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The Seismic Structure of the Western Approaches and the South Armorican Continental Shelf and its Geological Interpretation

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SUMMARY

Based on all available seismic refraction data, the seismic structure of the Western Approaches to the English Channel and the South Armorican continental shelf has been established. The correlation of seismic velocities showed a three-fold structure, related to geological layers as follows:

1. High-velocity, deep sequence (4.4–6.6km/sec): metamorphic basement and Lower to Middle Palaeozoic.
2. Intermediate sequence (3.6–4.3km/sec): Permo-Triassic (and Jurassic?) and possibly also Lower Cretaceous on the margin of the Western Approaches.
3. Upper sequence (1.9–3.6km/sec): Cretaceous and Cenozoic sediments.

An acoustic unconformity appears to be present between the Upper sequence and the High velocity and Intermediate sequences.

Different geomorphology characterizes these layers: the Palaeozoic is tectonized and generally follows the Hercynian structural trends; mainly Permo-Triassic sediments fill the depressions of the Palaeozoic floor, but only in the Western Approaches; eastwards-transgressive Cretaceous and Cenozoic sediments cover discordantly the preceding layers.

As inferred from the seismic structure, three major sedimentary phases characterize the geology of the Western Approaches and the South Armorican shelf:

1. a Palaeozoic sequence, ending with the Hercynian orogeny;
2. a continental-type sequence, from the Hercynian orogeny until the opening of the Bay of Biscay (only in the Western Approaches);
3. a mainly marine-type sequence, starting with the opening of the Bay of Biscay and continuing to present times.

INTRODUCTION

The Western Approaches to the English Channel is an approximately triangle-shaped region bordered by the two Palaeozoic land areas of Cornwall and of the Armorican Massif and, on the side of the open ocean, by the edge of the continental shelf. The sea covering the Western Approaches shallows eastwards from depths of about 200m to 60m. The bathymetry of the South Armorican margin shows the same tendency and the sea shallows from about 200m on the margin landwards.

Although the exploration of the seabed here began in the last century, only limited information on the surface geology of the Western Approaches and the adjacent shelf areas was available until the end of World War II (Dangeard, 1971). Since then, thanks to the shallow-penetration seismic profiling and core-sampling done by universities and other institutions, a remarkably detailed knowledge has been acquired of the morphology and structure of the mainly Mesozoic and Cenozoic strata, but only as far as about 7°W. It has been postulated on the basis of the data available that a rather deep, sediment-filled trough extends under the axial part of the floor of the Western Approaches (Andreieff *et al.*, 1971; Boillot *et al.*, 1971; Larsonneur, 1971; Vanney *et al.*, 1971). As a result of seismic refraction surveys, carried out mainly by British surveyors and by the Bureau de Recherches Géologiques et Minières (BRGM) between 1955 and 1968, more information on the deeper geological structure has been obtained (Bunce *et al.*, 1964; Day *et al.*, 1956; Frappa and Horn, 1971; Hill and King, 1953). The seismic data confirmed the presence of the subsurface axial trough and indicated that it was filled with about 3.5km of sediment underlain by a high-velocity substratum.

The Western Approaches trough gained the interest of the petroleum companies in the nineteen-sixties. The extensive seismic reflexion surveys which they have carried out since 1970, have led to a more precise definition of the geometry of this structure. To complement the reflexion data, a large scale seismic refraction survey was initiated in 1971 and completed by the Centre Océanologique de Bretagne in the fall of 1973. The surveyed area, which includes 28 refraction stations, extends from 47° 30′ to 49° 30′ N, and about 4° to 8° W.

The sonobuoy technique for the detection of seismic signals had to be adapted to cope with the high tidal currents in the surveyed area. Essentially, we used hydrophones or geophones positioned on the sea floor; the seismic signal from the bottom

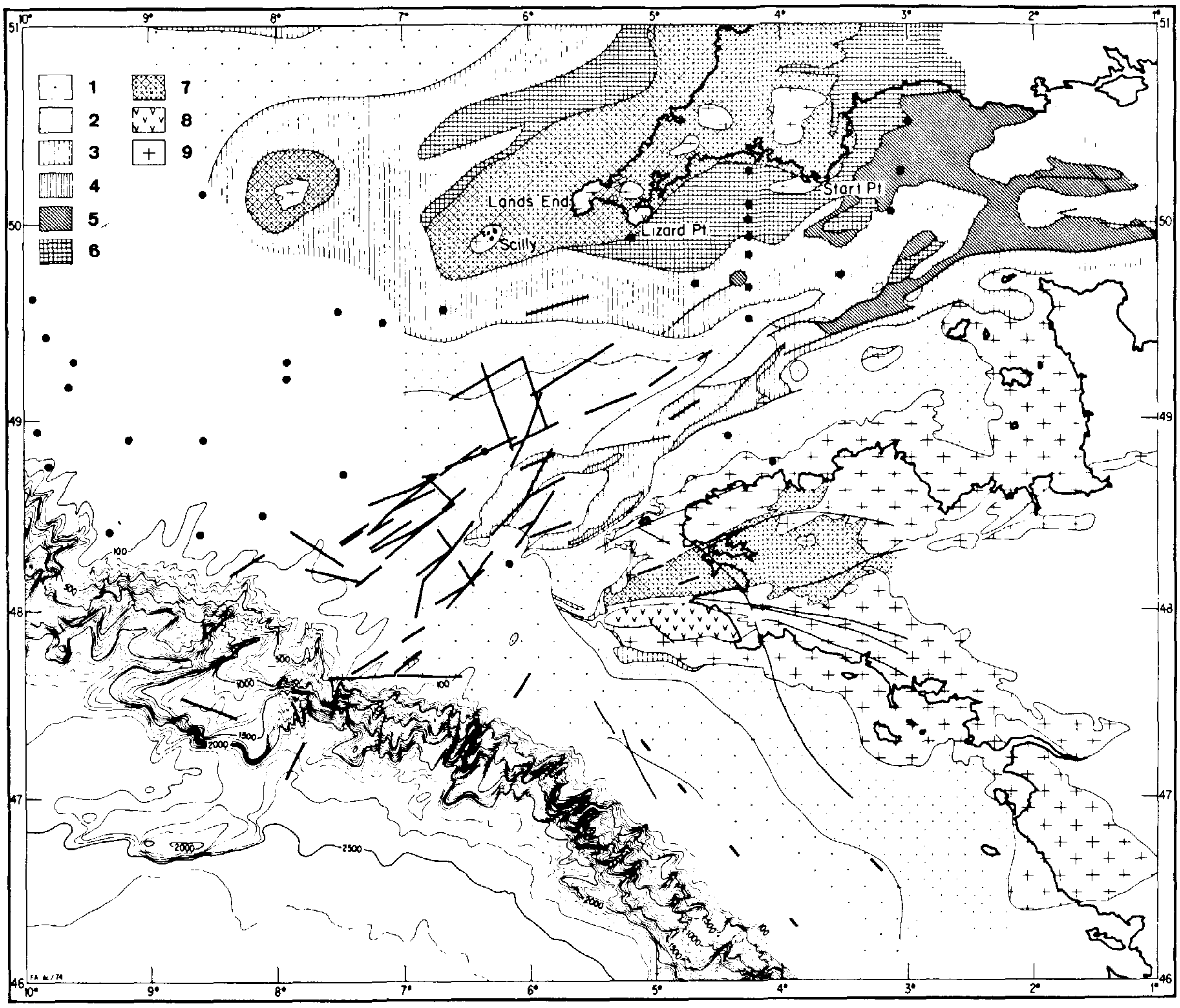

FIG 1. Schematic geological map of the Western Approaches and adjacent areas, showing the positions of the seismic refraction stations. 1—2: Cenozoic; 3: Upper Cretaceous; 4: Lower Cretaceous; 5: Jurassic; 6: Permo-Triassic; 7: Devonian; 8: "greenstones"; 9: granites. Dots and short lines: previous seismic refraction stations. Long lines: profiles by Centre Océanologique de Bretagne, Brest, in cruises 1971—73.

detector was fed through a conductor line to a radio transmitter on the sea-surface, and then received and recorded on the ship. This method ensured drift-free positioning of the detectors and led to a considerably better signal-to-noise ratio than that achieved by other systems of detection (Avedik and Renard, 1973).

The general trend of magnetic anomalies, which is assumed to reflect the structural trend, is mainly north-east to south-west in the Western Approaches and, close to the continental shelf edge it curves in to the north-west (Hill and Vine, 1965). Therefore, to minimize errors in the recorded velocities due to abrupt changes in dip, the chosen orientation of the profiles was mainly north-east to south-west, that is along the strike of the apparent structural trend (Fig 1). Generally the profiles were not reversed, or were run in two directions around a central receiving point. Reverse profiles were restricted to areas of presumed subsurface basins. This procedure seemed to be the best compromise for obtaining the maximum structural information and the least disturbed velocity records. The length of the profiles varied from about 20 to 50km and shots were fired about every 100m. The seismic source was a 360cu in air-gun. For about half of the profiles, two guns were used and shot simultaneously. Navigation was based on Decca and satellite fixes and the error between horizontal distances computed from navigational data and those deduced from direct arrivals ranged in most cases from 1 to 3 percent.

