, GLORIA character and structure as delineated by the seismic profiles.

1. The Interior Basin

The Galician marginal plateau is separated from the mainland by a broad depression some 100 km wide, referred to here as the Interior Basin (Figure 1).

The Iberian meseta is bounded by a marginal shelf, some 17 km wide off Cape Finisterre but widening to about 45 km north of the Nazare Canyon. The shelf break (~9°20'W) runs subparallel to the coastline and the seafloor rapidly drops

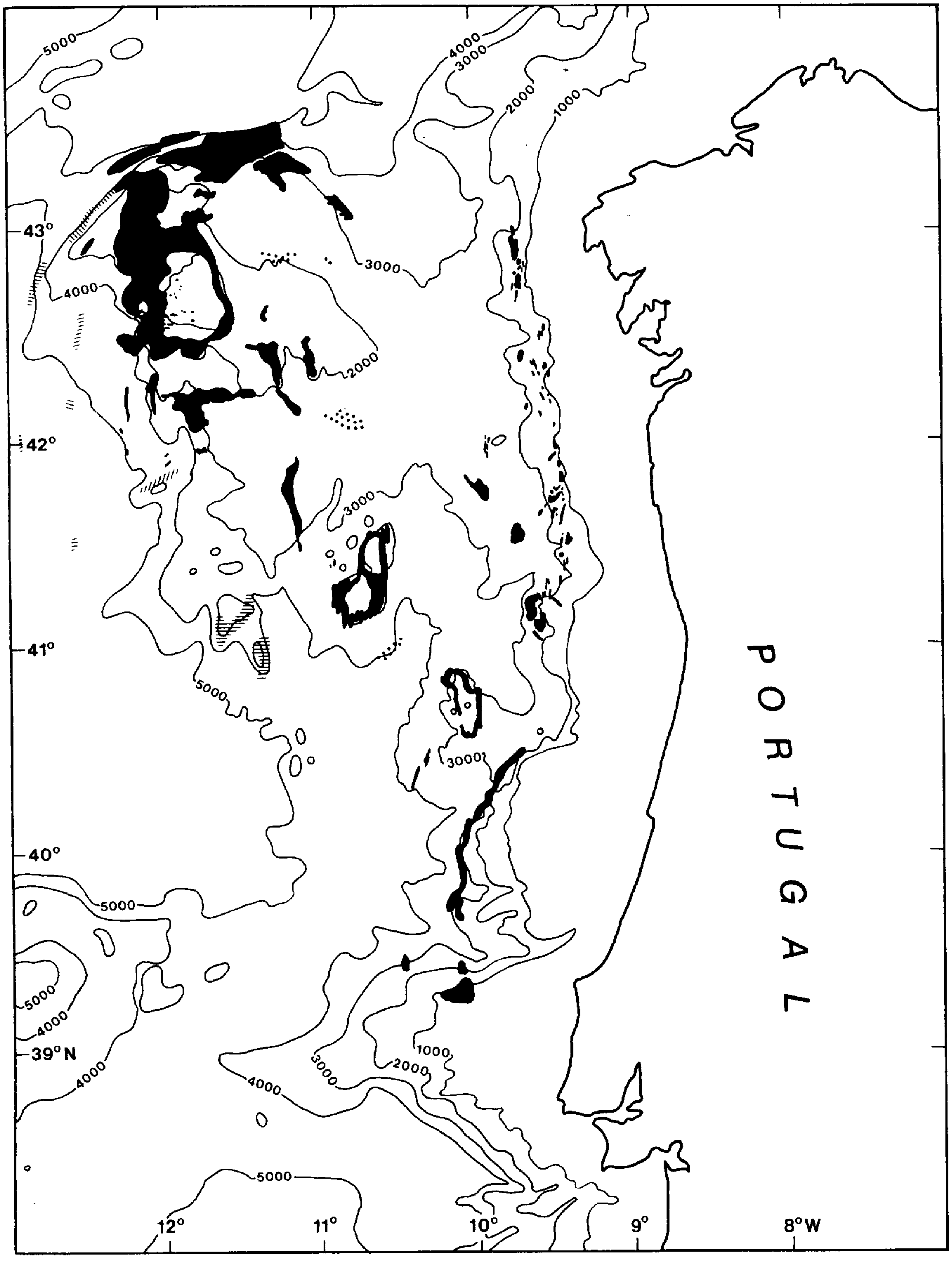


Figure 7. Northwestern Iberian margin: Basement outcrop map. Shaded areas are confirmed acoustic basement outcrop as mapped by GLORIA. Hatched areas are supposed basement outcrop out of GLORIA range, from previously published work (Groupe Galice, 1979). Dotted areas are unconfirmed basement outcrop.

