Canyons
Gullies
Slump folds
Continental slope
Sonographs
Canyons
Ravins
Plis de glissement
Pente continentale
Sonographes

Channels, canyons and slump folds on the continental slope between South-West Ireland and Spain

N. H. Kenyon, R. H. Belderson, A. H. Stride
Institute of Oceanographic Sciences, Wormley, Godalming, Surrey, England.

Received 27/12/77, in revised form 1/3/78, accepted 10/3/78.

ABSTRACT

Long-range sonographs provide plan view data relevant to the morphology of the continental slope between South-West Ireland and Spain. The relief viewed in this way includes: (1) sinuous flat-bottomed channels, 100-280 m deep and 1-5 km wide, flanked by terraces and developed on an half degree slope in the Porcupine Seabight; (2) the deeply canyoned, gullied and slumped continental slope West of the Celtic Sea and the Armorican Shelf, where the overall slope is from about 5 to 9°, with some remnants of undissected slope, and (3) numerous slump folds with wavelengths of 1.5 to 2.5 km that are developed on slopes of 3 to 5° bordering onto the Landes Marginal Plateau. The upper reaches of the canyons are notable for abundant dendritic side-gullies, which contrast with the ungullied sinuous channels and slump folds found elsewhere. Many of the canyons trend obliquely down-slope and have sharp changes in direction, indicating structural control. Within the area studied the steepness of the continental slope seems to be the dominant factor in determining its morphology.

Oceanol. Acta, 1978, **1**, 3, 369-380.

RÉSUMÉ

Chenaux, canyons, et plis de glissement sur la pente continentale entre le sud-ouest de l'Irlande et l'Espagne

Le sonar latéral à grand rayon d'action fournit de nouvelles données sur la morphologie de la pente continentale entre le sud-ouest de l'Irlande et l'Espagne. Grâce à cette méthode sont passés en revue : le système de chenaux disséquant la pente douce s'étendant à l'est du banc Porcupine; la pente continentale située à l'ouest de la Mer celtique et de l'Armorique, pente profondément entaillée par des canyons, des ravins et affectée de glissements; enfin les nombreux plis de glissement bordant le plateau marginal submergé des Landes. Les têtes des canyons sont caractérisées par une abondance de petits affluents organisés en réseaux dendritiques, ce qui les différencie des autres zones, des chenaux dépourvus d'affluents et des aires à plis de glissements. Un nombre important de canyons sont obliques par rapport à la pente continentale et présentent de plus de brusques changements de direction indiquant un contrôle structural de leurs directions.

Oceanol. Acta, 1978, **1**, 3, 369-380.

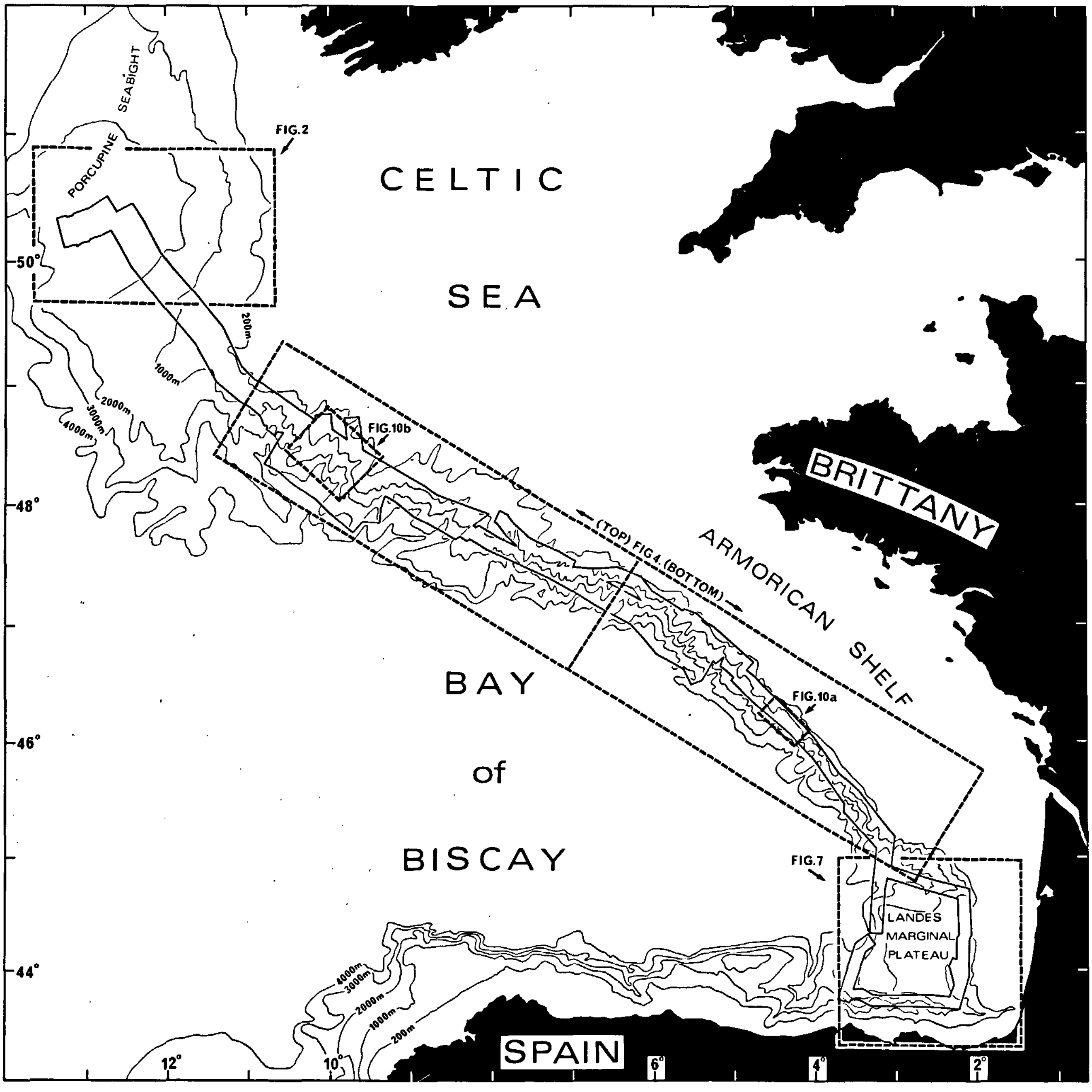
INTRODUCTION

Contoured bathymetric maps, based on soundings, have revealed, in progressively greater detail, the canyoned nature of the continental slope West of the Celtic Sea and France (e. g. Beaugé, 1937; Day, 1959; Berthois and Brenot, 1960; Brenot and Berthois, 1962; Hadley, 1964; Berthois and Brenot, 1966; Vanney, 1969; Pinot, 1974, and Laughton *et al.,* 1975). These maps are of rather variable quality, particularly because of the poor position fixing available in the early years, as well as the up and down-slope orientation of the majority of sounding lines. Moreover, depth was measured by means of the conventional broad beam echo-sounder, which introduces considerable interpretational difficulties on such rough sea floor because of the presence of numerous side echoes.

The advent of side-scan sonar, by providing full areal cover of the floor, has added a new dimension to the visualisation of the relief. Short-range (1 km) sonographs demonstrated the continuity of gullies, as well as their abundance in canyon heads (Belderson and Stride, 1969). Long-range sonographs revealed the canyons as a whole, with almost as much of an impact as aerial photographs (Belderson and Kenyon, 1976).

The present paper describes: (1) a channel system within the Porcupine Seabight; (2) the complex canyon systems on the continental slope West of the Celtic Sea and the Armorican Shelf, and (3) the well-developed slump folding bordering the Landes Marginal Plateau. The new data helps to evaluate the degree of confidence that can be placed in the relief indicated by the bathymetric contour maps, provides evidence of the real location

Figure 1
Generalised contours of the continental slope between South Western Ireland and North Western Spain, together with the areas examined by RRS Discovery while using long and short range side-scan sonar and sub-bottom profiling equipment. Boxes outline the areas shown in later figures.



and trends of canyons and slumps in the areas shown on Figure 1, and provides a firmer base for assessing their possible origins.