It is general practice to establish the seismic structure of an area on the basis of lateral correlation of similar velocities. It is then assumed that similar velocities represent the same geological layer. Clearly, this is not necessarily justified. Lateral velocity variations may occur within a layer due to lithological changes; high velocity carbonates could easily be confused with both metamorphosed and crystalline rocks because they generally fall roughly in the same velocity class;

there may also be layers geologically different with the same seismic velocities. Another potential difficulty is the "hidden-layer" problem of a layer resting under a higher velocity one. In this case the lower velocity surface does not constitute a refracting interface and the lower velocity layer generally remains undetected. Finally, in areas without deep boreholes, direct correlation between the subsurface geology and the seismic horizons is obviously impossible. In such areas (and these include the Western Approaches and the South Armorican shelf) only the geology of the surrounding land and the surface geology of the sea-floor yield guidelines for the interpretation of the seismic data. In spite of these difficulties and ambiguities, however, seismic refraction remains an indispensable tool for subsurface exploration.

GEOLOGICAL BACKGROUND

In order to provide a "geological guide" for the interpretation of the seismic structure, we briefly summarize the history of the area, as deduced from observations on the surrounding land areas and from what is known of the geology of the seabed (refer to Fig 1).

The oldest, north-east to south-west, structural trend recognized in Cambrian and Precambrian strata in north-eastern Brittany relates to the so-called Cadomian orogeny (550–600my). Ordovician, Silurian and Devonian sediments were deposited during subsequent Lower Palaeozoic transgressive phases. In Cornwall, the oldest sediments at surface belong to the Devonian. Interfingering of Devonian marine facies with continental Old Red Sandstone deposits in Cornwall, and also in Brittany, suggests that the southern shore-line of the "Old Red Sandstone Continent" (North Atlantic Continent) stretched across this area.

The Hercynian orogeny (~350my), accompanied by extensive metamorphic and intrusive activity, considerably remodelled the whole region. It involved the development of large east–west, north-west–south-east and, later again, roughly east–west trending arches through Brittany, Cornwall and Southern Ireland, and it seems likely that the creation of these arches reactivated older tectonic zones of weakness. In southern Brittany, the South Armorican shear-zone developed into a north-east to west curved arch whereas the main tectonic directions related to this orogeny in northern Brittany are north-east–south-west and north-west–south-east. After the Hercynian orogeny Cornwall and Brittany remained emerged, and mainly in Permian and possibly also in Triassic times these areas underwent extensive erosion. The geological evidence of this denudation are the continental-type New Red Sandstone deposits which are in direct contact with Devonian strata to the south of Cornwall.

A glance at the geological map of France and Great Britain shows that in lower Mesozoic times, there must have been some structural barrier between Start Point and Cotentin which protected the Western Approaches from an overall, westwards transgression, although channels may have breached this ridge between the present Western Approaches and the Paris Basin. There is presently no geological evidence of any important Lower Mesozoic transgression eastwards. However, Upper Cretaceous sediments, indicating a major eastwards transgression cover large areas of the present day Western Approaches and lie discordantly on the Devonian and Permo-Triassic deposits. The eastwards transgressive tendency was probably related to the opening of the North Atlantic and the Bay of Biscay.

The transgressive Upper Mesozoic deposits crossed the Start Point–Cotentin barrier and joined the Upper Mesozoic of the Paris Basin. With intermissions, the eastwards transgression continued into the Cenozoic. Approximately north-east–south-west trending faults, accompanied by linear swells of the post-Palaeozoic sediments from Cotentin to the western limit of the explored area have been detected on the seabed.

THE SEISMIC STRUCTURE

A preliminary interpretation based on the correlation of velocities found beneath a series of

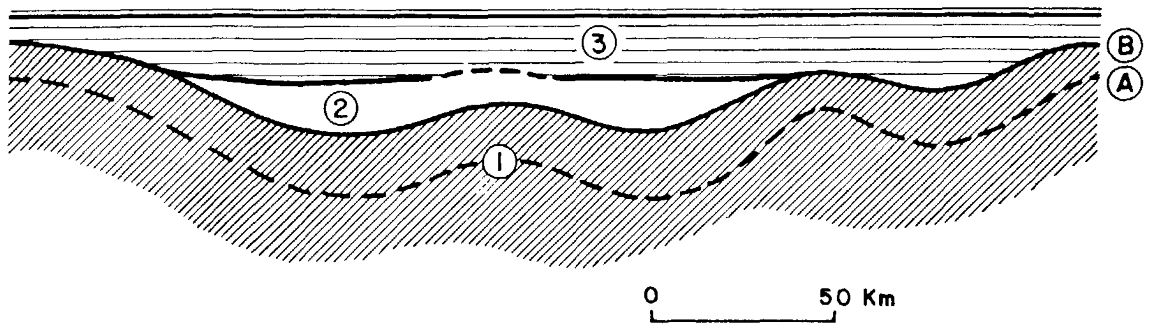

FIG 2. Schematic seismic structure of the Western Approaches along its axis from about 4° W to 7° W. (1) High velocity, deep sequence (4.4–6.6km/sec). (A) and (B) indicate layers "A" and "B". (2) Intermediate sequence (4.0–4.3km/sec). (3) Upper sequence (1.9—3.6km/sec).

stations aligned along a profile following the north-east–south-west axis of the Western Approaches was presented in February 1974 at the discussion meeting on the "Geology of the English Channel" (Avedik, 1974). This profile between approximately 4° and 7° W, revealed the following seismic structure (Fig 2):

1. a high-velocity, deep sequence, characterized by tectonized, conformable layers (velocity range from 4.4 to 6.6km/sec);
2. an intermediate sequence, filling depressions in the deep tectonized sequence (4.1–4.3km/sec);
3. an upper, low to medium velocity sequence, with almost horizontal layers (1.9–3.6 km/sec).

An acoustic unconformity appears to be present between the high-velocity, tectonized, deep sequence and the upper, horizontally layered sequence. This unconformity is correlated with the geological unconformity between the Palaeozoic and Cretaceous strata in the Western Approaches.

All available seismic refraction data have been compiled in this work to present an overall seismic structure of the Western Approaches and the South Armorican continental shelf.

Throughout the area the seismic structure is characterized by the same velocity groups as noted above, except for one additional velocity class (3.6–3.9km/sec). In this paper the three-fold classification of velocities is maintained and as a first approach, the 3.6–3.9km/sec velocity class is included with the intermediate sequence.

High Velocity Sequence (4.4–6.6km/sec). The velocities within the sequence may be split into two groups (Fig 2): (a) 5.3–6.6km/sec (layer "A"); (b) 4.4–5.0km/sec (layer "B").

(a) Layer "A" was detected beneath almost all stations in the Western Approaches and the South Armorican continental shelf. The isobath map (Fig 3) shows the rapid deepening of this high-velocity surface towards the axis of the Western Approaches, where it reaches its maximum depth of about 4.0–4.5km and forms an approximately

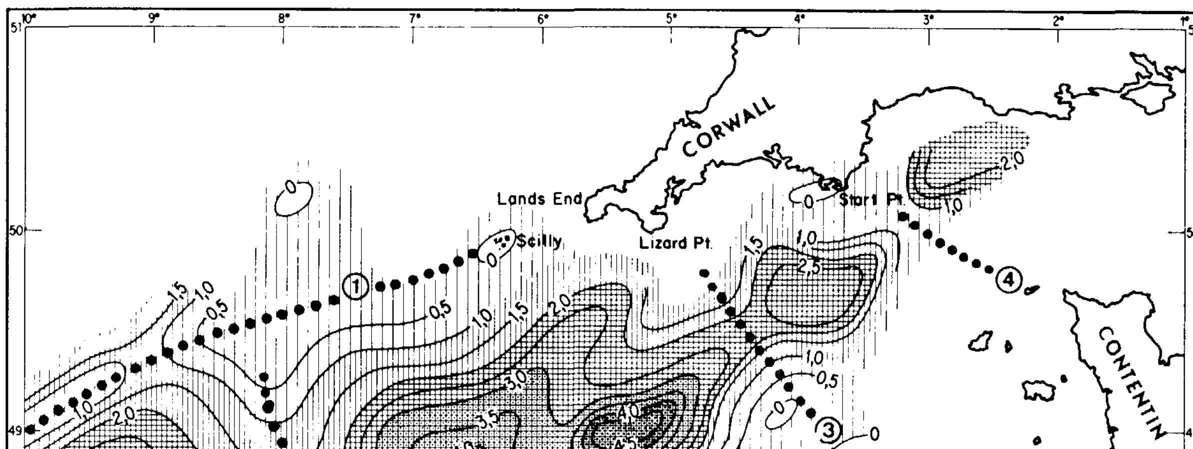

FIG 3. Schematic structure-contours of the metamorphic basement (depth in km). Structures: (1) Lands End—Scilly axis; (2) North-west—south-east basement high; (3) Lizard—Brittany ridge; (4) Start—Cotentin ridge; (5) North Armorican Fault; (6) South Armorican Shear Zone; (7) Meriadzek terrace.

triangle-shaped depression oriented north-east–south-west. West of Brittany, and on the South Armorican continental shelf, layer "A" slopes rather gently to the south-west and reaches the continental shelf edge at a subsurface depth of about 1.5–2.0km.