Figure 8

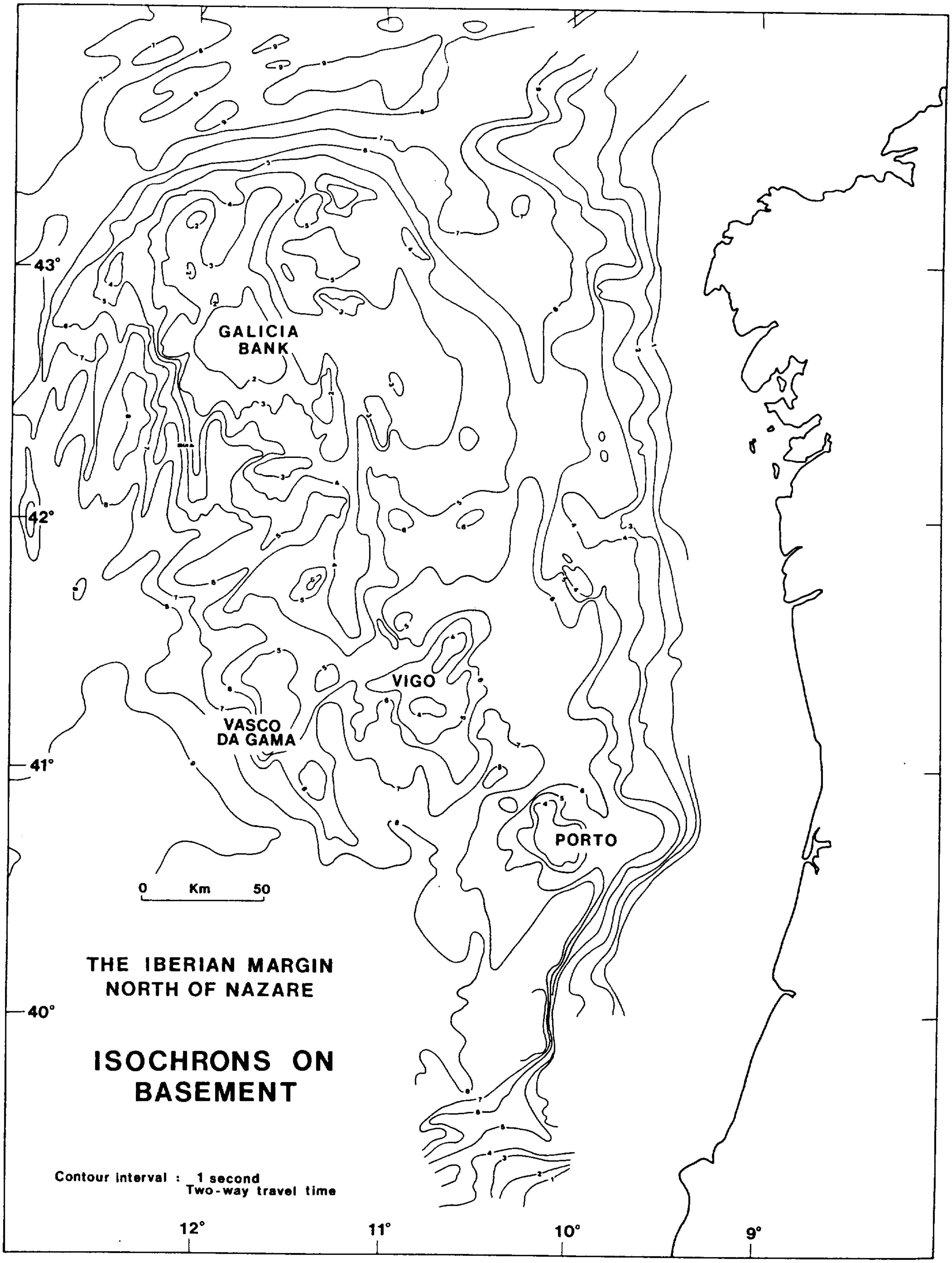
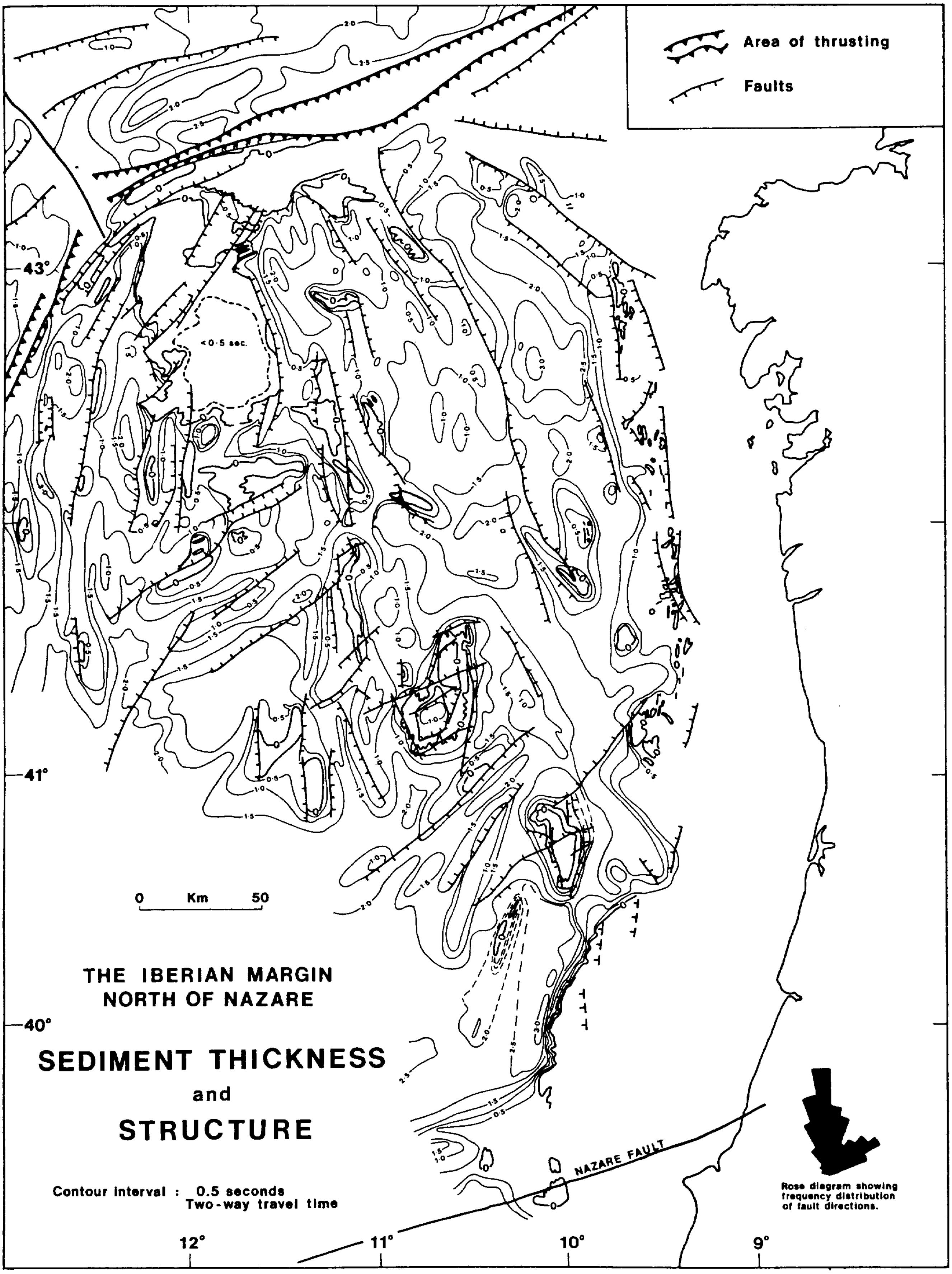

GALICIA BANK
VIGO
VASCO DA GAMA
PORTO
43°
42°
41°
40°
0 Km 50
THE IBERIAN MARGIN NORTH OF NAZARE
ISOCHRONS ON BASEMENT
Contour interval : 1 second Two-way travel time
12°
11°
10°
9°

Figure 9


Area of thrusting
Faults
43°
<0·5 sec.
41°
0 Km 50
THE IBERIAN MARGIN
NORTH OF NAZARE
40°
SEDIMENT THICKNESS
and
STRUCTURE
Contour interval : 0.5 seconds
Two-way travel time
NAZARE FAULT
Rose diagram showing frequency distribution of fault directions.
12°
11°
10°
9°

towards the west to about 2000m over a distance of 25 km. The slope contains numerous embayments and canyons, the most notable of which is Vigo Canyon, a major conduit for cross-margin sediment transport (Gardner and Kidd, in preparation).

Between Galicia Bank and the marginal shelf is a 2800m-deep saddle, some 100-km wide (Figure 2). This forms the surface expression of the Interior Basin. Northwards, the basin deepens and opens into the Biscay Abyssal Plain, while to the south it again deepens to 4000m and opens into the Iberian Abyssal Plain between Vigo and Oporto Seamounts. North of Vigo, the Interior Basin extends westwards until it becomes bounded by a long narrow ridge centred on 11°15'W, 41°40'N (Figure 2).

This 2800m-deep saddle is the reflection of a major north-south trending graben. South of Galicia, the graben extends westwards to form a major sedimentary basin, flanked to the north by the uplifted continental blocks which form the Galician marginal plateau and, to the south, Vigo Seamount. This basin contains two major structural highs (41°45'N, 9°55'W and 41°10'N, 10°10'W) which possibly represent foundered basement blocks (Figures 8, 9).

The Discovery Cruise 90 tracks were chosen to run parallel to the margin (except over Galicia Bank) and this enabled the entire saddle region (the Interior Basin [Figure 1]) to be insonified (Figure 5) over its total length. In addition, north-south, single-channel seismic profiles were run over the lower slope, saddle axis and over the saddle's westward extension, north of Vigo seamount (Figure 3).