METHODS

The main results to be described were obtained by reconnaissance with long-range side-scan sonar (Gloria) on two cruises of RRS "Discovery". In 1975 three ranges were used, to a maximum of 7, 13 and 28 km out to one side of the ship. In 1977 simultaneous two-way looking equipment was used, in this case to a maximum range of 15 km on each side of the ship. A description of the latest long-range side-scan sonar is given by Somers *et al.*, 1978. Short-range (up to 2.5 km each side of the ship) sonar was also used on both of these cruises, and to a range of 1 km on the 1965 and 1966 cruises to this region. On the lower part of the continental slope the short-range side-scan sonar was used as a narrow beam echo-sounder, whose profiles were not spoilt by side echoes. Sub-bottom profiles were obtained on all but the 1977 cruise. These are not referred to in detail here, although they have helped in the interpretation of the side-scan sonar records. Position fixing on the 1975 and 1977 cruises was by means of satellite navigation equipment.

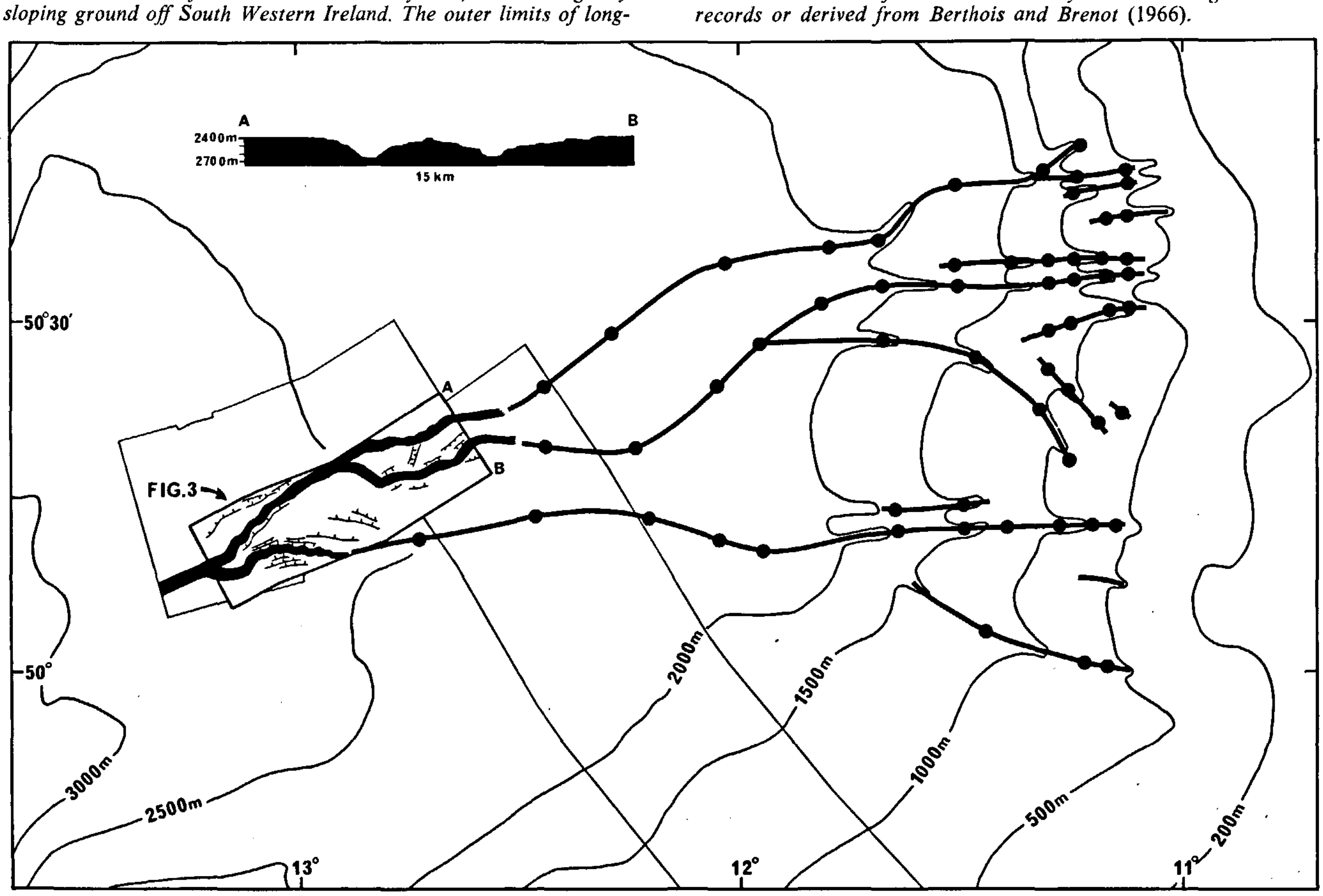
The long-range sonographs were reduced to the scale of the series of maps presented by Berthois and Brenot (1966) and arranged as a montage in their correct geographic location. Axes of canyons and side-gullies, along with other features such as slump folds and scarps and/or steep slopes were then plotted. Although the sonographs offer much greater scope for realistic visualisation of the topography than the bathymetric maps, they too have their limitations, as a relief feature will only be well shown if it offers a strong reflection or casts a strong acoustic shadow. Also, a linear feature will be shown to a greater or lesser degree according to the orientation of the ship's track relative to its trend. Fortunately the interpretation of some areas is based on views from both an upslope and a downslope direction (although, in general, viewing downslope tended to produce the better picture). The long-range sonographs resulting from the 1975 cruise were limited, by a mechanical fault, to starboard viewing only, which somewhat hampered the choice of ship's courses.

RESULTS

The Gollum Channel System

The presence of channels on the eastern slope of the Porcupine Seabight, off South Western Ireland, was first suggested on a bathymetric map by Brenot and Berthois (1962). Exploration with side-scan sonar is more extensive at the shorter ranges, as the two planned periods of long-range work both had to be cut short before completion. The part of this dendritic system (Fig. 2) seen on long-range sonographs is established on a slope of about 0.5°. Above this ground, where the slope is greater (about 2°), there are also indications on short-range side-scan sonar and echo-sounder records

Figure 2
Dendritic channels of the Gollum Channel System, located on gently sloping ground off South Western Ireland. The outer limits of long-range side-scan sonar coverage are shown by straight lines. Dots show the location of channels seen only on short range side-scan records or derived from Berthois and Brenot (1966).



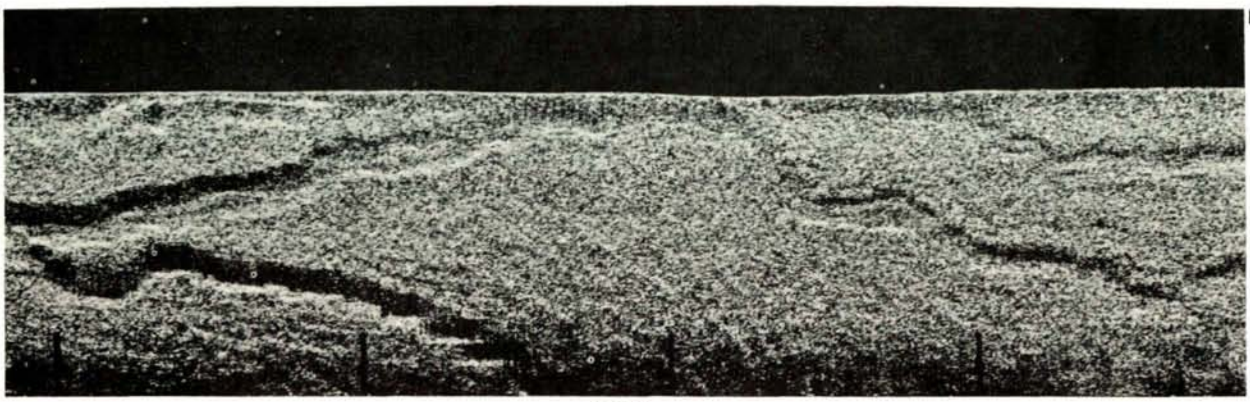


Figure 3
A plan view of junctions between three sinuous channels of the Gollum Channel System, off South Western Ireland. The interpretation of this sonograph, as shown in Figure 2, is strengthened by a view from a different direction. The direction of "illumination" is from the top of the page, with the side of a channel that is in shadow appearing black and the other side appearing light toned. The cross section A B was obtained by narrow beam sonar.