To infer the nature of the high-velocity layer "A", the correspondence between the observed velocities and those measured on outcrops or strata of known geological setting has to be established. The metamorphic and igneous rocks on the surrounding land areas have generally velocities in the 5 to 7km/sec range, which agree well with those obtained for the layer "A". The various stages of metamorphism displayed by these rocks in Brittany and the frequent acid or basic intrusives associated with them, explain the relatively large scatter of observed values in this velocity class. Possibly a similar geology characterizes the areas under the sea, in which case it seems unlikely that one could differentiate the different geological units solely on the basis of their seismic velocities. We shall refer therefore to layer "A" in a global way, designating it as the "metamorphic basement" comprised of rocks in various stages of metamorphism, often associated with acid and basic intrusives.

There is no difficulty in assigning the observed layer "A", which is found in a relatively shallow depth around the Armorican Massif, to the "metamorphic basement". The same is true close to the Lizard and the Scilly Islands, where basic intrusives and Hercynian granites crop out. Here layer "A" forms a shallow, southwards dipping surface. Away from land and outcrops, the layer plunges to great depth and it becomes increasingly difficult to decide whether its apparent continuity is indeed a continuation of the "metamorphic basement". In particular, the presence of high velocity carbonates, which may mask the "true" basement is possible. However, the depth of the numerous magnetic sources, computed from the magnetic anomalies, shows such close correspondence to the depth of layer "A" throughout the mapped area (Segoufin, 1974) that it seems reasonable to assume that the high-velocity surface of layer "A" corresponds closely to the "metamorphic basement".

The observed north-east–south-west, east-west and north-west–south-east structural features of the "metamorphic basement" in the Western Approaches and the South Armorican continental shelf can be logically related to the structural directions observed in Brittany and Cornwall. One

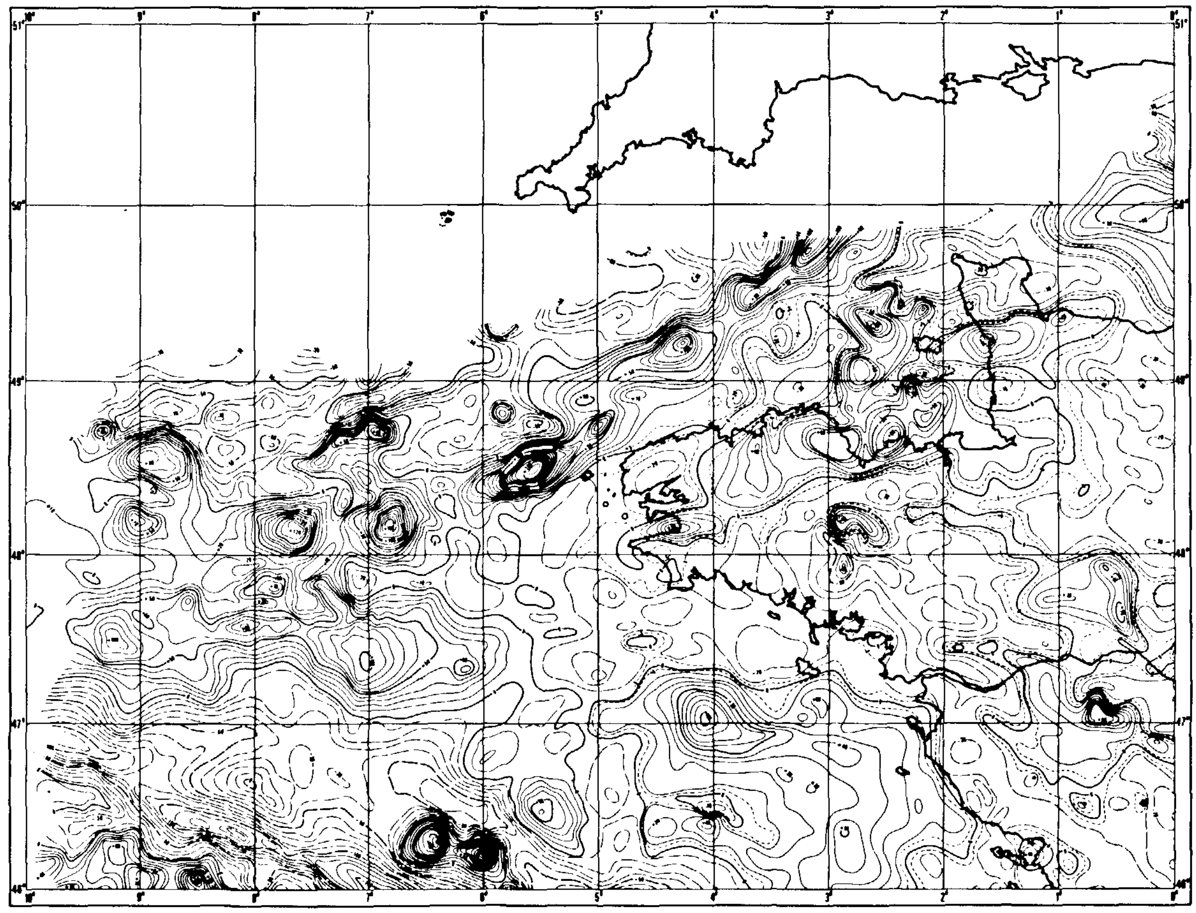

FIG 4. Magnetic anomaly map of the total magnetic field. CNRS—IPG (Paris) Surveys 1964—65 and 1969, 3000m, spacing 10γ.

of the outstanding structural features is the system of north-east–south-west faults (Fig 3). This system appears to cross the continental shelf edge south of the Meriadzek complex and seems to be accompanied by a sedimentary swell of similar orientation as evidenced by the surface geology of the seabed. In the forthcoming discussion I shall refer to this fault system as the North Armorican Fault.

The alignment of the strong magnetic anomalies associated with the North Armorican Fault, after a sharp south-eastwards turn in the vicinity of the Isle of Wight, appears to be linked to the north-west–south-east oriented anomalous magnetic zone in the Paris Basin (Fig 4). The lateral offset observed in the North Armorican Fault west of Brittany is also the locus of a strong magnetic anomaly. The computed source depths indicate the presence of basic material, possibly basalt, intruded at a relatively shallow depth in this fractured zone (around 1 to 2km) (Segoufin, 1974). Further, the seismic interface associated with the Conrad discontinuity which is detected at a depth of about 15km beneath the southern part of a north-west–south-east oriented refraction profile from Lands End to Morlaix in Brittany shows a large bulge (Holder and Bott, 1971), several kilometres high beneath the North Armorican Fault which might have been the source of the basic intrusions rising to much higher levels. If one accepts this two-level intrusive structure as typical for the North Armorican Fault, an alternative interpretation may also be considered, which regards these two stages as time-separated geological events. The first event, associated with the generalized extensive phases of the early Mesozoic produced a large swell of the mantle intruding into the dislocations. The second one occurred during a later reactivation of this weak zone of the crust and produced smaller intrusive bodies unwarping and invading sedimentary layers. I shall add some more comments on this feature in the third section of this chapter.

The North Armorican Fault, considering its north-east–south-west orientation, may be the remnant evidence of an old, possibly Cadomian (Caledonian?) phase of tectonic activity, reactivated successively during later events.

The structure of the basement high which separates the two deep central depressions is probably complex. It seems to be related as well to the north Armorican granite trend, characterized by low gravity anomalies (Fig 5) as to the north-east–south-west oriented basement high. The rather positive gravity anomalies appear to follow the trend of the latter basement high and possibly signify material of basic origin (Allan, 1961).

The north-west–south-east oriented ridges in the eastern area which induce a step-like, easterly shallowing of the basement and link the Lizard and Start Point complexes to Brittany and the Cotentin peninsula respectively, follow very closely the observed north-west–south-east Hercynian trend and probably originated during the Hercynian orogeny. Also, the high gravity values and their trend (Fig 5) clearly support the seismic interpretation. The ridges must have played a considerable role as eastern barriers during the post-Hercynian sedimentary history of the Western Approaches.

The basement high from Lands End to the continental margin—the Lands End–Scilly axis—is formed by a succession of Hercynian granite batholiths; on the surface at Lands End and the Scilly Islands, they plunge gently towards the continental margin. These deeper batholiths are also reflected in the north-east–south-west trend of low gravity values (Fig. 5) which are indicators of Hercynian granites in this area (Bott and Smithson, 1967). The very high seismic velocities (>6.2km/sec) and rather strong gravity anomalies south of this axis are strong evidence of high grade metamorphism associated with the batholiths. The nature of the relative basement high, which slopes and curves to the south-south-east, and its relation to the Lands End–Scilly axis is still unknown. The relatively high gravity and strong magnetic anomalies partially associated with this structure suggest the presence of material of basic origin.

