PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Seismic Refraction Survey in the Western Approaches to the English Channel: Preliminary Results [and Discussion]

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Seismic refraction survey in the Western Approaches to the English Channel: preliminary results†

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A seismic refraction survey of the Western Approaches was completed in the autumn of 1973, totalling 28 stations. In addition to a few sonobuoys, an improved method of detection was used, consisting of geophones or hydrophones positioned on the sea floor. The seismic signal was transmitted by radio to a shipboard receiving and recording apparatus. This new technique considerably improved the signal noise ratio.

The major structural trend in the Western Approaches to the Channel is NE–SW. Two large northeast–southwest fault systems border a large, downfaulted, elongated basin, floored by depressions and ridges. The seismic refraction data lead to the recognition of two distinct geological sequences. The first is associated with the tectonized, metamorphic floor with igneous intrusions and conformably layered Palaeozoic series. The second sequence is made up of nearly horizontal layers, consisting mainly of secondary and younger sediments. The two sequences seem to be separated by an unconformity. The relatively light sediments filling depressions of the Palaeozoic floor may partially cause the observed low free-air gravity anomalies. The basement has a block-faulted aspect, the blocks being tilted in a southeast and possibly also in a southwest direction.

1. INTRODUCTION

The quality of seismic reflexion surveys on continental shelves is, in general, greatly affected by multiple reflexions and processing is needed to eliminate the interference produced by such reflexions. In some cases, even processing cannot clear the picture. The question thus arises, to what extent can seismic refraction studies of continental shelves complement and support the results of reflexion surveys?

As is generally admitted, seismic refraction at sea is a slow, time- and energy-consuming procedure, and therefore its use has been quite restricted. This is particularly true for the classical operation in which two ships are used, one carrying the receiving apparatus and the other, the shooting ship, equipped with a seismic source to generate the necessary high-energy pulses. An alternative method replaces the receiving ship by a so-called 'sonobuoy', a free floating radio-transmitter equipped with hydrophone and seismic amplifier. The siesmic signal detected by the buoy's hydrophone is transmitted to the ship's receiving and recording apparatus.

With the use of sonobuoys, seismic refraction has become a more flexible and rapid operation. However, there are limitations which restrict the efficient use of sonobuoys. These include excessive drift of the buoy caused by high tidal or other surface currents and high acoustic noise-level due to wave and wind action. To overcome these difficulties, the best solution seems to be to position the detectors on the sea floor.

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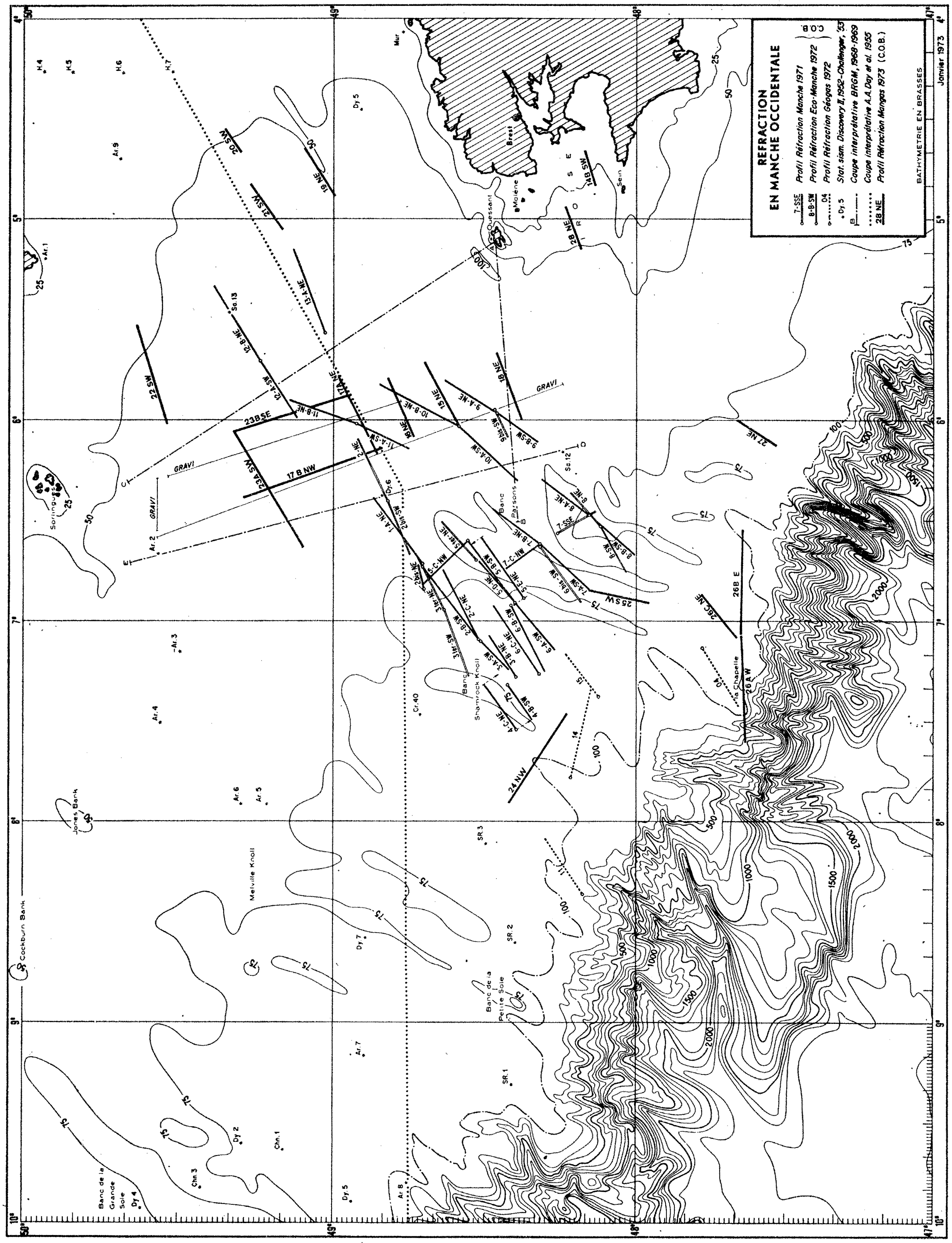