of slumps and slump folds. The sonograph in Figure 3 gives a plan view presentation of the nature of the relief, showing junctions between sinuous channels and indications of flanking terraces. There are no obvious gullies entering the sides of these channels, in contrast to the abundant well-developed gullies that are present on the slopes of the submarine canyons occurring further South. The terraces are confirmed and additional smaller ones seen both in plan view and in profile on the short-range sonographs (such as the profile A-B, Fig. 2) transverse to the channel axes. They may result either from lateral slumping towards channel axes, or from lateral channel migration at earlier stages. The channels are flat floored, from about 100 m up to 280 m deep and up to 1.5 km wide, with little evidence for flanking levees. The floors appear dark-toned on the short-range sonographs, indicating the presence of material coarser than that adjacent to the channels. This suggests that the channels are still active. In accordance with the nomenclature used by Roberts (1975), for the region further West from here, we propose that this channel system be named the Gollum Channel System.

The canyoned North-Biscay continental slope

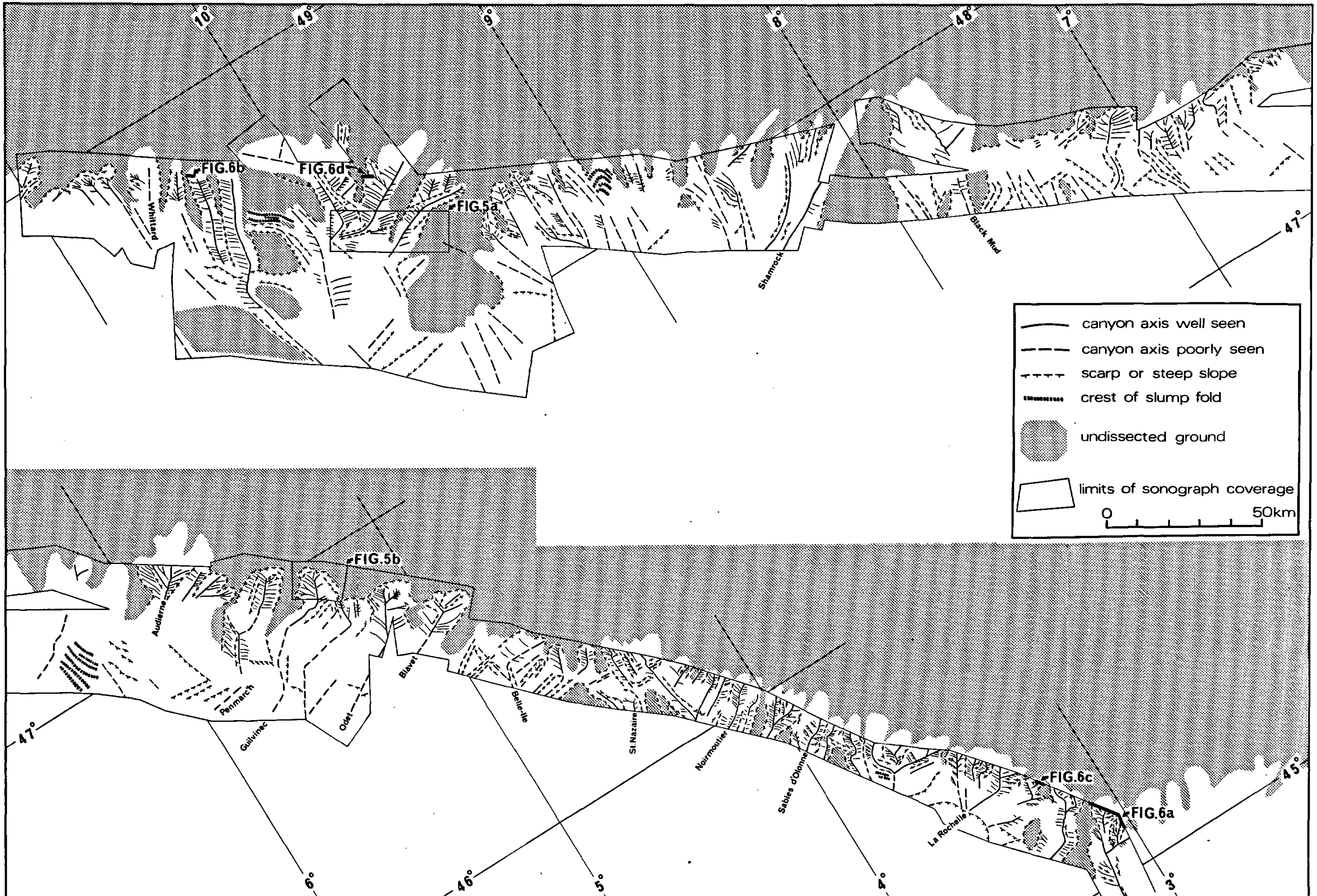
The canyons in this region are entrenched into slopes which average between about 5 and 9°. The main features revealed by the sonographs (with confirmation by narrow beam profiles, where these are usefully located) are shown in Figure 4. The only additional information included in this figure are some limits of canyon heads that have been taken from bathymetric maps. The continuity of the canyon axes can be followed unambiguously across the full width of many portions of the sonographs and the associated primary and secondary side-gullies can be mapped with relative ease. Gullies will be present in more places than indicated in Figure 4 since one side of a canyon may be preferentially seen, while the other lies in shadow. Features such as gullies may be less well seen in deeper water because of the steeper angle of view. However, gullies do seem to be less common on the lower parts of many canyons, suggesting a somewhat different mode of origin for that ground. With variations both in the quality of the sonographs (particularly at the far ranges) and in the nature of the relief, there are some areas where the canyon axes are poorly shown. Thus, on the lower part of the continental slope, scarps can be observed, but there is no certainty that canyons lie between them. In drawing up Figure 4 compromises have had to be made in order to clarify the presentation. Canyon axes are dashed where not clearly shown, and discontinued where sonograph evidence for them is lacking, although they must, in fact, continue.

Although relatively few main canyons join together, an overall dendritic pattern is imposed by the numerous secondary valleys and side-gullies. The canyon axes themselves vary from sinuous to straight, but with frequent sharp turns, of up to 90° in some cases. These are perhaps best shown by canyons in the lower portion of Figure 4. Some long-range sonographs from this region were shown by Belderson and Kenyon (1976). Other examples of long-range sonographs are given in Figure 5.

The canyon heads may generally be described as having the steep-rimmed "amphitheatre" shape typical of the area mapped by Pinot (1974) (e. g. the Guilvinec Canyon, Figs. 4 and 5 *b*). These are composed of a series of "leaf-like" elements which together lead into the main canyon (Figs. 5 *c* and 6).

The sonographs provide a mass of data about the presence and trend of gullies in the sides of canyons, details of which are rarely possible to put together effectively even from close-spaced echo-sounder lines. The sonographs show that in many instances the gullies head right back to the crest line of a sharp, arête-shaped interfluve. This is well shown in detail on the short-range sonographs (e. g. Fig. 6 *a*). There are some examples of canyons with an asymmetric cross-sectional profile, with the gullies better developed on the wider, less steep side, as (for example) in the canyon at 9°45′W on Figure 4, located with respect to Figure 6 *d*.

