MARINE GEOLOGY OF THE ATLANTIC CONTINENTAL MARGIN OF EUROPE

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[Plates 1 to 8]

CONTENTS

A geological reconnaissance has been made of the continental slope of western Europe between the Faeroe Isles and Lisbon by means of a 60 kJ reflexion profiler, supplemented by Boomer profiles and extensive Asdic (side-looking sonar) coverage of the continental shelf. A tentative interpretation of these profiles has been made by references to available rock samples and seismic refraction data. The first-formed continental slope deposits of the north-east Atlantic appear to be Cretaceous in age. Massive erosion (particularly of the continental shelf) preceded the Tertiary phase of downwarping which allowed upbuilding and outbuilding of the continental margin and was followed by a latest-Tertiary and Quaternary phase of important faulting, canyon erosion, slumping and deposition. This episodic evolution of the European continental margin is thought to indicate two phases of continental drift. In contrast to the ground west of the British Isles and France the steep and narrow northern and western continental margins of Iberia show only a little upbuilding and only local outbuilding. The work was done from aboard R.R.S. *Discovery II* or R.R.S. *Discovery* (with the exception of a Sparker profile obtained by H.M.T.S. *Alert*), the powerful profiler being used in 1965, the Asdic on many cruises between 1958 and 1967.

1. Introduction

The geology of much of western Europe is as well understood as that of any part of the world, but beyond the Atlantic seaboard only the relief is known on a regional basis and the only geological map refers to the English Channel trough. From this information, and

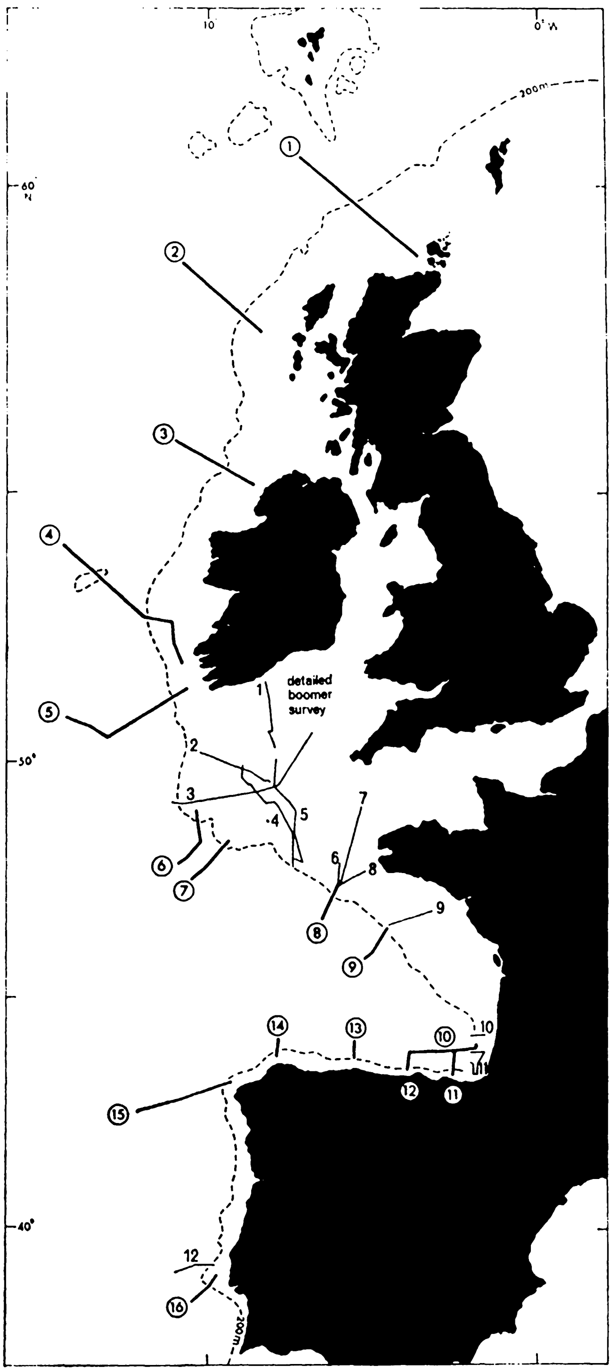

FIGURE 1

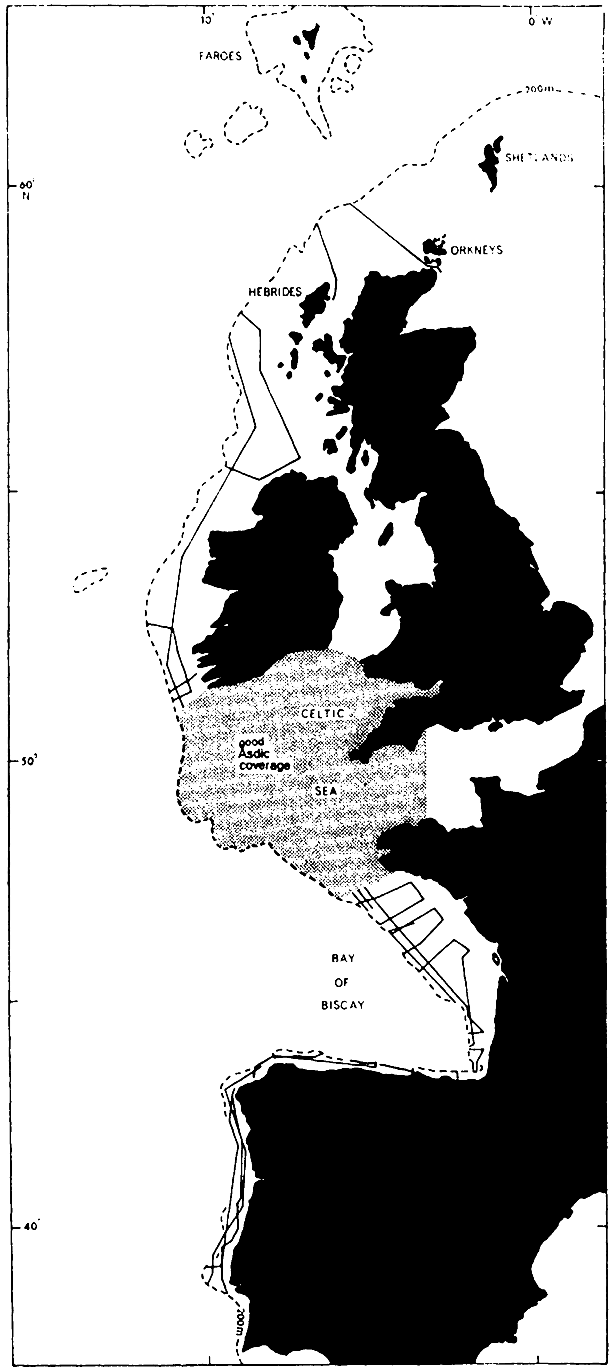

FIGURE 2

FIGURE 1. The lines along which continuous reflexion profiles were obtained by R.R.S. *Discovery II* and R.R.S. *Discovery* on the European continental margin. A 60 kJ Arcer was used along the sixteen courses shown as a broad line and a 1 or 5 kJ Boomer or Sparker where narrow lines are shown. Profile twelve was obtained with an Air Gun. For details see figures 4, 14, 17 and 27.

FIGURE 2. The ground searched for rock outcrops and strike lines by means of the Asdic (side-scan sonar) on R.R.S. *Discovery II* and R.R.S. *Discovery* between 1958 and 1967. Areas illustrated by acoustic maps are shown by black rectangles on figures 4, 14, 17 and 27.

from the more widely scattered data, it is impossible to obtain a regional view of the geology as satisfactory as those for some other continental margins.

The work to be described here was a geological reconnaissance of the continental margin between the Shetland Isles and Portugal, extending for 23° of latitude. The aims were to provide an outline of the post-Palaeozoic history of that region together with an indication of the age of the adjacent portion of the Atlantic Ocean. Brief mention of some aspects of this work has been made already (Curray, Moore, Belderson & Stride 1966; Stride, Belderson, Curray & Moore 1967).

Equipment

The exploration was made with continuous reflexion profiling equipment (figure 1) and Asdic (figure 2). A 60 kJ Arcer belonging to the Scripps Institution of Oceanography and the U.S. Marine Environment Division, N.U.W.C., gave sixteen well-spaced profiles of the continental slope. A 1 and a 5 kJ Boomer and Sparker provided profiles of the continental shelf within the Celtic Sea and west of France.

The continuous reflexion profiling systems used resemble an echo-sounder in principle. The outgoing pulse is reflected at interfaces where there is a change in acoustic impedance, such as at the sea floor and beneath it where suitable physical discontinuities are present in sediment or rock. These echoes were received by a linear hydrophone array, processed through filters and amplifiers and displayed on precision graphic recorders. The large profiling system made use of four 15 kJ electric arcs set at a depth of about 4 m around the stern, at the corners of a square with sides about 12 m. The hydrophone array, containing 5 to 25 units in a length of 75 m, was towed at a depth of about 15 m. The Boomer system made use of a 4 m long, 10-element hydrophone towed near to the water surface. The transducer of the 1 kJ Boomer was carried in a fibreglass dinghy, while the higher power model was housed vertically below a streamlined body (Bowers 1963). Towing speed for the profilers was usually between 5 and 8 knots, while for the Asdic alone the ship proceeded at up to 12 knots. The Asdic (side-looking sonar) equipment in use from 1965 onwards has a range of 1000 m and is a partially redesigned version of that already described (Tucker & Stubbs 1961).

2. Geological setting

There is a broad belt of old rocks along much of the western seaboard of Europe with a structural grain which is apparently unrelated to the adjacent continental margin of the Atlantic (figure 3). For example, in the Hebrides, south-west Ireland and north-west Spain the folds strike boldly out into the Atlantic, while in Brittany and northern Spain they reach the sea rather obliquely, and elsewhere the strike lies parallel with the shore. Such variation is in keeping with the now commonly held belief that the western edge of Europe was initiated by rupture and drift from North America. Associated with that movement was the postulated anticlockwise rotation of Spain, indicated by palaeomagnetic evidence (Girdler 1965; Van der Voo 1967; Van Dongen 1967), which opened up the Bay of Biscay.

The known thickness of post-Permo-Trias rocks on the land near to the continental margin shows considerable variation. In Scotland the whole of the Jurassic rock up to the Kimmeridgian is about 840 m thick, Cretaceous is thin and the Tertiary is absent. At the western end of the English Channel trough the rocks from Permo-Trias to Tertiary age reach about 3050 m (Day, Hill, Laughton & Swallow 1956). In the vicinity of Bordeaux there are about 1950 m. of Upper Cretaceous rocks, which appear to be thickening towards the continental shelf, while the maximum thickness of Tertiary strata in the vicinity seems to be about 900 m. Together, Upper Cretaceous and Tertiary rocks reach

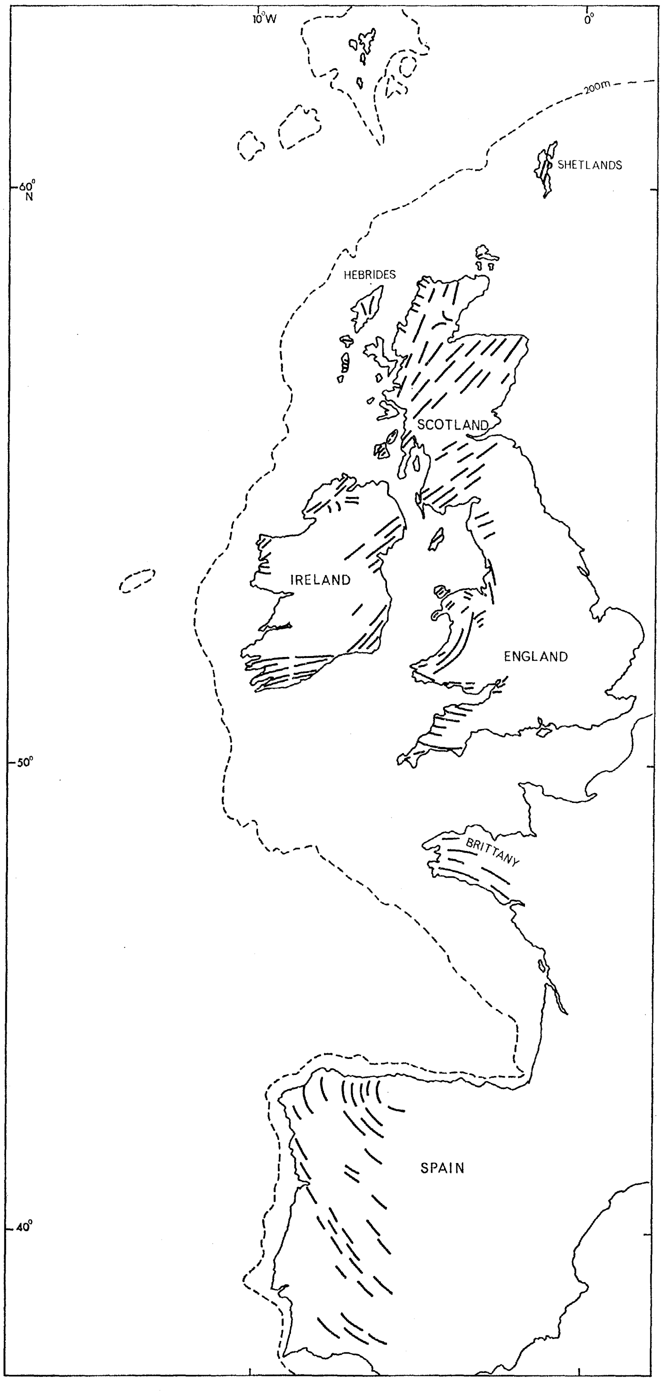

FIGURE 3. The structural grain of pre-Lias rocks cropping out on the western seaboard of Europe.

a maximum of almost 2100 m, with a maximum thickness of Mesozoic and Tertiary strata of about 3500 m, similar to that in the English Channel trough.

Marine transgressions and regressions which are recognized on the land and beneath the intervening seas are guides as to what to expect on the adjacent continental margin. The basal Lias and Upper Cretaceous are known to be transgressive in Scotland (Hallam 1965), Northern Ireland (Hancock 1961), the English Channel trough (Smith, Stride & Whittard 1965; Curry, Hersey, Martini & Whittard 1965*a*; Donovan & Stride 1961; King 1954), south Brittany (Ters 1961) and in Portugal. In addition, the Lias is transgressive in the Bristol Channel trough (Donovan, Savage, Stride & Stubbs 1961), and the Upper Cretaceous is transgressive in Eire (Walsh 1966). A further transgression took place during the Eocene in southern England, the English Channel (Curry *et al.* 1965*a*; Boillott & Millot 1962), and a later one during the Miocene in the English Channel trough (Curry, Murray & Whittard 1965*b*), south Brittany (Ters 1961), the Aquitaine basin (Berthois, Brenot & Ailloud 1965*a*; Schoeffler 1965*a*) and in Portugal.

Regressions are less easy to define. One appears to have begun soon after Upper Lias times in Northern Ireland but was delayed until upper Jurassic times in Scotland and Portugal. A second one commenced at about late Cretaceous times in Northern Ireland, Brittany, Portugal and possibly at Galicia Bank (Black, Hill, Laughton & Matthews 1964). The apparent absence of marine Oligocene or Pliocene strata on the continental shelf west of Europe probably indicates two other periods of regression, although it is possible that Oligocene rocks underly the Miocene strata.

On the western half of the English Channel trough seismic refraction work showed that Palaeozoic as well as younger rocks extended westwards beneath the continental slope (Day *et al.* 1956), while the magnetic anomalies showed the proximity of the basement (Hill & Vine 1965). The exposed rocks of this portion of shelf ranged from Upper Palaeozoic to Miocene in age but on the adjacent continental slope only Tertiary rocks were taken (Curry, Martini, Smith & Whittard 1962). Their apparent lack of stratigraphic order was tentatively interpreted as evidence of faulting (Curry *et al.* 1962; Donovan 1963). Faulting was also invoked west of France (Berthois *et al.* 1965*a*) as well as on the north and west sides of Iberia (Berthois, Brenot & Ailloud 1965*b*) and at Galicia Bank (Black *et al.* 1964), in order to account for the observed relief. Numerous authors (including Brenot & Berthois 1962; Hadley 1964) have drawn attention to the importance of the erosion indicated by the size and abundance of submarine canyons.

New samples of rock were taken by dredge at two stations on the continental slope around the Bay of Biscay by Mr N. A. Holme and Dr A. J. Southward and their microfauna and age has been reported on by Mr D. Curry. (These are in addition to samples described by other authors.)

Sa 4. 43° 39·2′ N, 03° 25·3′ W. About 1800 m.

R.V. *Sarsia*. Station 15. 17 July 1966.

The rock was a hard, buff coloured limestone; two sides of the samples were freshly fractured and one side was deeply bored. Mr D. Curry reported that the rock contained a moderate number of small and a few somewhat larger foraminiferida. The faunal assemblage and the absence of any planktonic types suggests deposition in a relatively shallow sea, less than about 200 m in depth. The assemblage of smaller forms suggested a Middle Eocene-Oligocene age although one rare species, *Linderina ovata*, is known elsewhere only from Upper Eocene levels. The larger forms, all of the same species belonged to the *Nummulites fabianii-intermedius* lineage, which ranges from Middle Eocene (perhaps Lower Upper Eocene) to Lower and Middle Oligocene. It was concluded by Mr Curry that the rock was probably Upper Eocene in age.

Sa 3. 47° 14·5′ N, 05° 47′ W. About 1040 m.

R.V. *Sarsia*. Haul 2. 17 May 1967.

The material obtained consisted of a large slab and fragments of pale buff-coloured limestone. Each piece showed fresh fractures while the two larger ones presented a rough and deeply bored surface which had been in contact with the sea. Mr D. Curry reported that the microfauna were plentiful; the abundant *Globigerinoides* of the *trilobus* group dated them as post-earliest Miocene, while the absence of *Orbulina* suggested a pre-Middle Miocene age, so that the samples could probably be referred to the upper part of the Lower Miocene.

Mr D. Curry has provided more precise ages for some samples of Tertiary and Cretaceous limestones from Station XXII off south-western Ireland (figure 4), which were taken by Cole & Crook (1910). Two small pieces of coarse-ground cream limestone contained abundant miliolids, with what appeared to be *Orbitolites* in one specimen. The other contained a sheet-forming alga known to occur in the Middle-Upper Eocene of the English Channel trough, together with what appeared to be *Linderina brugesi*. Mr Curry concluded that the rock is of Middle-Upper Eocene age. One small piece of pale-buff, very fine-grained limestone, with many microscopic cavities, moderately easily scratched with a knife, contained about ten poorly preserved foraminiferida, half of which were *Stensioeina*. Mr Curry concluded that an Upper Chalk (Coniacian–Maestrichtian) age is indicated.

The majority of samples from the continental slope were obtained by means of dredges. It is inevitable that in the intensely canyoned zone south of 49° N, there will be doubt as to the exact locations from which the samples were taken. In addition, it is difficult to decide which of the varied rock types obtained represent rock *in situ*. Diagnostic criteria include the localized abundance of particular rock types, especially if these show fresh faces which have not been in contact with the sea, the rock type is too friable to withstand much transport and no source area is known along probable supply paths, either by sea, rivers or Pleistocene ice.

3. Reflexion profiles and Asdic records of the continental margin

(*a*) *Methods of presentation and analysis*

It is difficult to present continuous reflexion profile data in a convincing manner. For example, photographic reduction of the original records obliterates much of the wanted data and what remains may not be easy to differentiate from multiple reflexions on half-tone illustrations. The alternative practice of constructing simple line drawings by means of a few interfaces recognizable in nearby profiles is also not entirely feasible for our study of the European margin because the profiles are located about 150 km apart, and because there is considerable variation between some profiles but only limited stratigraphic control. The chosen method of illustrating the profiles lies somewhere between the two extreme methods. Thus, a few photographs, at a reasonable scale of reduction, illustrate significant portions of the profiles. In addition, a line-drawing, traced from each record, shows the character or absence of bedding, significant interfaces such as unconformities (particularly where there is an onlap relationship), and surfaces within a conformable series which, as particularly good reflectors, suggest an appreciable age contrast or change in facies between adjacent beds. Wherever possible the line drawings incorporate data or otherwise benefit from neighbouring seismic refraction and rock sampling stations, the extensive Asdic coverage, the known geology at the landward end of the profiles and any data about the composition of the sea floor given on navigational charts. Thus *R* notations on these charts are usually considered to indicate Palaeozoic, metamorphic and igneous rocks but around Iberia they represent Mesozoic rocks as well. The horizontal scale of the line drawings is not constant (because the ship's speed was tied to water depth

TABLE 1. BEDDING PATTERNS AND OTHER INTERFACES USED FOR CORRELATION PURPOSES IN CONTINUOUS REFLEXION PROFILES OF THE EUROPEAN–ATLANTIC CONTINENTAL MARGIN

	criteria				
		relative reflectivity		bedding pattern	
layer	roughness of top surface	top surface	bedding	spatial continuity	degree of disturbance
Quarternary	smooth	good	good when present	short to long	flat to wavy
Tertiary	?	good	very good	very long	flat
Mesozoic	medium	good	good	medium	irregular
Palaeozoic	rough	very good	poor	short	folded
basement, metamorphic and igneous rocks of all ages	very rough	very good	—	—	—

and sea state). To allow for this the vertical exaggeration is given for relevant portions of the continental slope. These values do not apply to the underlying rocks, with their high *p* wave velocities, so that the location of a feature below the sea floor is given only as two-way travel time rather than being placed at its true (greater) depth. Similarly, the vertical exaggeration of scale gives interfaces a falsely large gradient, whereas, for instrumental reasons, surfaces steeper than 15° below the horizontal are unlikely to have to be detected. A comparison of all available data revealed that some, if not all, of the bedding patterns on the reflexion profiles had an age significance which could be used for correlation purposes (table 1) and that an important unconformity separates Mesozoic and Tertiary strata. Thus, it has been possible to present the line drawings as tentative geological sections of the continental margin. Material classed as 'Basement' is probably of different age and composition beneath the continents and oceans and also varies regionally. It is possible that some of the rough strongly reflecting surfaces which have been attributed to outcrops of basement type rock should be interpreted as brecciated rock resulting from intense faulting. The validity of the age assignments is discussed for each Arcer profile, but the profiles are not described in detail.

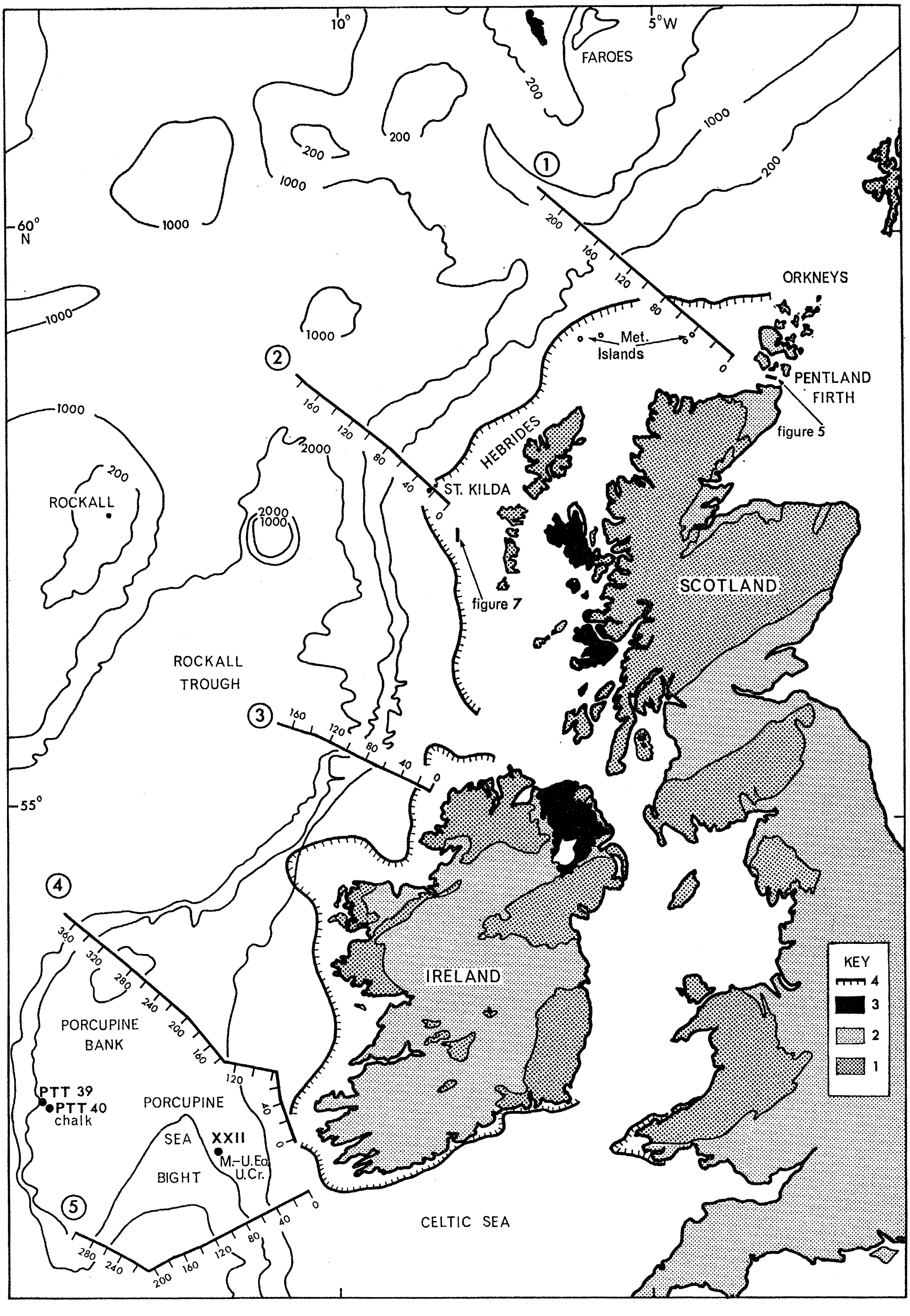

FIGURE 4. A simplified geological map of Scotland and Ireland, together with data for the adjacent continental margin. In the Key, 1 refers to Lower Palaeozoic sedimentary strata together with metamorphic and igneous rocks; 2 refers to Upper Palaeozoic strata. For convenience, outcrops of Mesozoic and Tertiary strata in southern England are not shown. 3, refers to Tertiary rocks; 4, the outer limit of rock notations on navigational charts, which is assumed to refer to Palaeozoic rocks in this figure. Continuous reflexion (Arcer) profiles ① to ③ are illustrated in figure 6 and profiles ④ and ⑤ in figure 10. Asdic was used along all courses on the continental shelf, including those shown in figure 2. Dredge stations are shown by a black dot; PTT refers to samples taken by the vessel *Président–Théodore–Tissier* (Berthois & Guilcher 1961), and XXII refers to a sample first described by Cole & Crook (1910), with further information on page 36. Abbreviations, Met. = metamorphic; Cret. = Cretaceous and Eo. = Eocene. Isobaths are given in metres and distances along the reflexion profiles in kilometres.

(b) *Region north and west of Scotland and Ireland*

The five continuous reflexion profiles within this region are particularly difficult to interpret because of the almost complete lack of marine post-Palaeozoic rocks at the coast, the Tertiary vulcanicity and the paucity of dated rock samples from the sea floor. Rock notations on charts suggest that Palaeozoic and older strata, including younger igneous rocks, extend almost to the edge of the continental shelf (figure 4), while chalks seem to be present on the continental slope west of Eire and on western side of the Porcupine Bank (Berthois & Guilcher 1961).

Profile ①: *Pentland*

An Asdic traverse of the Pentland Firth revealed a floor of rock with well-defined bedding broken by numerous joints (figure 5, plate 1). These rocks are probably of Old Red Sandstone age since they strike between broad outcrops of such strata on the Scottish and Orkney Isles sides of the channel, no more than 4 km distant. They have a low north-westerly (apparent) dip which continues as far west as the 60 km mark on the reflexion profile (profile ①, figure 6), and suggests union with such rocks at 04° 30′ W on the north coast of Scotland. On thickness grounds, it seems likely that Carboniferous rocks are present also. Islands such as the Sule Skerry and Stack Skerry remain as inliers of metamorphic rocks (Met. Islands on figure 4), presumably indicating the nature of the unbedded (basement) rocks, with a rough upper surface, occurring between the 60 and 80 km marks on this profile. The large area occupied by these Palaeozoic strata and metamorphic and igneous rocks to the north of Scotland and west of the Orkney Isles is indicated by the numerous rock notations on Admiralty charts of that ground (figure 4). Arcer profile ① shows that the irregular upper surface of these rocks is largely masked by supposedly Quaternary deposits, which are thickest at the bottom of the continental slope. West from near the 80 km mark the supposed Quaternary deposits lie upon bedded strata of Mesozoic or Tertiary aspect whose bedding is also parallel with the continental slope. As far as the 120 km mark a closer assessment of age is precluded by the small thickness of strata visible above the first multiple echo of the sea floor. Farther west the considerable lateral extent of bedding surfaces and their recognition to a thickness of about 1200 m (at an assumed p wave velocity of 2 km/s) suggest a Tertiary age, although the strata are somewhat disturbed. The nature and age of the underlying transparent material is not known, but may be Mesozoic, in keeping with the more southerly profiles. However, its apparent lateral extension (Stride *et al.* 1967) towards the Faeroe Islands, whose lavas have been re-dated as 50 to 60×10^6 years old (Dr D. H. Tarling, personal communication) suggests a Tertiary age.