FIGURE 1. Position of seismic stations. Number refer to serial number of station; letters indicate that detectors on sea-floor have been used; last letters indicate direction of survey. Stations of previous studies are also shown.

We have used bottom-positioned detectors during the refraction survey of the Western Approaches. The surveyed area extends roughly from 4° to 8° West and from 47° 30′ to 49° 30′ N (figure 1).

2. Methodology at sea

A relatively simple apparatus and procedure (figure 2) were developed at the Centre Océanologique de Bretagne for refraction surveys with bottom-moored detectors (Avedik & Renard 1973). It consists of (I) detector unit (pressure compensated hydrophone or geophone) resting on the sea-floor (II), an anchor (III), a steel conductor cable (IV), a surface float-transmitter unit. The signal is linked to the surface buoy by a 5 mm, single conductor steel-armoured cable. A steel container with grips and ballast (about 140 kg), clamped to the cable about 50 m from the detector assembly, serves as a anchor for the surface buoy. The signal transmitted by the buoy is received on the ship and recorded. The launching of the assembly takes (at water depths of about 150–200 m) from 15 to 20 min and recovery, depending on the weather, 30–60 min. Performance of detectors positioned on the sea-floor is usually superior to that of sonobuoys used in the same area under similar conditions (figures 3 and 4).

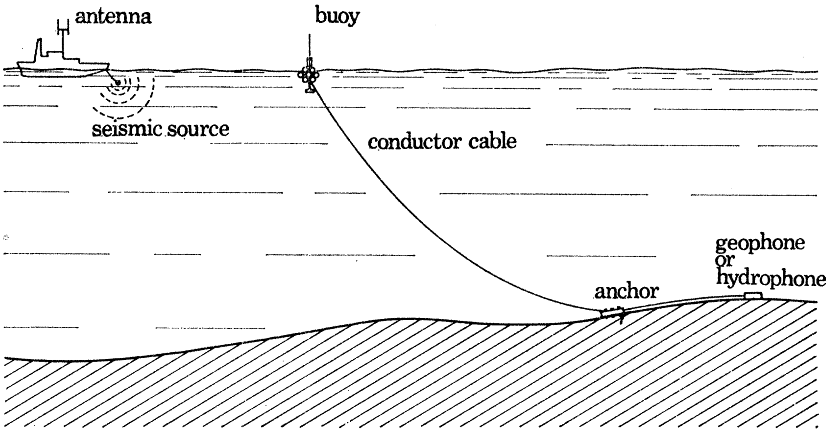

Figure 2. Method with detectors on the sea-floor.