Figure 4 ▶
The locations of submarine canyon axes and some slumps and slump folds, with intervening undissected ground, on the continental margin west of France, as derived from sonographs. Some canyon axes extend directly down the slope while others are markedly oblique to it.


10°
49°
9°
8°
48°
7°
47°
FIG.6b
FIG.6d
FIG.5a
Whittard
Shamrock
Black Mud
canyon axis well seen
canyon axis poorly seen
scarp or steep slope
crest of slump fold
undissected ground
limits of sonograph coverage
0
50km
FIG.5b
Audierne
Penmarch
Guilvinec
Odet
Blavet
Belle-Ile
St.Nazaire
Noirmoutier
Sables d'Olonne
La Rochelle
FIG.6c
FIG.6a
45°
47°
6°
46°
5°
4°
3°

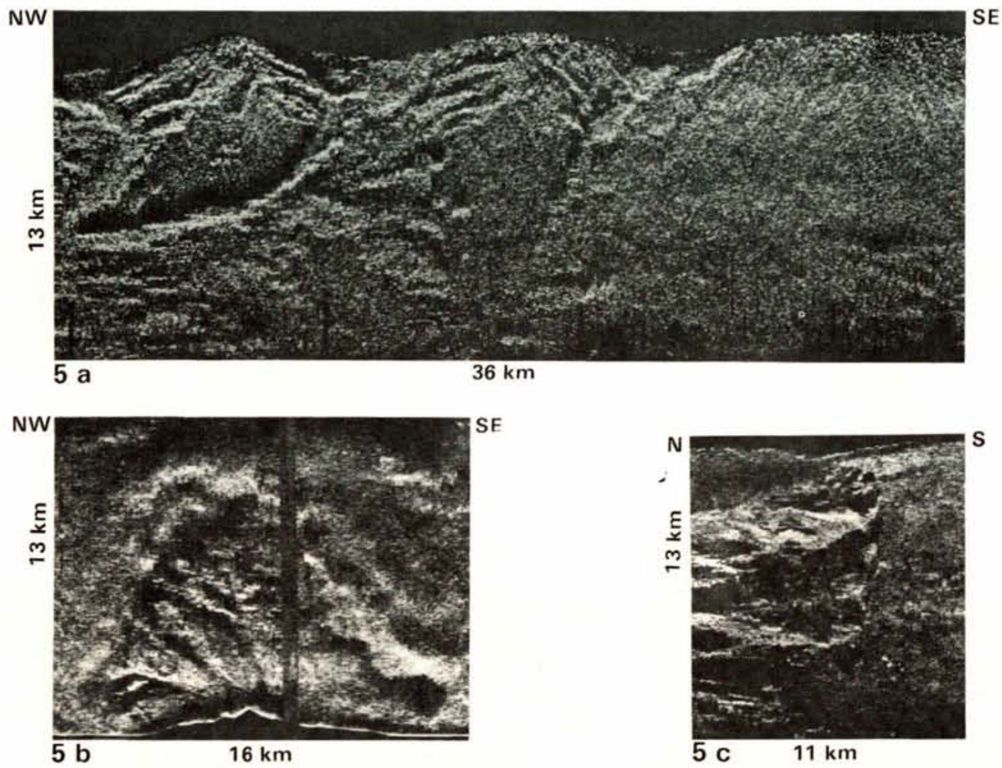


Figure 5

a) *A plan view of curved portions of submarine canyons that are markedly oblique to the regional slope (top to bottom of page). The interpretation of this sonograph is shown in Figure 4. The direction of "illumination" is from the top of the page (and down-slope). The shadowed slopes of the canyons and gullies appear black.*

b) *A plan view of the "amphitheatre" head of Guilvinec Canyon (looking up-slope). The interpretation of this sonograph is shown in Figure 4. The direction of "illumination" is towards the top of the page (and also up-slope). Shadows appear black.*

c) *A plan view showing the contrast between the smooth ground on the right and branches of the head of Cap Ferret Canyon. The interpretation of this sonograph is shown in Figure 7. The direction of "illumination" is down the page. Shadows appear black. For best effect view from the left.*

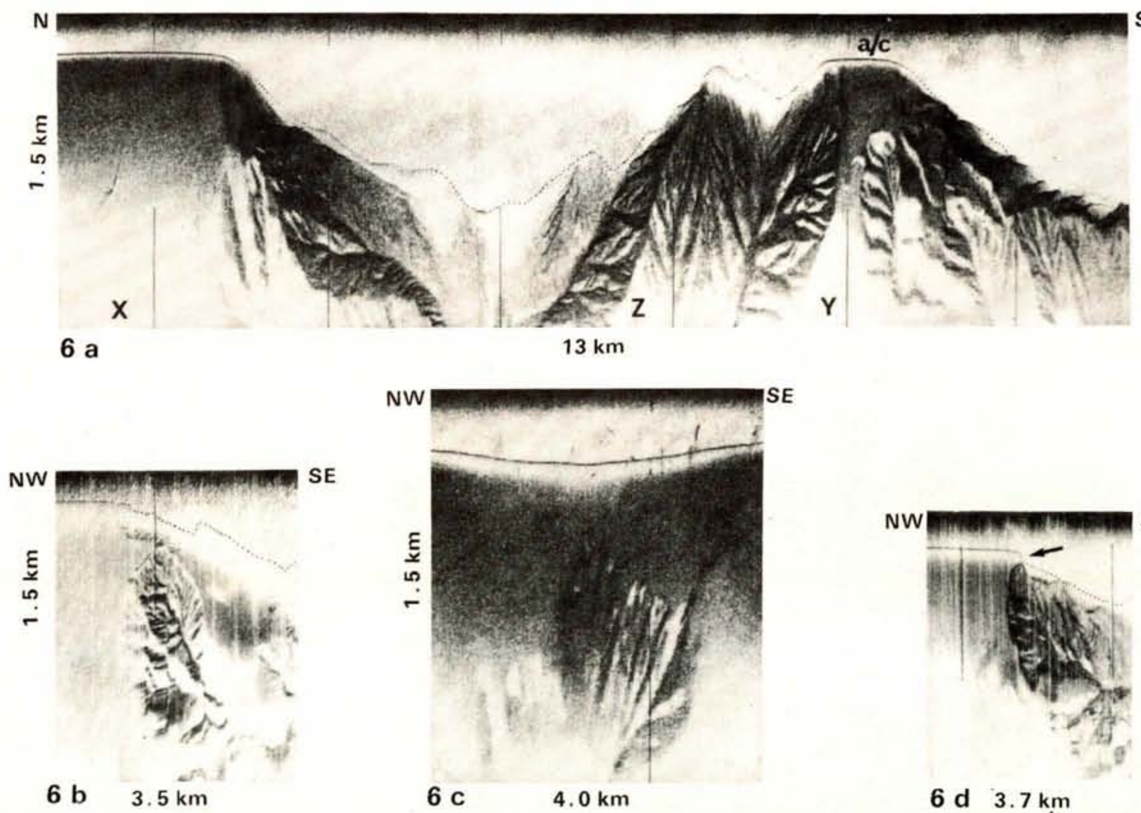


Figure 6

Short range sonographs showing details of canyon relief at the locations shown in Figure 4. The direction of "illumination" is down-slope (and down-page). Shadows appear white and strong reflections are black. Parts of the profile directly beneath the ship have been enhanced to make them more obvious when reproduced. Note, from the dimensions shown, that these sonographs are not true plan views.

a) *stages of dissection of ground between canyons, with the smooth slope as at (X), becoming narrow as at (Y), and giving way finally to an arête as at (Z), where gullies reach up to the crest from both sides. A/c indicates a small course change;*

b) *a leaf-like display of secondary gullies around a primary gully in a canyon head;*

c) *gullies on the gentle slopes of a canyon head;*

d) *canyon head complex with a steep rim (arrow).*

Figure 7

Trains of slump folds on the borders of the Landes Marginal Plateau, off South Western France. The limits of coverage with long-range side-scan sonar are indicated. The inset figure provides a profile across the slump folds. Slump folds are also observed on those portions of the sub-bottom profile 003 *(after Montadert, Damotte and Debyser,* et al., 1971*), and profile* 120 *(after Valery* et al., 1971*) that are shown on the figure.* ►