As in other parts of the margin, the GLORIA sonographs show two main acoustic facies (see Table III). Acoustic facies 1 is the dominant type in the Interior Basin, while acoustic facies 2 is relatively rare. However, insonification of the lower slope (Figures 2, 5), shows many small sub-linear coherent highly-reflective features below the shelf break which is marked by a diffuse band of backscatter (Figures 5, 7). Most of these features are under one kilometre in width and rarely extend for more than twelve km. The marginal slope off the Galician mainland is the site of a series of north-south trending en-echelon faults which mark the eastern boundary of the Interior Basin graben (Figure 9) (Montadert et al., 1974; Groupe Galice, 1979) and comparison of the acoustic character of these features with areas of known basement outcrop suggest that these, too, are areas of outcrop. These features probably represent parts of exposed fault scarps with only a thin veneer of sediment cover. On the small scale, the structure of the slope is complex and locally small basement blocks

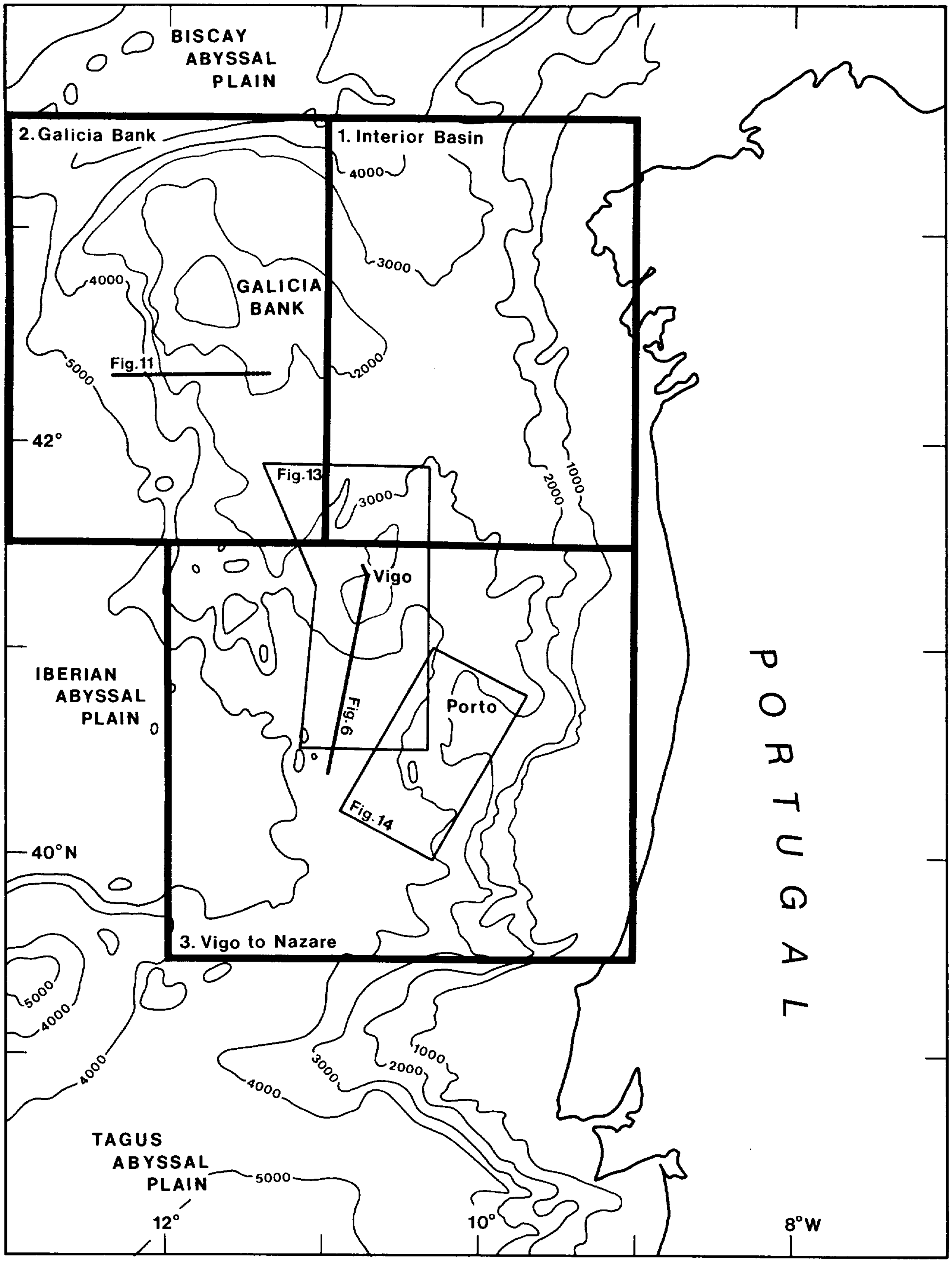


Figure 10. Northwestern Iberian margin: Profile and study area location map showing position of illustrated seismic reflection profiles and the three areas described in the discussion of the structural framework. The areas of GLORIA coverage shown in Figures 13 and 14 are also shown.

pierce the sediment cover to form discrete features (e.g. 41°30'N, 9°40'W and further south).

Northwards, the Interior Basin opens into the Biscay Abyssal Plain through a prominent embayment in the margin. To the northeast, the ground rises sharply from 3200m to 2600m to a narrow spur (43°27'N, 10°15'W), (Figure 2) seen in the far range of the GLORIA sonographs. There is no unequivocal evidence of basement outcrop on the southern slope although changes in backscattering do mark the abrupt change in slope. Published data (Grimaud, 1981) indicates that the promontary is a major NW-SE trending horst with large areas of acoustic basement outcropping along the top of the ridge and on its northern slope. Both areas were out of range of the GLORIA coverage, so this could not be confirmed.

Immediately to the south, Mugia Canyon (Figure 1) forms a prominent embayment in the slope. Northwards, above the canyon, a strongly-reflective feature follows the 2000m contour. This feature was cored by the Michail Lomonosov Cruise 4 (core 218: 43°14.6'N, 9°51.2'W), recovering limestone bedrock. GLORIA insonification of the northern marginal embayment which connects the Interior Basin with the Biscay Abyssal Plain detects a diffuse backscatter, interpreted as sedimentary cover.

At 42°00'N, 9°55'W (Figure 7) a series of sublinear highly-reflective features stand out in the near range. Twenty kilometres to the south a large target with similar acoustic facies is seen to straddle the ship's track. The seismic profiling shows this to be outcropping acoustic basement which bounds a major transform direction (Figures 8, 9) and represents a basement block that is partially covered with a veneer of sediment. Further south, the diffuse backscatter, representing the hemipelagic sediment cover, is uninterrupted.

Northwest of Vigo seamount, the Interior Basin is bounded by a major north-south trending ridge (informally named Alfonso by Vanney et al., 1979). This is seen by GLORIA as a narrow north-south trending linear echo some 50 km in length. Five kilometres to the east of the northern termination of this feature another linear feature, some 8 km in length, is seen to have the same trend. Seismic reflection profiles show a major fault lying between these two features and this probably causes the observed lateral displacement between them.

North of 42°N, an increase in backscattering intensity marks the change to the higher ground of the Galician marginal plateau and the northern boundary of the Interior Basin.