The ease of operation, the favourable signal-to-noise ratio obtained (even under bad weather conditions) as well as the relatively small cost of the equipment, which is re-usable, makes refraction surveys with anchored detectors a valuable and economic supplement to reflexion surveys on continental shelves.

The orientation of most of the profiles (figure 1) is NE–SW, the main structural direction. Errors in the recorded velocities resulting from abrupt changes in dip were thus reduced to a minimum. However, because of the complicated geological structure, profiles were also run across strike to cover two directions around a central receiving point. Reverse profiles, which are particularly time-consuming, were restricted mainly to areas where subsurface basins are presumed to be present. This procedure seemed to constitute the most efficient compromise for obtaining maximum structural information and the least disturbed velocity records.

Profiles 1–13 (figure 1) were run with one air-gun (5900 cm³) and profiles 14–28 with two 5900 cm³ air-guns shot simultaneously. The ship's speed was about 3 m/s (6–7 knots) and shot frequency was about 30 s. Decca and satellite fixes were used for navigation. The detector-shot distances, determined from direct arrivals ($V_{\text{water}} = 1.5$ km/s) are in good agreement with those obtained from the navigational data.

3. The velocity structure and its geological interpretation

Earlier work in the area, carried out mainly by British surveyors (Bullard & Gaskell 1941; Hill & King 1953; Day, Hill, Laughton & Swallow 1956) established several classes of velocities. They proposed the following geological correlations:

1.9–2.5 km/s	Recent to Mesozoic sediments.
2.8–3.6 km/s	Mainly Mesozoic and Permo-Triassic strata.
3.65–4.85 km/s	Palaeozoic and slightly metamorphosed sediments.
5.2–7.0 km/s	Metamorphic and granitic basement.

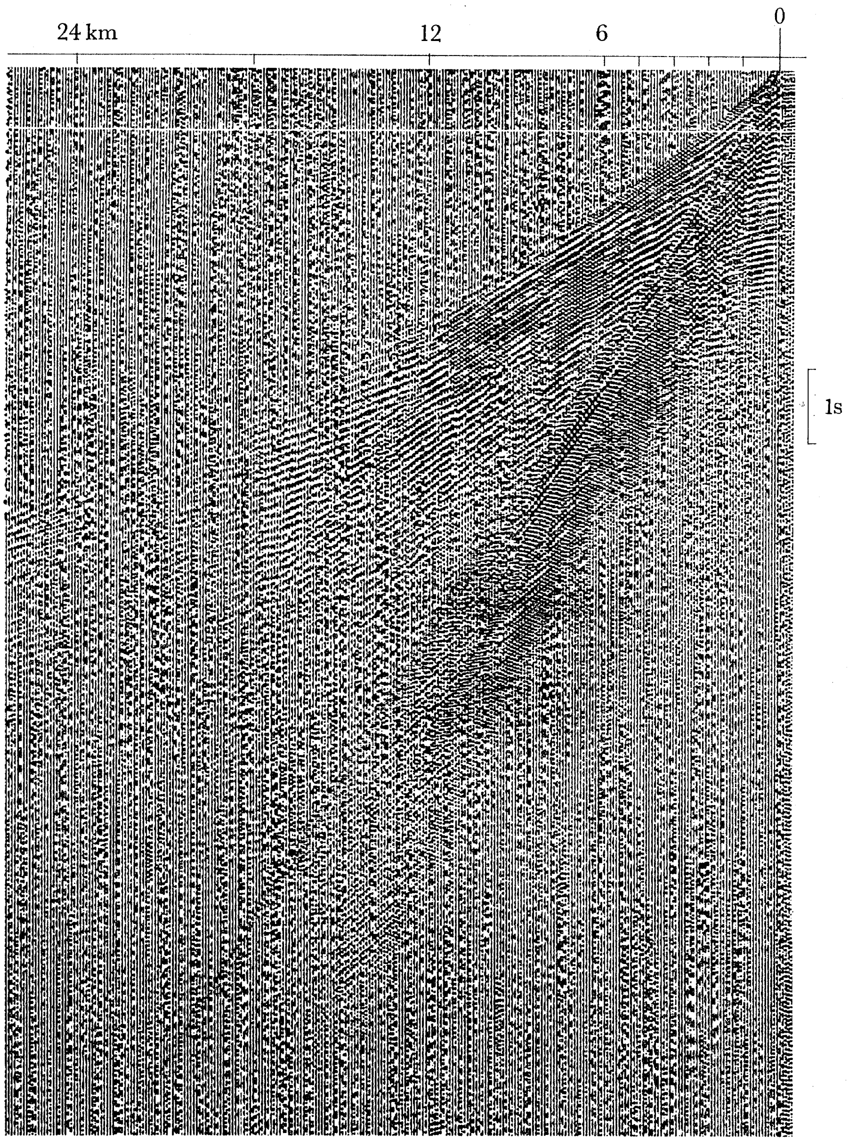

Figure 3. Conventional sonobuoy record (2×5900 cm^3 air-gun, calm seas, current about 0.25 m/s (0.5 knot)).