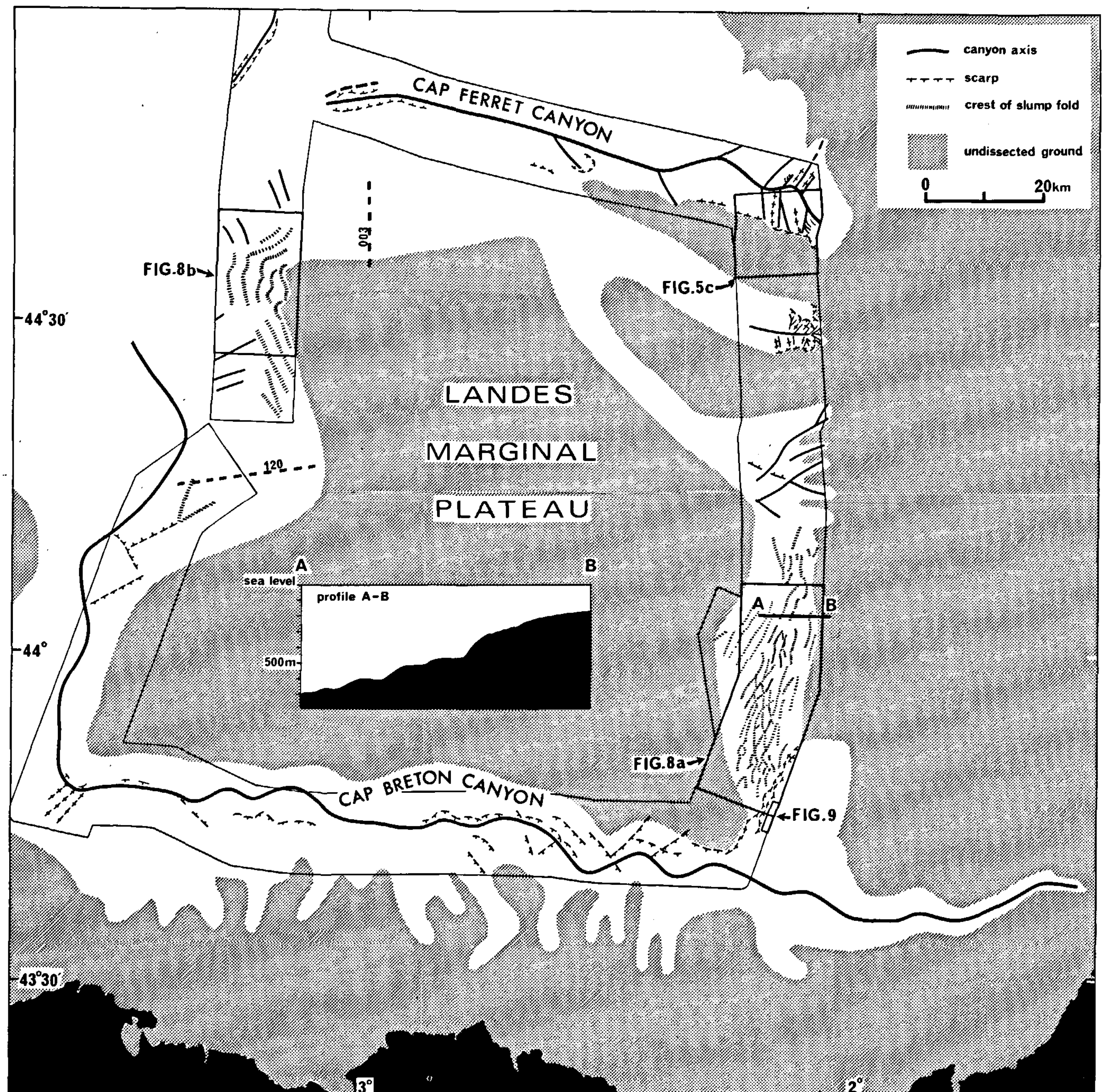
The canyons are normally V-shaped in cross-sectional profile, although some U-shaped profiles also occur. There are many examples of a steep-sided inner gorge along the canyon axis.

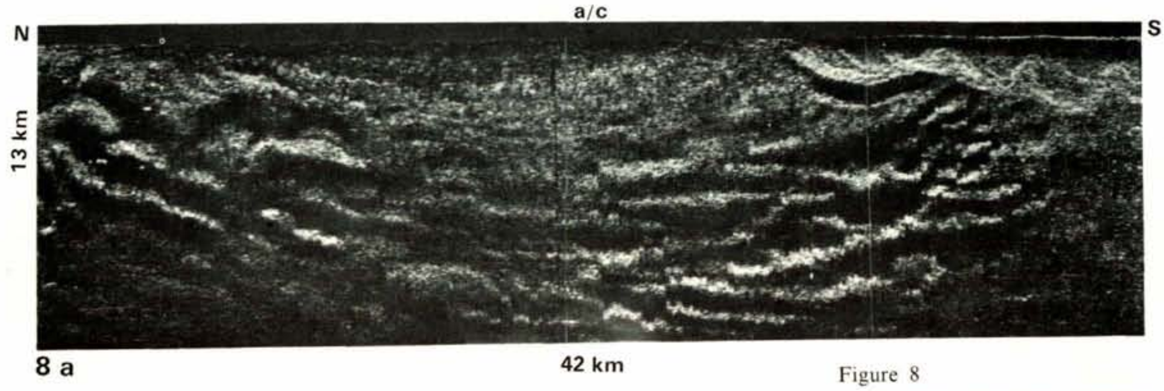
The "interfluves" are usually either sharp-crested (arêtes) or are portions of undissected continental slope extending down from the shelf edge (Fig. 4). There are also some examples of large undissected slope remnants isolated by erosion from one another near to the base of the continental slope. Some isolated slump blocks also have smooth surfaces. One of these, a large slump (about 12 km alongslope and 14 km downslope) at about 48°40′N, 10°15′W first observed at about the 55 km mark on sub-bottom profile No. 6 of Stride *et al.* (1969), was particularly well covered on sonographs from a variety of directions. Slump folds are sometimes apparent on the interfluves, although they are not as well seen as those described from the Landes Marginal Plateau in the next section. In profile, the smooth interfluves bordering on to the sides of the canyons and canyon heads generally bend into the canyon with a convex-slope, which ends abruptly at the head of the gully system. This convex slope may originate by a process of lateral canyonward gravity creep.

On the sonographs one can distinguish only between relative degrees of slope steepness, so that the differentiation between "scarps" and "relatively steep slopes" is not a clear one. Some of these scarps (and maybe many of them) are slump scars, resulting either from primary downslope slumping on uncanyoned portions of continental slope, or from secondary (lateral) slumping into canyons from the valley slopes that are undermined by canyon incision. Slump glide-planes of both types were also observed on sub-bottom profiles. The "steeper slopes", apart from indicating the side-walls of canyons, are probably often determined by underlying sediment-mantled faults in the "basement".