The Interior Basin as a whole forms a prominent, north-south trending structural trough with a thick infill. Seismic reflection profiles show it to be an ancient graben, bounded to the west by a major north-south fault of variable throw which may be traced for a distance of 290 km (Figure 9). The faulted eastern margin is more complex and appears to consist of two or more en-echelon faults, underlying and parallel to the marginal slope. This, of course, may be an over-simplification of a more complex picture (Figure 9). South of 42°N, there is a major lateral offset; the valley axis is displaced some 70 km to the west by a dextral transverse offset whose trend may be traced westwards across Galicia into the oceanic region (Figures 8, 9). The Interior Basin is thus a thick sedimentary basin which extends southwestwards into the mainland Lusitanian Basin, east of Porto seamount.

The sediment isopachs for the Interior basin closely reflect the underlying structural framework (Figures 8, 9), while the isochrons-on-basement map (Figure 8) reflects a young rifted morphology with a rugged relief produced during the Mesozoic rifting of the margin.

Seismic profiles, across the marginal shelf northwest of Nazare and east of Porto seamount, reveal many diapirs rising from depth (Boillot and Musellec, 1972; Montadert, 1974; Auxietre and Dunand, 1978). These diapiric structures are interpreted as salt domes and are also recorded from the mainland Lusitanian Basin around Nazare. Presumably, the offshore diapirs represent the seaward extension of the mainland diapir field. Auxietre and Dunand (1978) recorded diapiric structures within the acoustic basement from the axis of the Interior Basin north of 42°N which they interpreted as being due to mobile salt. In the seismic profile occupied by Cruise 90 down the Interior Basin axis seismic penetration is poor and, although the acoustic basement is seen in the southernmost parts of the valley, little evaluation of its structure is possible from our data and no unequivocal internal reflectors are seen. However, the presence of the offshore diapirs suggests the existence of a deep salt layer within the acoustic basement extending northwards into the Interior Basin from the mainland Lusitanian basin, probably related to an early stage of rifting. This salt layer of probable Triassic or Liassic age is probably related to the continuous deep sea salt layer, identified off many North Atlantic margins (Pautot et al., 1979) and is evidence of an earlier extensional phase to that of the Late Jurassic-Early Cretaceous.

Structural syntheses of the Iberian Margin (Auxietre and Dunand, 1978; Groupe Galice, 1979; Grimaud, 1981) suggest it was structured by two extensional episodes. During the early Mesozoic (Trias-Lias) the Hercynian meseta underwent plume-generated uplift and subsequent rifting; this resulted in dislocation and blockfaulting in a direction slightly oblique to the present coast and segmented by transcurrent faults (Groupe Galice, 1979). This initial rifting episode produced two main north-south trending fault troughs - the present Interior Basin and another west of Galicia Bank along the present margin. In these rift grabens were deposited sediments of continental and lagoonal facies together with evaporites. These evaporites have become increasingly mobilised through geological time under increasing overburden and result in the present diapirs seen both on and offshore throughout the Liassic basin.

The actual separation of the American and Euro-African plates is dated as Sinemurian (Middle Lias) off Morocco (Hinz et al., 1982) so it may be that the Interior Basin is floored by attenuated continental crust, as is the Moroccan Salt Basin (Hinz et al., 1982) and represents an aborted rift of the Triassic-Liassic tensional phase.

Sub-aerial erosion followed by subsidence resulted in the formation of sea-arms which gradually submerged the rift morphology. The Jurassic sediments deposited during this time probably resemble the neritic and reefal sediments seen in the North Portugal sedimentary basin (Mougenot, 1976).

A new phase of rifting of the margin commenced during the Late Jurassic/Early Cretaceous, which resulted in the reactivation of the Trias-Liassic basement horsts and their uplift to redefine the Interior Basin. This second rifting phase led to the separation with North America and the formation of the Atlantic Ocean. Formation 4 was deposited idn the sedimentary basins above the tilted rifted blocks during this time. Individualisation of the margin occurred during the mid-Cretaceous with the Interior Basin forming a marginal sea. However, the new marine troughs were long and narrow and probably had restricted circulation with the more open ocean to the south. The restricted circulation coupled with high organic productivity led to the deposition of the black shales (Formation 3) which form a thick sequence in the Interior Basin.

During the Late Cretaceous-Early Tertiary, there was a progressive marginal subsidence and the build up of a large continent rise (Formation 2). The influx of continental detritus infilled the Interior Basin, removing its topographic expression.

The Eocene compression (Pyrenean orogeny) resulted in the rejuvenation of the earlier rift structures of the Galician marginal plateau, marginal seamounts and, of course, the Interior Basin.

2. The Galician Marginal Plateau

In the present study, Galicia Bank is taken to refer to the flat-topped pedestal centred on 42°40'N, 11°40'W and bounded by the 1000m contour, while the Galician marginal plateau refers to the more extensive plateau bounded by the 2000m contour from which Galicia Bank arises (Figure 2).

Galicia Bank forms the major morpohological feature of the margin (Figure 1) with a surface area of some 1600 km standing some 4000m above the adjacent abyssal plains. The morphology of the Galician marginal plateau is shown in Figure 2.

The Cruise 90 ship's track was chosen to run east-west in the vicinity of Galicia Bank (Figure 3). This enabled insonification to be made of the entire plateau, except for some areas of the western lower slope proximal to the Iberian Abyssal Plain (Figure 5). These tracks provided a series of five east-west seismic profiles, spaced 35 km apart, across the Galician marginal plateau plus three short, north-south traverses parallel to the margin (Figure 3).

In contrast to those of the Interior Basin previously discussed, the GLORIA sonographs of the Galician marginal plateau show a marked difference in acoustic facies distribution. This correlates with a marked change in morphology. Galicia Bank itself is clearly defined by a high-contrast band of acoustic facies 2 (Table III) which follows its periphery, representing exposed fault scarps. The area corresponding to the top of the bank shows a diffuse backscatter (acoustic facies 1) which reflects a thin veneer of sediment.

The northern margin of the Galicia Plateau forms a steep escarpment having a gradient of 13% (7.5°). Along its base a series of bright linear echoes can be followed in the GLORIA sonographs. These were interpreted by Roberts et al. (1978) as the expression of the Pyrenean overthrust. These linear features mark the boundary between the Biscay Abyssal Plain (acoustic facies 1) with its complex channel system (Kidd, 1982) and the rocky outcrop of the northern escarpment of Galicia Bank (predominantly acoustic facies 2).