Profile ②: *St Kilda*

A north–south Asdic traverse located 40 km west of the Hebrides showed the presence of ragged rock outcrops (figure 4; figure 7, plate 1) almost devoid of either bedding or jointing (the intervening hollows being partially filled with loose sediment). The proximity of this line to the Hebrides, and the numerous rock notations indicated by charts for the intervening ground, suggest that the eastern end of this reflexion profile commenced on metamorphic rocks. Indeed, undoubted bedding was only recognized (profile ②, figure 6) beyond about 45 km west, the profile between 18 km and 28 km being in the vicinity of the Tertiary Igneous rocks and a presumed aureole, of the St Kilda group of islands. On the floor between St Kilda and Boreray the Asdic record showed the presence of a number of short, narrow ridges, interpreted as minor intrusions comparable to weathered outcrops in the adjacent cliffs. West of 45 km the (?) igneous and metamorphic basement type rocks are overlain by a sedimentary series with rather ill-defined, discontinuous bedding, with a low westerly (apparent) dip, decreasing progressively to the west, resembling that of the Old Red Sandstone seen in the Pentland Profile but classified here as of Palaeozoic aspect. Such rocks may possibly be present west of the 110 km mark, where they lie upon a rough floor of strongly contrasted material of basement aspect (profile ②, figure 6). However, as their bedding can be followed for somewhat greater distances both horizontally and in depth they are more likely to be Mesozoic in age, although their bedding pattern does not exactly match that of the Cretaceous rocks seen farther south.

Younger rocks, with clearly defined bedding traceable for long distances, and so assumed to be Tertiary, are present in much of the profile west of St Kilda, reaching greatest thickness beneath the deeper water where they have some local oblique interfaces of the type seen in profile ③. They lie discordantly on a rough surface of older rocks, each bed extending east of that below it. This progressive onlap appears to have been interrupted, for east of the 75 km mark the upper, almost transparent material has a marked contrast in acoustic impedance with the underlying rocks suggesting either a facies change or else an appreciable age difference. However, it seems unreasonable to suppose that there could be as much as 135 m of Quaternary sediments on this continental shelf. The required land-derived clastics are likely to have been in short supply, because the watersheds lie so close to the Atlantic coasts of Scotland and Ireland and also because much of the material reaching the sea is likely to be trapped in troughs, such as The Minch, which reach a depth as great as 200 m. If this upper layer is Quaternary it could hold a valuable record of events not present in many of the other profiles and missing on land. However, as there is no well-marked break in slope and much of the continental shelf is deep enough to have been beneath the sea during periods of low Pleistocene sea levels, it is possible that the almost transparent layer includes some Pliocene material, so adding to its interest as well as accounting more satisfactorily for the considerable thickness of the layer.

Profile ③: Bloody Foreland

Bottom notations on navigational charts show that old rocks crop out on the continental shelf for many kilometres north and west of Ireland and reach on to the continental slope at about 54½° N. The latter is in keeping with a continuous reflexion profile shown by

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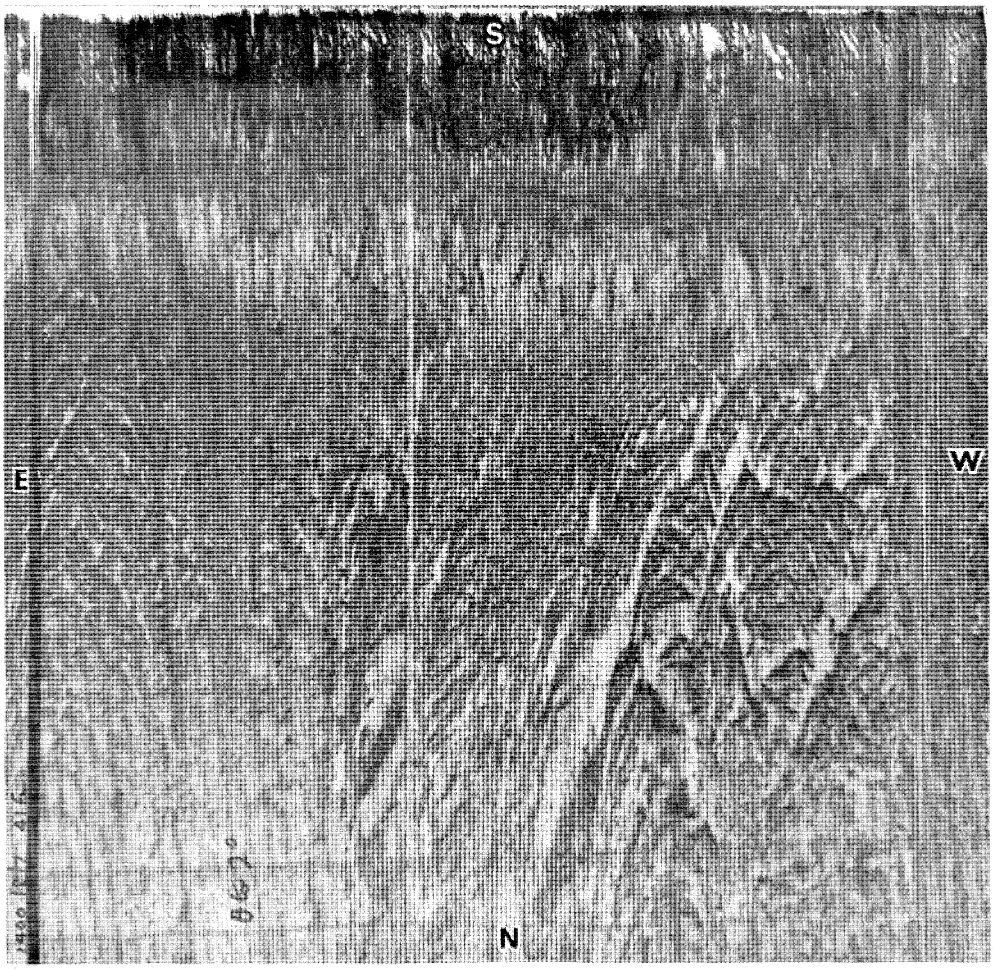
Description of plate 1

Figure 5. An acoustic (Asdic) map of 5·2 × 1 km of a rough floor beneath the Pentland Firth (black rectangle in figure 4), whose bedding character suggests correlation with the Old Red Sandstone strata in Orkney Isles and Scotland, some 4 km distant.

Figure 7. An acoustic map of 5·6 × 1 km of rough rock floor lying 50 km west of the metamorphic rocks in the Hebrides, and located by a black rectangle in figure 4.



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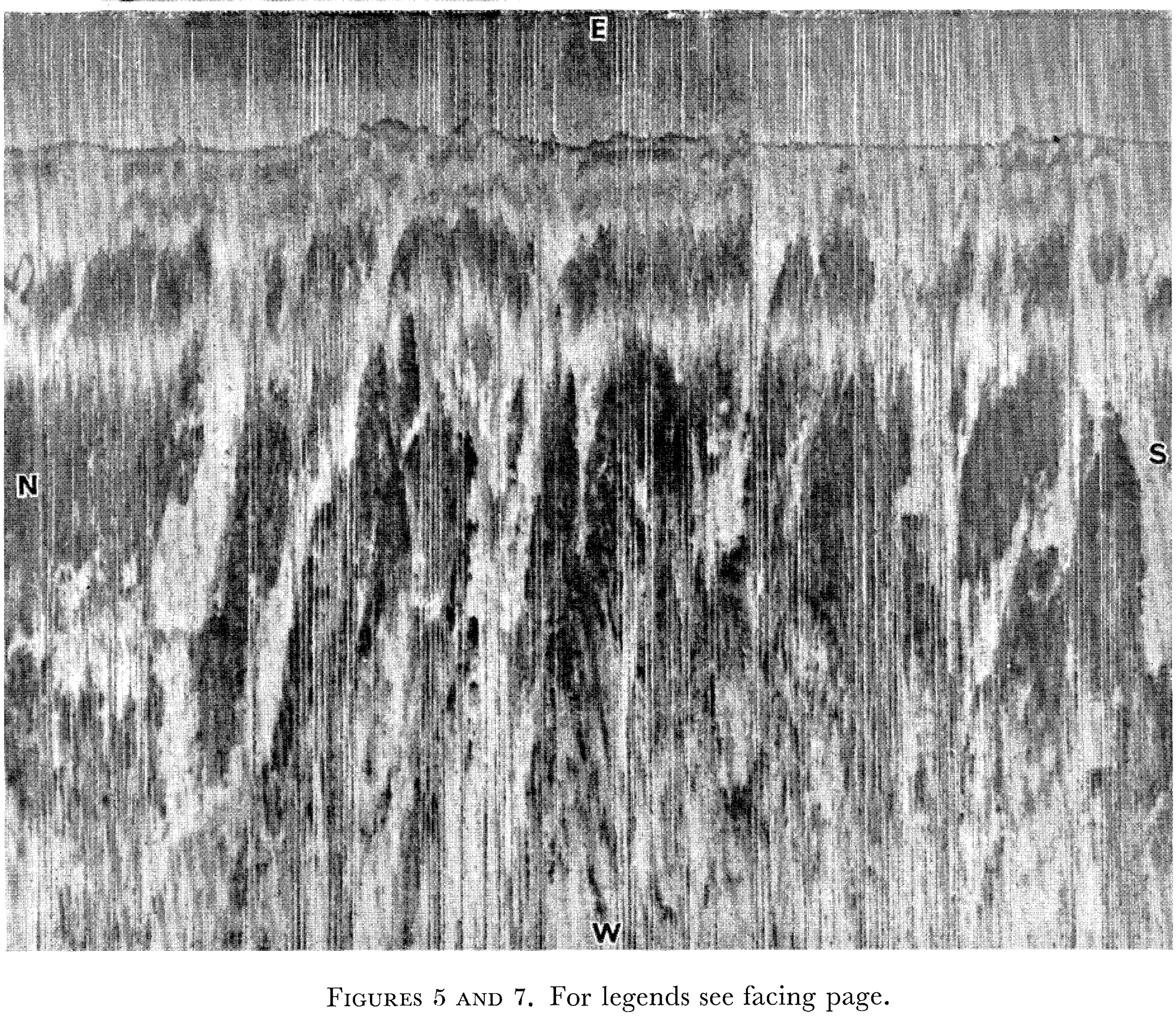

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FIGURES 5 AND 7. For legends see facing page.

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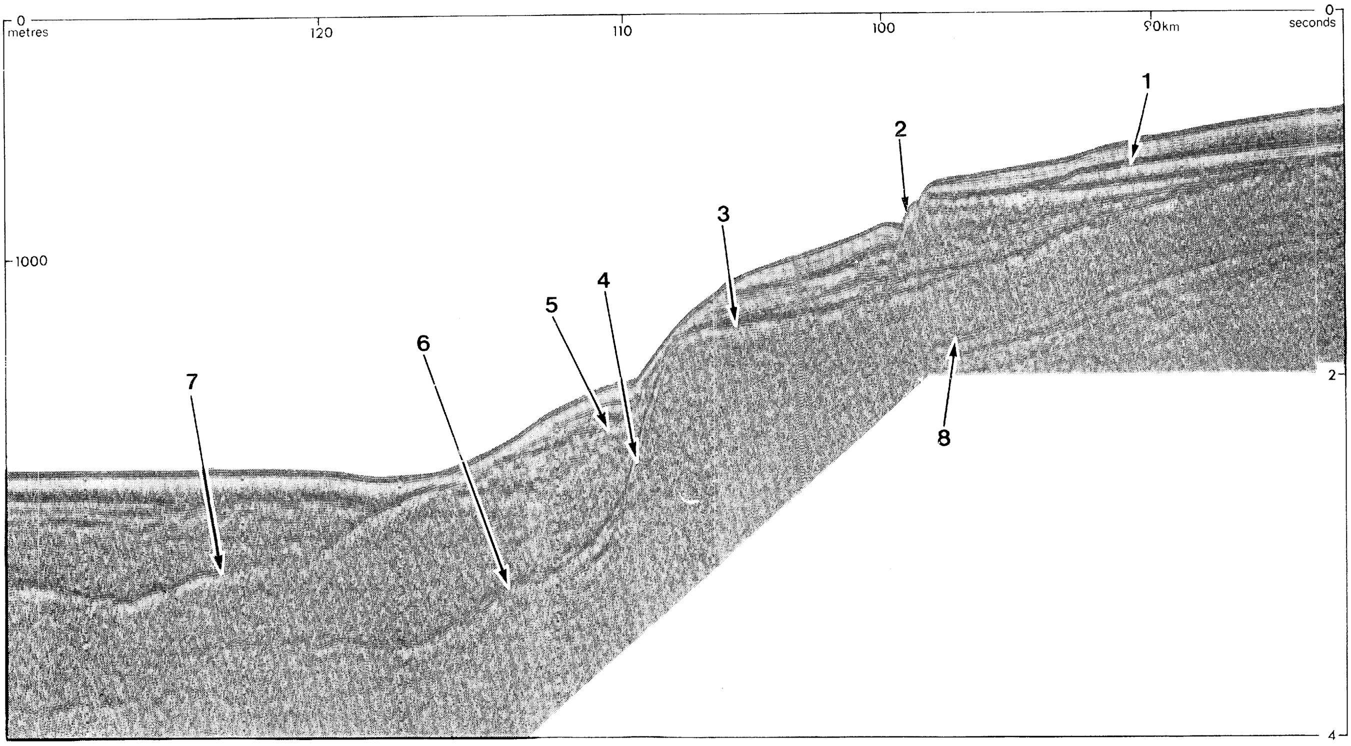

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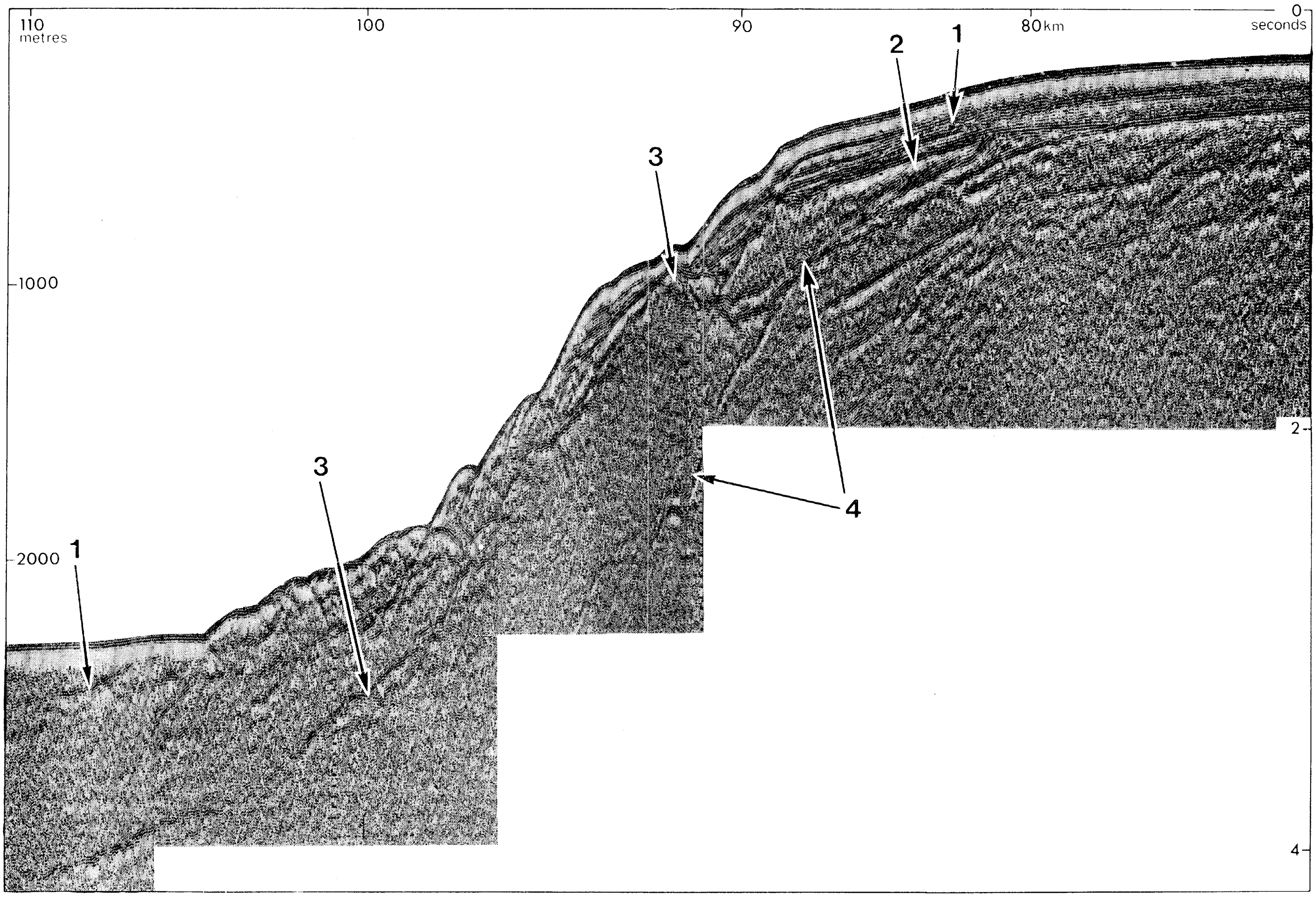

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FIGURES 8 AND 9. For legends see facing page.

Lagaay & Collette (1967). The metamorphic and igneous rock types of north-western Ireland, some 15 km beyond the eastern end of Arcer profile ③ (figure 4), must extend westwards to the 11 km mark on that profile, for no bedding is discernible on either side of the 90° change in course which took place at the 10 km mark (figure 6). Westward again these rocks appear to be overlain by strata with just detectable bedding which, at about the 11 km mark on the Asdic record appears to strike north-east and so have a westerly dip. The western limb of this gentle syncline, with a core apparently without stratification, can be followed into a complementary anticline. The bedding of these rocks has a Palaeozoic aspect suggesting correlation with those present just inshore from the nearby coast. The westerly (apparent) dipping beds beyond about the 60 km mark are probably Mesozoic in age since their bedding is well defined and because there appears to be no room for them in the eastern part of the profile. On the continental slope these rocks appear to butt against a rough surface of strongly reflecting material interpreted as the basement, but in reality they probably pass around the irregularities beyond the line of the profile. However, on the original record, it cannot be seen with certainty whether these beds should be equated with the lower series of bedded rocks beneath the deeper water, with which their bedding pattern is similar.

All the rocks described above (west of the 11 km mark) are overlain unconformably by rocks notable for the perfection of their bedding which, by analogy with more southerly profiles, suggests a Tertiary age. Dredge samples from the continental slope south of 55° N contained some flint and chalk (Cole & Crook 1910). These rocks are more than three times as thick beneath deeper water as on the continental shelf and are overlain in deeper water by a thin almost transparent layer believed to be Quaternary. The lumpy bedding of the presumed Tertiary strata at the foot of the continental slope and the oblique bedding further oceanwards may indicate slumping and disturbance of normal bedding, respectively.

Profile ④: Tralee

Well bedded, steeply dipping, Palaeozoic rocks strike from the land towards the north-north-west trending portion of this profile (figure 4), wherein a similar pattern of folds and a bedding pattern of Palaeozoic aspect are recognizable (figure 10, profile ④, and figure 11, plate 3). This correlation along the strike is almost beyond doubt, as well-defined strike

Description of plate 2

Figure 8. A photograph of the original Arcer record (within the limits shown by a double-headed arrow in profile ② of figure 6) for the continental margin west of Scotland (figure 4). Interface 1 is the supposed boundary between Quaternary and Tertiary strata; 2, a slump plane; 3, separates Tertiary strata from the 'basement'; 4, a fault plane, or perhaps the primitive continental edge; 5, a slump plane; 6, the contact between presumed Mesozoic and 'basement' rocks; 7, the boundary between Tertiary and Mesozoic; 8, multiple reflexion of the sea floor.

Figure 9. A photograph of the original Arcer record (within the limits set by a double headed arrow on profile ③ of figure 6) for the continental margin off north-western Ireland (figure 4). Interface 1 is assumed to separate Quaternary and Tertiary strata; 2, is assumed to separate Tertiary and Mesozoic strata; 3, is the top of the basement; 4, multiple reflexion of the sea floor.

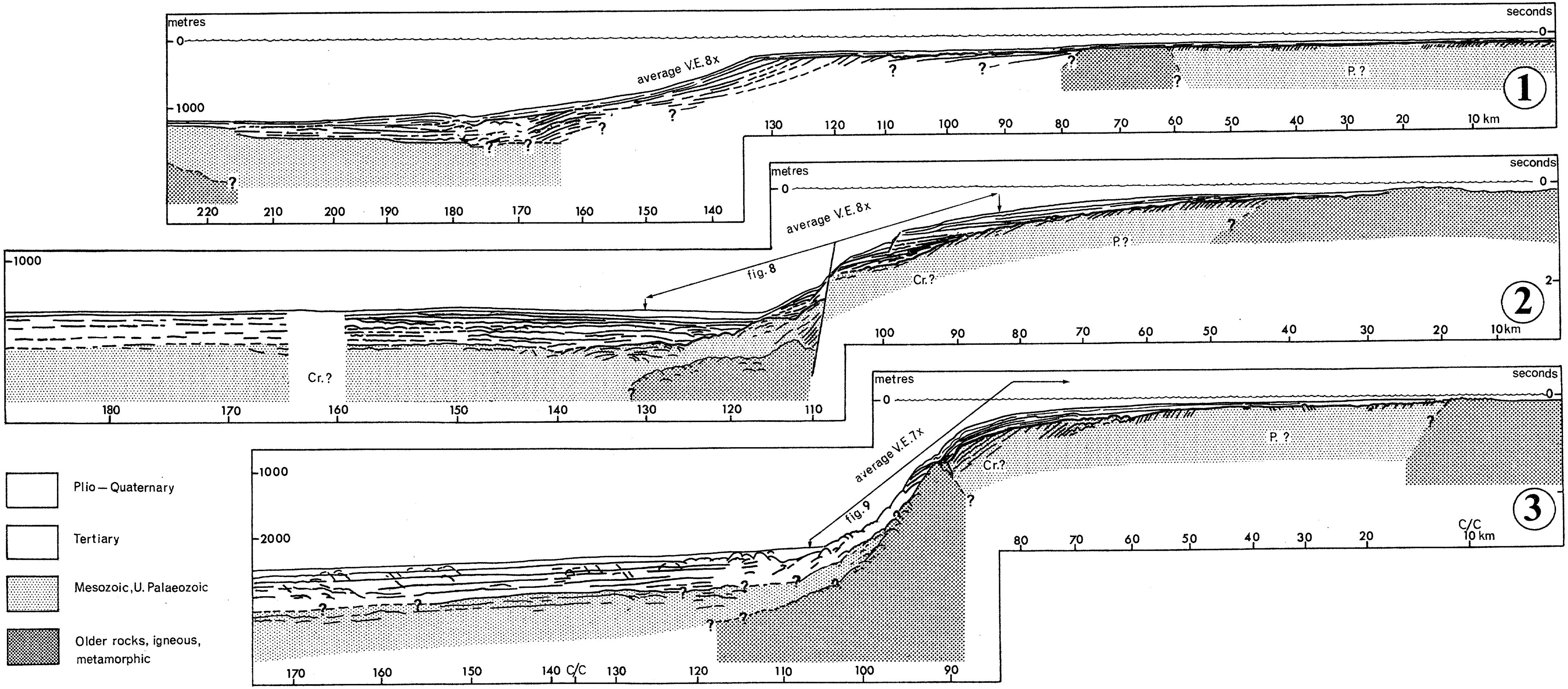


Figure 6. Line drawings of continuous reflexion (Arcer) profiles ① Pentland, ② St Kilda and ③ Bloody Foreland shown as tentative geological sections of the continental margin. The 20 km marks correspond with those on the courses shown in figure 4. Presumed Upper Palaeozoic and Cretaceous strata are shown by P. and Cr., respectively. Unconformities are shown by blue lines, and fault or slump planes by red lines.

ridges and associated rock notations on the charts, reach westwards to within about 1 km of the profile. However, in depths ranging from about 130 to 150 m, the sea floor along the north-north-west to south-south-eastern portion of the course was flat and devoid of rock outcrops on both the echo-sounder and Asdic records, so that the older rocks must be overlain with a veneer of younger rocks and Quaternary sediments.

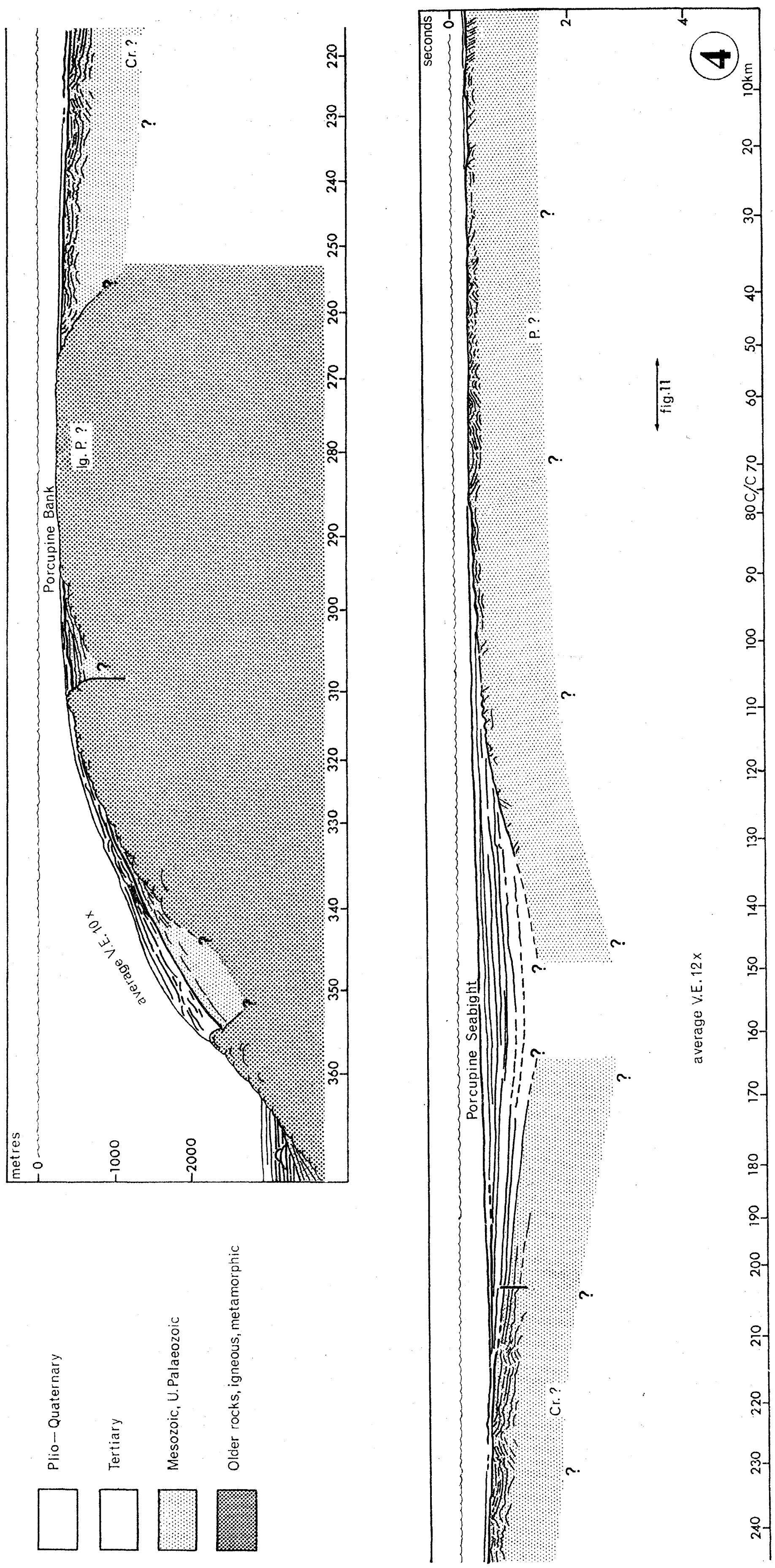
The rough top surface of the older rocks is traceable beneath the continental slope to about the 130 km mark, beyond which it lies below the depth of detection. Westwards from the 170 km mark a rough surface was also detected although the underlying rocks have a bedding pattern which is characteristic of the Cretaceous strata of Galicia Bank, rather than those of Palaeozoic aspect, as might be expected. It is presumed that these (?) Cretaceous rocks extend eastwards to where they butt against the Palaeozoic floor in the same way that the overlying material shown progressive overlap farther east. The rather contorted strata of Cretaceous aspect are overlain somewhat discordantly by well-bedded material of Tertiary aspect which is associated with Middle-Upper Eocene limestone (XXII on figure 4) described by Mr D. Curry on page 36. The uppermost layer of material has been tentatively taken as Quaternary in age, since it has an apparent erosional contact with the well bedded material beneath it and because its top surface is locally rough. In contrast to this, there is a smooth floor of almost uniform composition on the continental shelf off the south-west corner of Ireland which probably indicates the presence of present-day sediments.

Within the shoalest part of Porcupine Bank (265 to 295 km) no bedding was detected. This is in keeping with the finding there of pebbles of old sedimentary strata and of igneous and metamorphic rocks. The pebbles of gabbro, from its summit, almost certainly represent rock *in situ*, because of the character of the associated magnetic anomalies (Allan & Stride in press). Potassium-argon dates on the gabbro pebbles show that its age is Lower Palaeozoic to Pre-Cambrian (Dr F. J. Fitch & Dr J. A. Miller, personal communication).

Structureless, basement type rock with a rough, strongly reflecting surface is seen west of a small fault (310 km) preserving material of Cretaceous aspect, and is seen again near the foot of the continental slope (355 km). The sedimentary rocks of the west side of Porcupine Bank have been somewhat arbitrarily divided into two series, the upper with well-defined bedding separated from the lower by a slight discordance at a fairly prominent reflector. Their supposed ages are somewhat confirmed by dredge samples of chalk and flints taken at about 52° N on this side of Porcupine Bank (Berthois & Guilcher 1961). At the foot of the continental slope west of the 360 km mark the older sediments are ocean-ward dipping, while the younger sediments are flat lying like turbidites.