Slump folds bordering the Landes Marginal Plateau

The Landes Marginal Plateau (Fig. 7) at the South Eastern part of the Bay of Biscay is a structural conti-





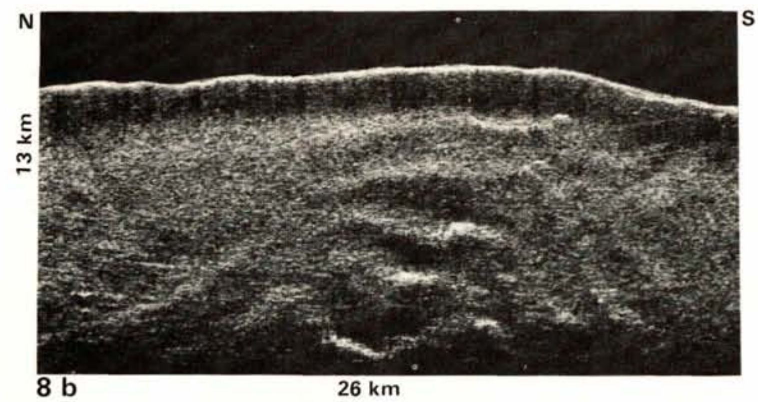


Figure 8

a) *An area with slump folds on the Eastern border of the Landes Marginal Plateau. This sonograph is interpreted in Figure 7 (which also benefits from views of the same ground taken from other directions). The feature extending along the top right corner is part of the large detached slump shown in Figure 9. The direction of illumination is (downslope) from the top of the page. Shadows appear black.*

b) *An area with slump folds of about 2.5 km wavelength on the lower edge of the Landes Marginal Plateau. This sonograph is interpreted in Figure 7. The direction of illumination is (upslope) from the top of the page. Shadows appear black.*

nuation of the Landes Platform of Aquitaine, and is underlain by thick Tertiary sediments. It is bounded to the North by the Cap Ferret Canyon, whose linearity is well seen on the sonographs, and to the South by the Cap Breton Canyon. The Landes Marginal Plateau has a gradient of only about 1°. There is a steepening of slope, both on its upper (Eastern) side leading up to the edge of the continental shelf and its lower (Western) side, leading down to the deep-sea floor. Both of these slopes are notable for their slump folds.

The easternmost slump folds are seen on Flexotir sub-bottom profile 04 of Cholet *et al.* (1968) and by Arcer sub-bottom profiler, boomer and short-range side-scan sonar by Stride *et al.* (1969). They are developed within young sediments on a slope of about 3°. The long-range sonographs taken in 1975 reveal the crest lengths and inter-relationship of the slump folds in plan view (e. g. Fig. 8 *a*). These folds are seen to be up to about 15 km long with wavelengths of about 1.5 km. They have a complexity in plan view which would be difficult to resolve by echo-souding alone (the plot of fold trends shown in Figure 7 has benefited from side-scan viewing from a variety of directions). This complexity, which seems to involve crossfolds, may be a result of more than one phase of downslope movement, or movement originating from more than one locality. The pattern of ridges with slight culminations surrounding lozenge-shaped lows, is comparable, for instance, to a simple interference pattern of the egg carton type produced by two successive foldings (Ramsay, 1967). A profile of the slump folds on a line A-B extending downslope is shown in Figure 7. This and some other profiles, including the sub-bottom profiles, give some suggestion of detachment at the head of the fold system. The greater resolution on the short-range sonographs has revealed no indication of surface breaks in the smooth slope, except at the head of the fold system, and occasional "pockmarks", which tend to be aligned along the fold crests. By analogy with the suggested origin of pockmarks elsewhere, these small, round depressions may be related to escape of gas from near-surface sediments. In this case their location may be controlled by the local tensional stress regime along the crests.

In contrast to the plastic deformation represented by these slump folds, there are strong indications further to the South-East of a large detached slump which has slid away laterally towards the Cap Breton Canyon. Figure 9 is a short-range sonograph depicting the chaotic, blocky surface relief of this slump, which has possibly evolved into a debris flow, such as described by Embley (1976), for instance.

The second series of major slump folds is found on the lower slope of the Landes Marginal Plateau, where the sea floor has a gradient of about 5°. A portion of the slump folds, situated on a nose projecting from the Plateau, is shown in plan view on Figure 8 *b*. The zone of slump folds is at least 65 km long and 10 km wide, as these features can also be recognised on sub-bottom profiles 003 and 120 located on Figure 7 (Montadert, Damotte, Debyser *et al.*, 1971, Figure 5, Profile 003; and Valery *et al.*, 1971, Figure 8, Profile 120). These slump folds have a somewhat larger wavelength (about 2.5 km) than those to the east.

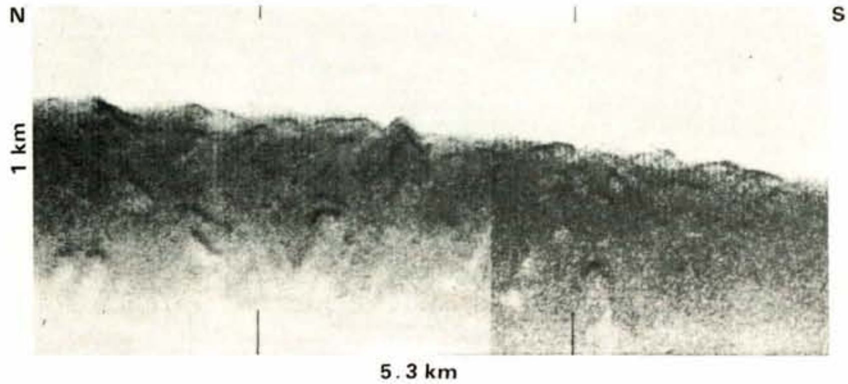


Figure 9

A plan view showing the chaotic relief of a detached slump at the edge of the Cap Breton Canyon. The location of this short range sonograph is shown in Figure 7. Shadows appear light toned. Note, from the dimensions shown, that this sonograph is not a true plan view.

DISCUSSION

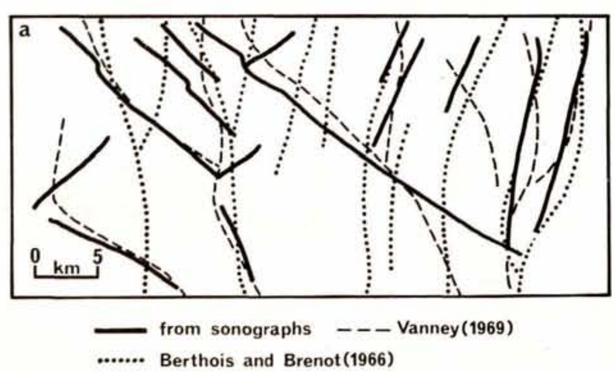
Validity of canyon axes on bathymetric maps

The major canyon axes, as now revealed, do not everywhere trend directly down the continental slope, as is the tendency to assume when compiling bathymetric maps from relatively sparse sounding lines. Indeed, the sonographs provide unequivocal evidence of substantial portions of canyon axes that pass obliquely across the continental slope, and in some cases of the existence of major relief features even extending along the contours. The oblique canyon between Saint-Nazaire and Noirmoutier Canyons is fed by smaller canyons that extend downslope from the edge of the continental shelf, and many other oblique trends are visible on Figure 4. Sonographs also provide direct evidence of abrupt changes in the trend of canyon axes. Such evidence will increase the confidence of cartographers in making similar interpretations that are based solely on echo-soundings, for even when detailed surveys are available there is a tendency to draw canyon axes as following gentle continuous curves, rather than showing some abrupt changes in direction. The sonographs likewise provide detail of the gully-systems that would be almost impossible to achieve by conventional mapping procedures and are rarely shown on bathymetric maps. Nevertheless, the general assumption of the dendritic nature of the junctions of secondary valleys with the main canyons is substantiated.

It is quite understandable that published bathymetric contour maps include some obvious anomalies. Thus, the earlier maps (such as Hadley, 1964) based on poor position fixing and with the majority of tracks aligned normal to the shelf edge, are less correct than the more reliable Berthois and Brenot (1966) series of maps. The most accurate maps in this region prove to be the detailed surveys by Vanney (1969) and Pinot (1974). The axis of Black Mud Canyon (one wall of which shows up particularly well as a narrow, sinuous, strong reflector), as seen on the sonographs, agrees well with the local echo-sounder survey of this canyon made by Francis (1962). Two examples of comparison between canyon axes, as shown on bathymetric maps and those seen on sonographs, are given in Figure 10. The substantial differences between the various surveys are a warning against the premature naming of canyons. There are several examples of ambiguous identification and false continuity of named canyons.