West of 12°10'W, the northwestern margin of the Galicia Plateau projects into the Iberia Abyssal Plain as a prominent spur (Figure 2) south of Theta Gap. This spur has two low, parallel southwest-trending ridges (Figure 2). The ridges extend into the Iberian Abyssal Plain, although with a reduced bathymetric expression distal to the margin. Of these ridges, only parts of one lie within the GLORIA insonified area, although in the far range this is seen as a band of increased backscatter containing several short, linear, highly-reflective discrete features. The Cruise 90 profiles do not traverse these features but published work (Auxietre and Dunand, 1978; Groupe Galice, 1979; Grimaud, 1981) show these ridges to be the crests of tilted basement blocks flanking the margin (Figures 9, 11). The changes in acoustic backscatter across these features probably reflect the thin sediment cover across the crests of the rotated fault blocks and the discrete features, the crests themselves, locally piercing the thin sediment cover. French seismic profiles show the rotated blocks to be bounded by listric-faults (de Charpal et al., 1978; Groupe Galice, 1979; Auxietre and Dunand, 1978) (Figure 11). Such a structure is typical of Biscay-type passive margins and follows the model postulated by Bott (1971) and others. The distal ridges are separated by wedges of sediments of up to 2 sec thickness (Figure 9) due to the infilling of the rift-graben between the rotating blocks by seismic unit 4 during the formation of the margin during the mid to Late Cretaceous. The crests of these rotated fault blocks can be traced southward for over 200 km and occasionally pierce the thin sediment cover, south of 42°N, but otherwise have little bathymetric expression and are mantled by pelagic sediment.

The western boundary of the Galician marginal plateau is a steep linear escarpment (having a gradient ~40% (22°) north of 42°30'N). This structure is marked by two underlying basement ridges which diverge southward (Figure 9) and bring acoustic basement to the surface (Figure 7). The crests of these two ridges can be traced south of Galicia Bank as strongly-reflective linear features (acoustic facies 2) normal to ship's track for a distance of 30 kilometres. At 42°20'N, the ridges are about 15 km apart. All of the basement ridges discussed above are separated by broad wedges of sediment - the infilling of the rotated continental blocks - and these are seen as relatively featureless expanses of acoustic facies 1 (Figure 11).

Insonification of the plateau southeast of Galicia Bank shows that the two prominent mesas above the 2000m contour are structurally-controlled basement highs (Figures 2, 7). Major areas of acoustic facies 2 (basement outcrop) are also seen to the south of Galicia Bank (Figure 7).

The compiled structure maps (Figures 8, 9) show the Galician marginal plateau to be a highly fractured continental remnant, dominated by a large basement horst (Galicia Bank). The faults mapped on the margin fall into two main sets, one trending north-south - the dominant set - and the second trending northeast-southwest (Figure 9). The first set of faults are clearly related to the Mesozoic rifting and at 41°48'N, 11°15'W (Figure 9) one of these is clearly offset by a member of the second set, trending northwest-southeast. This suggests the second set is later in age and Auxietre and Dunand (1978) have inferred that they are related to the Eocene diastrophism.

The Galician marginal plateau is clearly of continental origin (Black et al., 1964; Montadert et al., 1974) and represents a subsided block located between the failed rift of the Interior Basin and the successful rift which evolved into the present Atlantic Ocean. Although initially structured by rifting, the present morphology is due to the reactivation of synrift faults during the Eocene compression.

3. Vigo to Nazare

Below the 2000m contour, the southern extension of the Galician marginal plateau can be traced to the 41° parallel where a prominent offset displaces the continental rise by some 150 km to the east. This offset may represent a transform fault (Figures 2, 12) related an early stage of ocean formation. If this is correct, a subsequent change of spreading geometry must have occurred as the offset is not reflected in anomaly 32 to the west (Laughton et al., 1975).

Two major double-peaked seamounts are situated immediately to the north of this lateral offset: Vasco da Gama (the minimum depth for each peak being 2600m and 2695m) and Vigo (minimum depths 2026m and 2239m). Both are situated on the continental rise and are separated by a marked re-entrant of the 4000m contour (Figure 2).

Porto seamount (1940m), is a feature of complex morphology with at least three separate peaks (Figure 2). Porto seamount is linked to the lower continental slope adjacent to the mainland by a small 2400m-deep saddle. South of Porto, the continental slope is parallel to the coast and follows the 10° meridian to 39°30'N where the shelf is cut by the Nazare Canyon - a southwest-trending transverse-fault zone, probably transcurrent (Montadert et al., 1974) which makes a deep incision into the margin (Figure 2).

South of 42°N, the Cruise 90 ship's track makes four north-south traverses parallel to the margin (Figure 3). This provided an overlapping sonograph mosaic of over 150 km in width, extending from the shelf break to 11°15'W (Figure 5), giving continuous coverage of the margin, except for the southeast margin of the marginal plateau (including Vasco da Gama seamount) (Figures 2, 5).

The GLORIA sonographs again show two main acoustic facies: acoustic facies 1, representing the extensive sediment drift cover is the dominant facies while acoustic facies 2 is mainly restricted to the fault scarps of Vigo, Vasco da Gama and Porto seamounts and the lower shelf (Figure 7).