Southwards to the North Armorican Fault, around Brittany and beneath the South Armorican continental shelf, the metamorphic basement remains at a shallow depth, suggesting that it is an extension of the Armorican Massif as far as the continental margin. In this area the South Armorican Shear Zone constitutes a major Hercynian tectonic feature (Fig 3). The shear zone forms a large, north-east to west incurved arch in southern Brittany and geological observations indicate that it extends under the sea as far as 5° W. Considerable lateral displacements of the northern and southern sectors of the Armorican Massif are supposed to have taken place along the shear zone, but the sense of movement is controversial (Debelmas, 1974, pp. 125–38, 150–4). The shear zone, if its trend is extrapolated, seems to "butt" against the North Armorican Fault. The basement forms a large, elongated feature south to this hypothetical extension of the shear zone, which geometry suggests that the southern sector of the Armorican Massif may have been subjected to a left-lateral displacement. This sense of motion would fit the pattern of gravity anomalies on both sides of the shear zone (Sibuet, 1972). On the South Armorican continental shelf, close to 46° N, one has to note the westwards incurved isobaths which appear to indicate the northern slope of a westwards trending basement high. This basement high is probably a major structure which extends far to the south. One may regard this structural high as the separation of the South Armorican Continental Shelf and the Aquitanian domain.

It should be mentioned that beneath some longer profiles (>30km), mainly in the area of the large

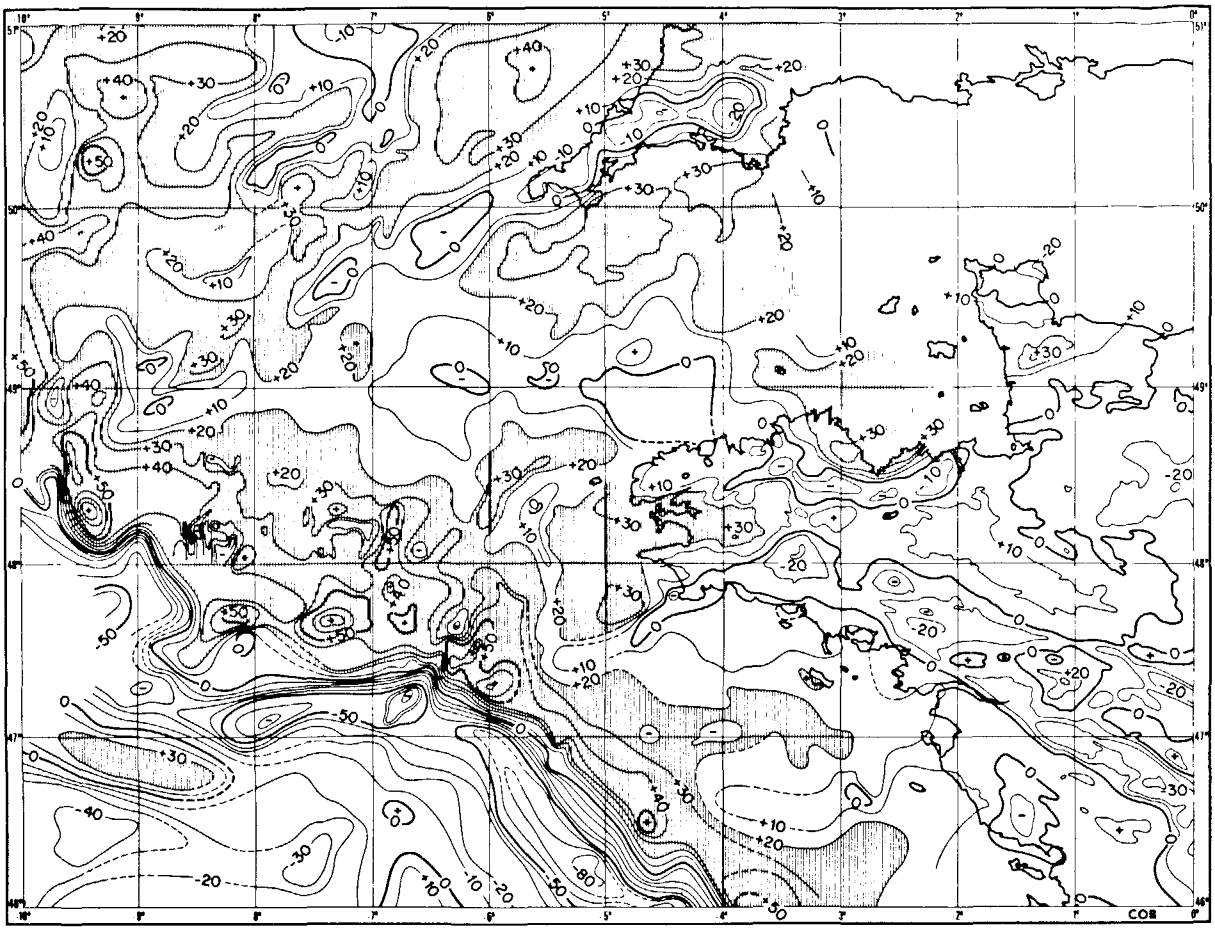

FIG 5. Free-air gravity anomalies (Bouguer anomalies on continents). Published by Bureau de Recherches et de Participation Minières, 1963, and Davey (1970).

central basin of the Western Approaches, secondary arrivals yielded velocities in the 6.5-7.3km/sec range. However, as these arrivals appeared at horizontal distances which were close to the maximum radio range of the emitters, it could not be investigated whether these events represent refracted waves or wide-angle reflections. The time-distance graph of the station at 48° 42′ N and 06° 43′ W (for the profile oriented north-east-south-west) shows an arrival which seems to correspond to a reflection with vertical two-way travel time of 3.6 seconds. On the basis of the available data it seems possible that a seismic interface is present in the central area of the Western Approaches at a depth of about 6-8km. The positions of stations featuring such deep arrivals, the measured apparent velocities and the corresponding depths of this seismic discontinuity are shown in the Appendix.

(b) Layer "B" (4.4-5.0km/sec) (Fig 2), is the second refracting interface in the high-velocity sequence and it is taken to represent a layer which covers the metamorphic basement. It is present over the major part of the mapped area. This material constitutes a north-north-westwards thinning sedimentary wedge which strikes north-east-south-west and shoulders against the North Armorican Fault, where it attains its maximum development of about 2km (Fig 6). The refracting surface of layer "B" is deepest in the central areas (about 2.5km) and follows the step-like shallowing of the "metamorphic basement" to the east. To the north, towards the Lands End-Scilly axis, layer "B" rises gradually to a shallow depth and appears to be linked to the large Devonian outcrop found around Lands End.

Southwards to the North Armorican Fault, around Brittany, and on the South Armorican continental shelf, layer "B" forms a rather thin sheet and wedges out toward the present land areas and also toward the basement high, which seems to separate the South Armorican and the Aquitanian continental shelves.

Two remarkable morphological features of layer "B" should be noted. One is its rather uniform thickness in the north-east-south-westwards trending depressions, and the other is its thinning over the observed Hercynian uplands (the Lizard-Brittany and Start-Cotentin ridges, and the Lands End-Scilly axis). The almost uniform thickness of the layer in a north-east-south-west direction which contrasts markedly with the observed westwards increase in the thickness of Mesozoic strata and the most probable erosion of