Origin of canyon trends

On the Northern side of the Bay of Biscay the main canyon trends show a distinct grouping into either downslope directions or W-SW and S to S-SE directions. An



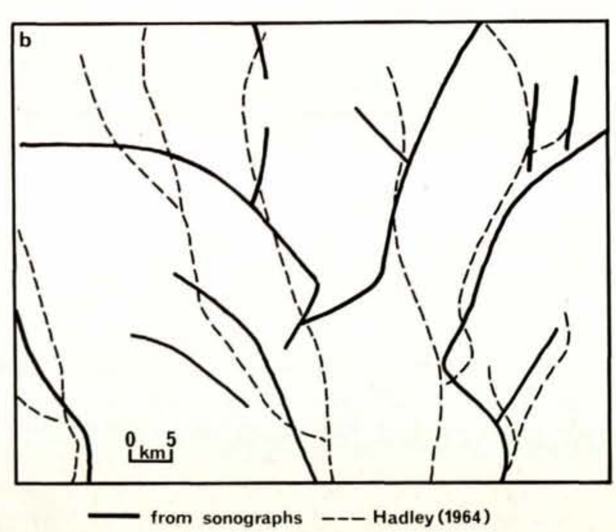
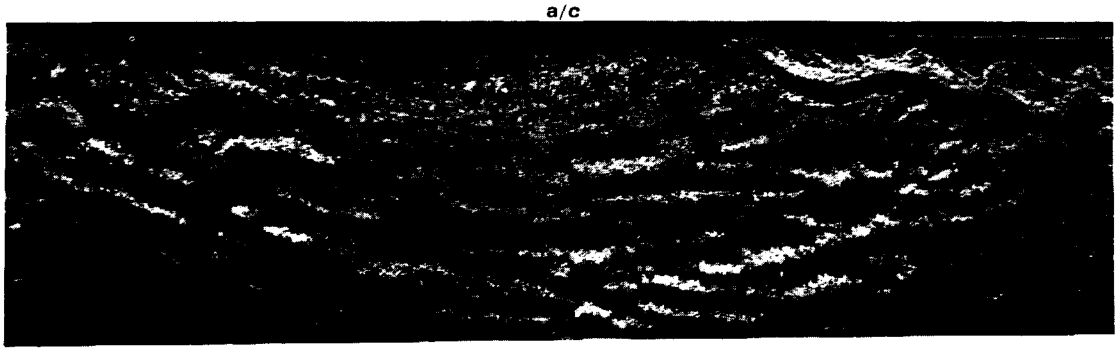


Figure 10

Two portions of continental slope (located in Figure 1) to illustrate the conflicting interpretations of canyon axes, as based either on limited echo-sounder data or as found from the full-cover side-scan sonar data used for this paper.



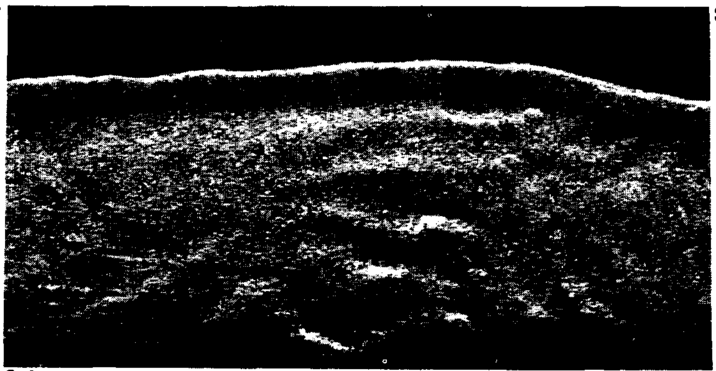


Figure 8

a) *An area with slump folds on the Eastern border of the Landes Marginal Plateau. This sonograph is interpreted in Figure 7 (which also benefits from views of the same ground taken from other directions). The feature extending along the top right corner is part of the large detached slump shown in Figure 9. The direction of illumination is (downslope) from the top of the page. Shadows appear black.*

b) *An area with slump folds of about 2.5 km wavelength on the lower edge of the Landes Marginal Plateau. This sonograph is interpreted in Figure 7. The direction of illumination is (upslope) from the top of the page. Shadows appear black.*

nuation of the Landes Platform of Aquitaine, and is underlain by thick Tertiary sediments. It is bounded to the North by the Cap Ferret Canyon, whose linearity is well seen on the sonographs, and to the South by the Cap Breton Canyon. The Landes Marginal Plateau has a gradient of only about 1°. There is a steepening of slope, both on its upper (Eastern) side leading up to the edge of the continental shelf and its lower (Western) side, leading down to the deep-sea floor. Both of these slopes are notable for their slump folds.

The easternmost slump folds are seen on Flexotir sub-bottom profile 04 of Cholet *et al.* (1968) and by Arcer sub-bottom profiler, boomer and short-range side-scan sonar by Stride *et al.* (1969). They are developed within young sediments on a slope of about 3°. The long-range sonographs taken in 1975 reveal the crest lengths and inter-relationship of the slump folds in plan view (e. g. Fig. 8 *a*). These folds are seen to be up to about 15 km long with wavelengths of about 1.5 km. They have a complexity in plan view which would be difficult to resolve by echo-souding alone (the plot of fold trends shown in Figure 7 has benefited from side-scan viewing from a variety of directions). This complexity, which seems to involve crossfolds, may be a result of more than one phase of downslope movement, or movement originating from more than one locality. The pattern of ridges with slight culminations surrounding lozenge-shaped lows, is comparable, for instance, to a simple interference pattern of the egg carton type produced by two successive foldings (Ramsay, 1967). A profile of the slump folds on a line A-B extending downslope is shown in Figure 7. This and some other profiles, including the sub-bottom profiles, give some suggestion of detachment at the head of the fold system. The greater resolution on the short-range sonographs has revealed no indication of surface breaks in the smooth slope, except at the head of the fold system, and occasional "pockmarks", which tend to be aligned along the fold crests. By analogy with the suggested origin of pockmarks elsewhere, these small, round depressions may be related to escape of gas from near-surface sediments. In this case their location may be controlled by the local tensional stress regime along the crests.

In contrast to the plastic deformation represented by these slump folds, there are strong indications further to the South-East of a large detached slump which has slid away laterally towards the Cap Breton Canyon. Figure 9 is a short-range sonograph depicting the chaotic, blocky surface relief of this slump, which has possibly evolved into a debris flow, such as described by Embley (1976), for instance.

The second series of major slump folds is found on the lower slope of the Landes Marginal Plateau, where the sea floor has a gradient of about 5°. A portion of the slump folds, situated on a nose projecting from the Plateau, is shown in plan view on Figure 8 *b*. The zone of slump folds is at least 65 km long and 10 km wide, as these features can also be recognised on sub-bottom profiles 003 and 120 located on Figure 7 (Montadert, Damotte, Debyser *et al.*, 1971, Figure 5, Profile 003; and Valery *et al.*, 1971, Figure 8, Profile 120). These slump folds have a somewhat larger wavelength (about 2.5 km) than those to the east.

and Matte, 1977) and may connect with these offsets. These Hercynian faults may have determined the location of transform faults associated with the opening of the Bay of Biscay.

Processes

We do not propose to enter here into detailed discussion concerning the processes of canyon formation, except to reaffirm the importance of slumping, and associated down-cutting by turbidity currents. The evidence of turbidites from Dsdp cores at sites 118 and 119 on the deep Bay of Biscay floor (Laughton, Berggren *et al.*, 1972) indicates that such activity has occurred on at least some part of the Biscay continental margin during much of Tertiary-Quaternary time, although the turbidity currents need not necessarily have passed down the French continental slope, particularly as the North Spanish continental slope is so much steeper. The channels of the Gollum System seem to be analogous to channels of the continental rise. They are presumed to be due to turbidity currents originating on the relatively steep slope above them.