Profile ⑤: Mizen Head

This profile begins 40 km along the strike from known outcrops of Upper Palaeozoic rocks, while the nearest rock notations on the intervening ground are no more than 10 km distant (figure 4). The rough upper surface of these rocks deepens to the west, as in the Tralee profile (profile ④, figure 10). The bedding beneath it is rather ill defined, presumably because the profile extends along the strike of the folds. This rough surface if projected westwards from the 25 km mark at the same gradient seems to correspond with an



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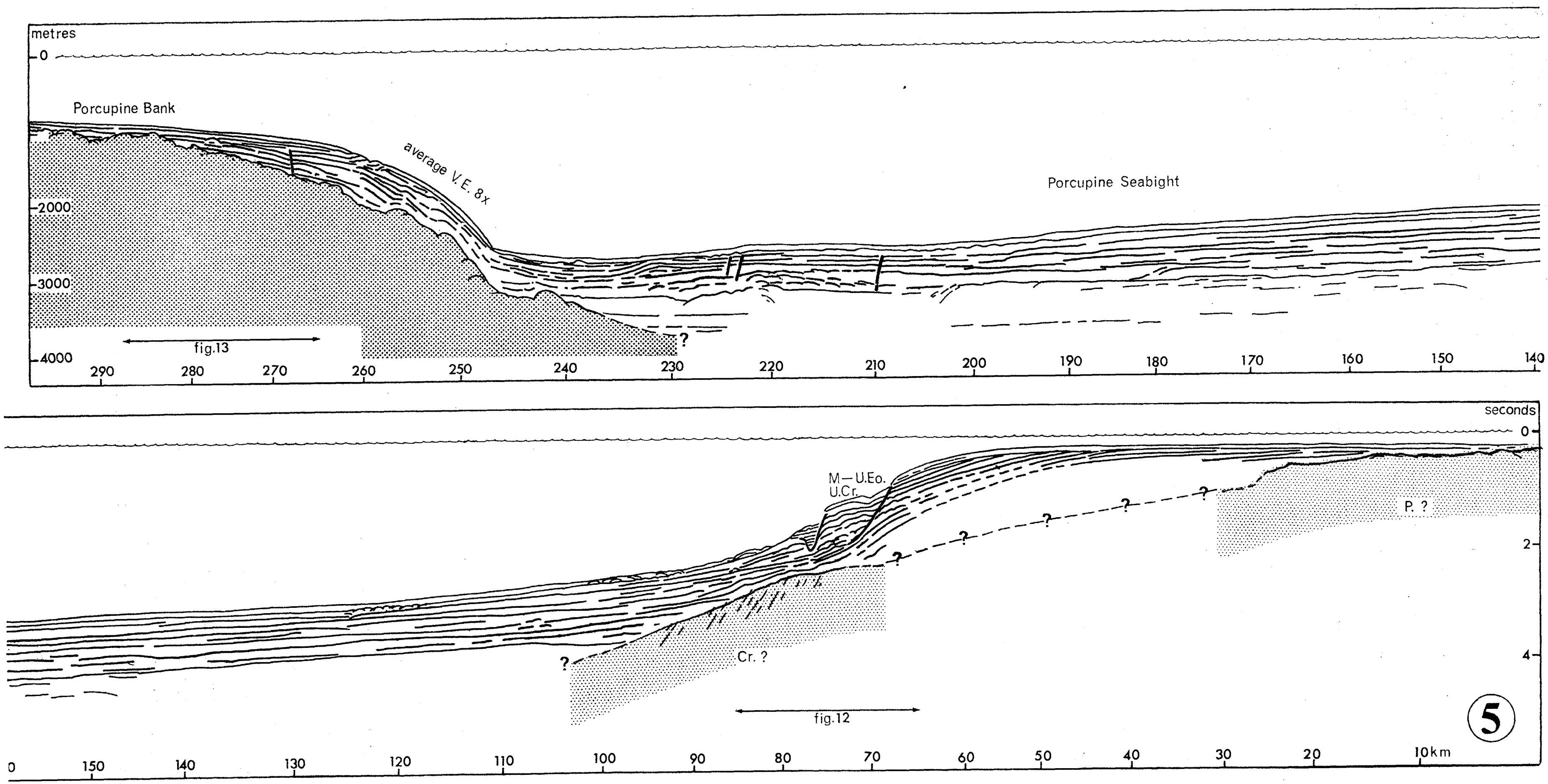

Figure 10. Line drawings of continuous reflexion (Arcer) profiles ④ Tralee and ⑤ Mizen Head, shown as tentative geological sections of the continental margin west of Ireland (figure 4). Unconformities are shown by blue lines, slump and fault planes by red lines. Abbreviations, P. = Palaeozoic; Ig. = igneous; while Cr. = Cretaceous and Eo. = Eocene are sample stations which have been projected into the profiles.

undulating interface between the 70 and 100 km marks. The bedding beneath this relatively deeply buried surface is better defined than farther east, perhaps indicating the presence of Mesozoic rocks. These are overlain by the well-bedded strata which overstep progressively eastwards and are associated with samples of Tertiary limestones (figure 4) obtained by Cole & Crook (1910). The same strata can be followed across to the west side of the Porcupine Sea-bight but there they overstep on to a much rougher surface devoid of any traces of bedding which is considered to be basement type rock (profile ⑤, figure 10, and figure 13, plate 3).

The base of the well-bedded series (which are taken as Tertiary in age, by reference to beds of known age farther south) is placed rather arbitrarily at a well-defined reflector below which the few visible bedding surfaces can be followed for no more than about 20 km, perhaps indicative of Pre-Tertiary rocks, although they lack the crenulation of those between 190 and 260 km on profile ④ (figure 10). The top of the (?) Tertiary is placed at the strongly reflecting, irregular interface just beneath the sea-floor, thought to be indicative of glacially deposited material and channelling on a smaller scale than between 75 and 77 km.

(*c*) *Region west of the English Channel trough*

The Boomer continuous reflexion profile 5 together with profile 4 nearby (figure 14), both of which lie more than 25 km westward along the axis of the known Miocene rocks, strongly suggest that these extend at least to 8° west. In addition, Boomer profile 4 (although not quite complete) seems to show that the same rocks extend to Sparker profile 3 (obtained by H.M.T.S. *Alert*) and Boomer profile 2 and from there the same strata extend towards the edge of the shelf, while on Boomer profile 2 they can be followed to the east as well. It seems likely that the flat-bedded uppermost rocks of Boomer profile 1 are also Tertiary in age, though not necessarily Miocene, as they overlie folded strata (figure 15, plate 4) which, when followed north, appear to extend as far as the known Cretaceous outcrops (figure 14) which were located by Curry, Gray, Hamilton & Smith (1967), while farther east folded strata appear to be present in a number of profiles suggesting structural correlation with the Bristol Channel trough (Donovan *et al.* 1961). Thus, it appears that on the northern side of the English Channel trough the Miocene

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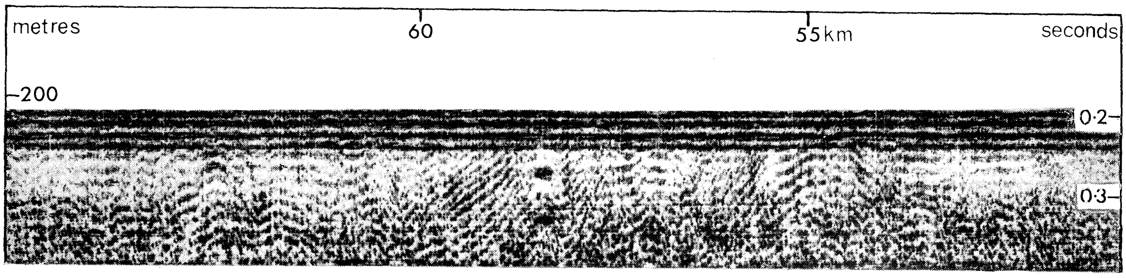
Description of plate 3

Figure 11. A photograph of the original Arcer record (within the limits set by the double-headed arrow in profile ④ of figure 10) showing that folded rocks of Palaeozoic aspect lie close to the surface of the continental shelf on a north–south section off south-west Ireland (figure 4).

Figure 12. A photograph of the original Arcer record (within the limits set by the double headed arrow in profile ⑤ of figure 10) for the continental margin south-west of Ireland (figure 4). The location of a filled submarine canyon: 1, the base of the Tertiary strata; 2, and multiple reflexion of the sea floor; 3, are shown.

Figure 13. A photograph of the original Arcer record showing the rough contact between presumed Tertiary strata and 'basement' rocks at the south-eastern corner of Porcupine Bank (figure 4), within the limits of the double headed arrow in profile ⑤ of figure 10. 1, indicates the contact between Tertiary strata and basement and 2, a fault along the line of the arrow.



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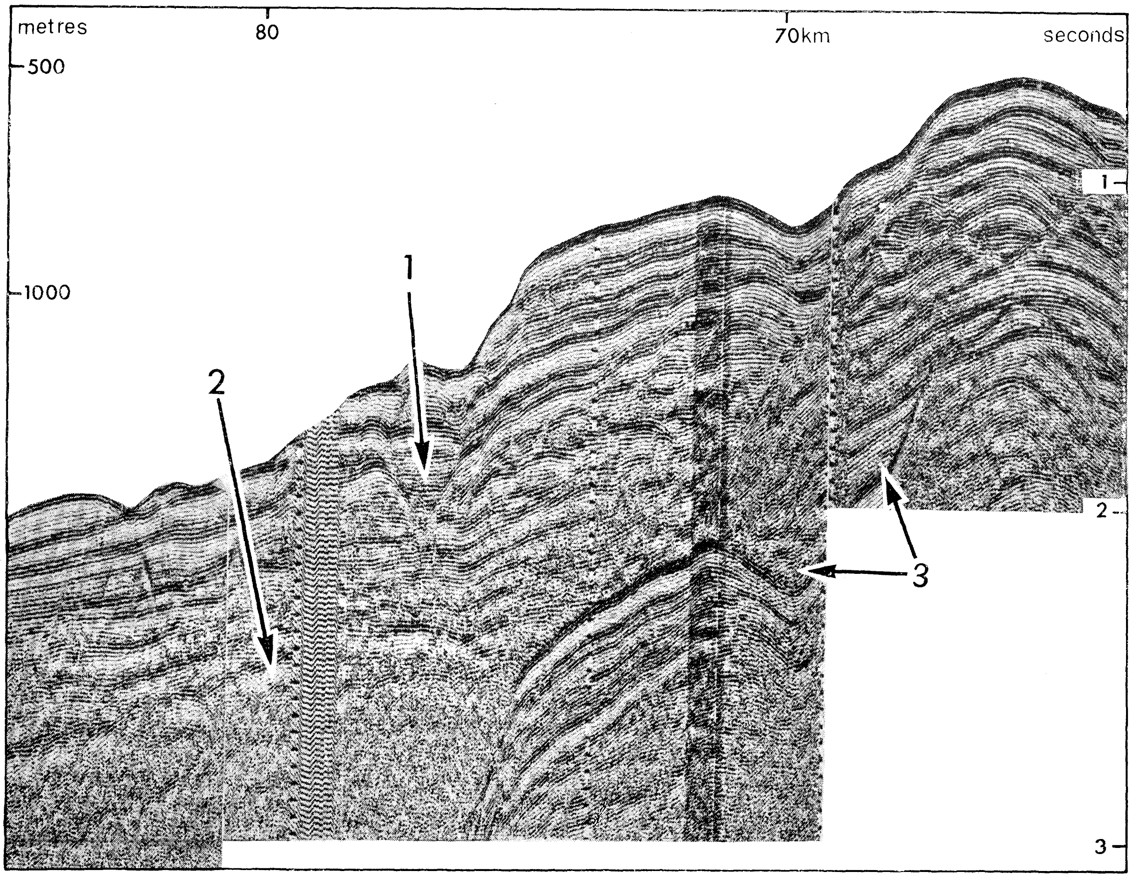

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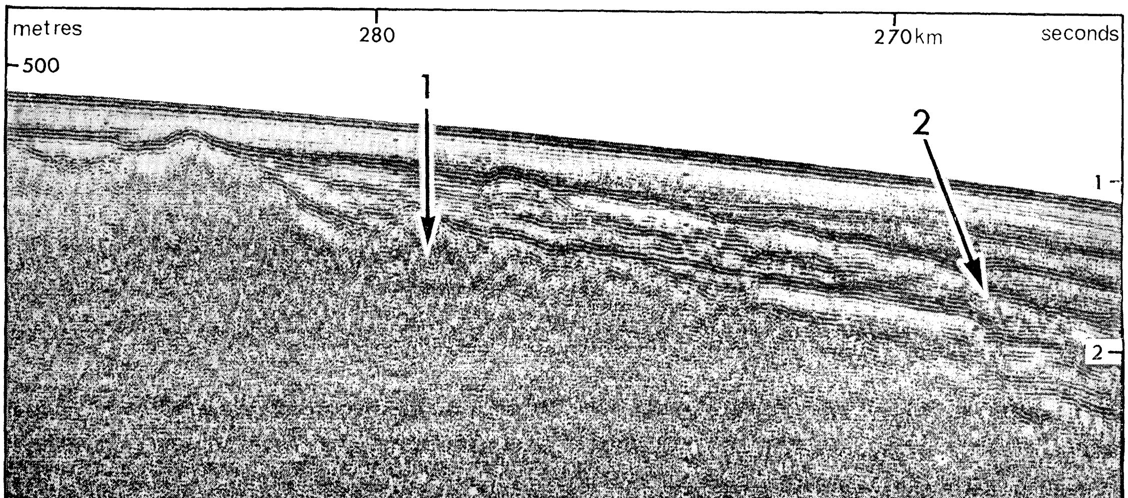

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FIGURES 11 TO 13. For legends see facing page.

(*Facing p.* 46)

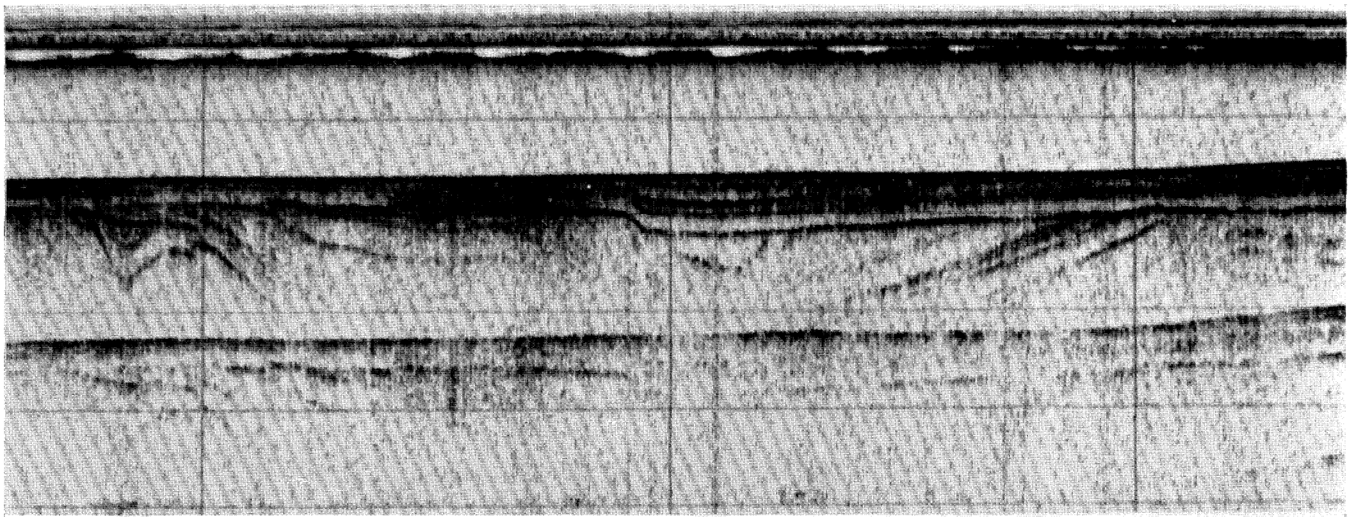


FIGURE 15. An 8 km long north–south section in the Celtic sea, south of Ireland, located on profile 1 of figure 14. A vertical scale, of 118 m is provided by the depth of water above the sea floor. Flat-lying, presumed Tertiary sediments broken by a fault, lie with marked discordance on gently folded strata of presumed Cretaceous age.

FIGURE 18. An acoustic map of 8 × 1 km of sea floor west of Brittany (black rectangle in figure 17) showing ragged outcrops (dark tones), of Palaeozoic or metamorphic aspect, separated by flat, sandy floor.

rocks cut across Eocene strata and possibly across the Cretaceous strata as well, in the same way as they are known to do on the southern side of that trough. At the northern end of Boomer profile 5 (figure 14) many of the presumed Miocene strata wedge out rapidly northwards. Farther north the supposed Cretaceous strata wedge out and overlap one

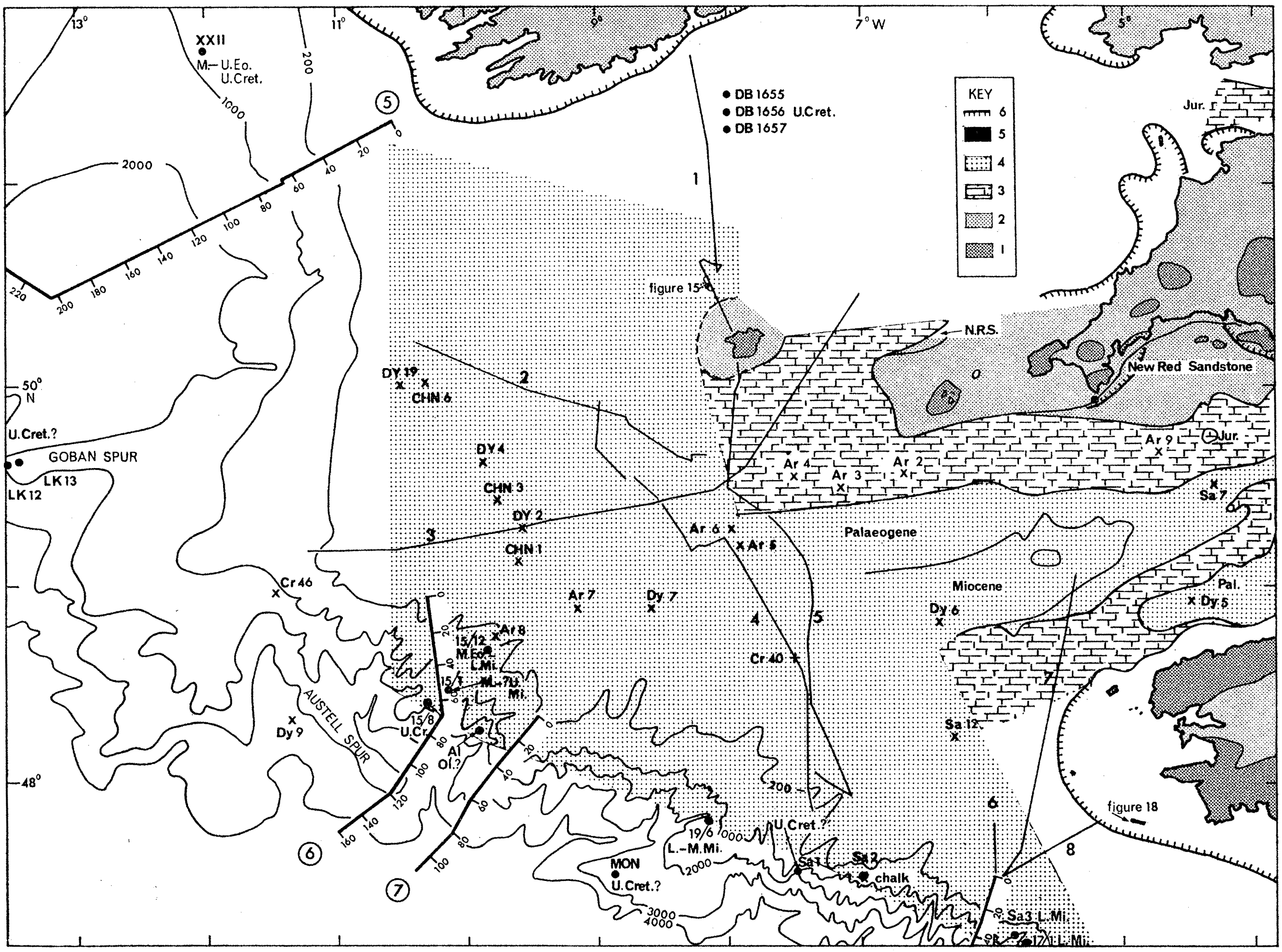


Figure 14. A simplified geological map for the Celtic Sea and neighbouring parts of the Bristol Channel and English Channel troughs. In the key 1 refers to metamorphic and igneous rocks (excluding Tertiary); 2 to Palaeozoic strata; 3 to Mesozoic and 4 to Tertiary strata, excluding Tertiary igneous rocks 5. Portions of the map with well-defined boundaries are based on published work, mentioned in the text. The approximate limit of pre-Mesozoic rocks is indicated by symbol 6. The exact limit of the Tertiary strata for much of the Celtic Sea is not known, but the stipple is so placed as to include known outcrops and continuations suggested by the continuous reflexion profiles 1 to 8, except on much of the continental slope where erosion has exposed a wider range of strata. Dredge stations are indicated by a black dot and seismic refraction stations by a cross, most of which can be identified by reference to Hersey & Whittard (1966). Samples from stations of *Lord Kelvin* (LK) are taken from Bradley (1940), while those of *Sarsia* 3 and XXII are described on page 36. The abbreviations used include: Cret. = Cretaceous, Eo. = Eocene, Ol. = Oligocene and Mi. = Miocene. Continuous reflexion (Arcer) profiles ⑥ and ⑦ (broad lines) are illustrated in figure 16. The remaining profiles, which are described in the text, were obtained by low-power continuous reflexion equipment. Isobaths are given in metres and distances along reflexion profiles in kilometres.

another within a short distance northwards. Boomer profile 2, nearly normal to the edge of the continental shelf, shows that almost the whole visible section wedges out towards the east.

These Boomer profiles show that the outcrop of the young Tertiary rocks broadens towards the west where the English Channel trough merges with the continental margin. This is also suggested by the relatively low compressional wave velocities known or assumed for the upper layer (mostly about 2 km/s, for Stations Sa 12, Dy 6, Cr 40, Dy 7, Ar 7–8, Chn 1–Dy 2–Chn 3–Dy 4, located east to west in figure 14). The chalk sample from Station 3137 (Day 1958) is considered to be Tertiary in age in view of the low *p* wave velocity of the top layer of Station Sa 12, nearby. The Boomer and Sparker reflexion profiles, including those of Hersey & Whittard (1966), show that much of the Cenozoic strata at the western end of the English Channel trough, and even up to the edge of the continental shelf, are gently folded. As these rocks approach the edge of the continental shelf they dip towards the ocean so that the bedding lay parallel with the continental slope prior to its erosion into canyons during Pliocene or Pleistocene times. Dredge samples from the upper part of this slope have shown that Eocene to Miocene rocks outcrop there (Curry *et al.* 1962), while Plio-Pleistocene strata may be present, also (Hersey & Whittard 1966).

Upper Cretaceous rocks crop out along both sides of the English Channel trough, together with traces of Lower Lias and a thicker development of New Red Sandstone. It seems likely that some of these, especially the Upper Cretaceous rocks, will extend to the western end of the trough, a distance of about 100 km. The presence of such Mesozoic rocks thereabouts is in keeping with the second layer in the velocity profiles at the westerly seismic refraction stations (figure 14).

Profile ⑥: *Great Sole*

The first part of the profile extended rather obliquely down the continental slope, so as to increase the chance of detecting bedding in spite of the numerous confusing echoes from the walls of the canyons, while beyond the 70 km mark the profile extends down the slope almost parallel to their axes (figure 14).

The eastern end of the profile commences 50 km beyond the group of refraction stations located near to the edge of the continental shelf (figure 14). The top of the supposed Mesozoic rocks lies at approximately the same depth as an interface on the reflexion profile which, followed westwards, is seen to be an unconformity (profile ⑥, figure 16). The profile shows that the rocks beneath it have a gentle seaward dip and have rather discontinuous, ill-defined bedding surfaces considered in other profiles to indicate rocks of Cretaceous age. This view is somewhat strengthened by the finding of a reworked Cretaceous fauna (Funnell 1964) in a depth of 1955 m at about 49·5° N, 13·5° W (figure 14). The refraction data projected into the 100 km mark show that the base of this layer was beyond the depth of detection by the continuous reflexion profiler. This material may extend beyond the western end of the profile as rocks with a velocity of 5·4 km/s are present at station Dy 9 (figure 14).

A rough, strongly reflecting surface extends between the 60 and 120 km marks, where its depth is the same as the top of the basement at Station DY 9 some 55 km distant

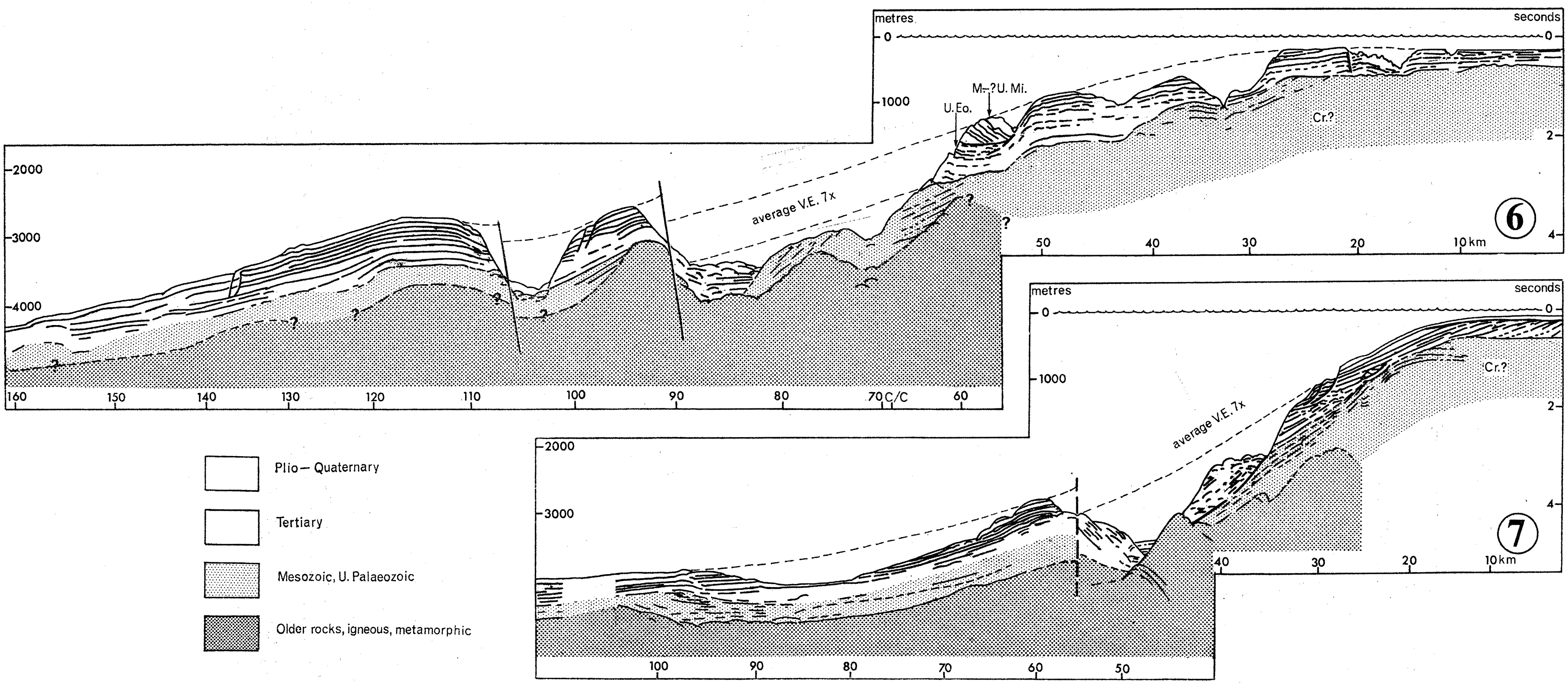


FIGURE 16. Line drawings of continuous reflexion (Arcer) profiles ⑥ Great Sole and ⑦ Little Sole, shown as tentative geological sections of the continental margin at the western end of the English Channel trough (figure 14). Unconformities are shown by blue lines and fault or slump planes by red lines. Abbreviations: Cr. = Cretaceous, while Eo. = Eocene and Mi. = Miocene are from sample stations projected into the profile.

7-2

along the continental slope. The sinuosity on this surface on the profile, although partly due to the differing thicknesses and p wave velocities of the overlying material, must also be of greater amplitude than other rock interfaces seen in the profile and its irregularities should be present in adjacent profiles farther along the continental slope.

The uppermost material, detected at seismic refraction Stations AR 7 and 8 (figure 14), with a velocity of 1·8 km/s, corresponds to the almost flat lying, well-bedded, uppermost strata of the continental shelf. Farther west the bedding dips parallel with the upper part of the continental slope (profile ⑥, figure 16). These beds are missing in the canyon zone, but the same type of bedding and dip direction are seen in the two portions of the Austell Spur whence they extend down beneath deeper water. Dredge samples (Curry *et al.* 1962) projected only a few kilometres into the profile show that these rocks are Tertiary in age; Upper Eocene at about 30 km, Middle and Upper Miocene at about 50 km. However, the profile suggests that the disturbed Middle Eocene to Oligocene sample at about the 70 km mark is unlikely to be *in situ*. The uppermost material between 80 and about 90 km has been interrupted as canyon fill (profile ⑥, figure 16). The only dated material of Pleistocene or Recent age was found at about the 60 km mark, although chart notations show the presence of sand and coarser grades on the continental slope and there must be Quaternary deposits at the lower end of the profile.

It is likely that the two portions of the Austell Spur may each be upthrown towards the ocean, for otherwise it is difficult to bring the separate portions of (?) Tertiary strata into a common depositional plane.

Profile ⑦: Little Sole

Refraction stations AR 7–8 near to the eastern end of this continuous reflexion profile (figure 14; profile ⑦, figure 16) indicated two upper layers, the lower of which, on velocity considerations, could be Mesozoic in age. The interface between them appears to lie at the same depth in the reflexion profile and can be followed to the 30 km mark beyond which the underlying oceanward dipping beds can be traced to the 40 km mark and may extend to the western end of the profile, for there appears to be space for them above the basement. The surface of the latter lay below the depth of detection at the eastern end of the profile but there are traces of a rough, good reflector between about 25 and the 45 km mark where it appears to outcrop on the side of a canyon and the same rough surface appears to extend to the western end of the profile.