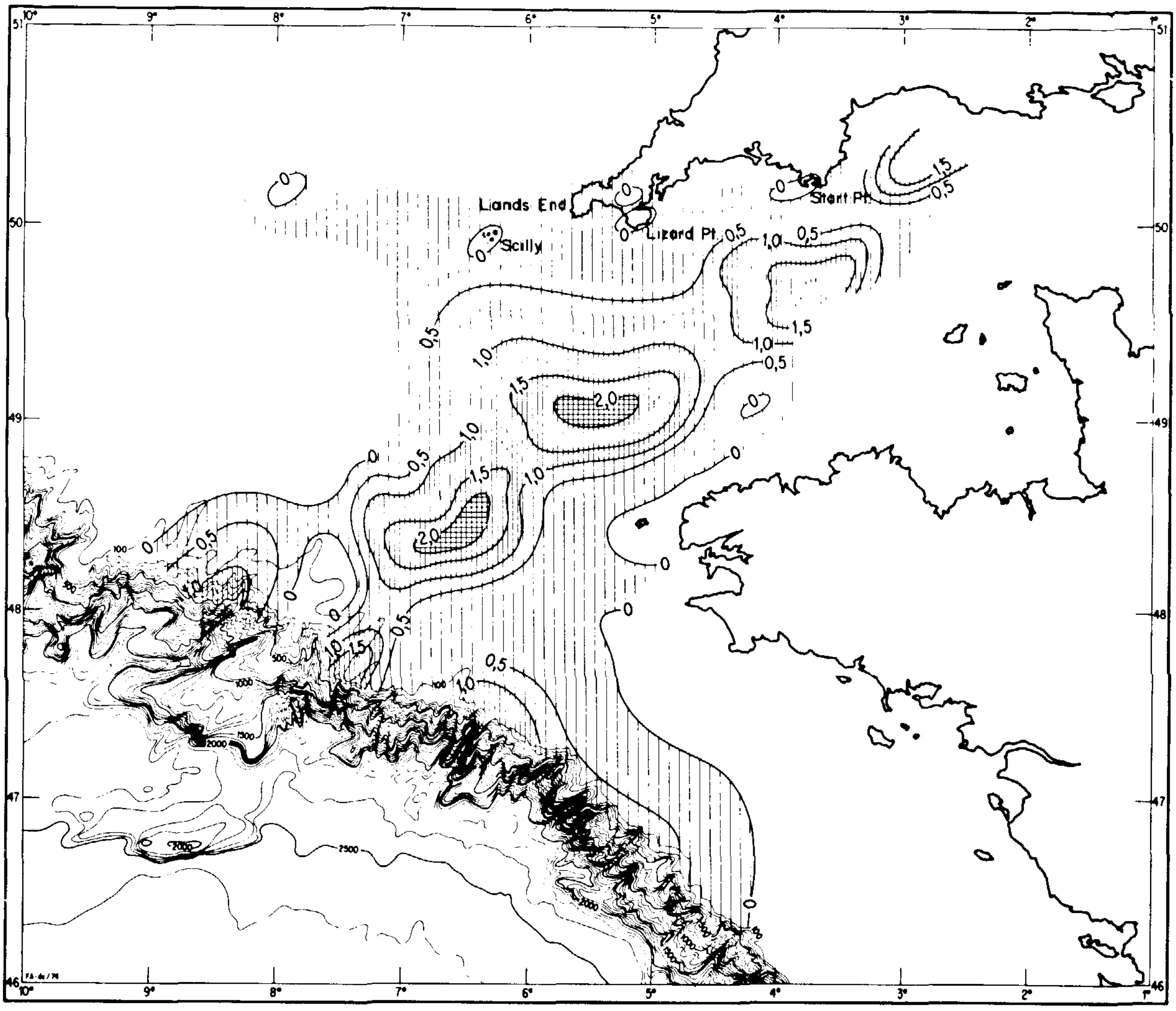

FIG 6. Isopachs of layer "B" (4.4—5.0km/sec), interpreted as Lower and Middle Palaeozoic. Contour interval 0.5km.

the Hercynian uplands may be evidence of the existence of an extensive sedimentary sequence before the Hercynian orogeny, that is in Lower and Middle Palaeozoic times. In addition, the seismic velocities measured on both continental and submarine outcrops fall in the same velocity class. One is thus led to the conclusion that layer "B" corresponds to Palaeozoic strata, and its refracting surface represents closely the "Palaeozoic floor".

The thinning of the Palaeozoic layer is not evident over the north-west-south-east basement high near the continental shelf edge of the Western Approaches, and this might signify that the structure, if only partially, originated in a later geological event.

The apparent absence of the Palaeozoic west of the previously mentioned basement high near the continental margin is dubious. Velocity determinations from sonobuoy data obtained on the Meriadzek terrace, beyond the continental slope, indicate the presence of a layer with a seismic velocity of 4.7km/sec. The correlation of this layer with the strata in the Western Approaches, which have a similar velocity and supposed to be Palaeozoic, is hypothetical. The station is remote from the continental margin and lies in a domain generally considered as a transition zone. On the other hand, the morphology of the Meriadzek terrace (Smith and Van Riessen, 1973), a unique feature on this portion of the continental margin, suggests gravity sliding, perhaps resulting from the collapse of the continental margin. Thus, the presence of Palaeozoic strata on the Meriadzek terrace appears quite possible and, if this interpretation is correct, it could explain the partial removal of this layer from the continental shelf edge. The collapse of the continental margin may have occurred with the rotation of Spain (Iberian craton) and possibly followed lines of weakness along the continental margin resulting from the combined effect of tectonics associated with the North Armorican Fault and the South Armorican Shear Zone.

Intermediate Sequence (3.6–4.3km/sec). The material characterized by velocities in the 3.6–4.3km/sec range (intermediate sequence) was detected under the Western Approaches only between the North Armorican Fault and what I may describe as the southern slope of the Lands End–Scilly axis. The sedimentary layers belonging

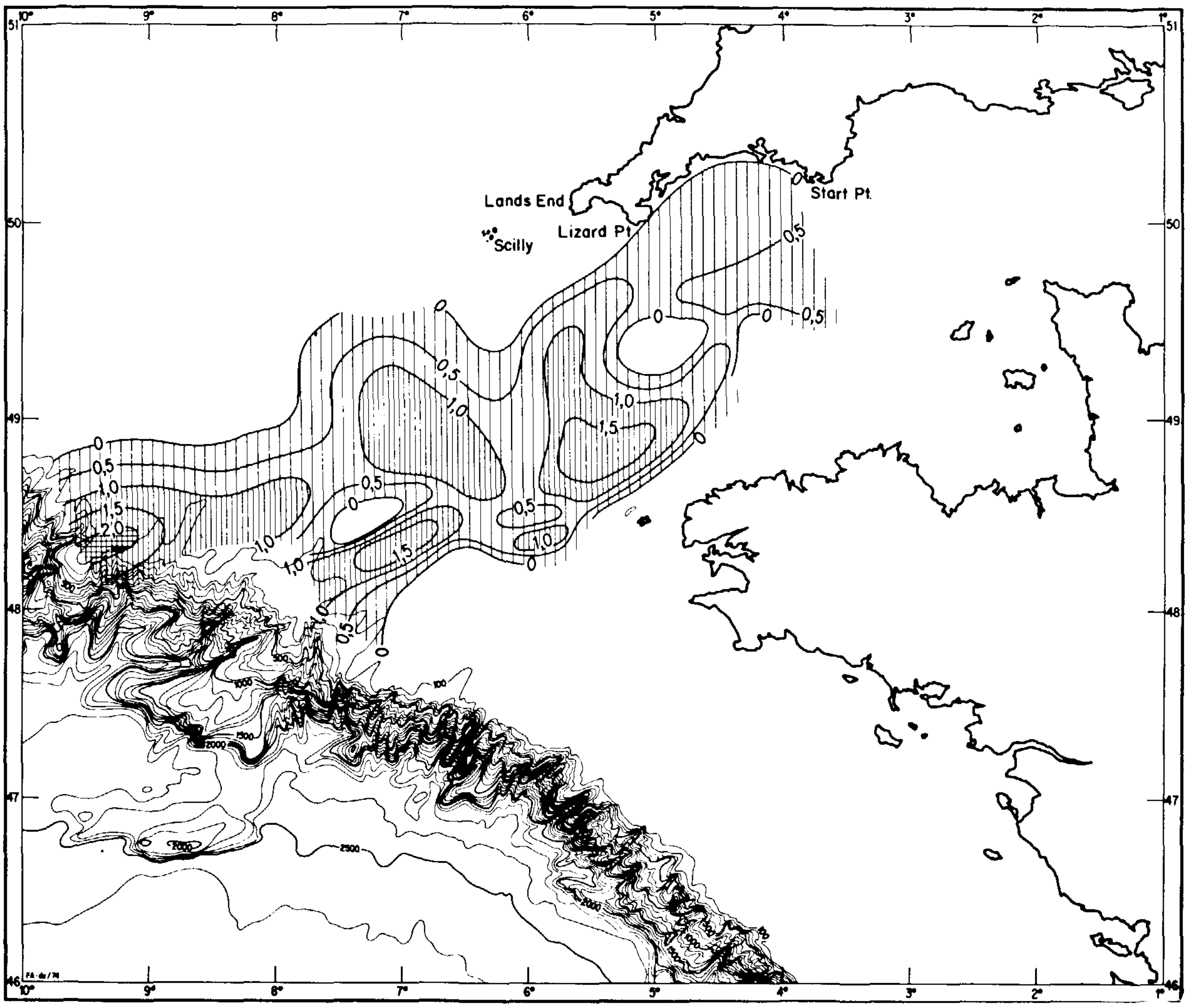

FIG 7. Isopachs of the intermediate seismic sequence (3.6—4.3km/sec), associated with Permo-Triassic (and Jurassic?), and possibly Lower-Cretaceous on the margin. Contour interval 0.5km.

to the intermediate seismic sequence appear to fill depressions in the Palaeozoic floor between the continental margin and the Lizard–Brittany and Start Point–Cotentin ridges, the latter forming a major structural barrier which seems to have separated the present Western Approaches and Paris Basin during the deposition of these layers (Fig 7).