The supposed relationship between the presence of submarine canyons and oceanward sand transport by present day tidal currents on the adjacent shelf of the Celtic Sea, proposed by Hadley (1964) and Roberts (1975), is probably coincidental when canyon occurrence is viewed in a wider geographical and temporal context. For instance sand is not at present being transported across much of the Armorican shelf into the numerous canyons found on the adjacent slope, since there is a central muddy area along this shelf. Even if this were so, the sand transport paths associated with present day sea level are ephemeral compared with the longer-term existence of the canyons.

The canyon heads, at least in some areas, seem to be related to the mouths of rivers as they existed during Pleistocene low sea levels, when large volumes of sediment were supplied directly to the shelf edge. For example, Pinot (1974) described extensive pebble spits at the edge of the Armorican shelf, marking the mouths of the main rivers associated with sea levels about 160 m below present, which are closely related to various canyon heads. Much larger rivers are thought to have reached the edge of the continental shelf off the Celtic Sea during Pleistocene low sea levels. Part of their load will have found its way down the canyons, while the remainder was left on the broad reaches of exposed continental shelf (where it was to be reworked during the Post Glacial trangression into the numerous giant sand banks now found on the floor of the Celtic Sea).

However, although the canyons will act as conduits for sand transport from off the shelf, particularly during low sea levels, it is probable in this region that slope steepness is the dominant factor determining which type of morphology is developed on the continental slope. Thus, in conclusion, for the continental slopes discussed here, sinuous, flat-floored channels are found on a slope of about 0.5°, slump folds (in the absence of large detached slumps and canyons) on slopes of about 3 to 5°, and the major North-Biscay canyons and associated slump blocks on slopes averaging between about 5 and 9°.

Acknowledgements

We thank the long-range sonar team, and particularly M. L. Somers and J. Revie for the continued development of this equipment and its successful operation at sea. A. R. Stubbs, J. G. Legg and C. G. Flewellen are thanked for their development and operation of short-range side-scan sonar and air-gun systems.

REFERENCES

Arthaud F., Matte P., 1977. Late Palaeozoic strike-slip faulting in southern Europe and northern Africa: result of a right-lateral shear zone between the Appalachians and the Urals, *Geol. Soc. Am. Bull.*, **88**, 1305-1320.

Beaugé L., 1937. Relevés hydrographiques exécutés au cours des quatre premières croisières, *Rev. Trav. Inst. Pêche marit.*, **10**, 117-231.

Belderson R. H., Kenyon N. H., 1976. Long-range sonar views of submarine canyons, *Mar. Geol.*, **22**, M69-M74.

Belderson R. H., Stride A. H., 1969. The shape of submarine canyon heads revealed by Asdic, *Deep-Sea Res.*, **16**, 103-104.

Berthois L., Brenot R., 1960. La morphologie sous-marine du talus du plateau continental entre le sud de l'Irlande et le Cap Ortegal (Espagne), *J. Cons. Int. Explor. Mer*, **25**, 111-114.

Berthois L., Brenot R., 1966. Cartes bathymétriques du talus du plateau continental en 11 feuilles éditées par Berthois L. avec le concours du Crns *Inst. Sci. et Tech. Pêch. marit.* (11 charts at 1 : 300,000).

Boillot G., Dupeuble P. A., Hennequin-Marchand I., Lamboy I., Lepretre J. P., Musellec P., 1974. Le rôle des décrochements « tardi-hercyniens » dans l'évolution structurale de la marge continentale et dans la localisation des grands canyons sous-marins à l'ouest et au nord de la Péninsule ibérique, *Rev. Géogr. Phys. Géol. Dyn.*, **16**, 75-86.

Brenot R., Berthois L., 1962. Bathymétrie du secteur Atlantique du banc Porcupine (ouest de l'Irlande) au Cap Finisterre (Espagne), *Rev. Trav., Inst. Pêch. marit.*, **26**, 219-246.

Caralp M., Dumon J. C., Frappa M., Klingebiel A., Latouche C., Martin G., Moyes J., Muraour P., Prud'homme R., Vigneaux M., 1971. Contribution à la connaissance géophysique et géologique du golfe de Gascogne, *Bull. Inst. Géol. Bassin d'Aquitaine*, numéro spécial, 142 p.

Carey S. W., 1958. A tectonic approach to continental drift, in *Continental drift: a symposium*, edited by S. W. Carey, University of Tasmania, Hobart, 177-355.

Cholet J., Damotte B., Grau G., Debyser J., Montadert L., 1968. Recherches préliminaires sur la structure géologique de la marge continentale du Golfe de Gascogne : commentaires sur quelques profils de sismique reflexion « flexotir », *Revue Inst. Fr. Pét.*, **23**, 1029-1045.

Day A. A., 1959. The continental margin between Brittany and Ireland, *Deep-Sea Res.*, **5**, 249-265.

Embley R. W., 1976. New evidence for occurrence of debris flow deposits in the deep sea, *Geology*, **4**, 371-374.

Francis T. J. G., 1962. Black Mud Canyon, *Deep-Sea Res.*, **9**, 457-464.

Hadley M. L., 1964. The continental margin southwest of the English Channel, *Deep-Sea Res.*, **11**, 767-779.

Laughton A. S., Berggren W. A., *et al.*, 1972. *Initial Reports of the Deep Sea Drilling Project*, **XII**, Washington (US Government Printing Office), 1 243 p.

Laughton A. S., Roberts D. G., Graves R., 1975. Bathymetry of the northeast Atlantic: Mid-Atlantic Ridge to southwest Europe, *Deep-Sea Res.*, **22**, 791-810.

Montadert L., Damotte B., Debyser J., Fail J. P., Delteil J. R., Valéry P., 1971. The continental margin in the Bay of Biscay, in *The geology of the east Atlantic continental margin*, edited by F. M. Delany (Inst. Geol. Sc. Rep. 70/15, 49-74).

Montadert L., Damotte B., Fail J. P., Delteil J. R., Valéry P., 1971. Structure géologique de la plaine abyssale du Golfe de Gascogne, in *Histoire structurale du Golfe de Gascogne*, **2**, Editions Technip, Paris, VI.14-1 to VI.14-42.

Pinot J. P., 1974. *Le précontinent Breton, entre Penmarc'h, Belle-Ile et l'escarpement continental, étude géomorphologique*, Lannion, Impram, 256 p.

Ramsay J. G., 1967. *Folding and fracturing of rocks*, McGraw-Hill, New York, 568 p.

Roberts D. G., 1975. Marine geology of the Rockall Plateau and Trough, *Phil. Trans. Roy. Soc.* A, **278**, 447-509.

Somers M. L., Carson R. M., Revie J. A., Edge R. H., Barrow B. J., Andrews A. G., 1978. Gloria II – an improved long-range side-scan sonar, *Proc. IEE sub-confer. on offshore instrumentation and communications*, Oceanology International 1978 J, 16-24.

Stride A. H., Curray J. R., Moore D. G., Belderson R. H., 1969. Marine geology of the Atlantic continental margin of Europe, *Phil. Trans. Roy. Soc.* A, **264**, 31-75.

Valéry P., Delteil J. R., Cottencon A., Montadert L., Damotte B., Fail J. P., 1971. La marge continentale d'Aquitaine, in *Histoire structurale du Golfe de Gascogne*, **1**, Editions Technip, Paris, IV.8-1 to IV.8-23.

Vanney J. R., 1968. La pente continentale au large des Charentes, *Trav. Cent. Rech. Étud. océanogr.*, **7**, 15-23.

Vanney J. R., 1969. *Le précontinent du centre du Golfe de Gascogne*, Mémoire No. 16, École Pratique des Hautes Études, Laboratoire de géomorphologie, Dinard, 365 p.