The young well-bedded strata, which correlate with the upper layer of seismic refraction Stations AR 7–8, have a gentle oceanward dip beneath the continental shelf and lie parallel with the original surface of the continental slope before its dissection. Their velocity, the similarity of their bedding patterns with those of the Great Sole profile (profile ⑥, figure 16) and the lithology and fauna of the available samples make it seem likely that they are Tertiary in age. These strata appear to be affected by slumps (profile ⑦, figure 16), indicated by bedding which is locally indistinct, contorted, or dipping landward as if rotated from the prevalent dip towards the ocean. The location of the soles of the slumps has only been inferred.

(*d*) *Region west of France*

Profile ⑧: Brest

At the north-west corner of France the old folded rocks strike boldly towards the continental margin (figure 3). From the Pointe du Raz a major strike ridge extends west to the Ille de Seine (latitude 48° N), and thence as a series of shoals extending for a total distance of about 40 km, with a smaller parallel ridge north of it. Portions of the north-western boundary of these old rocks have been defined by sampling (Curry *et al.* 1962; Barthe, Boillot & Deloffre 1967), a continuous reflexion survey (Boillot & Horn 1966) and by means of Asdic. Their southernmost outcrops are well jointed and present a rough top surface (figure 18, plate 4), which becomes progressively subdued and finally passes with low dip beneath younger strata. The lower part of these seem to be traceable along Boomer profiles 8 and 6 and Sparker profile 7 to outcrops of Chalk in the English Channel, although continuity needs to be proven by coring, as the beds are rather crumpled. They are buried by a narrow and shallow syncline of Tertiary strata at about $48\frac{1}{4}°$ N, and by flat-bedded strata which thickens towards the ocean on the southern ends of profiles 6 to 8. The boundary between the supposed Tertiary and Cretaceous strata projected to the 0 km mark on the Brest profile (profile ⑧, figure 19) appears to correspond with the base of the well-bedded strata. The apparent lack of bedding in the underlying material is probably due to the strength of the multiple reflexions and on the continental slope to the depth of burial by Tertiary strata. A rather more typical Cretaceous type bedding pattern is present beyond the 70 km mark where it overlies a rough strongly reflecting surface of basement type. The latter seems to outcrop between 60 and 70 km at the foot of the continental slope. The bedded strata of the top of the succession, while within 20 km of an Upper Eocene and a Lower Miocene sample, lack the perfect bedding typical of the known Tertiary rocks in other profiles. This may be an indication that slumping is more prevalent than has been suggested in profile ⑧ (figure 19).

It seems likely that there will be an appreciable thickness of Quaternary material beyond about 70 km, as a canyon debouches thereabouts. The base of these beds is placed rather arbitrarily at the interface where fairly well-bedded layers, which curve up on to the side of the basement, give way to horizontal strata presumed to be turbidites.

Profile ⑨: Loire

Palaeozoic rocks outcrop at the coast for many kilometres north and south of the Loire estuary (47° 20′ N) and they are present at Belle Ile and Ile d'Yeu, about 15 km west of that coast (figure 17). These rocks may also be present between the two islands as there are scattered rock notations on navigational charts for the intervening ground. However, here also have been taken samples of calcareous sandstone resembling the Eocene littoral deposits that occur near to the adjacent coast of France (Durand 1960), and like them probably rest on a rough surface of old rocks. Miocene rocks were taken from south of Belle Ile and in mid-shelf farther west (Berthois 1955), where they are probably unconformable as they are south of the Loire estuary (Ters 1961). Mesozoic rocks may be present, also, since this part of the continental shelf lies along the strike from outcrops on land, continuity of which is shown at a few localities near to the shore (Berthois 1955).

Boomer reflexion profile number 9, which commences 50 km west of the apparent

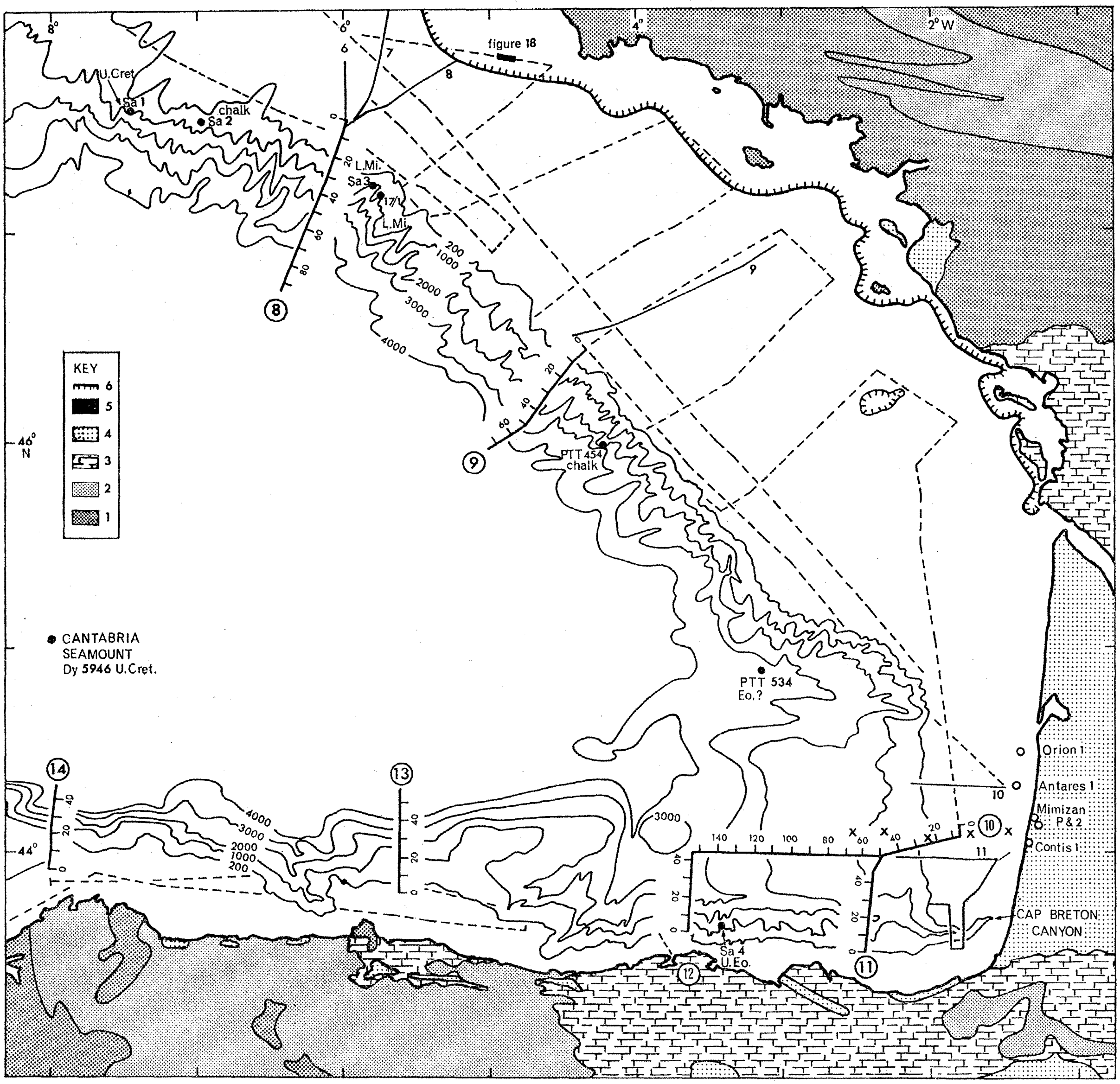


Figure 17. A simplified geological map for the edge of the Bay of Biscay. The rock units shown in the key are pre-Palaeozoic strata, including metamorphic and igneous rocks, 1; Palaeozoic, 2; Mesozoic, 3; Tertiary, 4. The oceanward limit of rock notations on navigational charts is taken to indicate the seaward extent of Palaeozoic and older rocks (absent west of the Aquitaine basin). To avoid confusion with other data this limit, 6, is not shown south of 44° N. Continuous reflexion (Arcer) profiles are indicated by broad lines, and Boomer profiles six to eleven by narrow lines. Profiles ⑧ Brest and ⑨ Loire are illustrated in figure 19, and profiles ⑩ Aquitaine, ⑪ Bilbao and ⑫ Santander are illustrated in figure 21. Pecked lines show the ground examined by Asdic. Crosses show the seismic refraction stations of Professor P. Muraour. Open circles indicate boreholes mentioned in the text. Dredge stations are shown by a black dot. Abbreviations PTT = *Président–Théodore–Tissier* (Furnestin 1937); *Sa* 3 and 4 = *Sarsia* (this paper page 35); Eo. = Eocene and Mi. = Miocene. Isobaths are given in metres and distances along reflexion profiles in kilometres.

western limit of Palaeozoic rocks (figure 17), revealed interfaces with a low westerly (apparent) dip and an upper surface which is somewhat irregular. The nature of the thin and patchy uppermost material is uncertain. It could perhaps be Miocene rock, in keeping with the two known outcrops and the expected unconformity beneath them, or

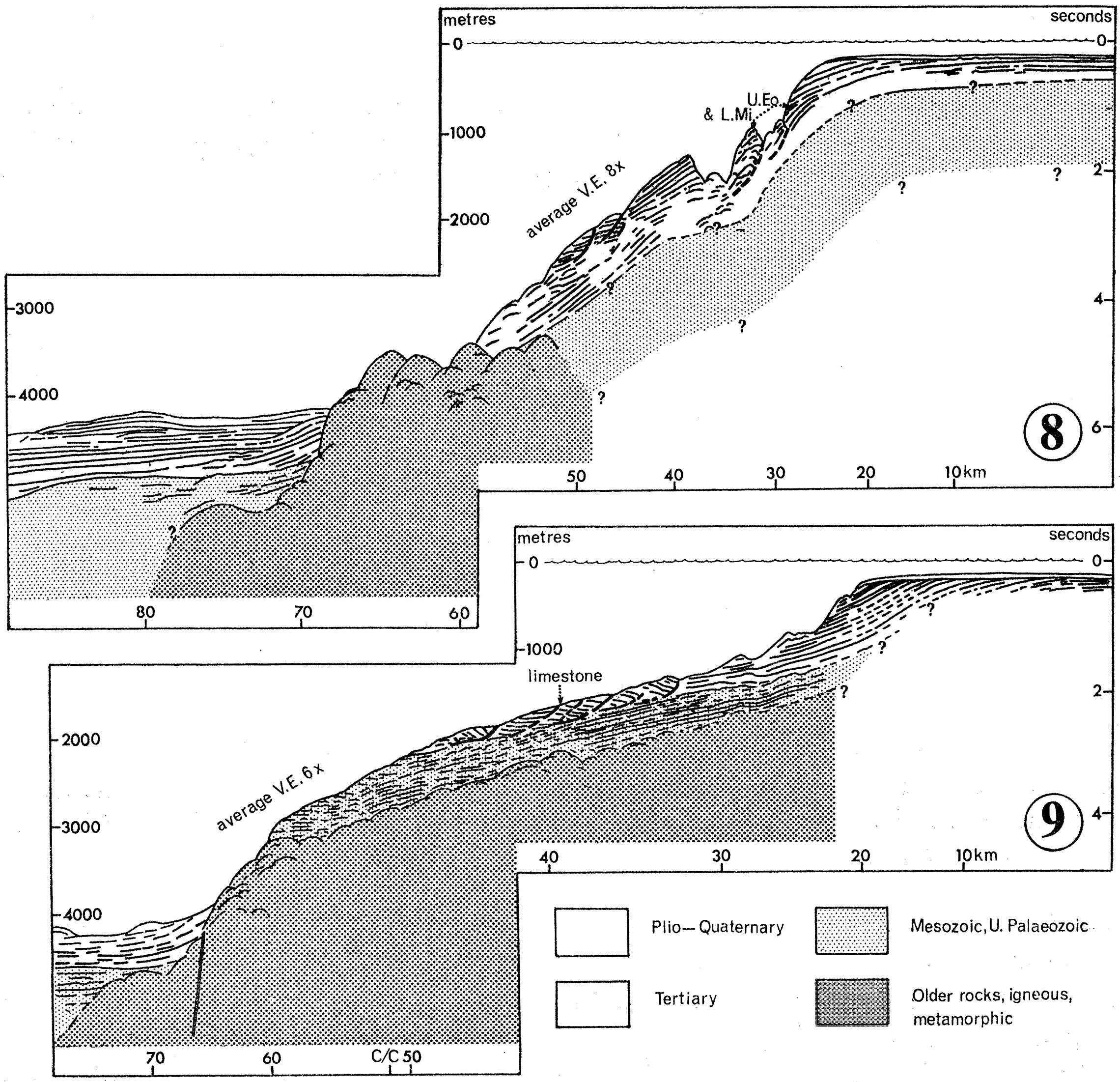


Figure 19. Line drawings of continuous reflexion (Arcer) profiles ⑧ Brest and ⑨ Loire, shown as tentative geological sections of the continental margin west of France (figure 17). Unconformities are shown by a blue line and fault or slump planes by a red line. Abbreviations, Eo. and Mi. refer to Eocene and Miocene sample stations projected into the profile.

it could be Quaternary material which is also present in the vicinity. The latter is most likely, as the underlying material, followed westward, seems to correspond with the well-bedded strata of Tertiary aspect present in profile ⑨ (figure 19). The only available sample was a soft limestone of Tertiary type taken about 45 km distant and at the same depth as the 40 km mark. On the continental slope these rocks appear to be thin and much affected by local rotational slumping which has given individual segments a landward dip. The location of a few possible, curved glide surfaces is indicated. The bedding of the rocks beneath are rather ill defined and seem to be rather crenulate, so that they are classed as Mesozoic in aspect. The underlying rough surfaced, structureless, basement type material appears to outcrop west of the 60 km mark. The abrupt descent of its surface at the foot of the continental slope for more than 1500 m is taken as indicating the location of a fault with westerly downthrow.

Profile ⑩: Aquitaine

The floor of the Aquitaine basin deepens southwards towards the trough extending along the north side of the Pyrenees, but is somewhat separated from it by a ridge following latitude 44¼° N (Carte Tectonique Internationale de l'Europe, 1:2500000). Available

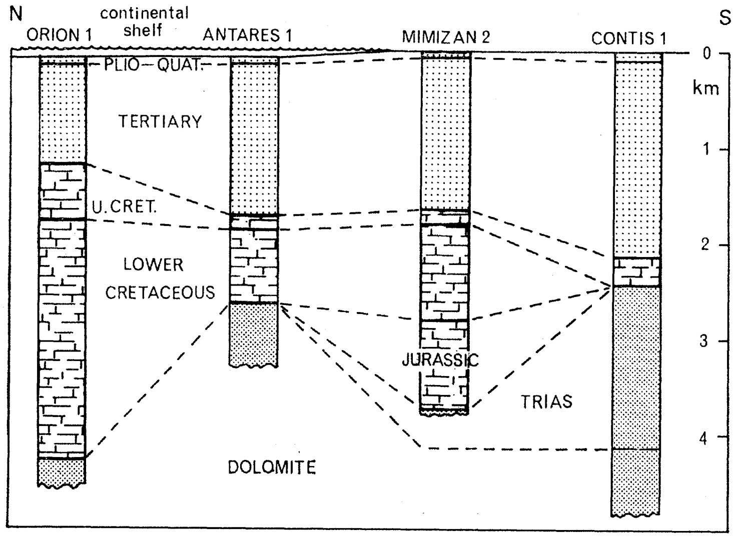


FIGURE 20. A simplified north–south section, about 50 km long, showing the strata underlying the present coast of the Aquitaine basin. It is based on the boreholes shown in figure 17 (data from Esso representative).

information from boreholes near to the coast south of about 44½° N (figures 17, 20) shows the extensive occurrence of Cretaceous strata at the western end of the Aquitaine basin, strongly suggesting that the marine portions extend westwards under the Bay of Biscay to join up with that present (figure 17) at Cantabria Seamount (Vanney 1967) and represented by Maestrichtian turbidites (Professor B. M. Funnell, personal communication).

The new information consists of Arcer profile ⑩ (figure 21) and Boomer profiles 10 and 11 (figure 17), together with seismic refraction data obtained by Professor P. Muraour (personal communication). The refraction work shows that rocks with a *p* wave velocity of 6 km/s are present at almost the same depth at stations 1 to 3 as is the thick Trias, at the Contis 1 borehole, with which he equates it tentatively. The same rocks may extend farther west beneath the deeper sea (near 40 and 60 km in figure 17), but their somewhat greater depth of occurrence and their position beneath deeper water suggests that they could be oceanic basalt, rather than Triassic sediments. Above this layer Professor Muraour shows three main layers with velocity 5000 to 4300, 3350 to 2596 and 1810 to 1795 m/s. By reference to a velocity log for the Mimizan Plage 1 borehole the lower layer is considered to be Lower and Upper Cretaceous while the remainder consist of Tertiary

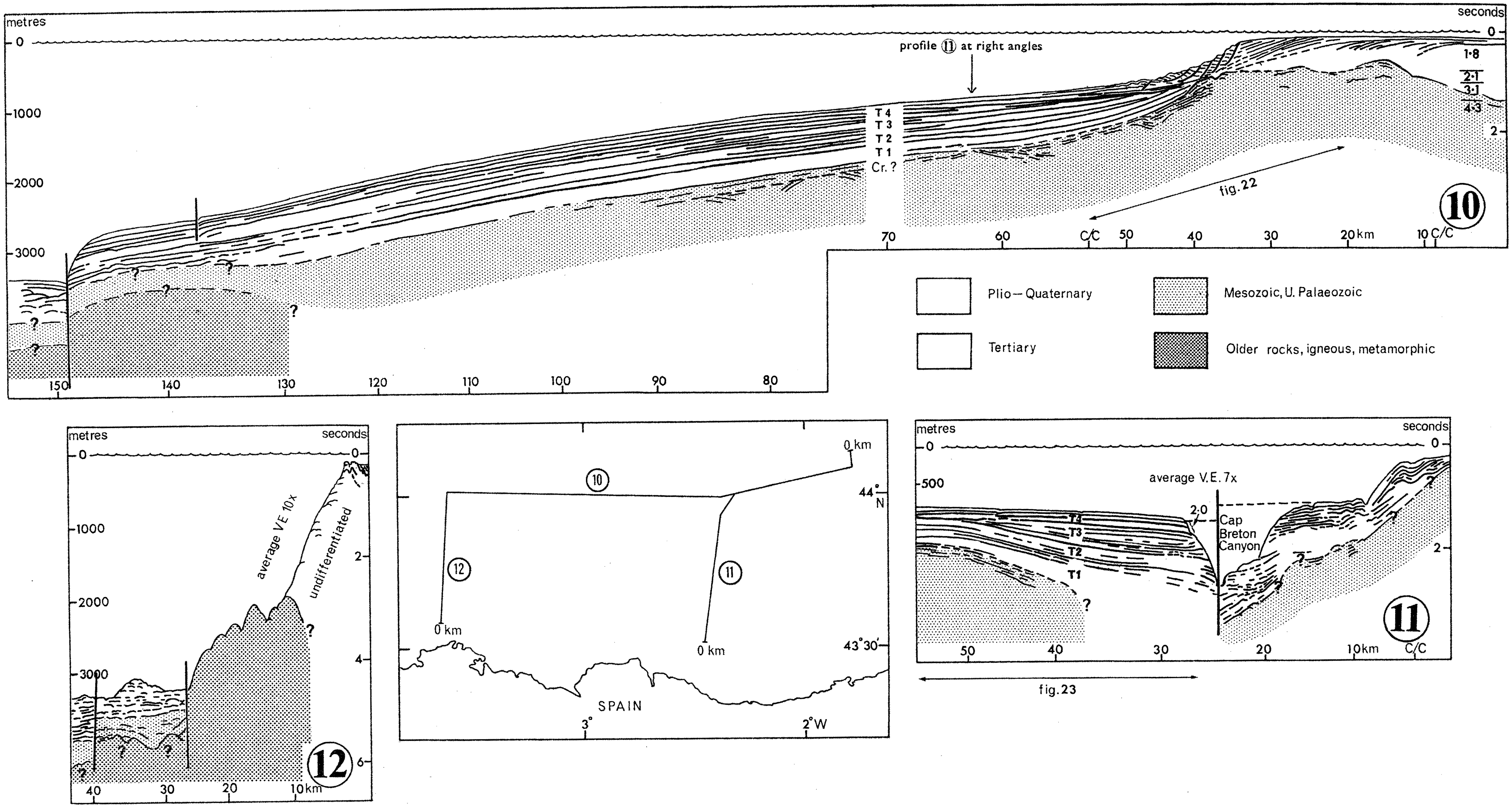


FIGURE 21. Line drawings of continuous reflexion (Arcer) profile (10) Aquitaine, (11) Bilbao and (12) Santander shown as tentative geological sections of the continental margin around the south-eastern corner of the Bay of Biscay (figure 17). The compressional wave velocities (km/s) for profile (10) were provided by Professor P. Muraour and the value given in profile (11) was derived from the apparent curvature of the strata. The abbreviation Cr. = Cretaceous, while T_1 to T_4 are provided for correlation with profile (11).

rocks. Thus, all of these rocks appear to extend from the landward portion of the Aquitaine basin down the continental slope to the bottom of the Bay of Biscay. The 2 km of such strata on the continental slope is within the thickness range known from the boreholes nearby.

The eastern end of Arcer profile ⑩ (figure 21) begins with a short portion with southerly trend (prior to the westerly trending portion which extends into deeper water). This revealed an interface rising towards the south from a depth of about 1840 m (profile ⑩, figure 21), which at the change in course, was followed up to a broad undulating crest with a least depth of about 600 m and a western edge near to the 40 km mark. This feature is considered to be the oceanward extension of the westerly trending ridge known as the Poteau Arch, at the bottom of the Aquitaine basin. Its upper surface, where the reflexion and the refraction profiles cross (figure 21), must on velocity considerations be equated with the top of the Cretaceous strata. This view is in keeping with the presence of Chalk at the Contis 1 borehole and with the poorly defined bedding of the associated rocks detected westwards from the 10 km mark in the continuous reflexion profile (figure 21). The presence of these rocks on the ridge and the absence of Lower Eocene (Schloeffler 1965*a*) above it may indicate some uplift of the ridge during Lower Eocene times. A Boomer reflexion profile 10 (figure 17), commencing 5 km west of the Antares borehole, shows that the bottom of the Plio-Quaternary is a strongly reflecting interface. When followed westwards the gradient of this surface, which is a Miocene continental shelf, increases until it lies parallel with the earlier as well as with the present-day continental slopes. Above these interfaces there is another marked interface again followed by renewed upbuilding, which may be an indication of a Quaternary fluctuation of sea level. 40 km farther south in Boomer profile 11 (figure 17) there is a similar pair of interfaces with the same pattern of upbuilding and outbuilding. If it is assumed that the interfaces of the two Boomer profiles can be equated, then the interpretation can be used for the Aquitaine Arcer profile, which continues the section from near the edge of the continental shelf down to the foot of the continental slope (profile ⑩, figure 21). The supposed Quaternary sediments are thickest at the break in slope where their crumpled appearance shows that they have slumped somewhat down the continental slope (figure 22, plate 5). The planes along which thinning of the bedding has taken place is suggested on the line drawing (profile ⑩, figure 21).

The inferred base of the Pliocene, projected down slope from beneath the continental shelf cuts across the (?) Miocene, between the 35 and 50 km marks, an event perhaps coinciding with the supposed rejuvenation of the Pyrenees during the Pliocene (deSitter 1965). The (?) Miocene appears to thicken westwards to about the 65 km mark, where the unconformity above it is no longer visible. Below this there is space for about 1400 m of Oligocene, Eocene and Paloeocene, only a little greater than the known thickness in the two boreholes located west of the coast (figure 20).

Profile ⑪: Bilbao

This profile ⑪ (figure 21) extends the geological section of profile ⑩ (figure 21) southwards across the Cap Breton canyon and up to the continental shelf of northern Spain. The section as far as the north wall of the canyon repeats that seen in profile ⑩,

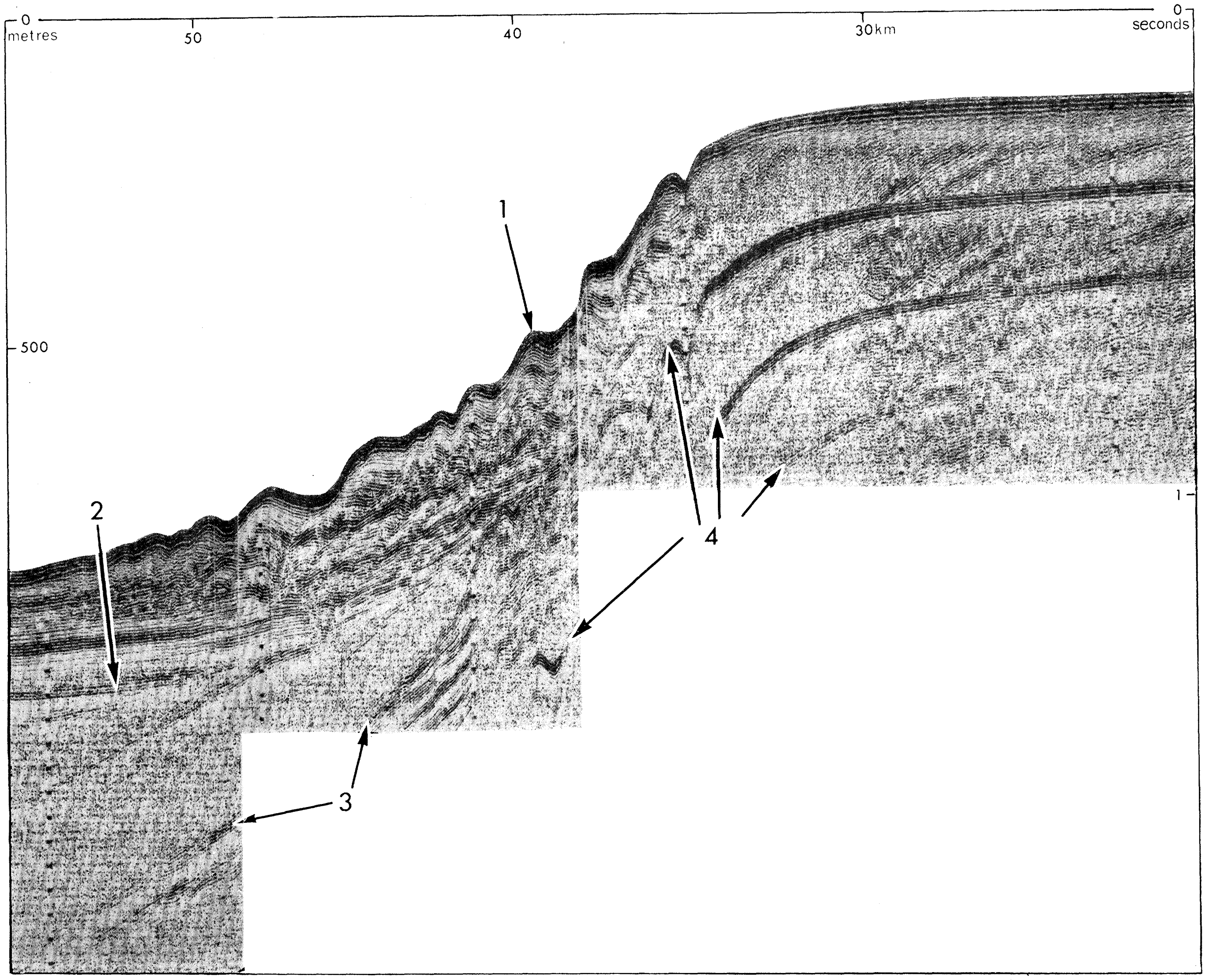


FIGURE 22. A photograph of the original Arcer record (within the limits set by the double headed arrow in profile ⑩ of figure 21) showing slump folds at the top of the continental slope off south-western France (figure 17). Undulations, 1, in the profile of the sea floor, which decrease progressively in amplitude within the underlying sediments, are interpreted as slumps. Interface 2, is the base of rock unit T_4, while interface 3 separates the supposed Tertiary and Cretaceous strata, and, 4 indicates multiple reflexions of the sea floor.