The analysis of velocities within the layer shows a predominance of higher velocities (4.0–4.3km/sec) in the central areas. In contrast, the somewhat lower velocities (3.6–3.9km/sec) characterize material deposited mainly on the eastern and western periphery, that is in the eastern channels and in the east-north-east–west-south-west oriented, eastwards-thinning sedimentary wedges on the continental margin. Here the 3.6–3.9km/sec material partially overlies the basement. The observed differentiation of velocities in the intermediate sequence is probably the expression of its variable lithological composition which, in turn, must reflect deposition under changing conditions or during different geological times.

Similar geological conclusions can be drawn from the acoustic discordance observed between the seismically different structures of the tectonized high-velocity sequence (Palaeozoic), whose depressions are filled by sediments represented by the intermediate sequence, and the upper, low- to medium-velocity sequence (see above; Fig 2), whose seismic structure shows almost horizontal layering. This acoustic unconformity appears to be similar to the geological unconformity observed in the Western Approaches between Cretaceous and Palaeozoic strata. The similarity between the acoustic and geological unconformities lead one to the conclusion that the sediments represented by the intermediate seismic sequence were likely to have been deposited during Devonian (Carboniferous?) to Cretaceous times. One of the sedimentary components of the sediment-fill may well be Permo-Triassic, mainly continental deposits that were a product of the extensive Permo-Triassic erosional phase. Such Permo-Triassic sediments are known to crop out south of Cornwall.

The opening of the North Atlantic and the particular position of Spain are clearly pertinent to understanding the late Palaeozoic and Lower Mesozoic sedimentary history of the Western Approaches and that of the South Armorican continental shelf. Various investigators (Bard *et al.*, 1971; Le Pichon *et al.*, 1971; Sibuet *et al.*, 1971; Stauffer and Tarling, 1971) place the northern limit of Spain, or the Iberian craton, in the vicinity of the Meriadzek terrace and have inferred that its separation from the present continental margin took place only in the post-Jurassic times. It seems possible that the Western Approaches may have been protected from widespread Lower Mesozoic transgression from the west because Spain blocked off the major part of the western outlets. In this case the deposition of Lower Mesozoic sediments (possibly Triassic marine and Jurassic Aquitanian or South Portugal type) would have been prevented. The two Hercynian uplands, the Lands End–Scilly axis and the Armorican Massif, may have formed barriers in the north and south respectively at this time.

The relatively thick sediment fill in the central areas wedges out in the eastern areas to a thin sheet of deposits or is lacking over the Lizard–Brittany and the Start–Cotentin Hercynian ridges. The thinning out is not an erosional feature only; it suggests that communication between the Western Approaches and the Paris Basin was considerably restricted in Lower Mesozoic times by these Hercynian structural highs. This does not exclude the possibility of a Lower Mesozoic "trough" linking the western, possibly oceanic areas, through the Western Approaches to the Paris Basin, but it greatly reduces its importance. Furthermore, the most westerly Jurassic outcrop so far found in the Western Approaches (about 4° 30′ W, slightly to the east of the Lizard–Brittany ridge) (Fig 1) has been dated as Lias and the younger Jurassic sediments clearly show an eastwards regressive tendency (Larsonneur, 1971).

Velocity measurements in the English Permo-Triassic show two velocity classes (Wyrobek, 1959). The continental-type deposits, similar to those observed south of Cornwall, are in the 3.0km/sec velocity range and rarely exceed 3.6km/sec even at greater depth. Evaporitic material in this formation raises the seismic velocity to about 4.1–4.3km/sec. The seismic velocity of Jurassic deposits in the Paris Basin is generally in the 3.6–3.9km/sec range and only exceptionally reaches about 4.2km/sec. The 3.8km/sec measured on Jurassic outcrops in the eastern part of the Western Approaches agrees well with velocities obtained in the Paris Basin. The Aquitanian or South-Portugal-type carbonates fall generally in the high-velocity class (about 4.4–4.6km/sec) and often show values which are comparable to those of metamorphic and igneous rocks. If the seismic velocities of these significant samples are compared with those comprising the intermediate sequence (3.6–3.9 and 4.0–4.3km/sec), one notices a rather close agreement between the velocity ranges, except for the class of high-velocity carbonates, and it seems a relatively simple matter to deduce the geological nature of this seismic sequence. But if we take into consideration the possible existence of sediments with a source lying to the west and deposited during eastwards transgressive phases, then the extrapolation of velocities (measured, for example, in the eastern areas and belonging to a different geological domain) becomes questionable. Indeed, we lack geological evidence on the existence of the Lower Mesozoic transgressional phases originating in the west and on the westwards extension of sedimentary sequences derived from the east. Moreover, because we have no borehole data from the western areas of the Approaches, it is not possible to formulate any really sure conclusions on the geological nature of the intermediate sequence.

It can be postulated that Permo-Triassic continental-type deposits partially fill the central depressions and the eastern "channels" (Fig 7). These deposits, due to their lower velocities (3.0–3.6km/sec), are possibly masked ("hidden layers") in the central depressions by the higher velocity cover (4.0–4.3km/sec), which might be the expression of an evaporitic layer or the remnants of an eastwards transgressive Triassic or Jurassic phase. In the eastern "channels" the Permo-Triassic deposits may be present under thin, higher-velocity (3.8km/sec) Jurassic material linked to the Paris Basin facies.

The east-north-east–west-south-west oriented wedges on the continental margin (Fig 7) are filled with sediments whose seismic velocity falls in the 3.6–3.9km/sec class and correspond closely to the velocities measured on Jurassic outcrops on the eastern periphery of the Western Approaches. However, because of the eastwards transgressive aspect of these wedges, association of this material with the Jurassic found in the eastern areas is questionable. In addition, the velocity of these sediments does not match the generally higher ones of the Jurassic of the South Portugal or Aquitanian type. It therefore seems advisable to link the origin of this material to a post-Jurassic geological event.

To summarize evidence on the geological nature of the intermediate seismic sequence representing the infilling of depressions of the Palaeozoic floor, it appears that the sequence in the central depressions is composed of Permo-Triassic continental-type deposits, overlain by an evaporitic layer or remnants of Triassic or Jurassic sediments originating from an eastwards transgressive phase. This transgression may have found its way through the previously mentioned structural barriers formed by the Lands End–Scilly axis, the Iberian craton and the Armorican Massif, respectively in the north, west and south. In the eastern channels, except for the "Permian basin" south of Cornwall, the Permo-Triassic appears to be covered by the westwards transgressive Jurassic phase linked to the Paris Basin, with this westwards extension limited by the Lizard–Brittany and Start–Cotentin ridges. The sedimentary wedges on the margin are possibly post-Jurassic.

Upper Sequence (1.9–3.6km/sec). The seismic structure of the upper, low- to medium-velocity sequence indicates almost horizontally layered strata discordantly covering the high-velocity and intermediate sequences, that is, both the Palaeozoic floor and the fill of its depressions. This "acoustic unconformity" located at the base of the upper sequence is interpreted as being the geological unconformity observed in the Western Approaches between Cretaceous layers and Palaeozoic strata. Therefore, one should seek correlations between the seismic layers of this sequence and the Cretaceous and Cenozoic strata present on the seabed over the major part of the Western Approaches and the South Armorican continental shelf.

Three distinct velocity groups have been detected in the Upper sequence: (a) 3.2–3.6km/sec, average 3.4km/sec, layer C_1; (b) 2.6–2.9km/sec, average 2.8km/sec, layer C_2; and (c) 1.9–2.4km/sec, layer C_3.

(a) Layer C_1 (~3.4km/sec) appears to cover discordantly the high-velocity and the intermediate sequences, that is the Palaeozoic and the fill of its depressions, which is interpreted as Permo-Triassic (and Jurassic?) deposits. Layer C_1 is present on the South Armorican continental shelf (maximum thickness about 400–600m) as well as under the Western Approaches, mainly between the North Armorican Fault and the southern slope of the Lands End–Scilly axis. In both areas it is characterized by an eastwards thinning sedimentary wedge, whose thickness reaches about 1.5–2km on the margin of the Approaches decreasing to about 500–600m in the central areas and even less towards the eastern Lizard–Brittany and Start Point–Cotentin ridges which seem to block its eastwards extension. Also it seems to thin out and to disappear on the southern slope of the Lands End–Scilly axis as well as south to the North Armorican Fault in the eastern and central Western Approaches. The wedging out of this layer is also observed towards the basement high interpreted as the separation of the South Armorican shelf and the Aquitanian basin. In the eastern areas its discrimination from the Permo-Triassic is not evident because of only slight velocity contrast. Based on the fact that velocities in the 3.2–3.6km/sec range appeared as the first discernible velocities on the time–distance graphs close to the few Lower Cretaceous outcrops, it seems probable that Layer C_1 represents, at least partially, the Lower Cretaceous. The somewhat higher velocity observed (3.6–3.9km/sec) in the marginal wedges of the intermediate sequence, associated with the Lower Cretaceous on the basis of geological inferences, can possibly be due to a different facies of this geological layer.