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More recent surveys (Andreieff, Bouysse, Horn & Monciardini 1971) indicated practically the same classes of velocities.

To establish the schematic seismic structure of the Western Approaches parallel to the main NE–SW structural trend, the data for all stations has been compiled, including two from Hill & King (1953) and Day *et al.* (1956), which cover a line from about 3° 30′ (station DY-4) extending southwest to the continental margin. This lines follows the axis of the Channel and Western Approaches.

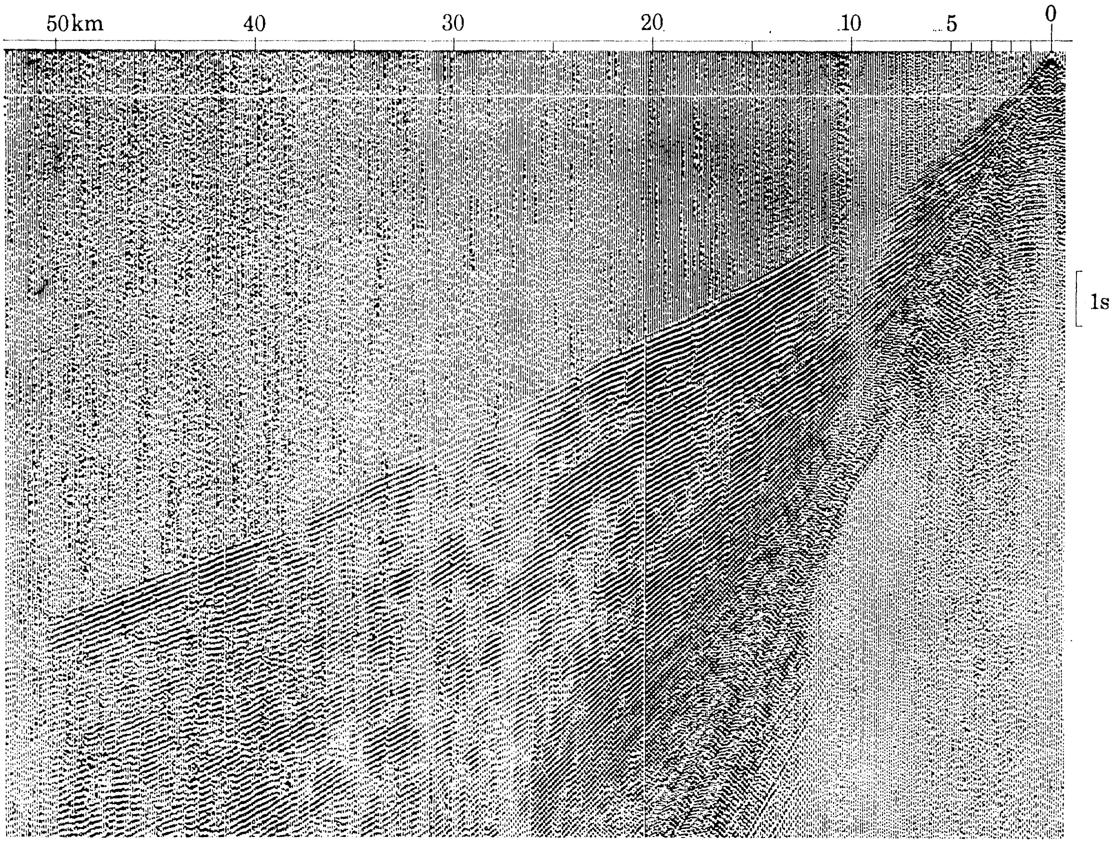

Figure 4. Record with hydrophone on sea-floor (2×5900 cm^3 air-gun, current about 0.5 m/s (1 knot)). The observed diminution of signal is caused by the emitter's automatic gain control, which diminishes amplification due to higher ambiant noise level. This increase of noise level was caused by heavy rainfalls in the area of the detector (radar observations).