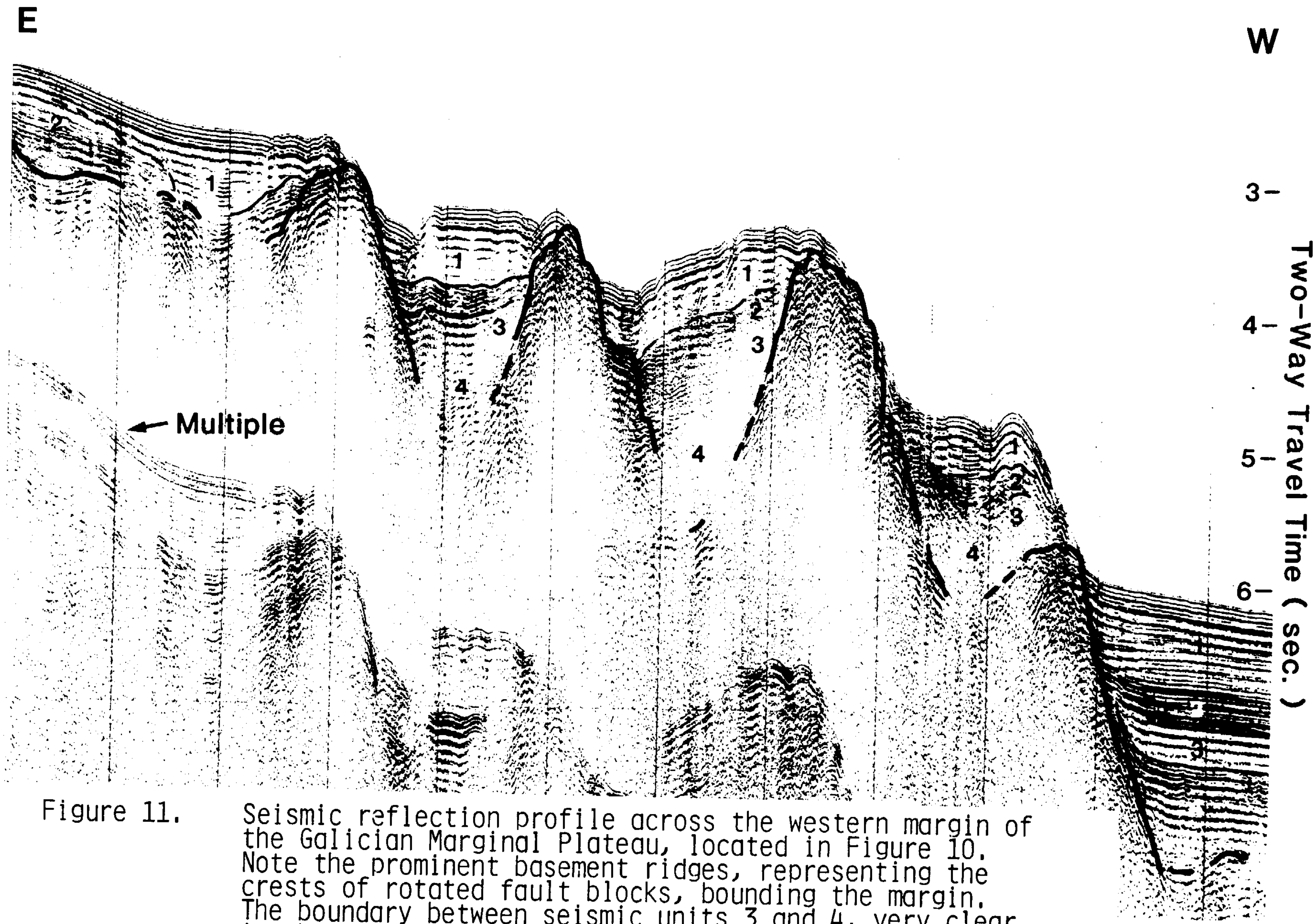


Figure 11. Seismic reflection profile across the western margin of the Galician Marginal Plateau, located in Figure 10. Note the prominent basement ridges, representing the crests of rotated fault blocks, bounding the margin. The boundary between seismic units 3 and 4, very clear in the French multichannel data, is indistinct in this profile.

The southwestern portion of the marginal plateau lies beyond the GLORIA coverage but published data (Auxietre and Dunand, 1978; Groupe Galice, 1979; Grimaud, 1981) shows it to be a deeply fractured region, dominated by a series of southwest trending faults (trending 055°) which dissect the margin (Figures 2, 9). These probably relate to the Eocene tectonics (Auxietre and Dunand, 1978). Dissection of the margin along these faults has led to a series of subparallel linear troughs with thick sedimentary infill of the same trend (055°) (Figure 9).

Vasco da Gama seamount is a major double horst located on the southern margin of a basement high (Figure 7). Its northern peak forms a flat peak (2600m) with a surface area of 240 sq. km., bounded on the east and west by north-south trending normal faults. Acoustic basement is exposed on its western, southern and eastern slopes. Dredging across the basement (A09, H20, H57, Figure 4, Table II) has recovered Upper Jurassic-Lower Cretaceous micritic and pellitoidal limestones (Dupeuble et al., 1976; Boillot et al., 1979), deposited on the margins of the new ocean during the Late Jurassic-Early Cretaceous extensional phase. The southern peak of Vasco da Gama seamount (2695m) is separated from the northerly peak by a small col some 8 km wide (Figure 2). It is a smaller feature (surface area ~50 sq. km.) with a north-south elongation but is also structurally controlled, being bounded by north-south trending normal faults on the east and west. French surveys suggest that much of this peak is basement outcrop (Figure 9). The two horsts are laterally offset by some 12 km. The north-south bounding faults which bound the horsts of Vasco da Gama seamount were probably formed during the rifting of the margin in the Mesozoic but were possibly reactivated during the Eocene compression with subsequent uplift, as with Galicia Bank and Vigo seamount.

One of the most conspicuous features of the structural maps is the prominent north-south trending basement ridge which follows the 11° meridian (Figures 7, 8, 9). This feature may be followed on the sonographs from south of the Galician marginal plateau to 41°20'N, a distance of over 120 km. Along its eastern edge thick sediment drifts have accumulated (Gardner and Kidd, in preparation) (Figure 9). This ridge forms the eastern boundary of the Interior Basin, previously discussed, and possibly represents the western escarpment of the Triassic rift. GLORIA insonification of the feature reveals that a continuous band of acoustic basement (~50 km) is exposed on its eastern slope. The structural control of this feature has been previously described in the discussion of the Interior Basin.

Vigo seamount is a conspicuous feature on the continental rise north of the

41° parallel (Figure 9). It consists of two peaks, orientated north-south, separated by a narrow col (Figure 2). Seismic profiles show this col to be the expression of a north-east trending fault which obliquely cuts the feature (Figure 9). South Vigo is the dominant peak, being 17 km wide at the 2400m isobath. North Vigo is only 7 km wide at the 2400m isobath. The GLORIA sonographs (Figure 13) show a broad band of acoustic basement outcrop around the periphery of Vigo seamount and across the connecting col. This corresponds to pre-rift rocks being brought to the surface along normal fault scarps. These fault scarps have been extensively dredged (Black et al., 1964; Dupeuble et al., 1976; Boillot et al., 1979). Dredging from the southern slope of south Vigo and the northern slope of north Vigo recovered fine-grained to pelletoidal limestones with an Upper Jurassic to Lower Cretaceous microfauna (Table II, Figure 4). Mid-Tertiary foraminiferal ooze was recovered from the summit of the seamount. Seismic profiles show that the Vigo peaks are structured by north-south trending faults, probably related to Mesozoic rifting cut by east-west trending faults, possibly related to the Eocene compressional event (Figure 9). South Vigo is notable for containing a central depression with a thick sedimentary infill of 1.3 sec in which all the major seismostratigraphic units are preserved (Figure 6). Thus, Vigo seamount is a composite structure consisting of three adjacent horsts, structured by complex intersecting fractures (Figure 9), and owes its present morphology to both the Mesozoic rifting and the Eocene compression.

Porto seamount (Figure 2) is the topographic expression of a major basement horst capped by a thin sedimentary sequence (Figures 9, 14). It is bounded by north-south trending faults and is cut by a major fault of NE-SW orientation whose position can be clearly seen on the GLORIA sonographs (Figure 14). Between Porto seamount and the continental slope is a small sedimentary basin about 30 km wide which links the Interior Basin with the mainland Portuguese Lusitanian Basin (Figure 9). Mobilisation of the deep salt layer has resulted in extensive diapirism in the region (Auxietre and Dunand, 1978).

South of Porto to the Nazare Canyon, the wide undissected continental slope follows the 10° meridian and runs subparallel to the coast (Figure 2). As further north, the slope is underlain by a series of north-south trending faults but their course is imperfectly known (Figure 9). At the base of the slope a thick sedimentary sequence (2.5-3 sec) underlies the continental rise and extends westwards underneath the Iberian Abyssal Plain. Twenty-five km southwest of Porto seamount, two aligned linear features of acoustic facies 2 are seen in the

GLORIA near field. By analogy, these features are suggestive of acoustic basement outcrop and, if this is so, then the feature may represent the crest of a submerged basement ridge. However, there are no seismic profiles over the feature so its true nature must remain in doubt (Figure 14).

DISCUSSION

A widely-supported model of continental rifting envisages the opening of a new ocean being initiated through domal uplift of continental crust, possibly over thermal mantle plumes. Such domal uplifts have been interpreted as "isostatic responses to mass deficiencies produced by partial melting at the base of the lithosphere" (Burke and Whiteman, 1973). Trilete fractures form on the plume-generated uplifts, developing triple junctions. Magmatic upwelling within the rifts leads to the onset of seafloor spreading, further rifting and the formation of the new ocean basin.

Northwest of Cape Finisterre, the Biscay, Euro-American and Lusitanian spreading axes converge and their junction marks the site of the Cape Finisterre plume-generated swell (Wilson, 1975). A second plume-generated triple junction has been postulated off Lisbon but the evidence for this is much more tenuous (Burke and Dewey, 1973; Wilson, 1975). Wilson (1975) has documented the stratigraphic evidence for the Cape Finisterre uplift in the context of the wider geological setting.