(b) Layer C_2 (~2.8km/sec) represents a fairly good refracting surface and appears to cover a much larger surface than layer C_1 both on the South Armorican shelf and in the Western Approaches. However its structure is closely similar to that of layer C_1, that is an eastwards thinning sedimentary wedge, whose thickness decreases from a maximum of about 2km on the margin of the Approaches to about 600m in the central and 300m in the eastern areas, but breaches over the eastern ridges towards the Paris basin. On the South Armorican shelf, layer C_2 reaches only about 300m and wedges out rapidly towards land.

Velocity measurements on outcropping Upper Cretaceous strata fall generally in the 2.6–2.9km/sec range, thus it was deduced that Layer C_2 is representative of Upper Cretaceous sediments.

The isopachs (Fig 8) show the combined thickness of Layers C_1 and C_2, that is the total Cretaceous in the Western Approaches and the South Armorican continental shelf.

In the Western Approaches the Cretaceous represents an approximately triangle-shaped, eastwards thinning sedimentary wedge, extending mainly between the southern slope of the Lands End–Scilly axis and the North Armorican Fault. In the eastern channel, over the ridges, only the Upper Cretaceous appears to be present.

On the South Armorican shelf, southwards to the North Armorican Fault, only a limited thickness of Cretaceous sediments seems to have accumulated. Nevertheless, its eastwards transgressive tendency is similar to the one observed in the Western Approaches.

The clearly eastwards transgressive character of the Cretaceous layers signifies a major subsidence phase which generally follows the rifting and break up of the continent at its margin (Beck, 1972). This phenomenon is most likely a long lasting event, possibly occurring in phases. The physical process which takes place after the separation of continents, and which causes the subsidence of marginal areas is as yet not well understood, but it is observed on the margins of all the continents. It is likely an isostatic process accompanied by the migration of basic mantle material towards the continent from beneath the growing basin beyond the continental slope.

The transgressive tendency of the Lower and Upper Cretaceous in the Western Approaches and South Armorican shelf is thus most probably related to the break up of the Iberian craton from the Armorican Massif and adjacent areas, which was possibly initiated in late Jurassic times. The timing of this event, deduced from purely seismic data agrees well with the results of palaeomagnetic interpretation on samples and other data from the Bay of Biscay (Sibuet, 1972).

An interesting feature is the partial removal of

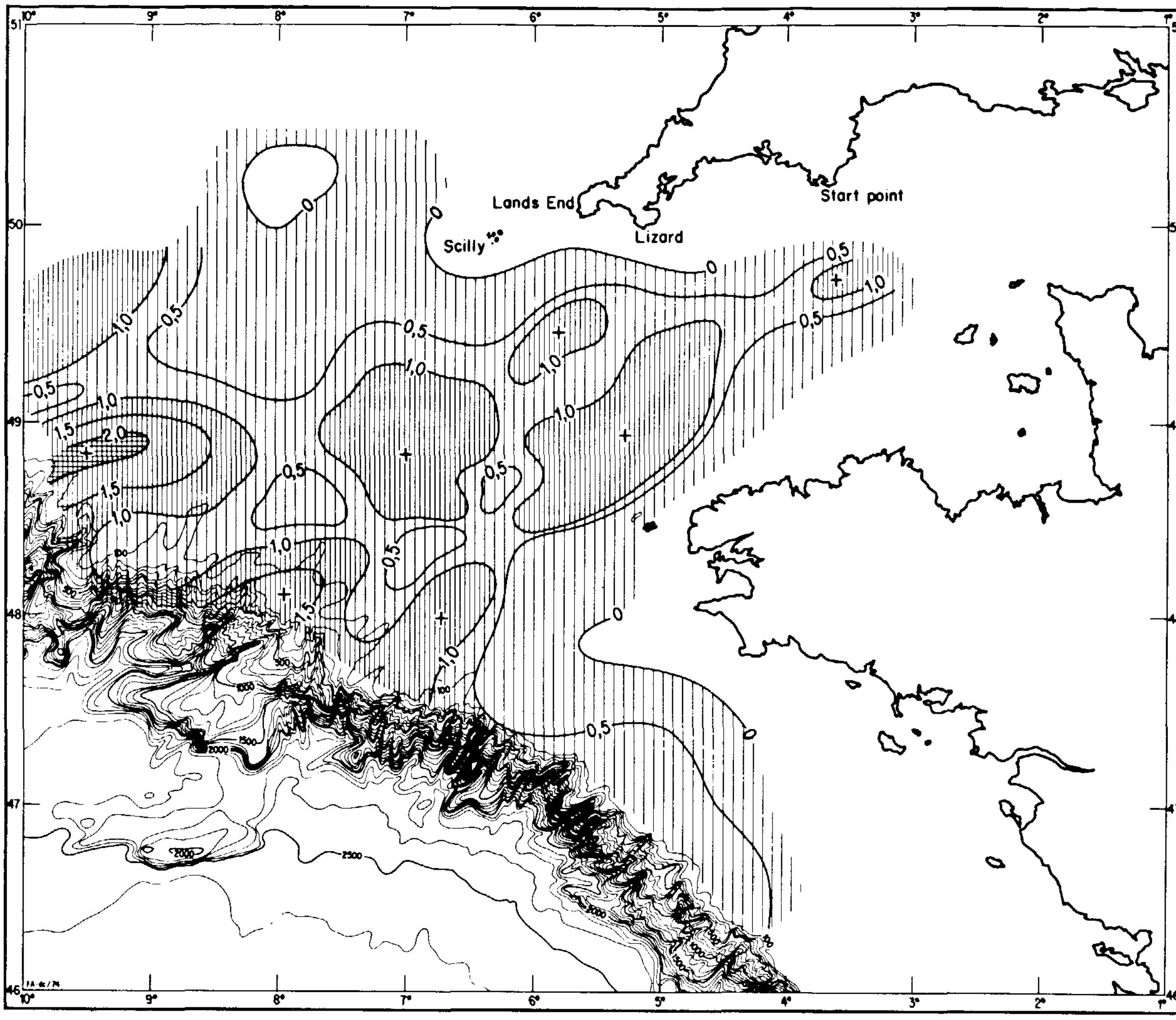

FIG 8. Isopachs of the upper sequence (1.9—3.6km/sec) representing the Lower and Upper Cretaceous. Contour interval 0.5km.

the Upper Cretaceous sediments from the sedimentary swells over parts of the north-west–south-east basement high near the continental margin and the linear swell following the trend of the North Armorican Fault. Both features relate to strong magnetic and positive gravity anomalies, suggesting basic intrusions. In attempting to explain and date these features one must take account of the considerable bulging of the deep seismic interface beneath the North Armorican Fault and the relative shallow depth of smaller intrusive bodies (see discussion on the high-velocity sequence, layer "A"). In short, it appears very difficult to associate the height and width of the deep intrusion with the relatively small sedimentary swell, the height of which seems to be only some hundred metres. Thus two-stage intrusive activity seems probable, the first and deep phase associated with the extensions of the early Mesozoic which led to the break up of continents, the second with a later, possibly Eocene phase, related to the Alpine movements.

(c) Layer C_3 (1.9–2.4km/sec) the reliability of velocity determinations is often dubious because of the limited vertical extent of these sediments. Layer C_3 apparently contains Cenozoic material, whose thickness reaches about 300–500m in the central areas of the Western Approaches and about 600–800m on the continental margins. Where thicker Cenozoic is present, a distinctive refracting surface with velocities in the 2.2–2.4km/sec range seems to belong to the Eocene or Palaeocene.

CONCLUDING REMARKS ON THE POST-PALAEOZOIC SEDIMENTARY HISTORY, INCLUDING THE PERMO-TRIASSIC

It has been shown that the sedimentary history of the Western Approaches and the South Armorican continental shelf involved the deposition of at least three distinctive sedimentary sequences related to different, major geological events: (1) a Palaeozoic sequence, ending with the Hercynian orogeny; (2) a mainly continental-type sedimentary sequence, from the Hercynian orogeny until the opening of the Bay of Biscay; and (3) the mainly marine-type,