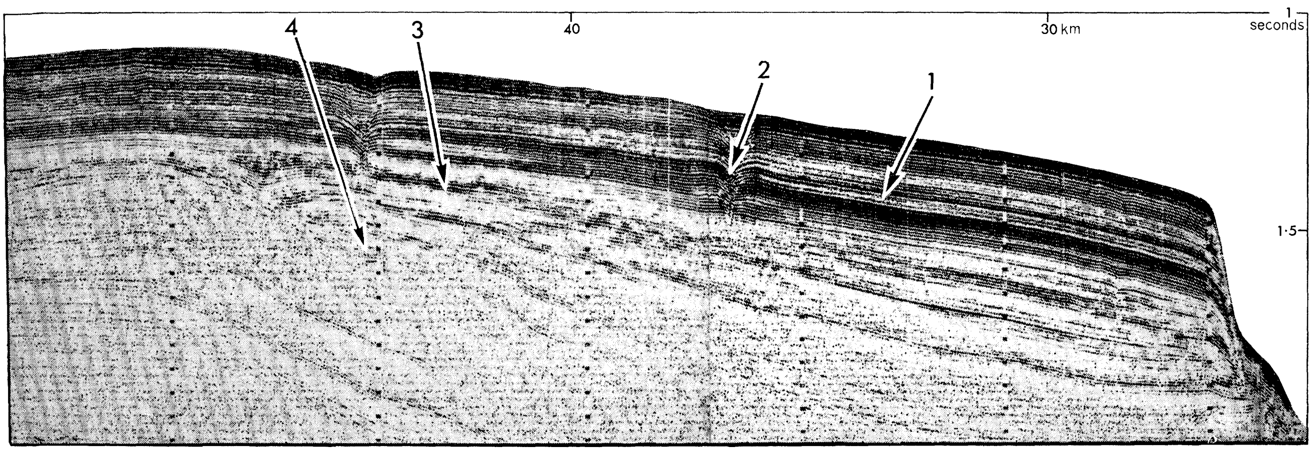
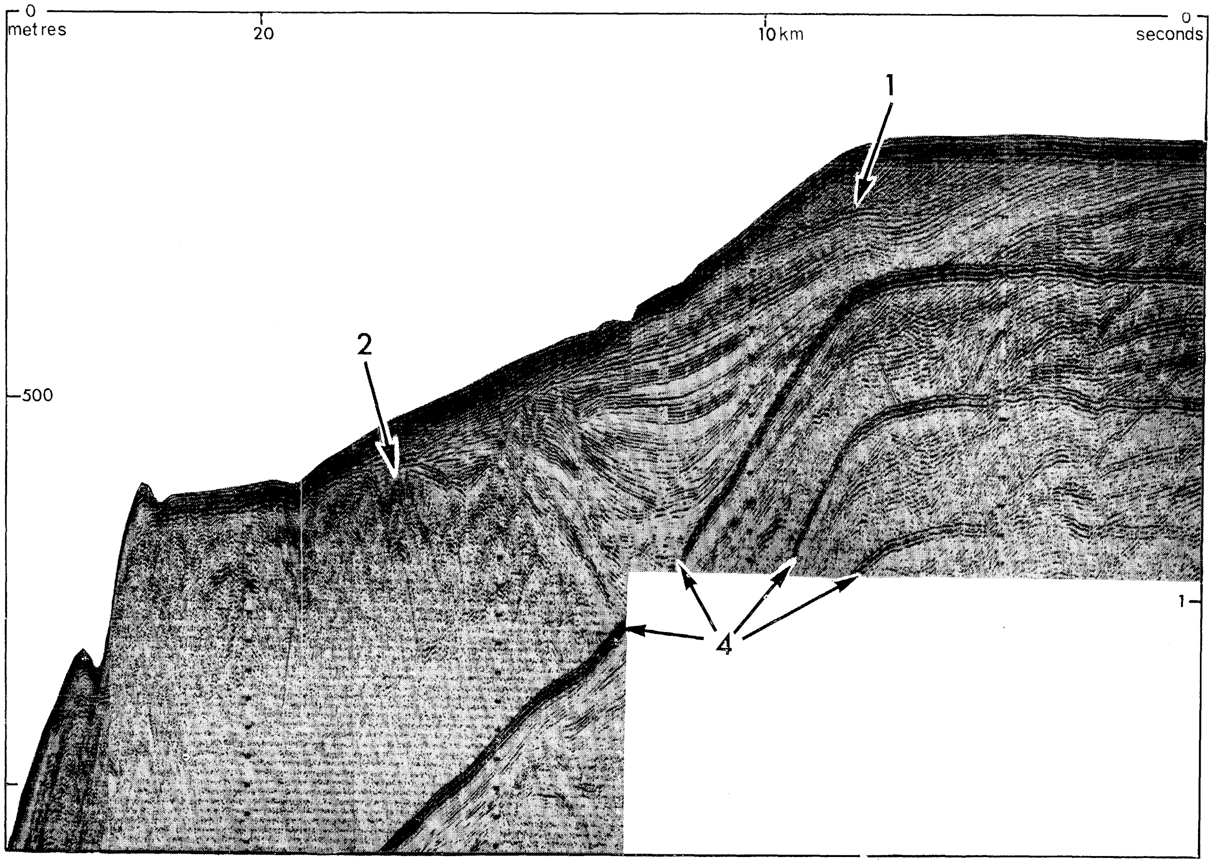


FIGURE 23. A photograph of the original Arcer record (within the limits set by a double headed arrow in profile ⑪ of figure 21) showing strata on the continental slope which dips towards the north wall of the Cap Breton canyon and Northern Spain (figure 17). The assumed boundary between Quaternary and Tertiary sediments is shown by 1; a channel filled with Quaternary sediments by 2; the base of rock unit T_4 by 3; and the base unit T_3 by 4.

(*Facing p.* 56)



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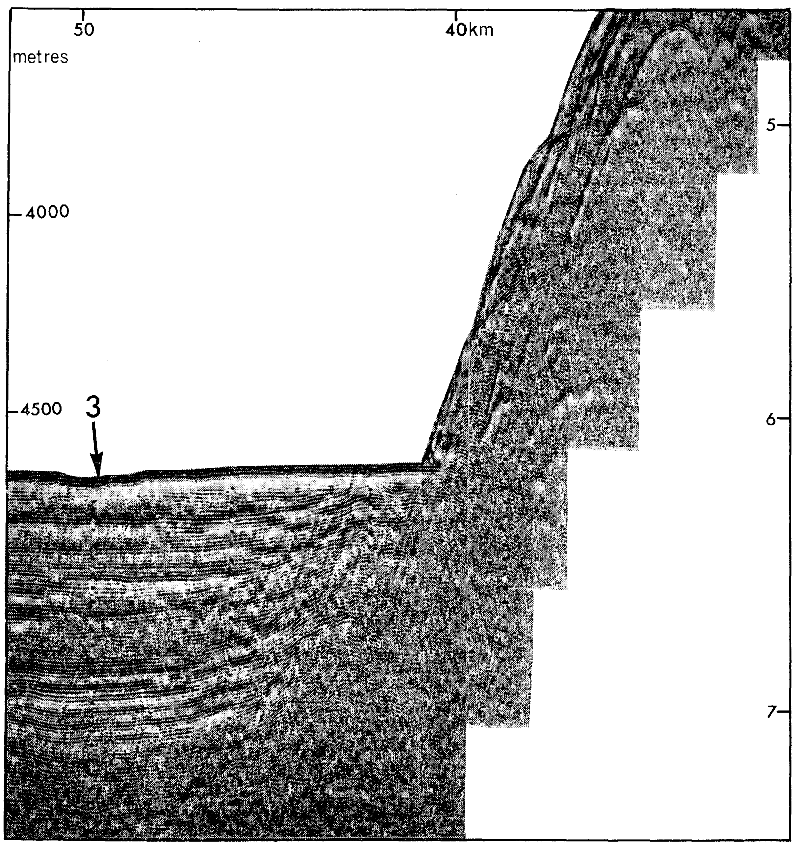

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FIGURES 25 AND 26. For legends see facing page.

both in terms of the thickness of Tertiary strata and the relationship of the beds to one another (T1 to T4 in profiles ⑩ and ⑪, figure 21). The velocity of the uppermost Tertiary strata, derived from their apparent curvature as they approach the north wall of the canyon, is again about 2 km/s, almost repeating the value given by Professor Muraour for his upper layer in profile ⑩ and the value for the Plio-Quaternary of the Orion borehole (figure 20). Quaternary deposits fill channels cut into the surface of the presumed Pliocene strata and may have originated during that period.

Well bedded rocks of Tertiary aspect can be recognized south of the canyon, in spite of their distortion (profile ⑪, figure 21, and figure 23, plate 5). Their base, which is taken at the lowest extensive interface, slopes down towards the floor of the canyon just as it does on its northern side. The relative thinness and distortion of the well-bedded strata on the south side of the canyon, as well as the greater height of their upper surface, have been taken to indicate the existence of a fault (rather than a slump), with an apparent upthrow of about 300 m to the south, which affects the whole Tertiary sequence. This origin and direction of throw is confirmed by the two north–south portions of Boomer profile 11 (figure 17) in which almost horizontal strata north of the canyon are present at the same depth as the somewhat folded strata of its southern side. The greater age of the uppermost rock on the southern portion of continental shelf is suggested by the preponderance of rock notations recorded for it on navigational charts. The northerly downthrow of this fault, which is presumed to extend eastwards along the north side of the Pyrenees, is in the opposite sense to that already proposed (Berthois *et al.* 1965*a*).

(*e*) *Region north-west and west of Iberia*

Profile ⑫: Santander

Mesozoic rocks occur at the coast, 10 km beyond the southern end of this profile ⑫ (on figure 17), while a trough of Tertiary rocks, which reach the sea some 60 km farther east, has a strike which suggests their continuation on the intervening continental shelf. They may also extend down the upper part of the continental slope, as a limestone sample of Upper Eocene age was taken at a depth of 1800 m (Sa 4 in figure 17 and on page 35) some 20 km east of this profile.

The portion of reflexion profile for the continental shelf (profile ⑫, figure 21) shows the presence of folded shoreward dipping rocks probably giving rise to strike ridges, whose age is assumed to be Tertiary. The upper half of the continental slope must be slightly rough, as there are numerous small side-echoes on the record. It is possible that more structure would have been detected had this record been of better quality. The lower half

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Description of plate 6

Figure 25. A photograph of the original Arcer record (with the limits set by a double headed arrow in profile ⑬ of figure 24) showing the outer part of the continental shelf north of Spain (figure 17). The base of supposedly Pleistocene, low sea level, foreset delta deposits and the top of the 'basement' are shown by 1 and 2, respectively, and multiple reflexions of the sea floor, 4.

Figure 26. A photograph of the original Arcer record (within the limits set by a double-headed arrow in profile ⑬ of figure 24) showing the bottom of the continental slope north of figure 25. A channel, 3, has been cut into abyssal plain deposits of Quaternary and supposedly Tertiary ages.

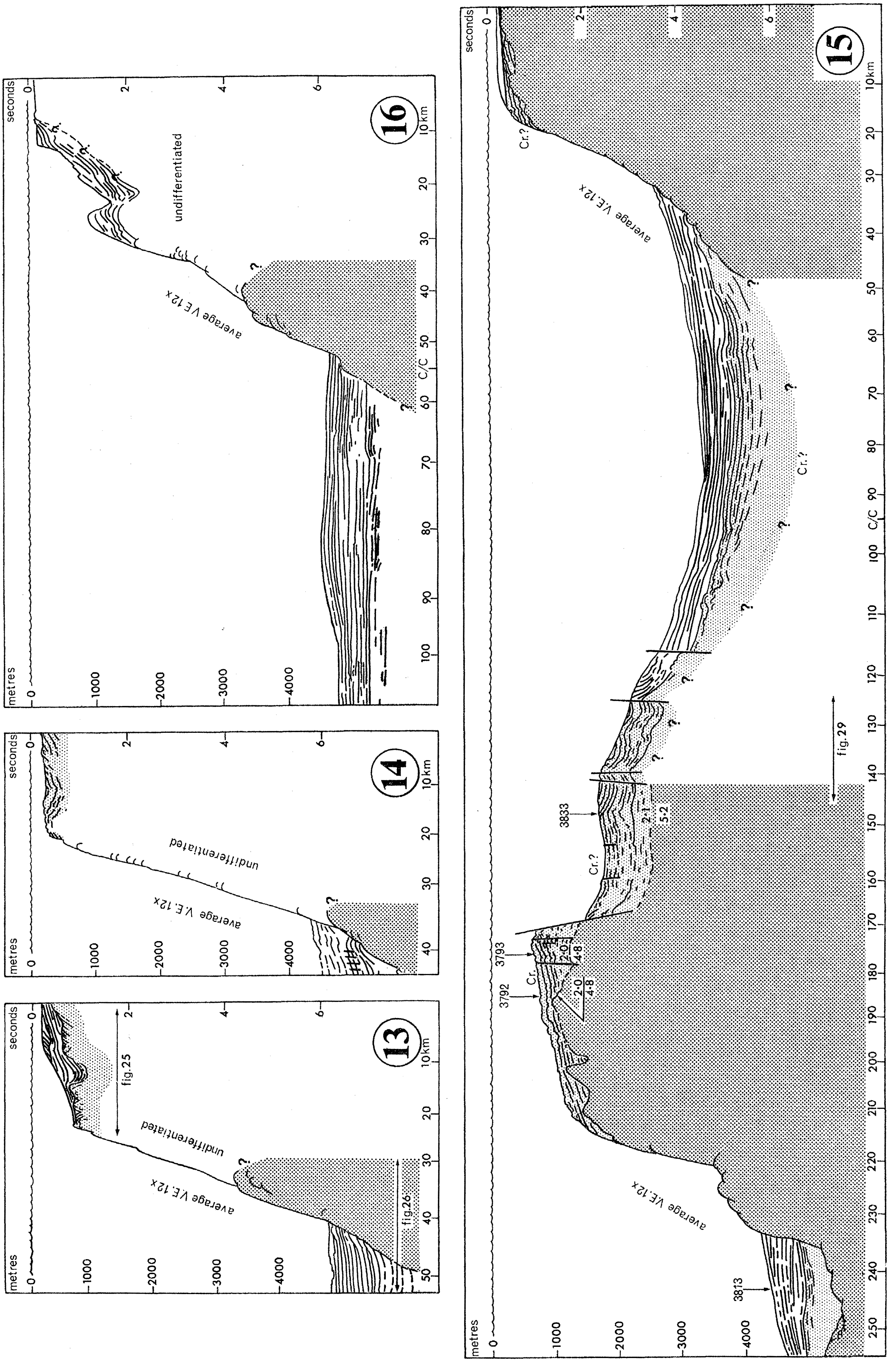

FIGURE 24. Line drawings of continuous reflexion Arcer profiles ⑬ Oviedo, ⑭ La Coruna, ⑮ Finisterre and ⑯ Lisbon, shown as tentative geological sections of the continental margin around Iberia (figure 27). Unconformities are shown by blue lines and fault planes by red lines. Abbreviation: Cr. = Cretaceous.

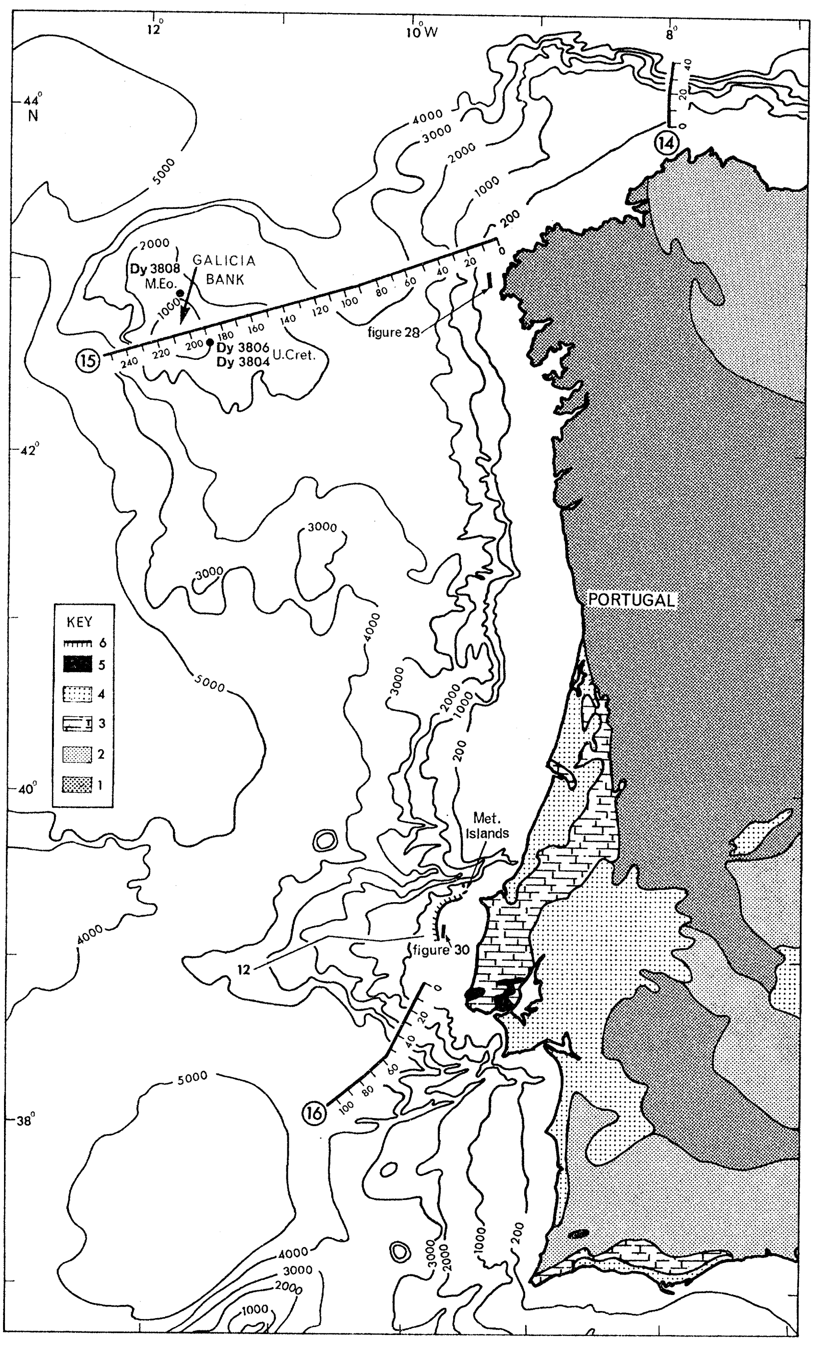

FIGURE 27. A simplified geological map of the western part of Iberia, together with an indication of the oceanward edge, 6, of the Portuguese Mesozoic trough. The rocks listed in the key are Tertiary igneous, 5, and Tertiary sedimentary, 4; Mesozoic, 3; Palaeozoic, 2; and Pre-Palaeozoic strata, including metamorphic and igneous rocks, 1. Continuous reflexion (Arcer) profiles, indicated by broad lines with distances in kilometres are illustrated in figure 24; profile 12 was obtained with an Air Gun. Dredge stations are shown by a black dot. Dy refers to samples taken by R.R.S. *Discovery II* (Black *et al.* 1964). Depths are given in metres. The abbreviations, Met. = metamorphic, Cret. = Cretaceous, Eo. = Eocene.

of the continental slope, which is much rougher, devoid of bedding and has a bench-like top, is thought to be an outcrop of the basement. Its abrupt burial near to the 25 km mark and the abrupt displacement of the contact between well-bedded (Tertiary aspect) and almost unbedded rocks at the 40 km mark may indicate the location of two faults upthrowing to the south. The former is thought to be the westerly trending Cap Breton fault, since it defines the south wall of the canyon here, as in the Bilbao profile (profile ⑪, figure 21), while the latter is the much smaller fault recognized almost at the western end of the Aquitaine profile, and so has an approximate northerly trend. The absence of Quaternary sediments is in keeping with the relief.

Profile ⑬: Oviedo

The youngest material at the edge of the continental shelf (profile ⑬, figure 24) looks as if it was deposited as a delta during a period of low sea level, in the manner described for the Gulf of California (Curray & Moore 1964). The underlying well-bedded strata of Tertiary aspect were laid on a rough surface of folded rocks whose relief is not entirely subdued even at the top of the succession. The older rocks are classed as Palaeozoic in aspect in keeping with the outcrops of such rocks at the coast, 20 km distant (figure 17). Such rocks may well occur beneath the upper half of the continental slope but would not be detected because of its steepness. The rougher, lower part of the continental slope may indicate an outcrop of the basement. The whole feature could be fault determined.

Beyond the foot of the continental slope there is a thick succession of beds ascribed to the Quaternary. Thus, at the present sea floor there is a channel with three terraces, and further channels are present in the underlying strata. In addition, groups of beds butting against the basement, alternate with groups which were laid on the lower part of the continental slope, suggesting an alternation between turbidite and hemi-pelagic deposits. On thickness grounds, as well as the steepness and age of the continental slope, it could be argued that Tertiary sediments may also be present in the observed section.

Profile ⑭: La Coruña

Asdic records suggest that the northerly striking Palaeozoic rocks (figure 27) extend at least half way across the adjacent continental shelf, although there appears to be no sign of them in profile ⑭ (figure 24), which seems to commence rather west of their boundary with metamorphic rocks at about 07° 40′ west. However, on the continental shelf such rocks are masked by a trough containing rather crumpled strata resembling that of Cretaceous age at Galicia Bank (profile ⑮, figure 24). No bedding was detected within the rocks of the continental slope presumably because the gradient is too steep. The rougher, buried foot of the continental slope is of basement aspect, while the lowest well bedded rocks above it resemble Tertiary strata. The upper, rather disturbed, bedding sloping towards the foot of a nearby canyon, and whose surface appears to be channelled, is probably a Quaternary fan.

Profile ⑮: Finisterre

From near La Coruña (about 08° west on the north coast of Spain) to Oporto (about 41° N in western Portugal) the coast is largely made of igneous and metamorphic rocks and by Pre-Cambrian strata. Beyond the coast bottom notations and the relief on navigational charts, together with the evidence of unbedded, well jointed rock on the Asdic records (figure 28, plate 7), suggest that the coastal rock types extend locally out to much of this portion of the continental shelf. A few rock notations are given for the continental slope, also. The eastern end of the reflexion profile (profile ⑮, figure 24) revealed a rough surface of old rocks overlain by a westerly dipping strata of Mesozoic or perhaps Tertiary aspect upon which there is a thin development of horizontal material.

Westwards the profile includes the whole of Galicia Bank and the intervening col which resemble part of a continental borderland. Beyond the 150 km mark on the reflexion profile 15 (figure 24) the refraction velocities and the lack of magnetic relief indicate that the deeper rocks are probably consolidated sedimentary strata, whose outcrop lithology at the 170 km mark may be indicated by the hard limestones dredged from the same cliff only 13 km distant (Black *et al.* 1964). Part of the variation in velocity may indicate that they vary laterally in composition or in age. For example, they might include Lower Cretaceous strata which has the same velocity in the Orion borehole (figure 17).

Late Cretaceous limestones capping the top of Galicia Bank (Stations 3804 and 3806 of Black *et al.* 1964) have a crenulate bedding which, with the same velocity at the 150 km mark, indicates their continuation eastwards to the 125 km mark (figure 24). Their style of folding may be the same as that in Portugal and their softness is in keeping with their low apparent velocity. However, the latter could indicate that some Tertiary strata have been included with them.

The almost uncontorted bedding and considerable lateral extent of the upper sediments on both sides of the bank, are taken as indicating the presence of Tertiary strata, probably with a relatively insignificant cover of younger material. Eocene rocks are known from the northern flank of the bank, but may be present only as the infillings of burrows on its summit. The reflexion profile ⑮, (figure 24) between 170 and 210 km, shows that part of the top surface of the bank lies parallel to the bedding beneath it (in a profile of this orientation) and so could be on almost unaltered bedding plane of late Cretaceous to Tertiary age.

Profile ⑯: Lisbon

In western Portugal a trough of Mesozoic and Tertiary rocks, reaching a thickness of about 4 km, extends southwards from latitude 41° N (figure 27). At the coast, as far south as $39\frac{1}{2}$° N, these are masked by Quaternary deposits. The absence of rock notations on the adjacent part of the continental shelf suggests that the uppermost rock there, as on land, is Tertiary or Cretaceous in age. Southwards of $39\frac{1}{2}$° N, however, Jurassic rocks are prevalent on land and on the adjacent continental shelf. Admiralty charts indicate rough ground and numerous rock notations, while the Asdic records show that the outcrops are large, with hard and soft layers interbedded with one another (figure 30, plate 8). These rocks strike a few degrees west of south and their apparent northerly facing scarps indicate a gentle easterly dip. They form the submarine western part of the Portugese trough. At about 38° 47′ N, an extensive elongate shoal suggests the westerly extent of a ridge of plutonic rocks present at the coast. The western edge of the trough is indicated locally by islands of older rock at about $39\frac{1}{2}$° N and by a boundary on the Asdic records (figure 27).

Rock is also indicated on the upper part of the adjacent continental slope both west of the islands and in the vicinity of 38° 50′ N. Profile 12 (figure 27), obtained by means of an Air Gun, on this portion of the continental slope revealed that the sea floor was a good reflector, but failed to detect any bedding beneath it. From this it is concluded that basement type rocks probably extend from the western side of the trough down to a depth of at least 1500 fathoms.

The Lisbon profile ⑯ (figure 24) shows that well-bedded rocks of Tertiary aspect extend from the outer part of the continental shelf down the upper part of the continental slope and are underlain by undifferentiated rocks. Below this, a prominent bench with a rough upper surface, is interpreted as an outcrop of basement type rock.

The deep water portion of the profile shows a thick section of well-bedded material which may well be Quaternary in age, in view of its flatness and the relationship of its bedding with the base of the rock slope, as well as its location at the foot of a substantial canyon. Underneath, a persistent interface, with some signs of erosion, may indicate the top of Tertiary material.

4. Sequence and magnitude of processes shaping the continental margin

(a) *Sequence*

The continental margin of western Europe seems to have passed through five main developmental stages. It originated during the Mesozoic. There was deposition and downwarping during the (?) Cretaceous. During late Cretaceous to early Tertiary times there was an erosional interlude. Then, deposition and downwarping recommenced. During the late Tertiary and the Quaternary there was a second erosional phase, known to include faulting, slumping and canyon cutting. The magnitude and possible origin of each process is discussed below, at first separately and then in a broader context.

(b) *Continental rifting*

Rocks of basement aspect seem to be recognizable in many profiles, both beneath younger rocks and even appearing to crop out, particularly along the foot of the continental slope. Rocks of Palaeozoic aspect are prevalent on and beneath the continental shelf as far south as profile ⑤. Thence, the apparent absence of these rocks as far south as profile ⑩ is merely an indication of the greater thickness of overburden. Palaeozoic rocks

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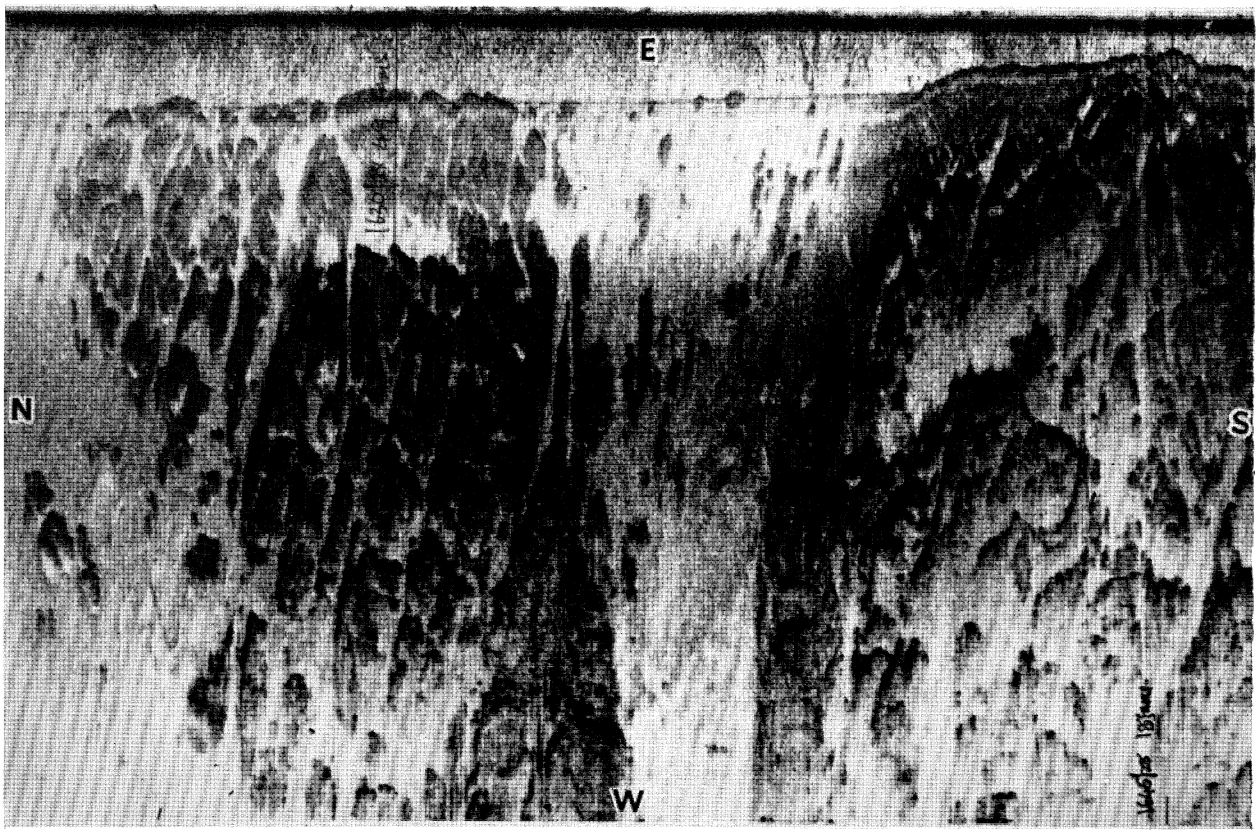
Description of plate 7

Figure 28. An acoustic map of 7·2 × 1 km of sea floor, on the continental shelf between north-western Spain and the eastern end of profile ⑮ (black rectangle in figure 27). Patches with a dark tone are ragged outcrops of rock, while the pale-toned intervening floor is probably flat and sandy. The massive rock in the left half of the figure is probably igneous, while the remainder may be somewhat altered sedimentary strata. Both rock types are broken by two sets of joints.

Figure 29. A photograph of the original Arcer record (within the limits shown by the double headed arrow in profile ⑮ of figure 24) on the eastern flank of Galicia Bank, off western Spain. The wavy bedding, with suggestions of small faults is also seen in the Cretaceous limestones on the top of Galicia Bank.