However, the early history of this part of the Atlantic Ocean is more complex than basic theory suggests and the Mesozoic extension of the margin occurred in two stages (Groupe Galice, 1979). The initial rifting phase occurred during the Triassic (~200 my BP) and structured the Interior Basin which separates the Galician marginal plateau from the mainland. A second Triassic-Liassic rift formed west of Galicia Bank and was reactivated during the second stage of rifting during the Late Jurassic-Early Cretaceous (~140 my BP) (Groupe Galice, 1979). Seismic reflection profiling has revealed the presence of salt diapirs, probably of Triassic age in the Lusitanian Basin and these have been identified as far west as Porto seamount. These evaporites are probably related to the continuous deep sea salt layer off the North Atlantic margins, first documented by Pautot et al. (1970). The parent salt layer from which these diapirs arise is also thought to floor the Interior Basin (Auxietre and Dunand, 1978). The closest modern analogue to this early ocean in both climatic and morphologic terms is the present Red Sea. The initial rifted landscape was similar to that developed further north (the Bay of Biscay and the Western

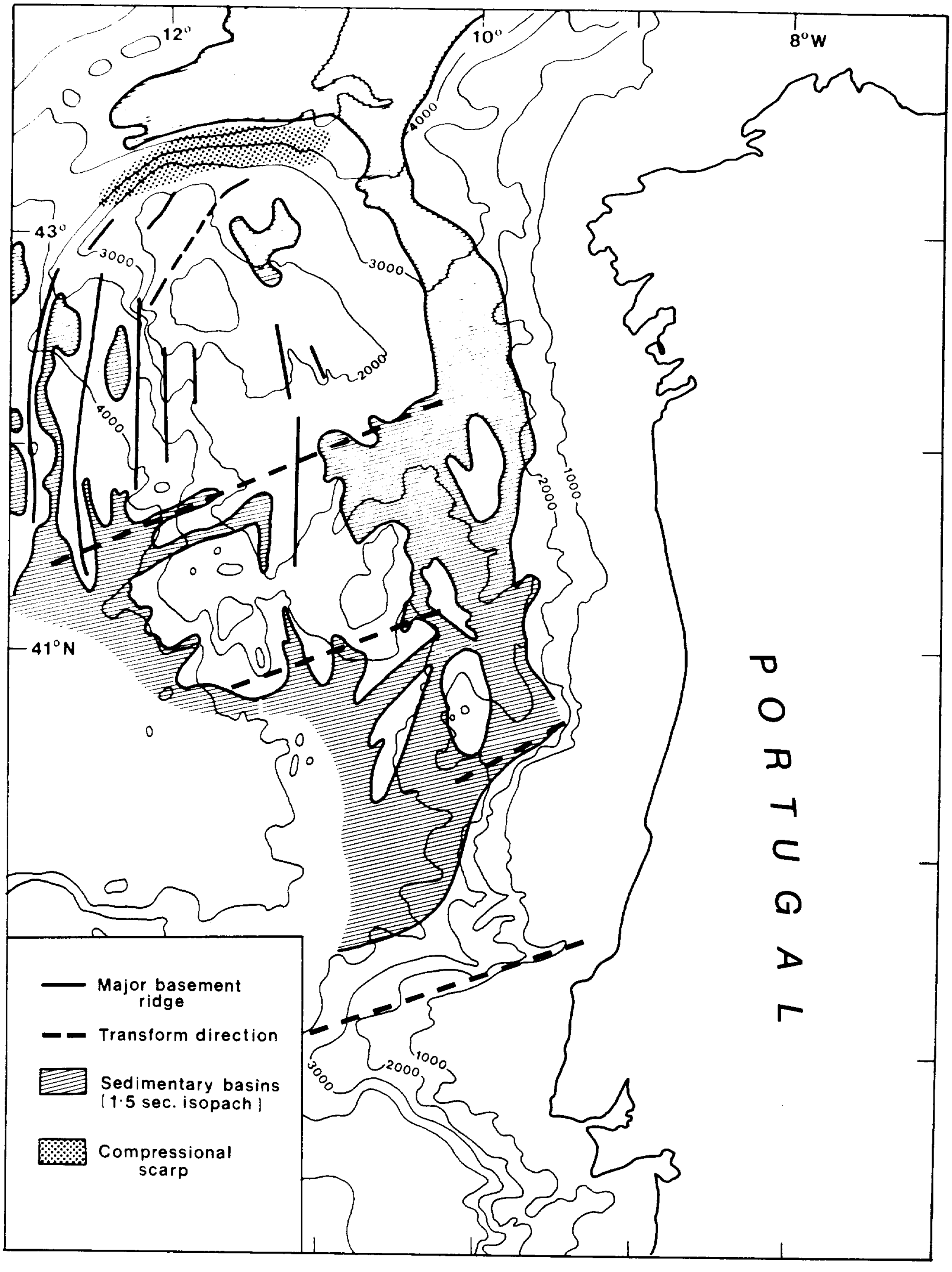


Figure 12. Northwestern Iberian margin: structural synopsis, showing major basement ridges, transform directions and the areas of thick sediments as delineated by the 1.5 second isopach (two-way travel time).

Approaches) and on the Canadian margin during the same period (Montadert et al., 1971; Jansa and Wade, 1975; De Charpal et al., 1978; Montadert et al., 1979).

The initial Triassic rifting was followed by subsidence and the formation of sea-arms with neritic and reefal environments. The second rifting phase occurred during the Late Jurassic and Early Cretaceous and resulted in the separation of North America and Europe. It was during this time that seismic unit 4 (Late Barremian-Upper Aptian, 115-100 my BP, Ness et al., 1980) was deposited, infilling the half grabens between the tilting blocks.

Further subsidence of the young continental margin is evidenced by the deposition of unit 3 - laminated black shales of Lower Albian to Middle Cenomanian in age (100-93 my BP; Lowrie and Alvarez, 1981). These were deposited in the structural lows and at the base of the new continental slope. During the Late Cretaceous to early Tertiary subsidence continued and the whole margin was submerged. This resulted in the build up of a large continental rise sediment wedge (seismic unit 2). The deposits of unit 2 resulted in a marked levelling of the local relief with Vasco da Gama seamount and some other basement ridges (the crests of buried tilted blocks) being the only major features (Vanney et al., 1979).

This period of relative tectonic quiescence came to an end in the Eocene with the Pyrenean orogeny which resulted in the rejuvenation of the ancient basement horsts, leading to a pronounced change in margin morphology. The Pyrenean orogeny has been the main cause of the present shelf morphology of Iberia (Boillot et al., 1979).

The main Pyrenean event caused the northward displacement of the Iberian margin and the development of a compressional scarp which forms the northern boundary to the Galician marginal plateau, together with the uplift of the marginal plateau and related seamounts (Galicia, Vigo, Vasco da Gama and Porto seamount) (Boillot et al., 1979).