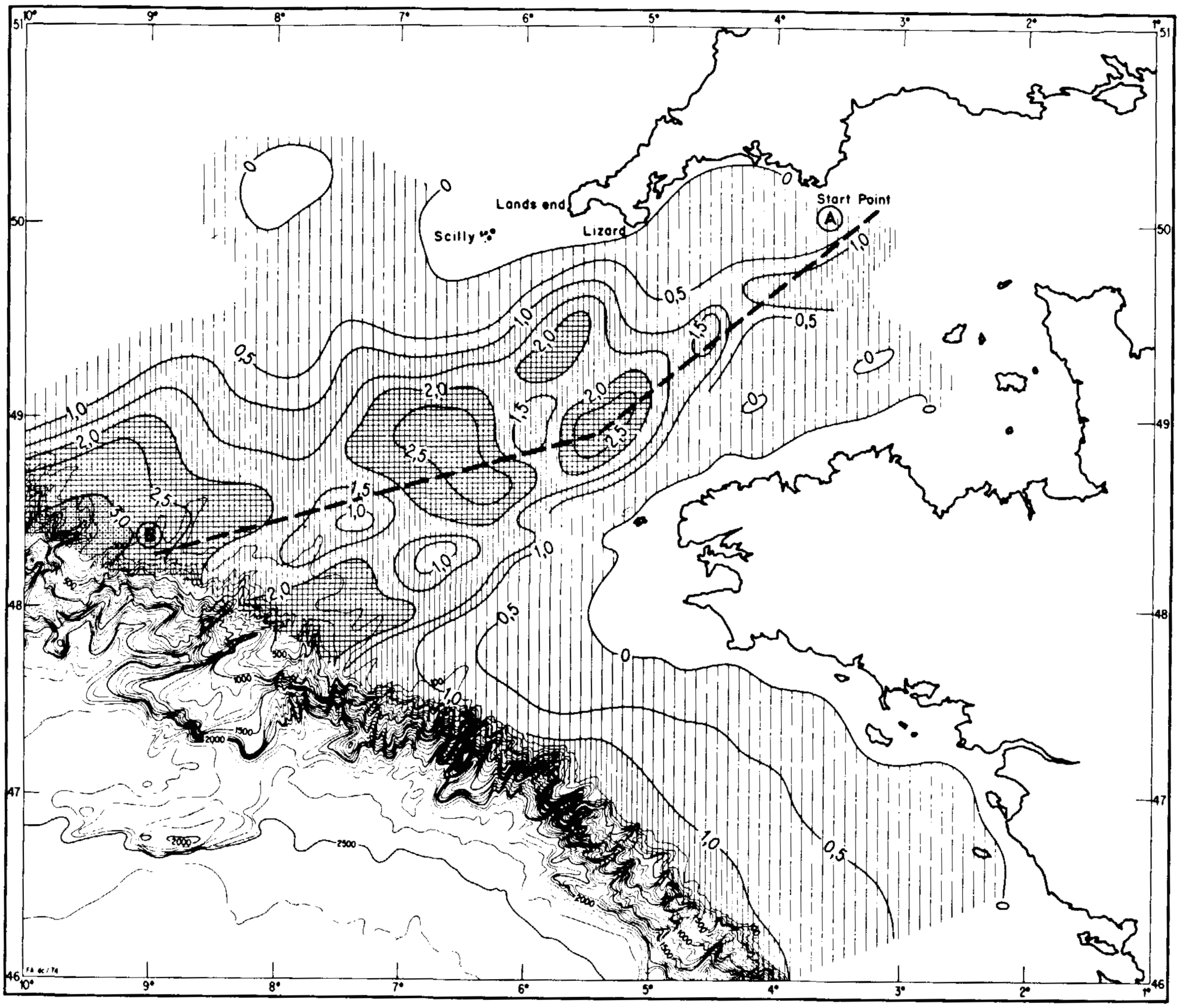

FIG 9. Isopachs of post-Palaeozoic sediments including the Permo-Triassic. Contour intervals 0.5km.

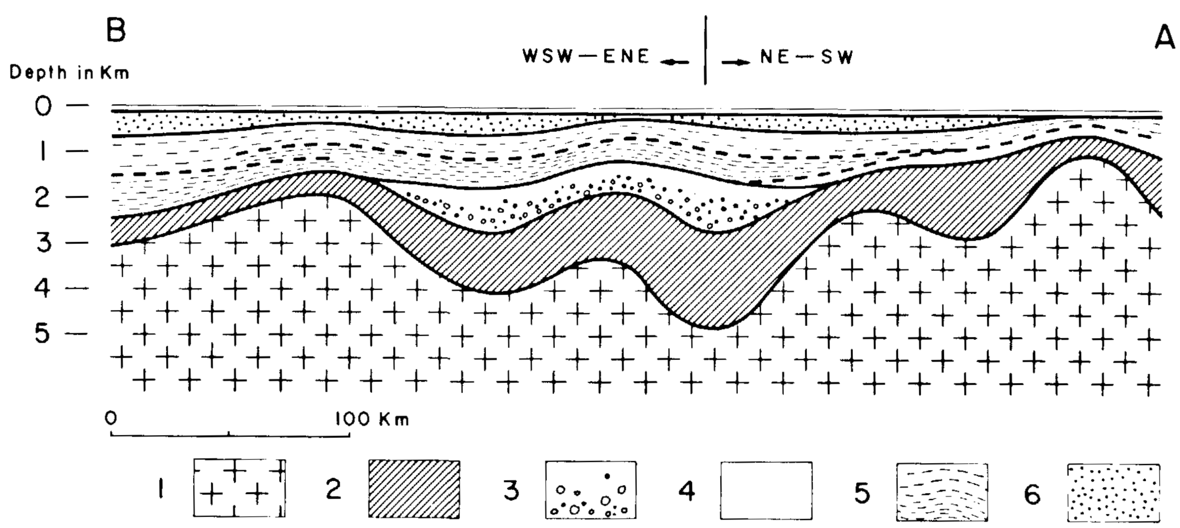

FIG 10. Schematic geological section along line A B as shown on Fig 9. (1) Metamorphic basement with acid and basic intrusions; (2) Lower and Middle Palaeozoic; (3) Permo-Triassic (and Jurassic?); (4) Jurassic (and Permo-Triassic?); (5) Lower and Upper Cretaceous; (6) Cenozoic.

Upper Mesozoic and Cenozoic sequence, which represents sedimentation starting with the opening of the Bay of Biscay and continuing to present times.

The Palaeozoic geosyncline was considerably remodelled during the Hercynian orogeny when uplands and depressions were formed along east–west, north-east–south-west and north-west–south-east structural trends. At the end of the orogeny, the Western Approaches formed a closed area bordered by the Hercynian uplands—the Lands End–Scilly axis in the north and the Lizard–Brittany and Start–Cotentin ridges to the east. The southern and western structural borders of the area were respectively the Armorican craton, whose northern limit seems to be the North Armorican Fault, and the Iberian craton. The sediments of the mainly continental-type post-Hercynian sequence were laid down in the north-east–south-west oriented basin, floored by depressions and smaller ridges. At the end of this sedimentary phase some evaporitic material may have been laid down in the central depressions.

Alternatively, early Mesozoic material may have accumulated on the top of continental-type deposits prior to the large transgressive phase, possibly following the opening of the Bay of Biscay. Whatever the nature of this layer, it appears that its deposition represented the end of the accumulation of mainly continental-type sedimentary sequences in the Western Approaches. The area was a peneplain with the depressions of the Palaeozoic floor filled in. The resulting total thickness of the deposits in the central depressions reached about 1.0–1.5km.

The opening of the Bay of Biscay, possibly in early Cretaceous times, moved the Iberian craton, the western barriers of the Western Approaches and the South Armorican continental shelf towards the North Atlantic. The eastwards transgression flooded the area and deposition of the marine Cretaceous and Cenozoic sedimentary sequence began. Because of the rapid subsidence of the margin between the Lands End–Scilly axis and the North Armorican Fault, approximately 2–3km of sediments accumulated. Towards the east, however, the thickness of the deposits decreased to about 1.0km or less. Southwards to the North Armorican Fault, a geologically different domain is present—the Armorican craton. Due to a lower subsidence rate of its peripheries, a sedimentary cover of only about 1.0–1.5km accumulated on the South Armorican continental shelf, wedging out landwards. This mainly marine sedimentary sequence is still in process of accumulation in the Western Approaches and on the South Armorican continental shelf.

Figure 9 shows the thickness of post-Palaeozoic sediments, including the Permo-Triassic. The total thickness in the central depressions of the Western Approaches reaches about 2.0–2.5km in which the probable Permo-Triassic (and Jurassic?) represent about 1.0–1.5km. On the margin about 2–3km, mainly Cretaceous and Cenozoic sediments have been accumulated. On the South Armorican continental shelf only about 1.0–1.3km of Cretaceous and Cenozoic cover is present and this wedges out towards land.

The geological section (Fig 10) along line A–B (of Fig. 9) clearly shows the different sedimentary sequences: the tectonized Palaeozoic sediments, the fill-in of depressions of the Palaeozoic floor and the transgressive Cretaceous and Cenozoic sedimentary phase.

In conclusion it is emphasized that the sedimentary history which I have outlined was deduced to a great extent from indirect geophysical data of limited extent. The interpretation of such data, by its nature, is controversial and will remain so until enough borehole data are available.

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APPENDIX

Position of stations	Apparent horizontal velocity in km/sec	Depth in km
48° 42′ N 06° 43′ W	6.6	6.8
48° 49′ N 06° 24′ W	6.5	6.1
48° 38′ N 06° 59′ W	6.8	5.1
48° 33′ N 06° 36′ W	7.3	7.7
48° 35′ N 06° 02′ W	7.2	7.9
48° 51′ N 06° 10′ W	7.0	11.3 (?)
49° 19′ N 06° 24′ W	7.1	7.1
48° 22′ N 05° 59′ W	6.6	4.4

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