Based on our measurements, the following classification of velocities is proposed:

1.9, 2.4 km/s 2.6, 2.9 km/s 3.2, 3.7 km/s 4.1, 4.3 km/s
4.5, 4.9 km/s 5.2, 6.0 km/s > 6.3 km/s.

These velocities seem to be associated with three distinctive geological sequences (figure 5):

(*a*) conformably layered, tectonized deep horizons;

(*b*) almost horizontally layered, upper sequences;

(*c*) in-fill of pocket-like depressions.

A velocity–depth diagram (figure 6) constructed with the data of stations over basin areas to minimize the depth scatter, seems to show the same sequences as are observed on the NE–SW profile (figure 5). The lower portion of the curve corresponds to the tectonized, high velocity

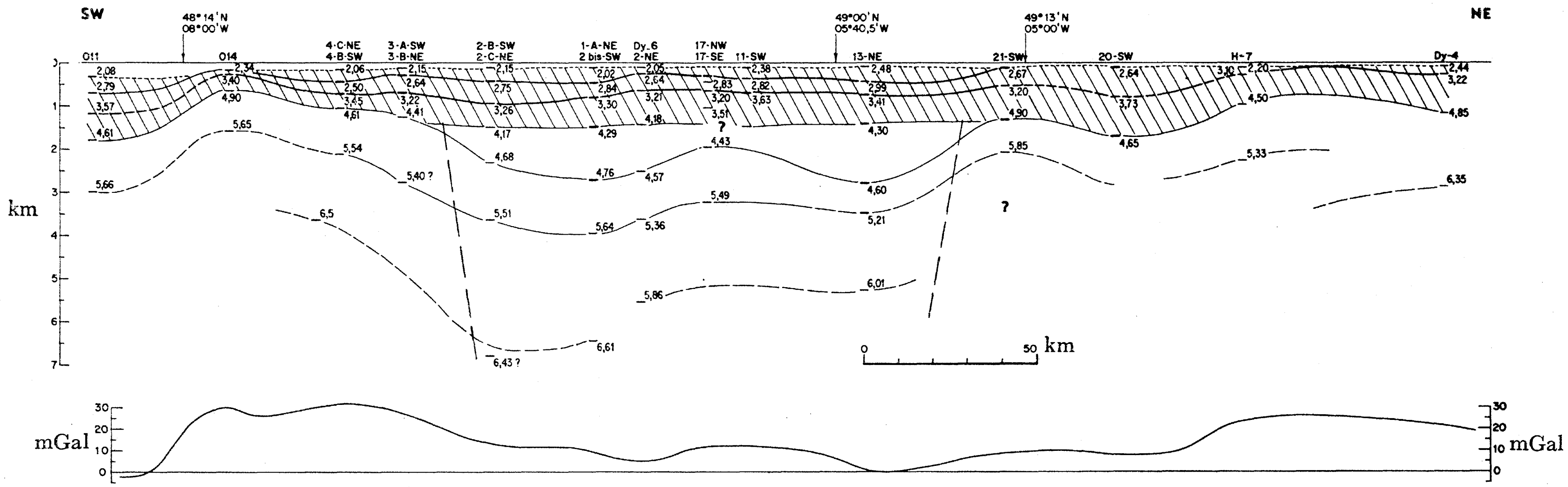

FIGURE 5. Section along a NE–SW line, in the axis of the Western Approaches (velocity in km/s, depth in kilometres, free-air gravity anomalies in milligals (10^{-5} m s^{-2}). Station H-7 after Hill *et al.* (1953), DY-4 after Day *et al.* (1956).

series ($V \geqslant 4.5$ km/s), the upper part of the curve with the almost horizontally layered sequence covering the high velocity series and the 'break' between the two curves, situated at about 1500 m (velocity approximately 4.2 km/s) corresponds to the observed 'pockets' or depressions.

(a) *The tectonized, deep horizons*

These fall mainly in the high seismic velocity class (> 4.5 km/s).

On a few stations, secondary arrivals yielded velocities in the 6.5 km/s range. The corresponding depth is about 4–7 km. The validity of these determinations is doubtful and further analysis will be necessary to determine the source of the arrivals.