Seismic profiles show that the Galician escarpment fault zone changes laterally to a flexure in the deeper areas to the southwest. It is seen that this flexure affects seismostratigraphic unit 2 (Senonian to Upper Eocene, 89-40 my BP; Lowrie and Alvarez, 1981) but not the overlying unit 1 (Oligocene-Recent) and so the diastrophism correlates with the Pyrenean event. The vertical displacement observed along the fault scarps is more than 3000m. Consequently, the Galician marginal plateau must have been uplifted by this amount in the early Tertiary and this vertical displacement decreases gradually to the south (Auxietre and Dunand, 1978; Boillot et al., 1979). During the

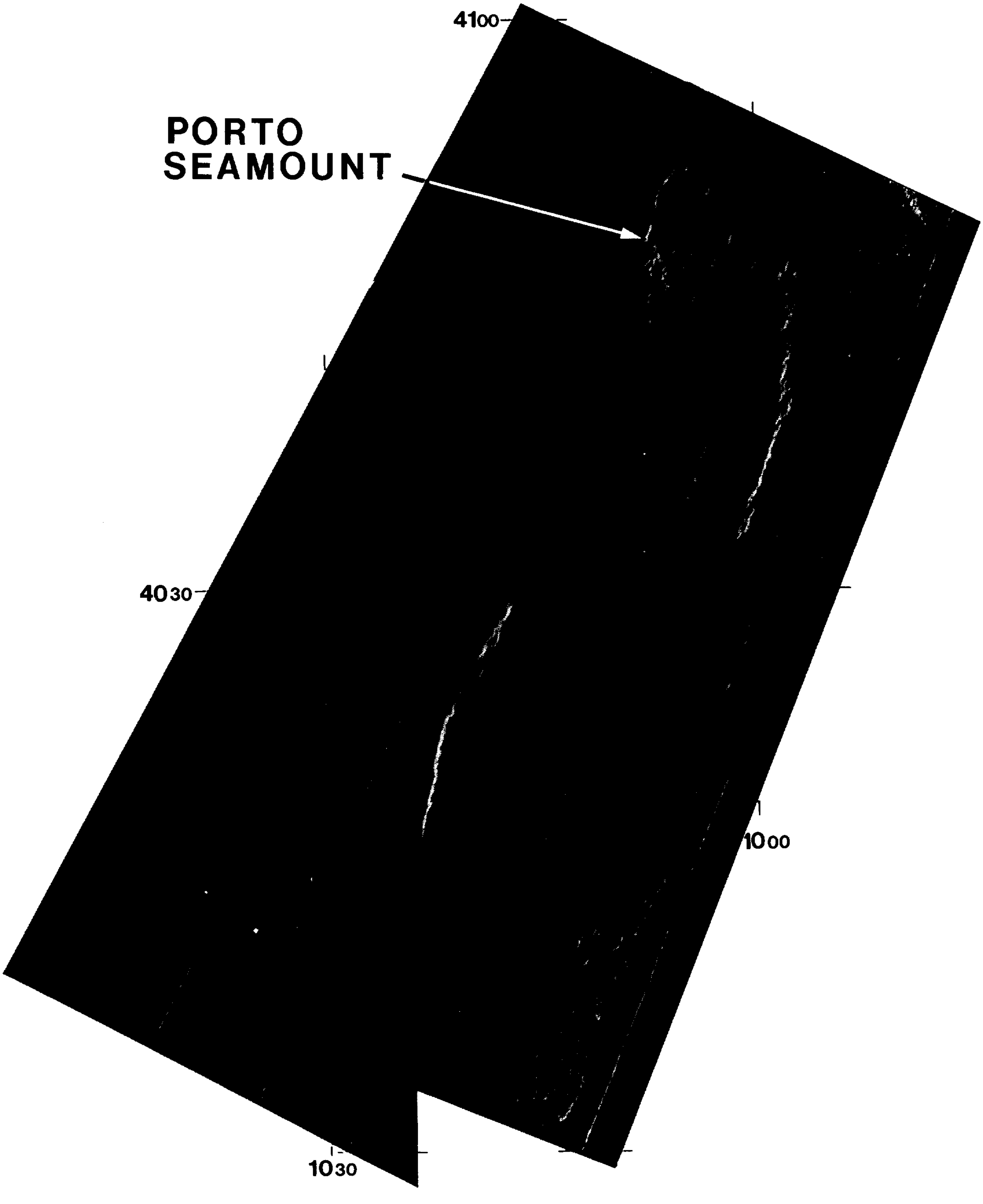


Figure 14. GLORIA-II mosaic: area around Porto Seamount.

Eocene, much of the continental shelf, especially Galicia Bank, was uplifted above sea-level and underwent subaerial erosion.

Since the Eocene compression, the whole margin has undergone a continuous regional subsidence. Concurrent with this subsidence and particularly since the Oligocene, the structural framework of the margin has been progressively mantled with extensive drift sediments developed by northward-flowing bottom water masses. A marked hiatus within the drift unit has been related to the dessication of the Mediterranean during the Messinian (Gardner and Kidd, in preparation).

CONCLUSIONS

This study results from a compilation and reassessment of published data in the light of the GLORIA-II side-scan coverage and seismic reflection profiles obtained during RRS Discovery Cruise 90. The GLORIA-II plan views have enabled the construction to be made of the first accurate basement outcrop map of the margin and provided additional information on the tectonic lineaments. This data has also provided the basis for improved regional structure maps.

The continuous sonograph coverage of the margin provided by the GLORIA technique shows the spatial relationship of the major structural units as delineated by changes in backscattering. Maps of acoustic basement outcrop have been previously published by Auxietre and Dunand (1978), Groupe Galice (1979) and Grimaud (1981). Although the Cruise 90 study broadly confirms previous mapping, the new geophysical data has provided significant modification in detail. Areas of previously unrecorded basement outcrop are recorded in the southeast Interior Basin and along the continental slope off the Galician mainland (Figure 7). These are interpreted as where foundered basement blocks pierce the sedimentary cover or as areas of exposed fault scarps. Similar features are recorded along the base of the continental slope south of Porto seamount and in the Nazare Canyon. Several minor unrecorded basement ridges and other small features are identified, e.g. southwest of Porto seamount, southeast and east of Galicia Bank (Figure 7). Further, the outcrop of acoustic basement along the 11° meridian ridge, northwest of Vigo seamount is shown to be continuous.

The GLORIA sonographs show continuous acoustic basement outcrop around the periphery of Galicia Bank, reflecting basement outcropping along fault scarps. The continuity of the outcrop has not been previously mapped. The new geophysical data obtained during Cruise 90 has provided a significant refinement of previous French work.

The evolution of the Iberian Margin may be summarised as a series of tectonic events.

1. Triassic extension, resulting in the formation of the Interior Basin and a young rifted morphology.
2. An interruption of rifting in the Early Jurassic leading to subaerial erosion followed by subsidence with the deposition of neritic sediments.
3. Renewed rifting in the Late Jurassic-Early Cretaceous with the reactivation of the Triassic rifts culminating in the separation from North America and the formation of the Atlantic Ocean.
4. Progressive subsidence of the young margin with the build-up of a large continental rise sediment wedge mantling the rifted morphology (Late Cretaceous-Palaeocene).
5. Eocene compression (correlated with the Pyrenean orogeny) results in the rejuvenation of the rifted morphology, with the uplift of Galicia Bank and the other marginal seamounts.
6. Progressive regional subsidence with minor tilting.

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