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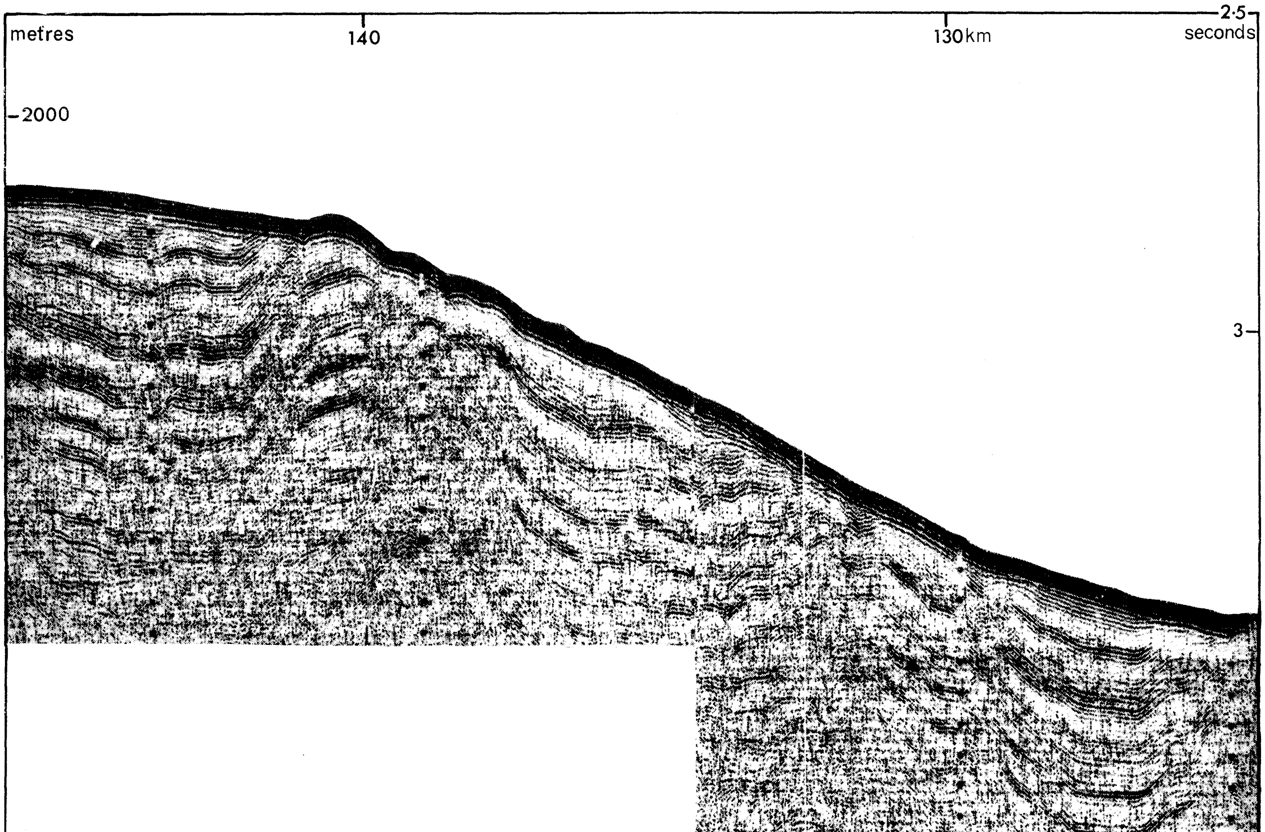

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FIGURES 28 AND 29. For legends see facing page.

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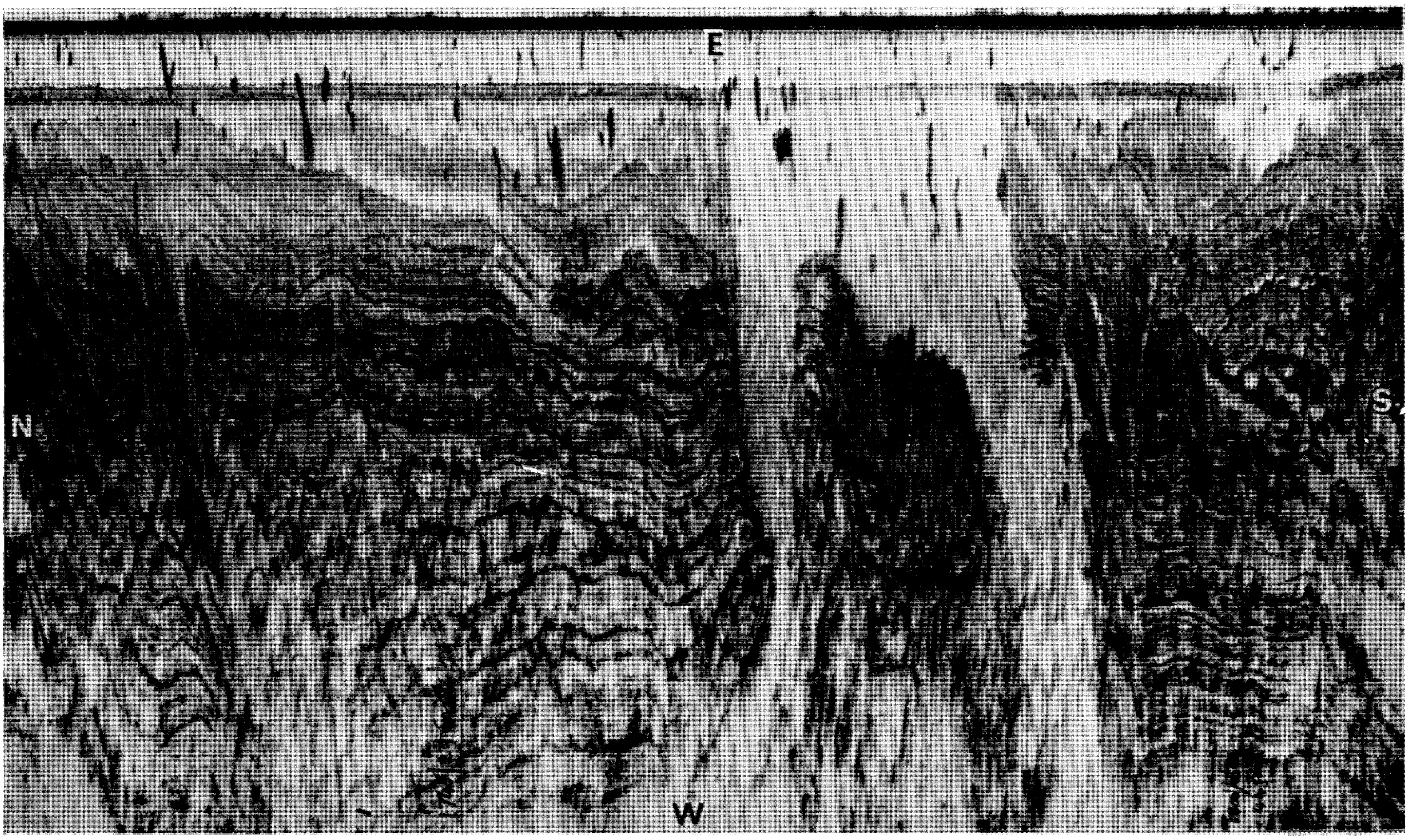

FIGURE 30. An acoustic map of 8×1 km of continental shelf located 25 km oceanward of the Jurassic rocks of western Portugal (black rectangle in figure 27) showing three large outcrops of sedimentary strata separated by relatively flat floors of sandy material. Adjacent beds of rock are of somewhat variable hardness such that the more resistant layers stand proud as scarps (narrow dark lines) and the gentle dip slopes (broader grey bands) face towards Portugal. The prominent black blobs in the upper part of the record are echoes from fish or plankton.

appear to be present beneath the continental shelf of profile ⑬, as would be expected from their presence at the nearby shore. They could be present in the sections of undifferentiated rocks which outcrop on the continental slopes around Iberia but would not have been detected because of the high gradient. The outermost Palaeozoic rocks appear to have no structural relationship with the older rocks that would favour the proposed thesis of a Palaeozoic Atlantic Ocean (Wilson 1966*a*). In contrast, there is a dramatic transition from old rocks (whose age relationship and structural grain are devoid of any special relationship with the present continental margin) to the well-bedded young rocks laid as continental slope deposits by the present sea (cf. figures 3 and 31). This transition represents the most profound event in the geological history of the European continental margin, which involved formation of the Atlantic Ocean and the marking out of the western edge of Europe, much as it appears at the present time. This episode probably included the separation of Rockall Bank (assumed to be a continental fragment) from Europe by relative translation of about 400 km from the continental margin west of Scotland, where there is a scar of suitable size and shape (figure 4). Similarly, profiles ④ and ⑤ show that the Porcupine Seabight was originally deeper and so suggest that it was initiated by a few tens of kilometres of northward and westward translation of Porcupine Bank with respect to the continental margin west of Ireland, where there is also a scar of suitable size and shape. Such a replacement would avoid the apparent overlap of Porcupine Bank with the western side of the Atlantic in reconstructions of the supposed pre-continental drift land (Bullard, Everett & Smith 1965). Similarly, the Bay of Biscay could have been formed during the same period, if it was the result of the relative anti-clockwise rotation of Iberia (Girdler 1965; Van der Voo 1967; Van Dongen 1967), rather than relative westward translation of that landmass. The beginning of this rotation may be post-basal Upper Jurassic, if it was the cause of the abrupt change from northern to Tethyan lithology and fauna which took place in Portugal (Professor T. Barnard, personal communication). Galicia Bank and the old rocks forming the western boundary of the Portugese trough were probably also continental fragments.

(*c*) *Deposition*

The reflexion profiles and available rock samples suggest that the oldest continental slope deposits of the present sea are Cretaceous in age (figure 31). This is in keeping with the western side of the Atlantic Ocean (Stetson 1949; Uchupi & Emery 1967), although the Jurassic rocks, known from the Portugese trough, may be more widespread.

Outbuilding of the continental slope recommenced during the Tertiary and was associated with considerable up-building of the adjacent continental shelf and the floors of neighbouring epicontinental seas. An indication of the thickness of Cenozoic strata on the European Atlantic margin is given in figure 32. The values chosen for the continental slope south of 49° N, represent the maximum thickness still present between the submarine canyons, together with a small additional amount (profiles ⑥ and ⑦, figure 16) needed to make the profile of the continental slope resemble that of undissected continental margin in the vicinity. In general, the Cenozoic deposits are thickest on the continental slope, wedging out towards the land because of both the onlap relationship between layers and the decrease in layer thickness in the same direction. Similarly, the strata thin out

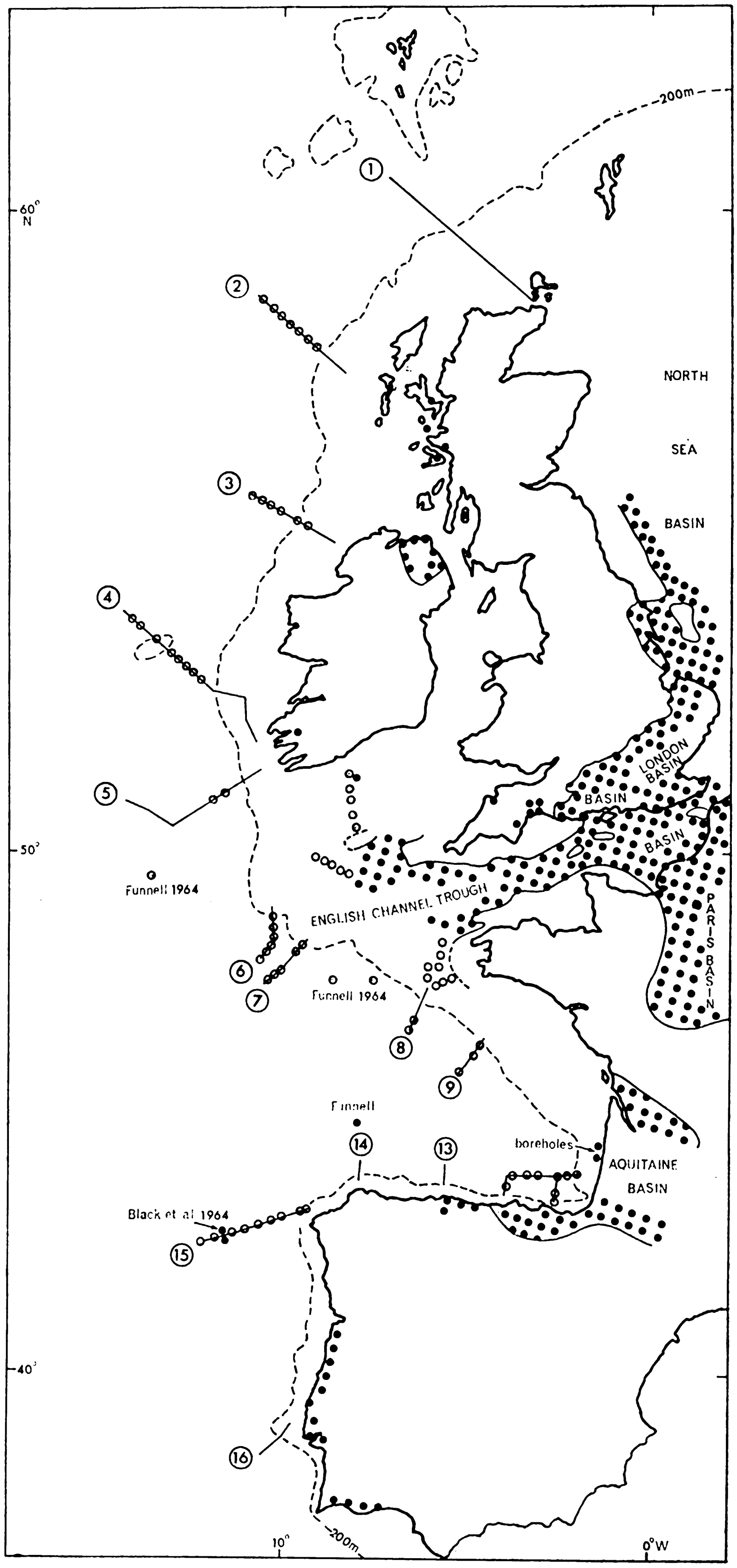

FIGURE 31. The known outcrop of Cretaceous strata (black dots) near the western seaboard of Europe and the probable occurrence of such rocks (white dots) along the line of the continuous reflexion profiles.

towards the eastern sides of both the Porcupine Bank (profiles (4) and (5), figure 10) and Galicia Bank (profile (15), figure 24). Seismic refraction work has shown that the actual thickness of post-rift sediments in the western part of the English Channel trough and

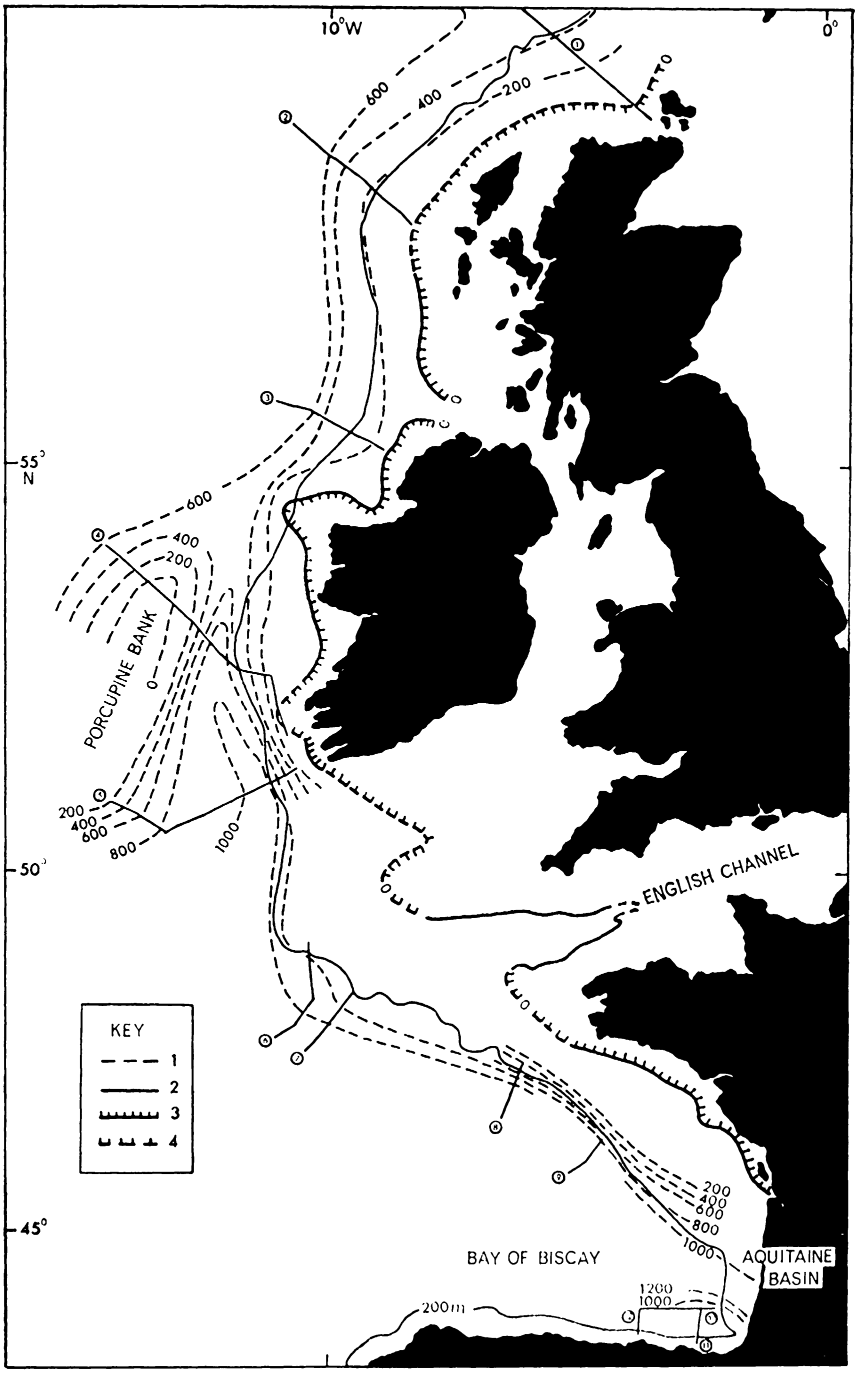

FIGURE 32. The approximate thickness in metres of Cenozoic strata on the Atlantic continental margin of Europe, assuming a sound velocity of 2 km/s. Thickness contours are shown as pecked lines, 1. The landward limit of the strata is shown by a solid line, 2, where it is based on sampling and by symbol, 3, where it is based on the seaward limit of the rock notations on navigational charts or by, 4, where it is surmised.

Aquitaine basin are about 4 km. Similar amounts must be present on the adjacent continental slope. This pattern of deposition with upbuilding of the continental shelf and outbuilding of the continental slope is analogous to that found around North America, although the thickness on the western side of the north Atlantic is far greater than that off western Europe. Nevertheless, the thickness is sufficient to mask the original shape of the edge of Europe, supposedly resulting from continental drift, so lessening the perfection of its fit with North America and Greenland (page 63). The original Bay of Biscay may well have extended eastwards beneath a part or the whole of the Aquitaine basin, almost to the Mediterranean Sea, so that its two sides were originally almost parallel (Schloeffler 1965 *b*).

The reflexion profiles show that off Western Europe the deposits were laid over a large area of the continental margin at the same time and that they must be marine. Individual bedding surfaces seem to be traceable for distances of up to 170 km; they can be followed beneath the whole length of the continental slope or from the latter beneath the continental shelf. The low frequency, long pulse length Arcer system shows that these extensive beds can be as little as 30 m apart while the higher frequency, shorter pulse length Boomer reveals that there are extensive beds less than 6 m apart. The bedding interfaces may be due, in part, to lithological contrast since small differences in composition are known from the Tertiary sequence (Curry *et al.* 1962).

(*d*) *Downwarping*

There must have been considerable downwarping of the continental margin during the Mesozoic, to allow deposition of marine strata on the whole of the continental slope, the upper part of which must previously have been above sea level. However, no estimate can be made of its magnitude because of subsequent vertical movements and associated erosional episodes.

The thickness and structure of the presumed Cenozoic deposits of the continental shelf, which mask an unconformity, give a measure of the amount and rate of sinking of the continental margin (erosion resulting from its relative uplift is discussed on page 68). The greatest observed thickness of such strata with continental shelf aspect (outside local features such as the English Channel trough and the Aquitaine basin) is seen in profile ② (figure 6), where 600 m are present. If it is assumed that these include the whole sequence and that the shoreward extent of the first and last layers had the same relationship with sea level, then the average rate of sinking of the margin in that profile was about 0·1 cm per 1000 years, compared with a 10 times greater rate reported for the east side of the United States (Uchupi & Emery 1967). However, the initial rate of relative sinking must have been more rapid, for what appears to be the first layer extended landward for as much as about 10 km (profile ②, figure 6). The subsequent slow settlement seems to have continued right up to the present time, for in this profile as in profiles ③ to ⑤ (figures 6, 10) successive beds overlap one another landwards for a maximum distance of more than 60 km. On each of the profiles the upper surface of the supposed Cenozoic deposits has a more gentle oceanward gradient than that of the unconformity beneath them, rather suggesting that the amount of sinking increases outwards from the present land, with a hinge line not far west of it. The progressive onlap which took place west of Scotland and Ireland was associated with the easterly tilt of most of the British Isles towards the North

Sea trough (Kent 1967), as recorded there and in the rocks of south eastern England. The outer limit of Palaeozoic and older rocks show that the uplifted ground resembles a dome (figure 33), the later development of which is mentioned on page 71.

The western half of the English Channel trough holds a sedimentary record of its own evolution as well as that of the continental margin, although these two records cannot be

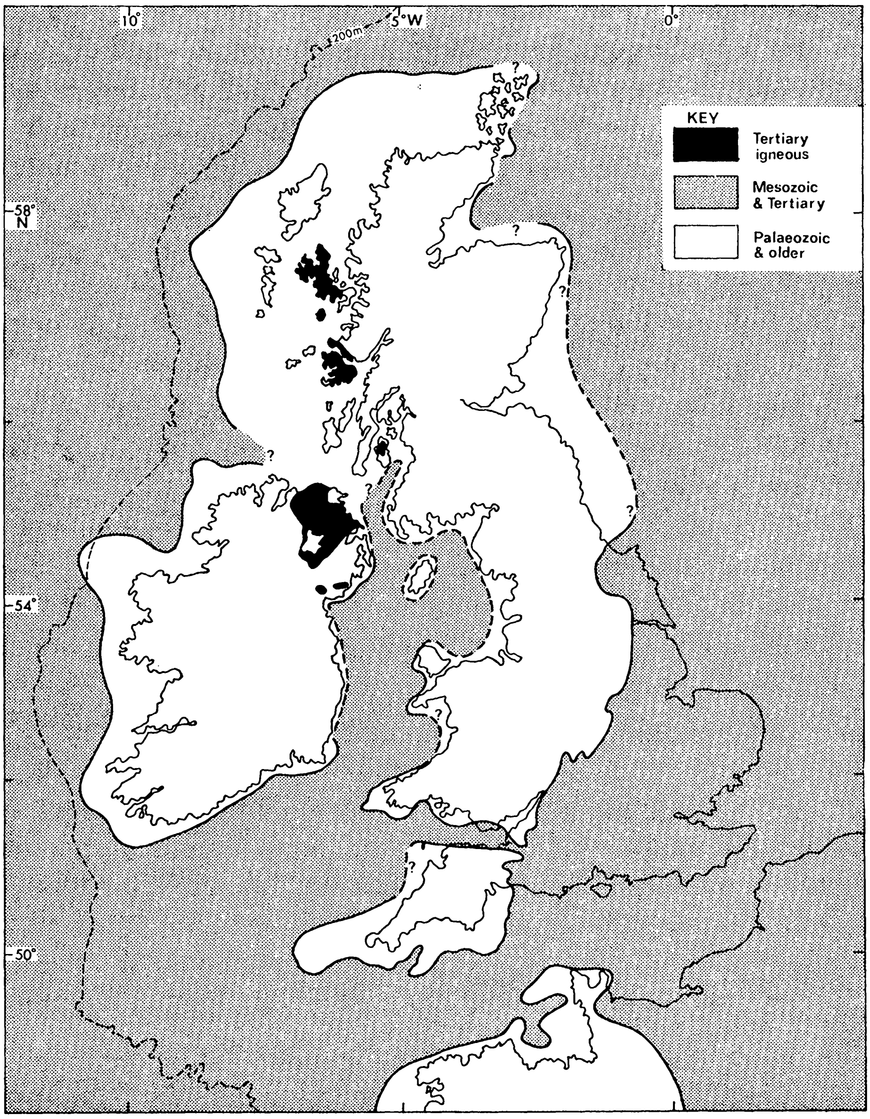

FIGURE 33. The probable limit of outcrop of Palaeozoic, igneous and metamorphic rocks around the British Isles (after Stride 1967) with location of Tertiary igneous rocks (black) along the supposed graben (Cloos 1939).

fully separated at the present time. It seems that the location of a tongue of Tertiary strata depends on the formation of a westerly trending trough, while the length of a tongue gives an indication of the downwarping or uplift of the continental margin normal to it. The infilling of these troughs (even that of Cretaceous age) was partly accomplished by a progressive decrease in bed thickness towards the sides. Thus, the varied age of rock outcropping on the floor of the western half of the English Channel (that has been examined by the authors) cannot be taken solely at its face value as an indication of an erosion surface of Pliocene or Quaternary age, although there has been some erosion of such ages.

(*e*) *Erosion*

A well-defined, rather rough, unconformity is present in profiles ② to ⑦ and in ⑩ (figures 6, 10, 16 and 21), but lies below the depth of detection in profile ⑨. It extends from beneath the continental shelf to a water depth of up to almost 3000 m on the continental slope. It represents an hiatus between the top of the oceanward dipping, supposedly Cretaceous strata and the base of the Tertiary rocks, the whole thickness of the former being missing locally beneath the continental shelf. Removal of much pre-Tertiary material from the continental margin occurred during a regression known on both sides of the Atlantic, which was associated with turbidite deposition. One sample of such Maestrichtian material was taken from Cantabria Seamount (Professor B. M. Funnell, personal communication) in the Bay of Biscay (figure 17) and related turbidites are likely to be as abundant beneath the north-east Atlantic as they are known to be beneath its western basin (Ewing, Worzell, Ewing & Windisch 1966). However, turbidite deposition in the vicinity of the Bay of Biscay could extend over a longer period, if the northern continental slope of Iberia has always been as steep as it is at the present time.

Late Cenozoic erosion of the continental slope is impressive south of 49° N (e.g. Hadley 1964; Berthois *et al.* 1965*a*, *b*). The floors of canyons have been cut as much as 1000 m below the surface of seemingly unaffected inter-canyon areas, exposing rocks of Mesozoic and basement aspects (profiles ⑥ and ⑦, figure 16). The principal agents of canyon and gully cutting could be slope failure due to excess pore water pressures, which gave rise to turbidity currents, with slumping on its own apparently a less important mechanism for the removal of slope deposits. Thus, the canyons and gullies are probably the products of the ubiquitous late Cenozoic maximum regression, when rivers dumped their sedimentary loads on localized parts of the upper part of the continental slope. In contrast, the continuous reflexion profiles of the continental shelf do not appear to show much evidence of erosion of late Tertiary strata except perhaps between the 110 and 130 km marks in profile ① (figure 6). The varied rocks outcropping on the floor at the western end of the English Channel trough are not proof of an erosional origin for the deeper-lying continental shelf thereabouts (see page 46). However, with Pleistocene sea levels as much as 110 m below that of today it is not surprising that there is evidence on the inner part of the continental shelf, such as around Brittany, of local valley floors about 17 m below the general depth of the neighbouring sea floor (Horn, Vanney, Boillot, Bouysse & Leclaire 1966). It has been suggested that cemented pebbles at the bottom of a trench called the Hurd Deep (in the western English Channel) indicate that localized subaerial erosion reached down to about 165 m below present sea level (Boillot 1964).

(*f*) *Folding and faulting*

There is little sign of pre-Tertiary folding in the European continental margin beyond that shown by geological maps of the English Channel trough. Continuous reflexion profiles have revealed that the supposed Cretaceous strata between Ireland and Porcupine Bank lie in gentle rather irregular folds (profile ④, figure 10) and there is some disturbance in the broad arch of such rocks in profile ⑩ (figure 21). The Cretaceous rocks of Galicia Bank are crumpled, while those of its eastern flank lie in broad folds as well (profile ⑮, figure 24). In the other profiles these movements are only suggested by the pre-Tertiary unconformity.

Tertiary folding appears to be even more restricted. Geological maps show that there was both pre- and post-Miocene folding in the English Channel trough. Tertiary folding also took place in northern Spain, for which there is some evidence of the southern end of profile ⑪ (figure 21). However, it is possible that the latter is due to faulting or slumping. Elsewhere the continental slope appears to be unaffected.

Faults have been recognized on the continuous reflexion profiles at sites where there is some displacement of bedding, particularly if this is associated with a step in the profile of the sea floor indicating the same direction of movement (profiles ⑥ and ⑦, figure 16). Less commonly it is suggested by local distortion of the bedding (profile ⑪, figure 21). With such control it has been possible to infer something of the lateral extent of certain faults by means of the relief and to show the validity of some faults whose existence has already been suggested (Berthois *et al.* 1965 *a*, *b*). The faults seem to be fairly widespread on the continental slope (profiles ②, ④ to ⑦, ⑩ to ⑫, ⑭ and ⑮) and they may to some extent define the outcrops of basement type rocks at its foot west of both the English Channel trough and France as well as around Iberia. The largest throw which can be demonstrated seems to be about 500 m (profile ⑥, figure 16). There appears to be no preferred direction of throw.

The approximate age of the faults is indicated by the strata affected. One of pre-Tertiary age has been recognized beneath the shelf on profile ⑧ (figure 19). The faults defining the eastern and western sides of Galicia Bank (profile 15, figure 24) are younger than the Cretaceous rocks occurring there and could be the same age as those cutting the supposed Tertiary strata in the eastern half of that profile. Late Tertiary faulting is important, as demonstrated by profiles ⑥, ⑦, ⑩ and ⑪ and probably also by profiles ②, ④, ⑤ and ⑫. The Cap Breton fault moved on the occasion of the uplift of Iberia, but is probably of much greater age and may not have always moved in the same manner.

In addition to these faults, it has been suggested (Cloos 1939) that the British Isles dome (figure 33) was broken by a graben located along the line of deeps between mainland Scotland and the Hebrides (figure 4), associated with which there was considerable igneous activity during the Lower Tertiary. The same tensional structure or a monocline, may extend along the local deeps of the western half of the Irish Sea, so accounting for the lack of a westerly continuation for the highest erosion surface of Wales.