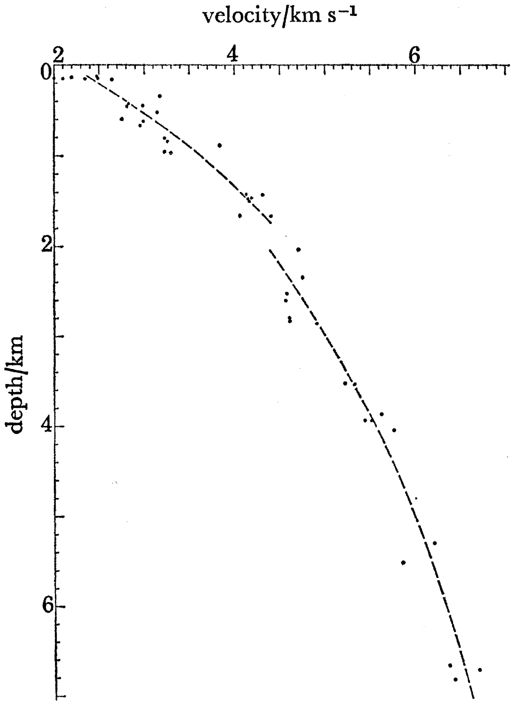

Figure 6. Velocity–depth function. Only data from basin areas are used.

The velocities of the first deep layer fall in the 5.2–6.0 km/s velocity range and correspond closely to the class 4 velocities established by previous work (Hill & King 1953; Day *et al.* 1956), and correlated with their 'metamorphic basement'. This layer gives rise to pronounced, low frequency first arrivals.

Laboratory data and velocity measurements on outcrops of metamorphosed and igneous rocks in this area show a large scatter of velocities roughly in the 5.0–7.0 km/s range. Also, the surrounding land areas exhibit a quite complex Precambrian, Cambrian and Palaeozoic geology, further complicated by granitic and basic intrusions. Possibly a similar geology characterizes the Western Approaches, in which case it seems unlikely that one could differentiate the different geological units solely on the basis of seismic velocities.

At this stage of investigations, we can refer to the lowest layer (5.2–6.0 km/s) only in a global way, designating it as 'metamorphic basement', comprised of rocks in different stages of metamorphism, pierced by acid and basic intrusions.

The 'metamorphic basement' is conformably covered by a layer characterized by velocities of the 4.4–4.9 km/s range, with an average thickness of about 1.0–1.5 km. On the eastern part of the profile (figure 5) the velocities correlate well with those obtained by Hill & King (1953) and Day *et al.* (1956) on stations H-7 and DY-4. Measurements on outcropping Palaeozoic strata on land and sea indicate similar velocities. On this basis, we may correlate the 4.4–4.9 km/s layer with Palaeozoic strata, possibly slates and sandstones.

(*b*) *The upper sequence*

The upper horizontally layered sequence is formed by low to medium velocity material.

On the major part of the profile, low-velocity sediments of the 2.0–2.4 km/s category form the sea bed.

The second layer, with velocities in the 2.6–2.8 km/s velocity class produces well-determined segments on the time–distance graph. This layer seems to outcrop or comes close to the surface of the sea-bed, in the eastern and western part of the profile. The average thickness is about 300–500 m.

The velocities measured for the third, upper layer are in the 3.2–3.7 km/s range. Most of the corresponding first arrival segments on the time–distance graphs are short and the variation of velocities within the layer is quite appreciable. In general, the layers in the upper sequence produce relatively high frequency first arrivals.

The velocity class from 2.0–2.8 km/s is, on evidence of geological sampling in the area of our investigation, associated mainly with late-Mesozoic to Recent sediments. The geological correlation within the 3.2–3.7 km/s layer is rather difficult; borehole data suggests that lower Cretaceous, Jurassic and Permo-Triassic sediments have about the same seismic velocities.

The frontier between the two seismically different sequences (the lower, high-velocity tectonized layers and the upper, almost horizontally layered, low-to-medium velocity strata) may be located at the base or within the 3.2–3.7 km/s layer. This 'acoustic unconformity' may be correlated with the geological unconformity recognized in the Channel between Palaeozoic and Mesozoic and younger strata.

(*c*) *The in-fill of the pocket-like depressions*

The cover of the depressions, observed between the horizontally layered upper sequence and the tectonized lower series, shows a very flat surface with seismic velocities of about 4.2 km/s. The corresponding segments on the time–distance graphs are generally formed by weak, high-frequency arrivals.

We face considerable difficulties when attempting to assign this material to a particular geological horizon. The anomaly in the velocity–depth function (figure 6) as well as the high-frequency, weak arrivals may suggest a rather thin layer, characterized by the 4.2 km/s velocity, and covering lower-velocity sediments masked by the higher velocity layer. As a possible interpretation, we may suggest a thin evaporitic cover on upper or middle Palaeozoic sediments, which are known to be in the medium velocity class. An other alternative is to associate this material with eroded carbonate fragments of early Mesozoic origin.

Whatever may be the identity of the 4.2 km/s layer or, in more general terms, the nature of the in-fill of these depressions, a simple gravity model shows that the relative lows in the free-air gravity anomalies (figure 5) are mainly controlled by these pocket-like depressions and that the density contrast, assuming a granitic basement, should be about 0.30 g/cm^3. This means that these depressions should be filled with material of an average density of about 2.30–2.40 g/cm^3.

The structure of the 'metamorphic basement' of the Western Approaches (figure 7) shows several remarkable features. One of these is the NE–SW fault system, with a total vertical offset of about 1.5–2.0 km, which seems to be associated with the high magnetic anomalies north of the Brittany coast. Later readjustment and injection of probably basic material (causing the magnetic anomalies) in this fault system may have induced significant vertical displacements in the secondary and younger sedimentary cover. A second, approximately NW–SE trending fault system of more limited importance does not seem to have much affected the secondary and younger cover. This fact is seen on the NE–SW profile (figure 5). Another characteristic feature of the metamorphic basement of the Western Approaches is the large elongated basin or trough, floored by a NE–SW trending system of depressions and ridges (figure 7). This basin is bordered in the south by the main, NE–SW running fault system, and in the north by an almost parallel fault system, south of the Scilly Islands.

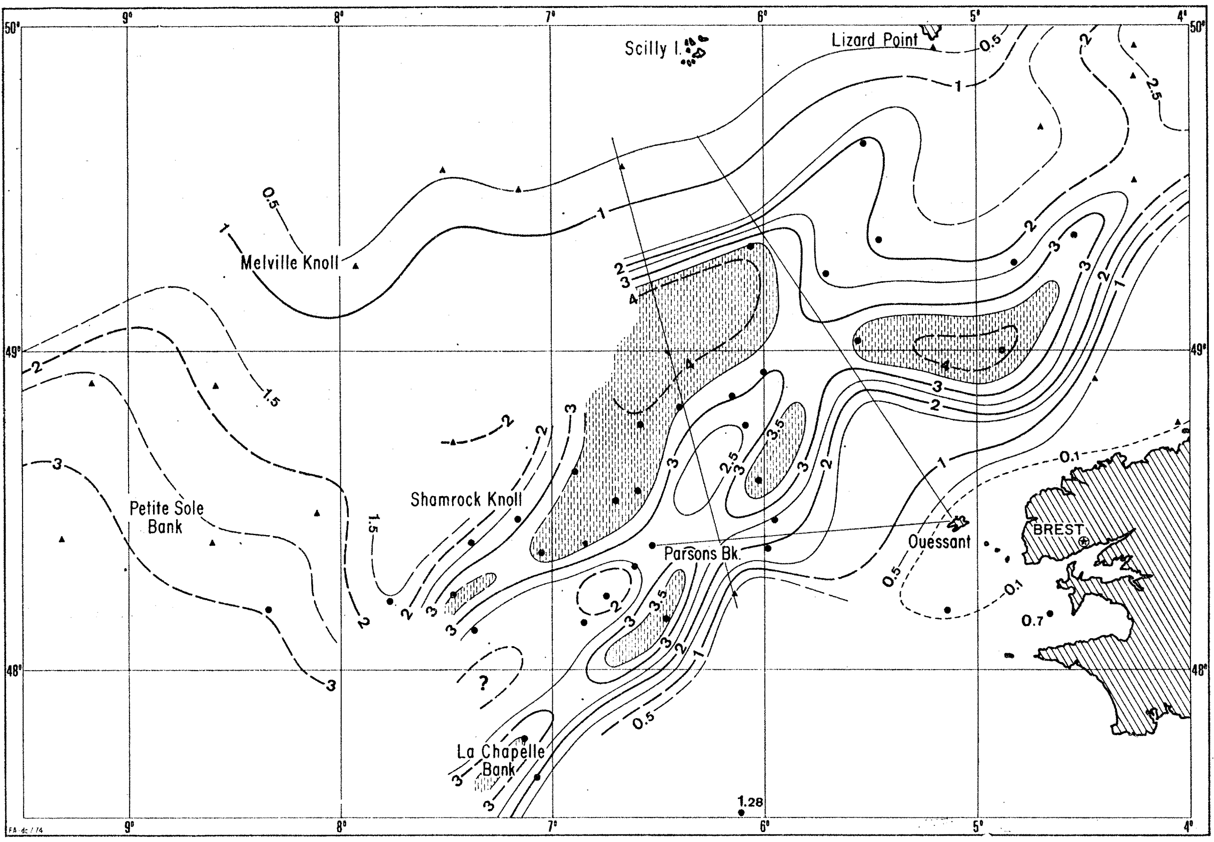

FIGURE 7. Schematic isobath map of the 'metamorphic basement' (5.2–5.8 km/s). Depth in kilometres. Compilation of available data.