(*g*) *Slumping*

Slumps occur on the continental slope on one profile west of Scotland and on five profiles to the west of the Celtic Sea and France. Their presentation at the sea floor varies between a wave-like to a stepped profile. In depth, they are seen as folded bedding or as blocks that have been rotated as a unit, even to the extent of receiving a landward dip. The curved soles of the discrete blocks are detected locally as reflecting surfaces, although more commonly they are indicated by the localized distortion or absence of bedding. In the following account it must be borne in mind that the broad beam, low frequency and long pulse length of the equipment that was used, set a minimum size to features that can be recognized and mask the real gradient of sloping surfaces. The resolution of the Arcer equipment is about 30 m, so that the features which can be recognized beneath the sea floor must be about an order larger than those commonly described in the geological literature.

Slumps are well developed on the upper part of the continental slope in profile ⑩ (figure 21). The upper units present a stepped profile suggesting that they are separated from one another by soles up to 1 km apart, which have allowed as much as 80 m of relative vertical movement between units. Lower down the slope there appears to have been some pile up of the slumped material, while in the vicinity of the 50 km mark the slumps resemble gentle folds with crests about half a kilometre apart, which reach about 20 m above their adjacent troughs. Slump folds five times higher have been described for the continental slope south of Portugal (Roberts & Stride 1968). Elsewhere the largest apparently individual slump block to be recognized seems to extend down the continental slope for about 6 km and to affect a thickness of about 300 m of strata (profile ②, figure 6). In contrast, the longest group of slumps appears to extend as much as 20 km down gradient, about half the length of the continental slope thereabouts (profile ⑨, figure 19).

There appear to be three main causes for the slumps which have been recognized in the European continental margin. The slumps of profile ⑩ affect the uppermost material which must, partly or wholly, be Quaternary in age. They are thought to have occurred because the deposition rate was so high that the sedimentary load exceeded the bearing capacity of the lower material, which had not had time to gain strength by compaction. However, Berthois *et al.* (1965*a*) concluded that a fault, trending almost normal to profile ⑩, must be the cause of the steep uppermost part of the continental slope lying west of the landward portion of the Aquitaine basin. The new data given in profile ⑩ do not support the fault hypothesis; nor does that profile appear to indicate step faulting, as the steps in the sea floor do not correspond in position or vertical displacement with irregularities in the unconformity at the top of the supposed Cretaceous strata. Rapid deposition followed by an increase in the gradient of the continental slope is thought to be the origin of the large slumps of late Tertiary age occurring south of Portugal (Roberts & Stride 1968). A similar mechanism may be applicable to the disturbed beds of profile ⑪, on the north side of Iberia. An increase in gradient may have resulted from downwarping of the continental margin off France and the British Isles. There, the slumps are associated with gradients in excess of $2\frac{1}{2}^\circ$ as on profiles ② and ⑩ but not on profile ① where it is only 2°. However, it seems more likely that most of the slumps of that ground are due either to faults, which trend along the continental slope (profile ②, figure 6 and profile ⑨, figure 19), or to deep canyons which trend down the slope (profiles ⑤ to ⑧, figures 9, 16 and 19). Both types of feature have made cliffs whose angle of inclination exceeds the depositional dip of the Tertiary strata and so invites its subsequent collapse.

The evidence given above shows that there was an episode of slumping in late Cenozoic time, which may still be active today. There may also have been a late-Cretaceous to early Tertiary phase, as there is disturbed bedding near to the foot of the continental slope in profiles ① to ③. Its geographical association with centres of Lower Tertiary igneous activity may indicate a causal relationship.

(*h*) *Indications of continental drift*

Evidence favouring the origin of the present Atlantic Ocean by the drifting apart of continents has been mentioned by many authors and is supported, off Europe, by the dramatic appearance of continental slope deposits during the Mesozoic. It has been suggested recently that the considerable thickness of Cretaceous and perhaps older sediments on the eastern and western sides of the deep Atlantic, and their apparent absence along the crestal part of the Mid-Atlantic Ridge, may indicate that there has been a second but minor phase of ocean widening (Ewing *et al.* 1966). It seems worthwhile viewing this concept of interrupted continental drift in the light of the repeated events described in the preceding part of the paper, which are on such a scale as to suggest the operation of a single primary process. The present work shows that the continental margin has been affected by two periods of massive deposition (involving both out-building and up-building), which were associated with marine transgressions on both sides of the Atlantic. It was also affected by two periods of considerable erosion (with faulting and slumping and by turbidite deposition in the deep sea). In the present discussion the depositional and erosional phases are taken to indicate that convection cells and (sometimes) continental drift were in or out of operation, respectively. The supposed mechanism is that the descending portion of a convection cell causes a lowering of the adjacent land, which was only free to rise again when the stress was removed or reduced. It follows that continental drift was occurring up to late Cretaceous times (Maestrichtian, presumably) and also during the period from Eocene to Miocene, but was unimportant between late Cretaceous and Eocene and during the Plio-Quaternary. Such a view provides a reason for the presence of Miocene sediments in a trough of the Mid-Atlantic ridge, whereas the even more recent second phase of drift postulated by Ewing *et al.* (1966) should have carried them away from it.

Further vagaries in the drift of continents seem to be suggested by the graben-like features of supposedly tensional origin which occur in the vicinity of broken continental margins. The pre-Cretaceous group seems to be represented by the Norwegian Channel (Wilson 1967*b*), Rockall Trough, Porcupine Seabight and the Bay of Biscay (called by Carey (1958) a sphenochasm). The late Cretaceous to early Tertiary group is represented by the trough (with its abundant igneous rocks) at the western edge of Scotland and may extend southwards down the Irish Sea. It also appears to include Porcupine Seabight (where a second phase of movement is required to disturb its supposedly Cretaceous strata), and also includes the origin of the col between Galicia Bank and Iberia. The form of all these supposedly related features varies from the Scottish example, with mainly vertical displacement, to Porcupine Seabight and Rockall trough involving tens to hundreds of kilometres of displacement and even to the Bay of Biscay, where there has been considerable rotation as well.

Perhaps these graben-like features indicate portions of continental margin which were receiving less of a push from the supposed convection cells responsible for drift, and so got left behind. It seems less likely that they could result from a continent's momentum moving it away from loose fragments, once the driving force was reduced. A more extreme mode of origin would invoke variation in relative strength of apparently opposed convection cells (such as those forming a V around the eastern and western sides of Africa) so that the continental drift was somewhat oscillatory rather than unidirectional. However, even with such a mechanism it would still be necessary to invoke localized variation in the strength of the push given to continents.

5. Main conclusions

1. The continuous reflexion profiles show that rocks of basement type occur farther oceanward than the depth of 500 fathoms (914 m) chosen by Bullard *et al.* (1965) to define the edge of Europe resulting from continental drift.

2. Cretaceous rocks appear to be the earliest continental slope deposits present at the eastern side of the North Atlantic. They are widespread, so that the Atlantic Ocean (including Rockall trough, Porcupine Seabight and the Bay of Biscay) had been formed by then.

3. There was an episode of erosion of the continental margin during the late Cretaceous to early Tertiary times.

4. Tertiary continental slope and shelf deposits are widespread. The latter encroached progressively on to the edge of the continental block as it was downwarped but are unlikely to have been laid on much of Scotland and Ireland as the axis of downwarping lay west of the present coast.

5. Cenozoic rocks are thickest west of both the English Channel trough and the Aquitaine basin with upbuilding amounting to 4 km and outbuilding of many kilometres. In general, the amount of downwarping and the thickness of continental margin deposits is small compared with corresponding values for the eastern continental margin of U.S.A.

6. Faults probably of pre-late Cretaceous age appear to define the steep northern and western sides of Iberia.

7. Important faulting, canyon cutting and slumping took place on the continental margin towards the end of the Cenozoic time.

8. The present continental shelf may range from early Tertiary to Quaternary in age.

9. The episodic evolution of the European continental margin may be an indication that the Atlantic Ocean was formed during two periods of continental drift.

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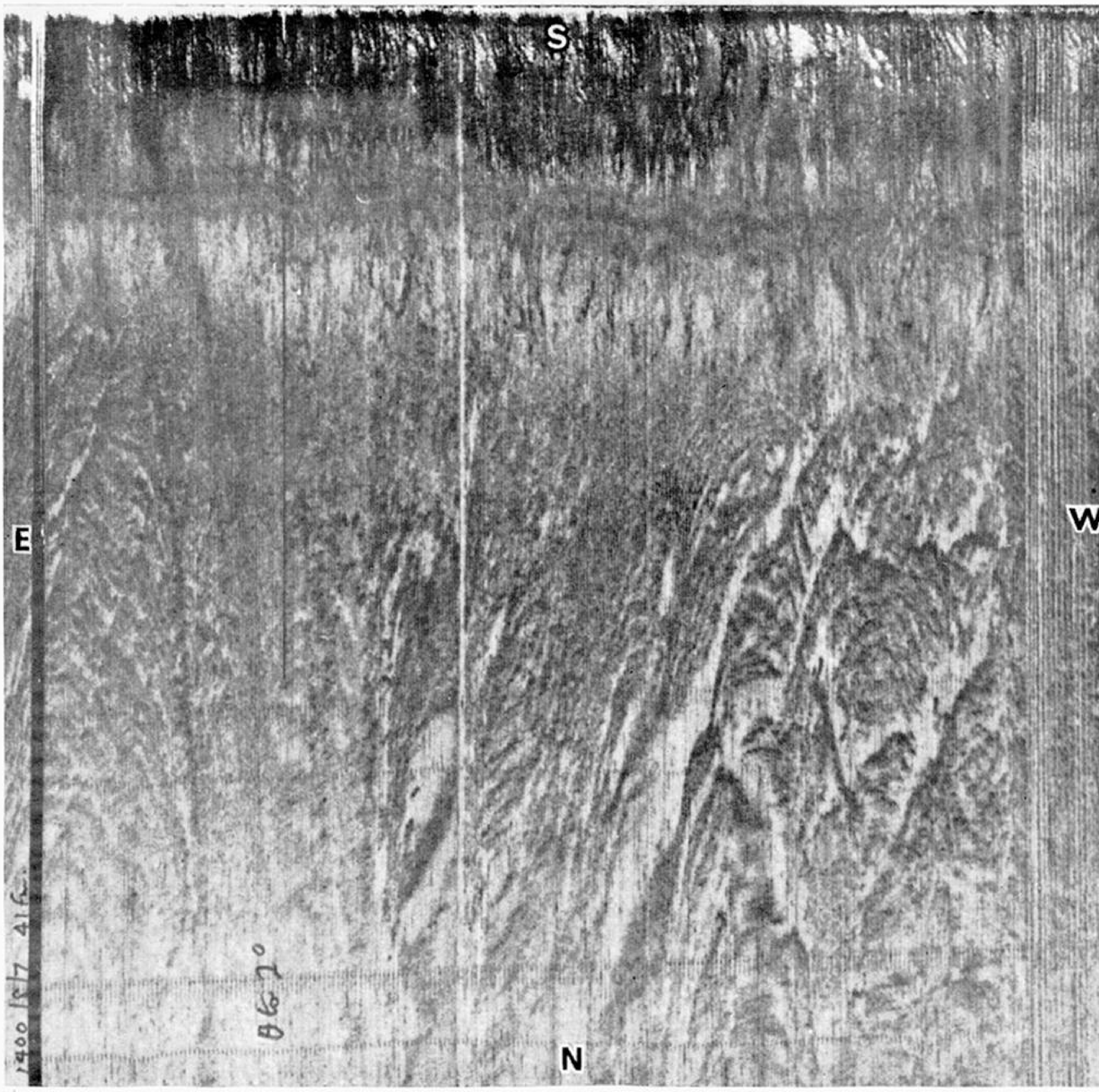

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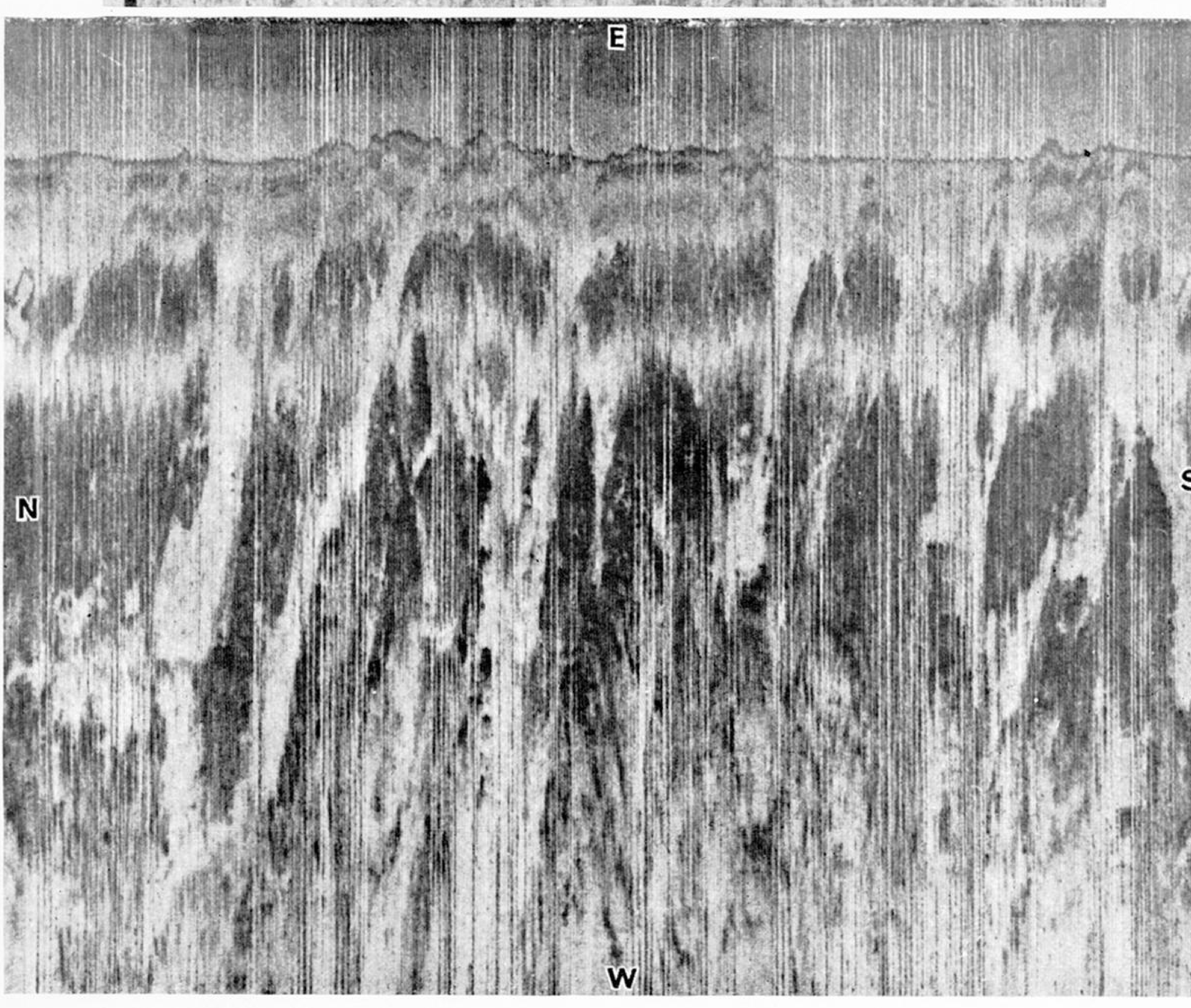

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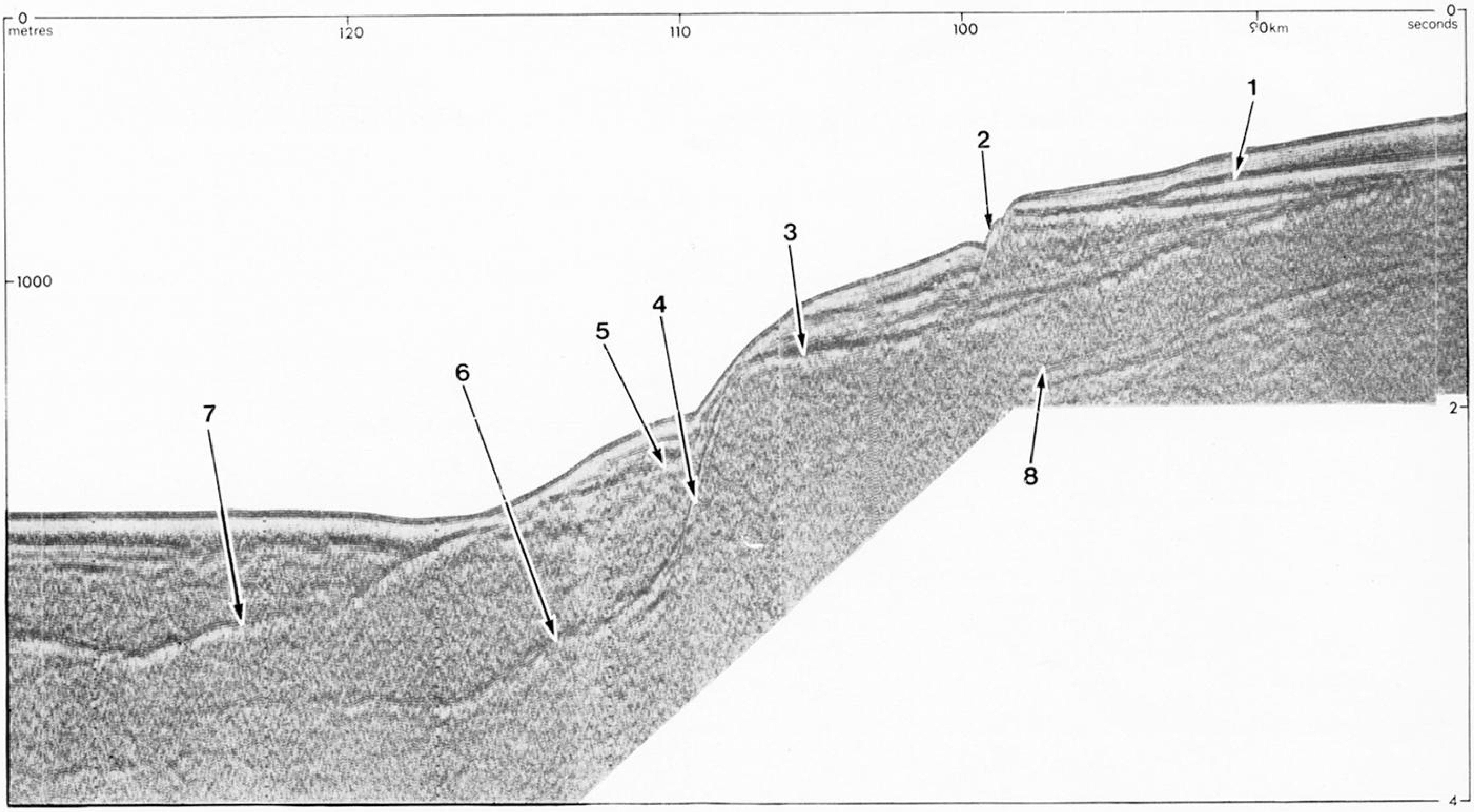
FIGURES 5 AND 7. For legends see facing page.



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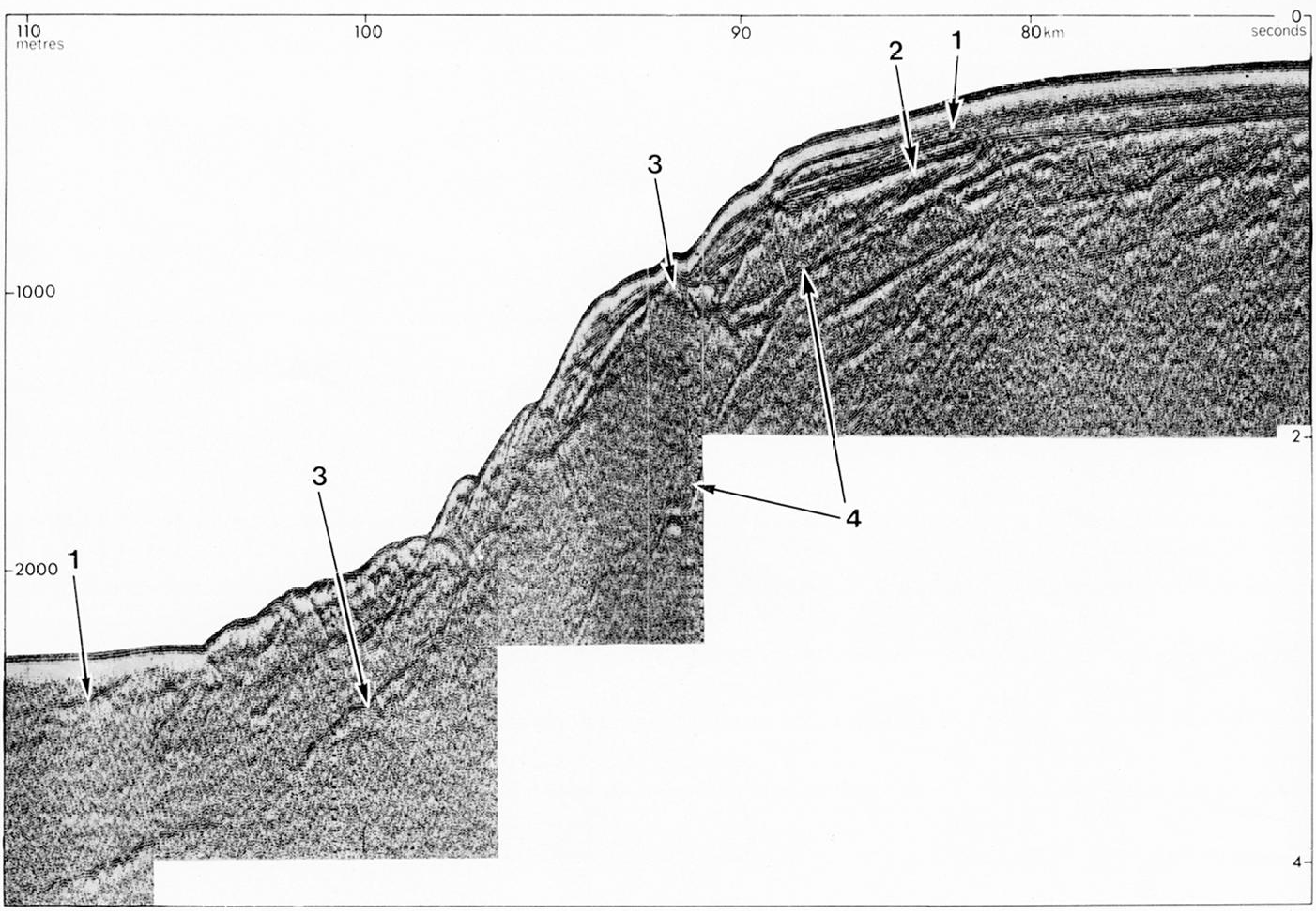

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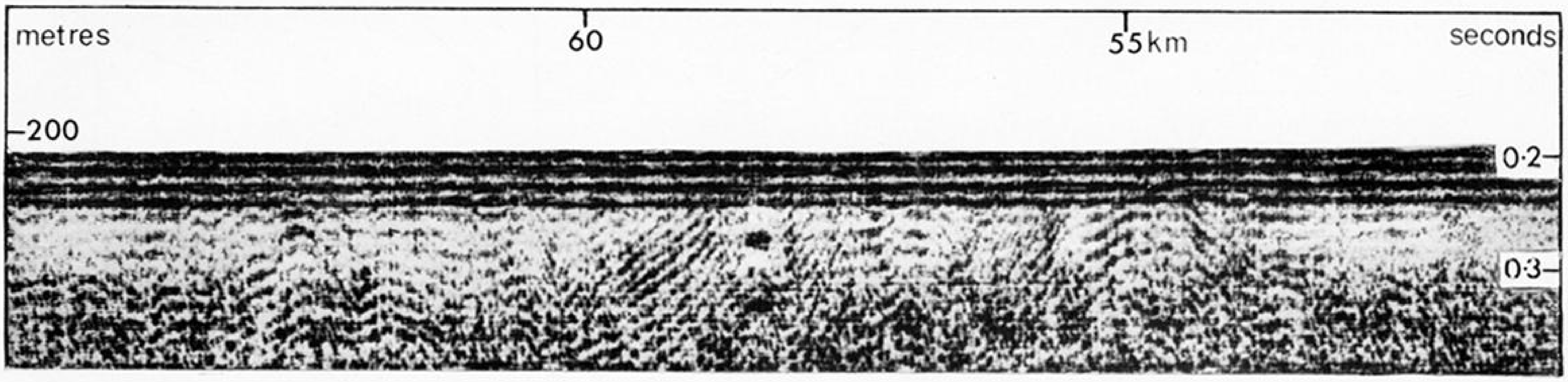
FIGURES 8 AND 9. For legends see facing page.

FIGURE 6. Line drawings of continuous reflexion (Arcer) profiles ① Pentland, ② St Kilda and ③ Bloody Foreland shown as tentative geological sections of the continental margin. The 20 km marks correspond with those on the courses shown in figure 4. Presumed Upper Palaeozoic and Cretaceous strata are shown by P. and Cr., respectively. Unconformities are shown by blue lines, and fault or slump planes by red lines.

For legend see facing page.

FIGURE 10. Line drawings of continuous reflexion (Arcer) profiles ④ Tralee and ⑤ Mizen Head, shown as tentative geological sections of the continental margin west of Ireland (figure 4). Unconformities are shown by blue lines, slump and fault planes by red lines. Abbreviations, P. = Palaeozoic; Ig. = igneous; while Cr. = Cretaceous and Eo. = Eocene are sample stations which have been projected into the profiles.



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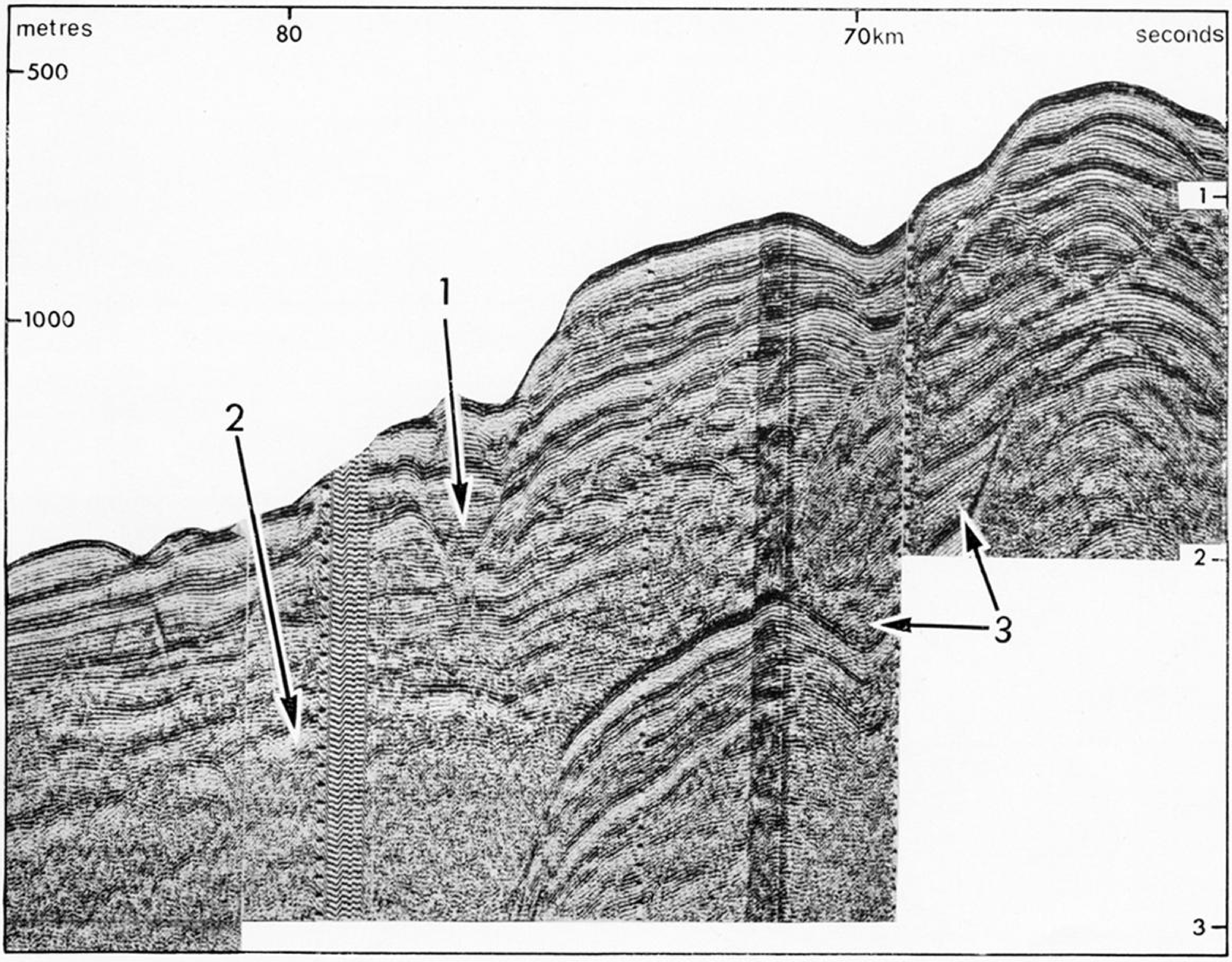

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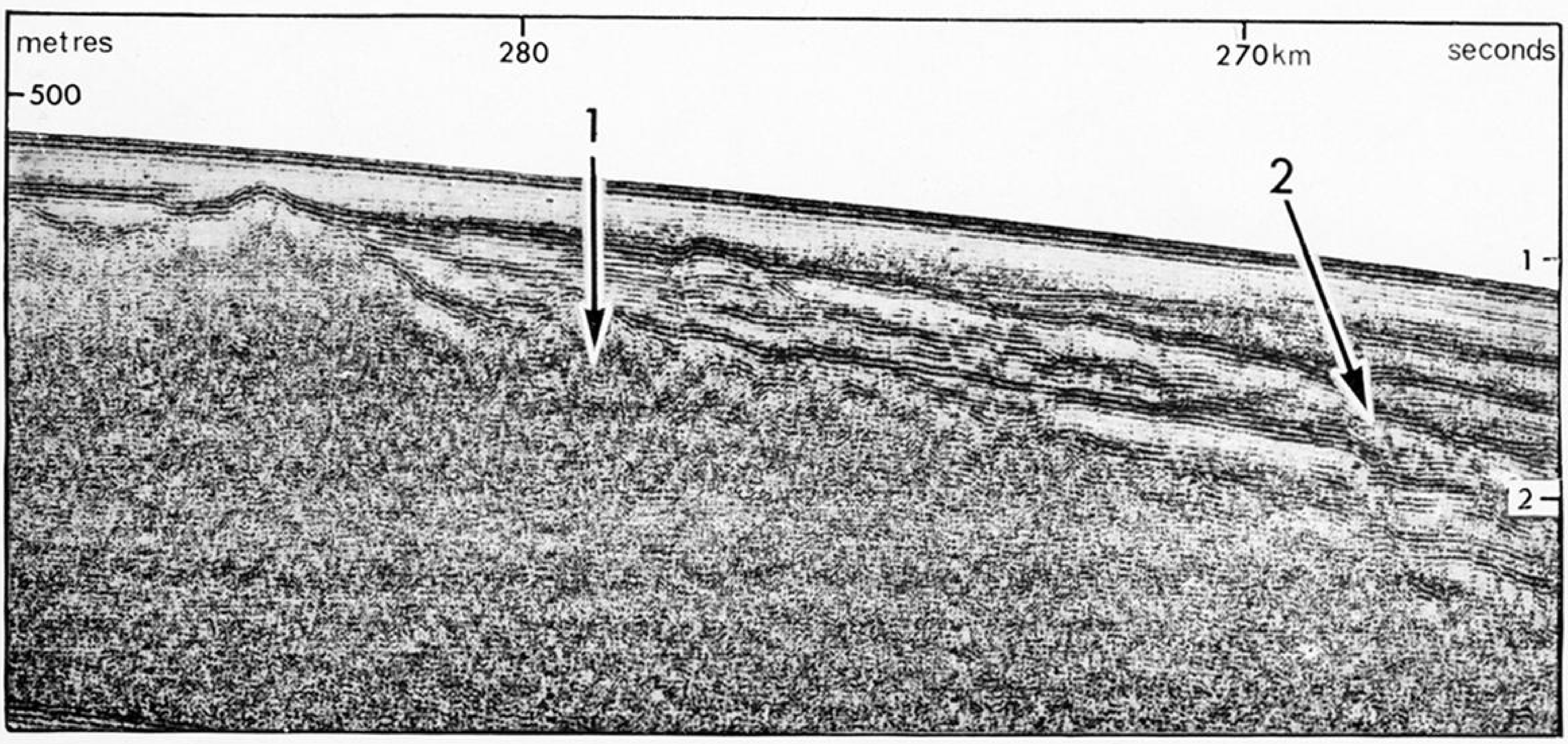

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FIGURES 11 TO 13. For legends see facing page.