As a whole, the 'metamorphis basement' shows a block-faulted aspect of NE–SW and NW–SE trend. The blocks seem to be tilted in a southeasterly, possibly also in a southwesterly direction.

4. CONCLUSION

This first interpretation of the seismic data for the Western Approaches is intended to give a guideline for further, more elaborate analysis which is now being undertaken.

On the evidence we have so far, we may draw the following conclusions:

(*a*) The use of detectors positioned on the sea-floor constitutes a relatively simple and economic operation on continental shelves and considerably improves the signal-to-noise ratio.

(*b*) The seismic structure of the continental shelf parallel to the main NE–SW structural trend and in the axis of the Western Approaches shows three distinctive sequences. The suggested geological correlation is: (1) The tectonized, high-velocity sequence (4.5–6.0 km/s) with Palaeozoic strata covering conformably a metamorphic basement with acid and basic intrusions. (2) The upper, almost horizontally layered series (2.0–3.7 km/s) with mainly Mesozoic and probably locally some upper Palaeozoic beds and younger strata. This upper sequence and the tectonized lower series are separated by an unconformity. (3) The in-fill of pocket-like depressions with relatively low-density (2.3–2.4 g/cm^3) and medium-velocity, upper or middle Palaeozoic strata and a relative high velocity (4.1–4.3 km/s) evaporitic or perhaps Jurassic carbonate cover.

(*c*) The most characteristic structures of the 'metamorphic basement' (5.2–6.0 km/s) are: the large, elongated basin between two major, almost parallel running NE–SW faults. The NW–SE faults do not seem to affect the secondary and younger cover; the block-faulted aspect of the basement, the blocks being tilted in northeasterly, possibly also in southwesterly directions.

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Discussion

Dr A. J. Smith (*Department of Geology, University College London, Gower Street, London, WC1E 6BT*)

Dr A. J. Smith asked the author if he had considered the possibility of the presence of igneous rocks, particularly extrusive igneous rocks in the Permian and succeeding successions. If he had not, did he consider that existence of such igneous rocks would be compatible with his interpretations?

F. Avedik. Such extrusives are probably associated with faults but it is unlikely that they constitute wide-spread and thick layers. Consequently, they may have remained undetected by seismic refraction measurements. In such a way, the presence of Permian and younger extrusives is quite possible and do not necessarily alter the interpretation.

R. A. Dardel (*Esso Rep, 213 cours Victor Hugo, 33321-Begles, France*)

I think that the geological interpretation given to the velocity classes is much too restrictive.

The velocities defined by reflexion seismology in the neighbouring Cenozoic and Mesozoic sedimentary basins are indeed commonly much higher than those attributed to the same section in the Western Approaches. In addition they are very sensitive to the lateral lithologic evolution in a given layer, and to compaction effect. In widespread areas they can even reach values comparable to those assigned to some crystalline and metamorphic rocks: average velocities above 5 km/s are common in all the limestone sections, regardless of their geological age. In thick and compacted clastic formations they frequently reach 4–4.5 km/s.

These results are obtained by velocity analyses in reflexion seismic records and controlled by velocity logs in bore holes.

It seems therefore difficult to affirm that there are no Mesozoics in the refraction layers where the velocity exceeds 3.7 km/s.

F. Avedik. It is well known that compact carbonates can have very high velocities, comparable to those of crystalline rocks (in the 5–6 km/s and even higher range). The only question is whether or not such carbonates exist in the Western Approaches.

On geological evidence, it seems that in Jurassic times the Western Approaches were open towards the east, the present Paris basin. We still lack evidence on possible Western connexions. Borehole data from the Paris Basin indicate average velocities for Mesozoic sections which are generally lower than 4.0 km/s. Only an upper Jurassic section, as far as I can recall in the eastern part of the Basin, has velocities in the 4.2 km/s range. Therefore, on present evidence, it seems unlikely that such high velocity Mesozoic carbonate sections occur in the Western Approaches.