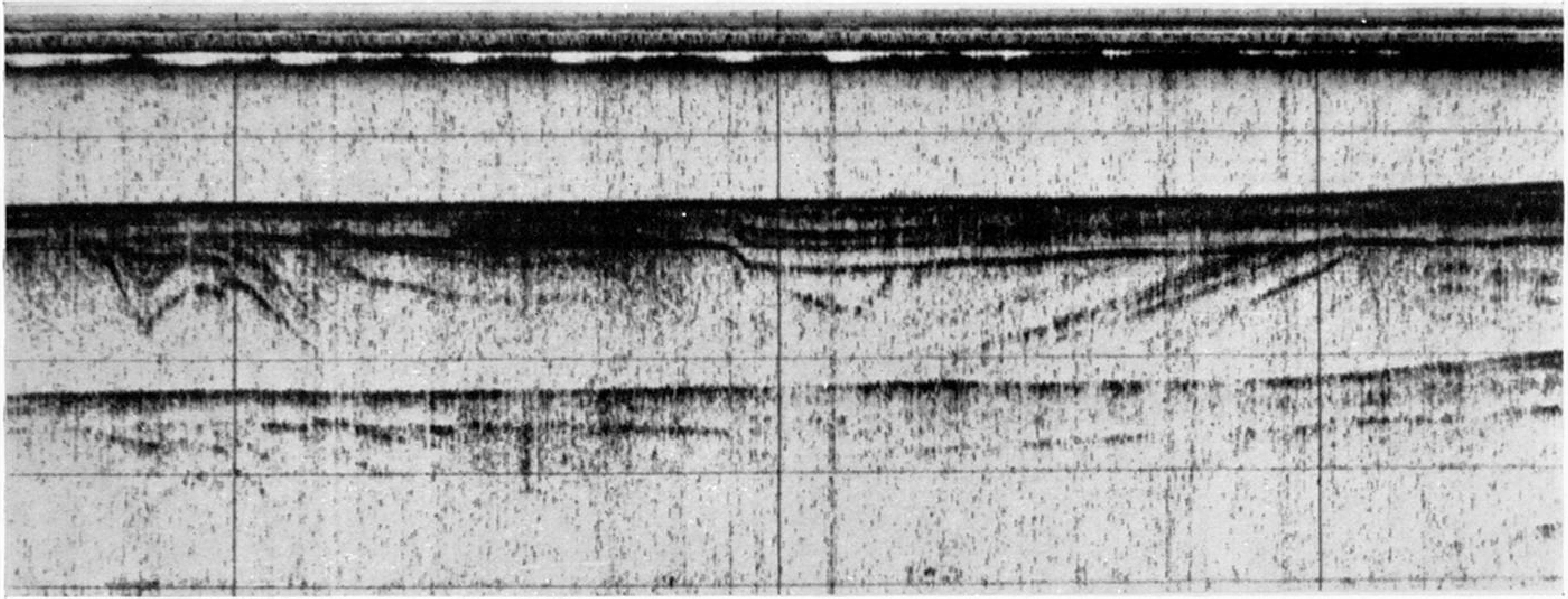


FIGURE 15. An 8 km long north–south section in the Celtic sea, south of Ireland, located on profile 1 of figure 14. A vertical scale, of 118 m is provided by the depth of water above the sea floor. Flat-lying, presumed Tertiary sediments broken by a fault, lie with marked discordance on gently folded strata of presumed Cretaceous age.

FIGURE 18. An acoustic map of 8 × 1 km of sea floor west of Brittany (black rectangle in figure 17) showing ragged outcrops (dark tones), of Palaeozoic or metamorphic aspect, separated by flat, sandy floor.

FIGURE 16. Line drawings of continuous reflexion (Arcer) profiles ⑥ Great Sole and ⑦ Little Sole, shown as tentative geological sections of the continental margin at the western end of the English Channel trough (figure 14). Unconformities are shown by blue lines and fault or slump planes by red lines. Abbreviations: Cr. = Cretaceous, while Eo. = Eocene and Mi. = Miocene are from sample stations projected into the profile.

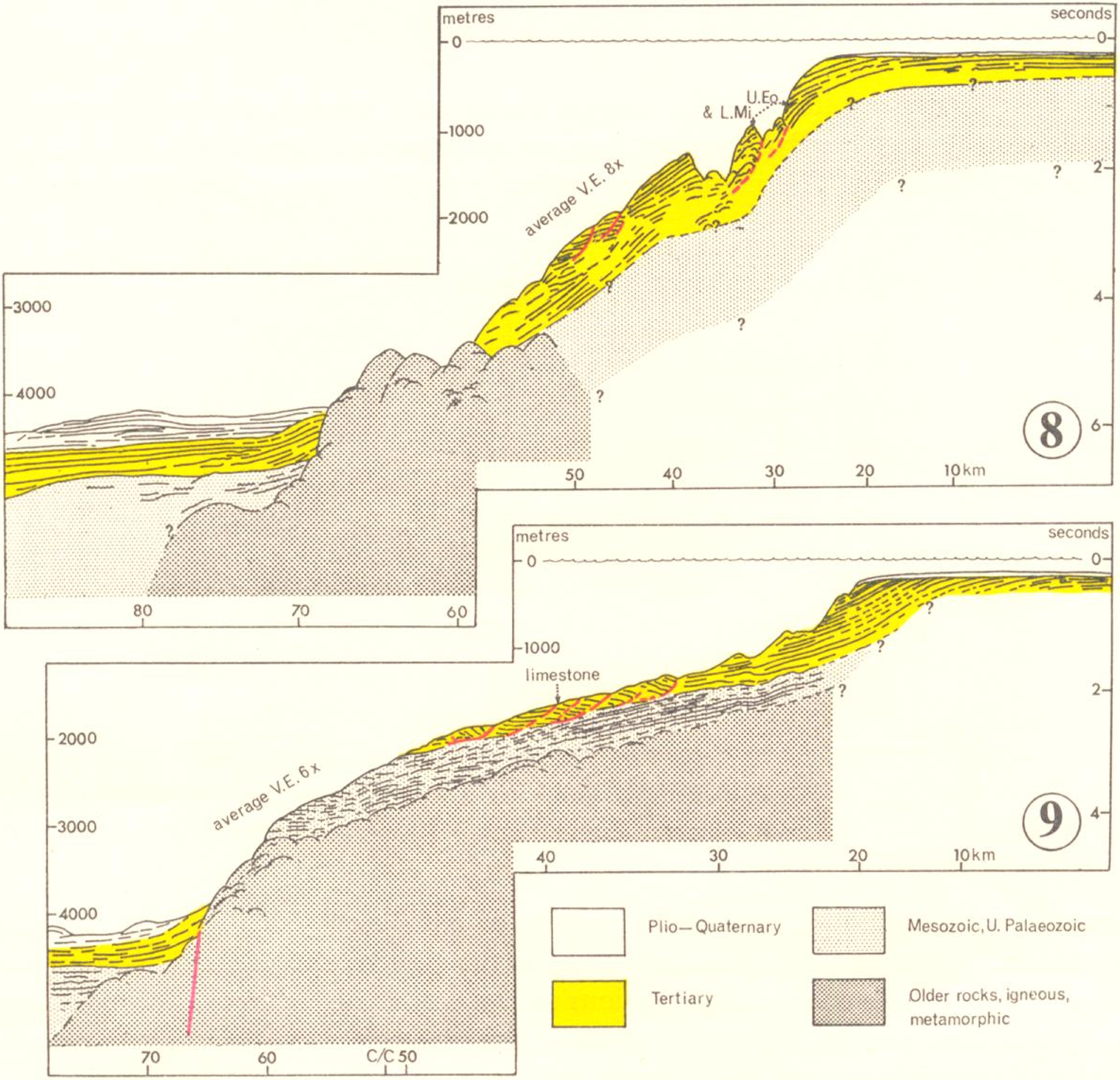


FIGURE 19. Line drawings of continuous reflexion (Arcer) profiles ⑧ Brest and ⑨ Loire, shown as tentative geological sections of the continental margin west of France (figure 17). Unconformities are shown by a blue line and fault or slump planes by a red line. Abbreviations, Eo. and Mi. refer to Eocene and Miocene sample stations projected into the profile.

FIGURE 21. Line drawings of continuous reflexion (Arcer) profile ⑩ Aquitaine, ⑪ Bilbao and ⑫ Santander shown as tentative geological sections of the continental margin around the south-eastern corner of the Bay of Biscay (figure 17). The compressional wave velocities (km/s) for profile ⑩ were provided by Professor P. Muraour and the value given in profile ⑪ was derived from the apparent curvature of the strata. The abbreviation Cr. = Cretaceous, while T_1 to T_4 are provided for correlation with profile ⑪.

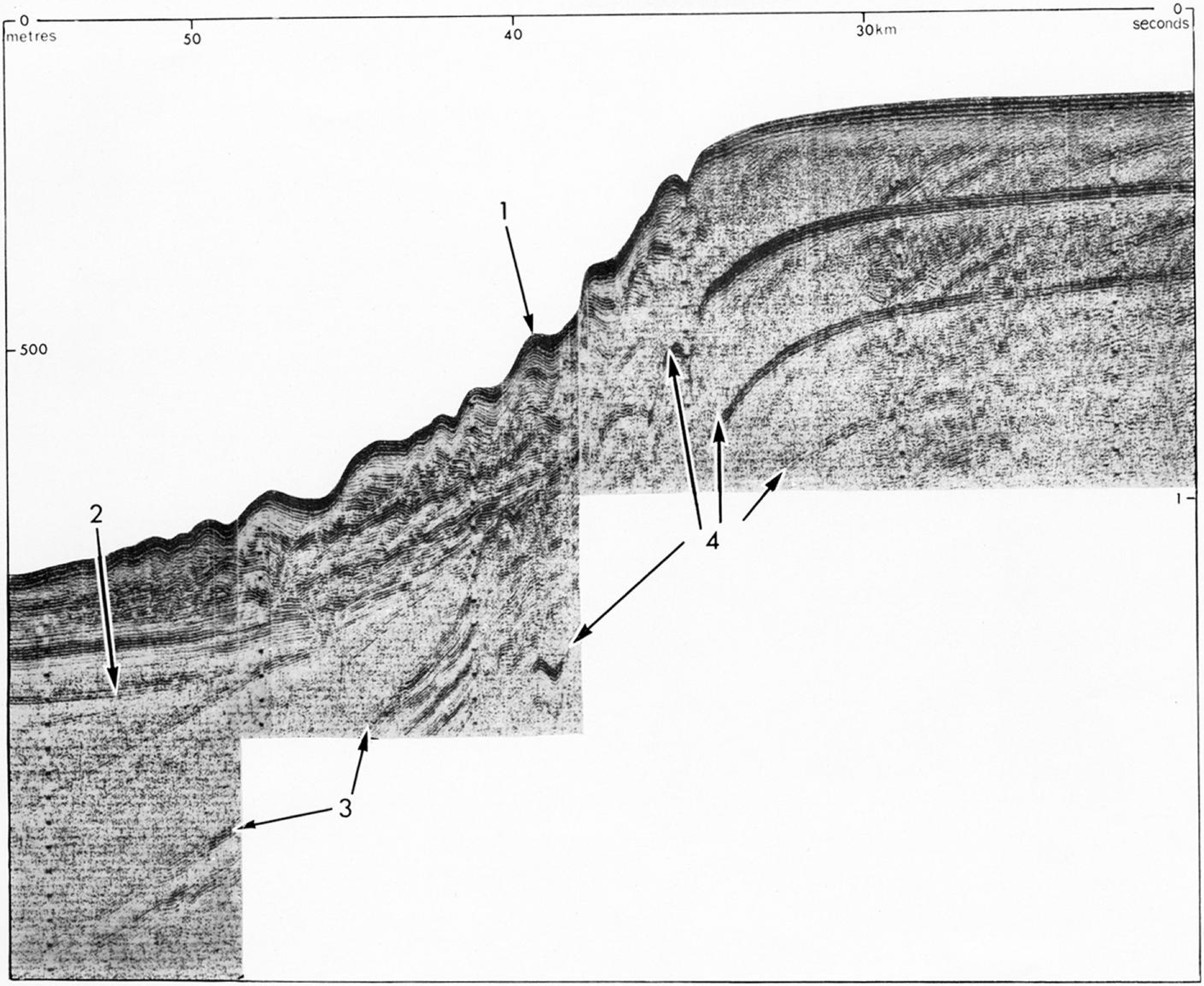


FIGURE 22. A photograph of the original Arcer record (within the limits set by the double headed arrow in profile ⑩ of figure 21) showing slump folds at the top of the continental slope off south-western France (figure 17). Undulations, 1, in the profile of the sea floor, which decrease progressively in amplitude within the underlying sediments, are interpreted as slumps. Interface 2, is the base of rock unit T_4, while interface 3 separates the supposed Tertiary and Cretaceous strata, and, 4 indicates multiple reflexions of the sea floor.

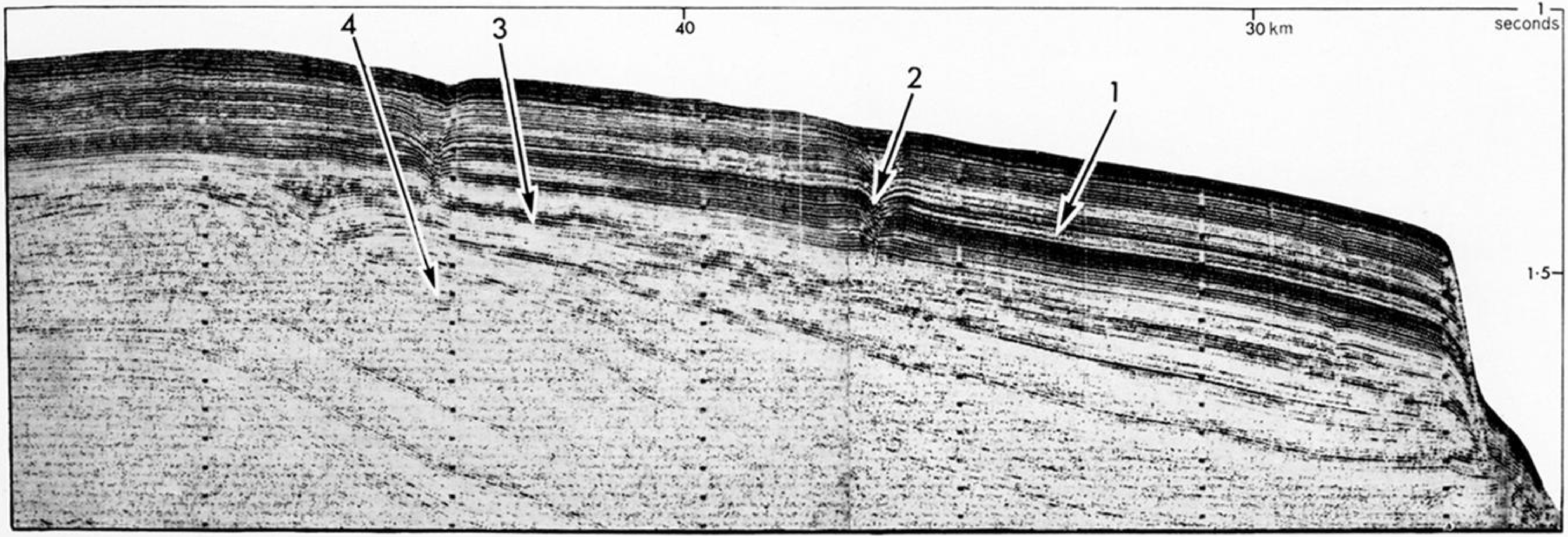
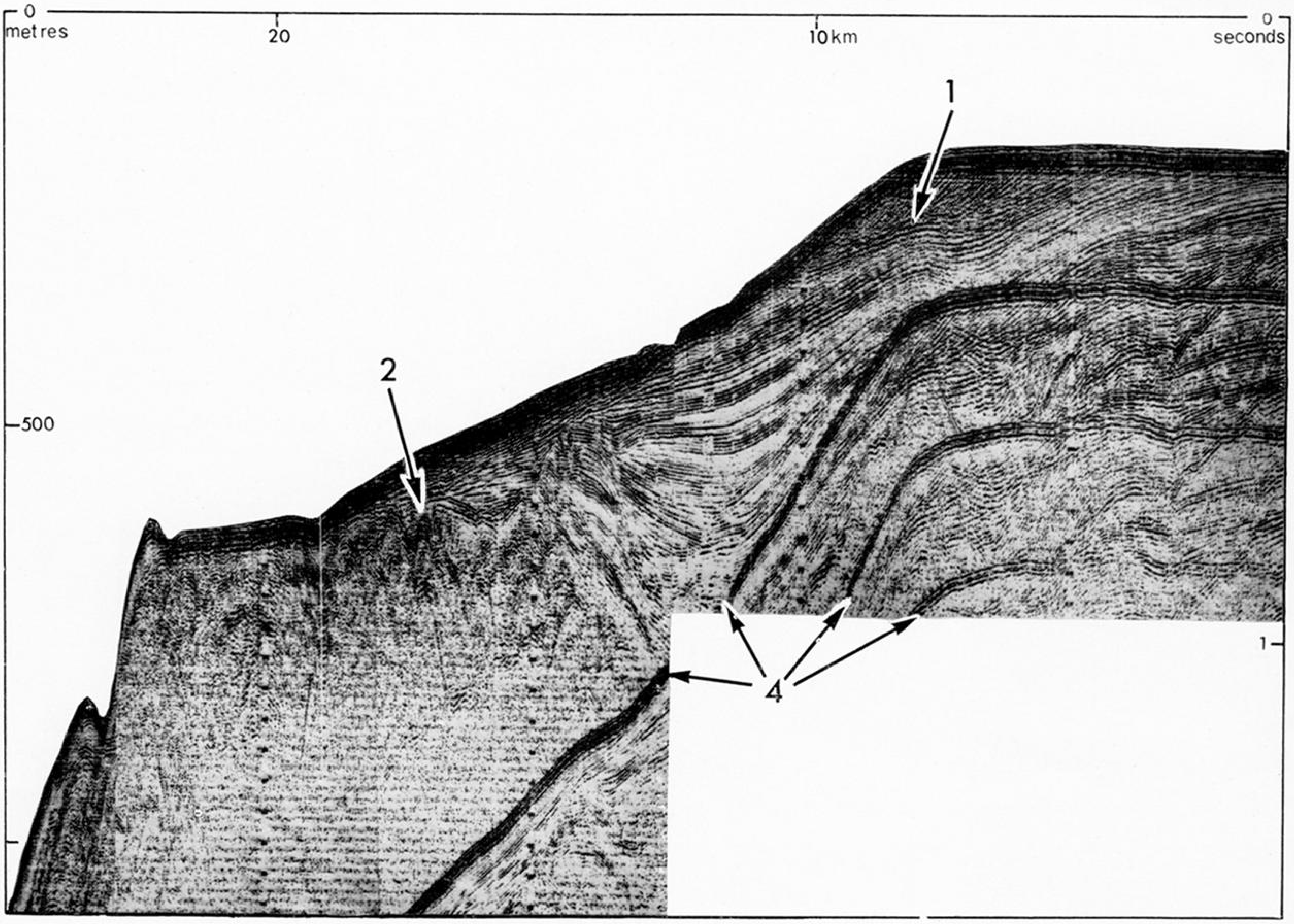
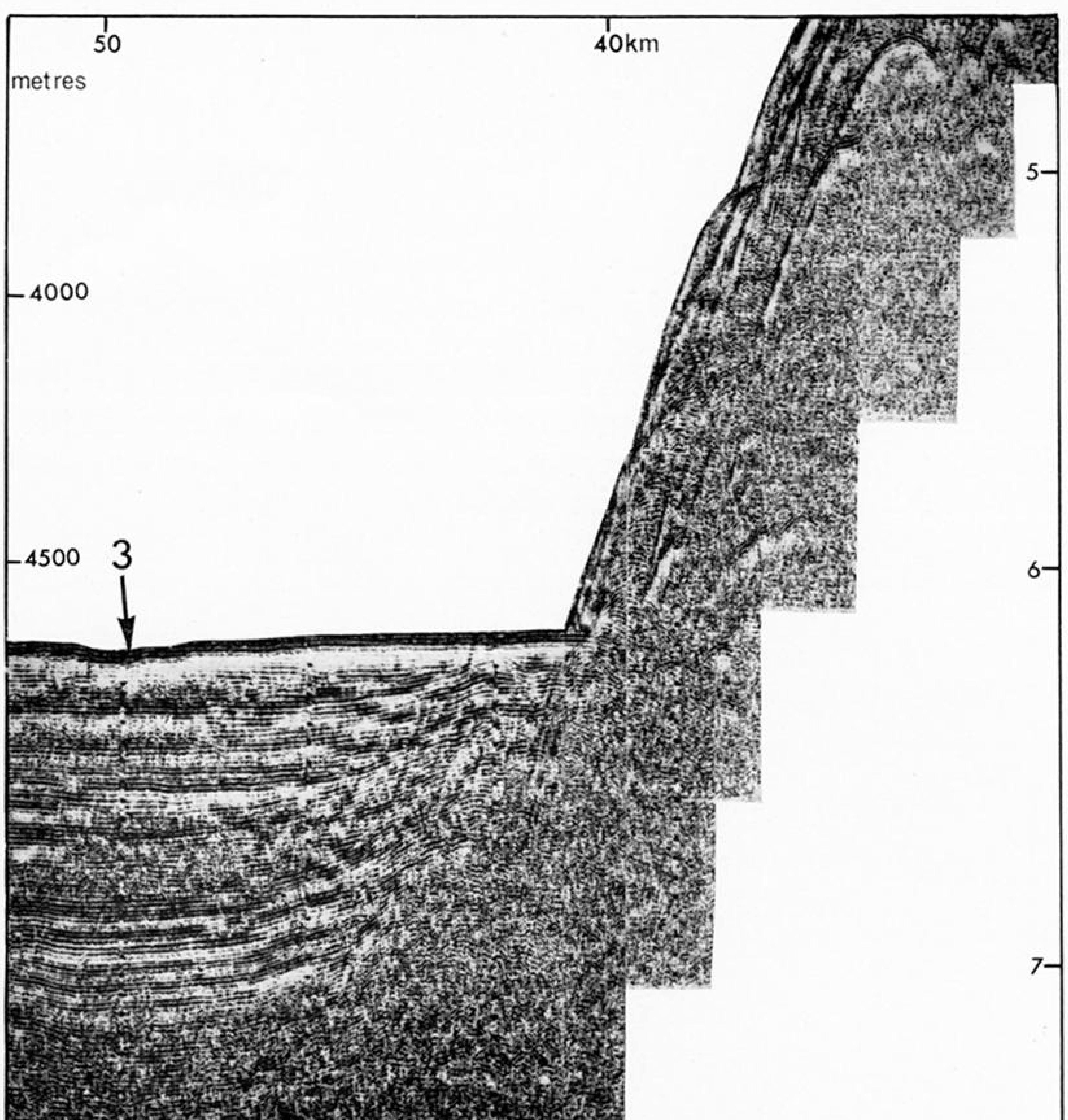


FIGURE 23. A photograph of the original Arcer record (within the limits set by a double headed arrow in profile ⑪ of figure 21) showing strata on the continental slope which dips towards the north wall of the Cap Breton canyon and Northern Spain (figure 17). The assumed boundary between Quaternary and Tertiary sediments is shown by 1; a channel filled with Quaternary sediments by 2; the base of rock unit T_4 by 3; and the base unit T_3 by 4.



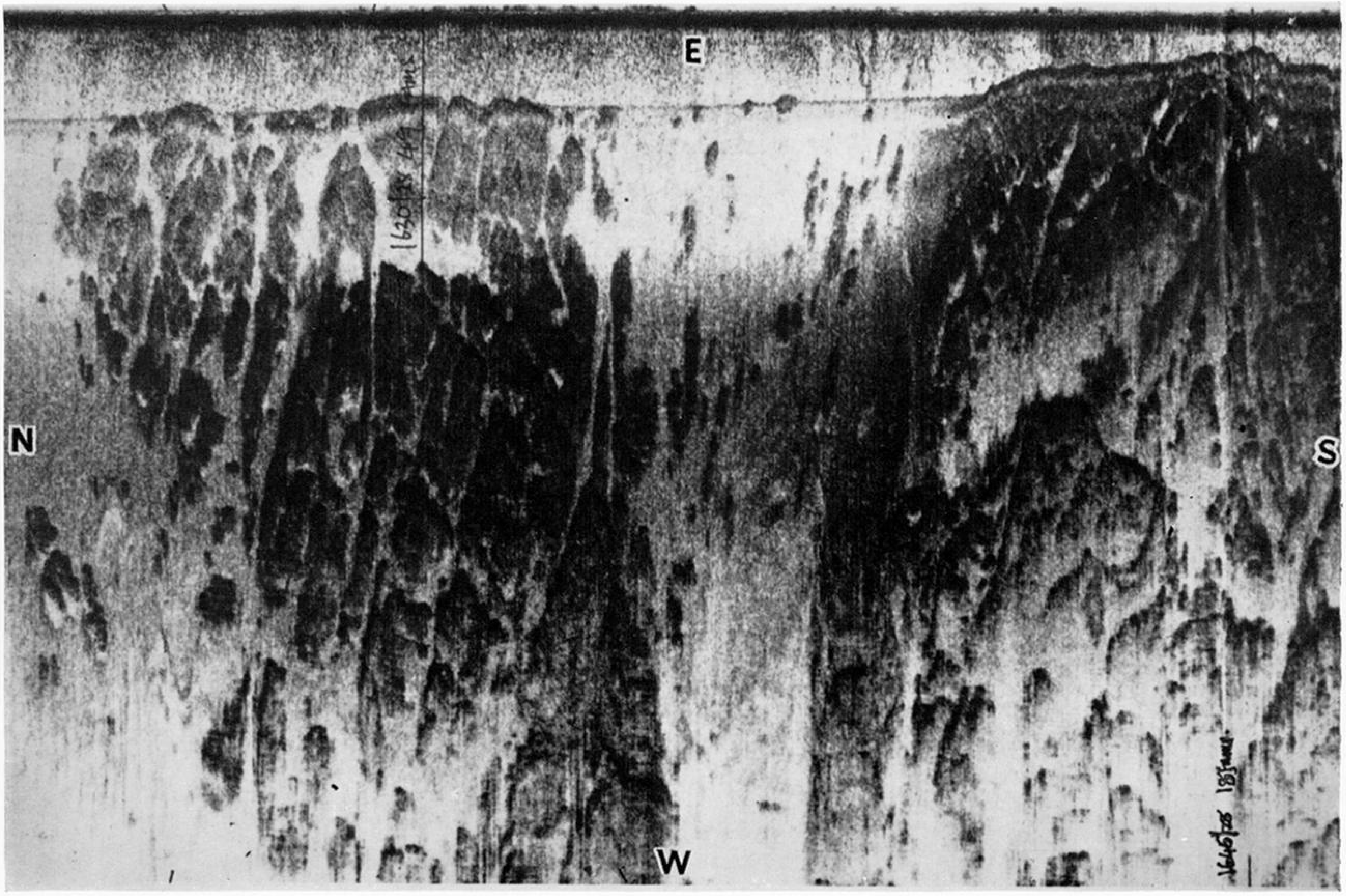
25



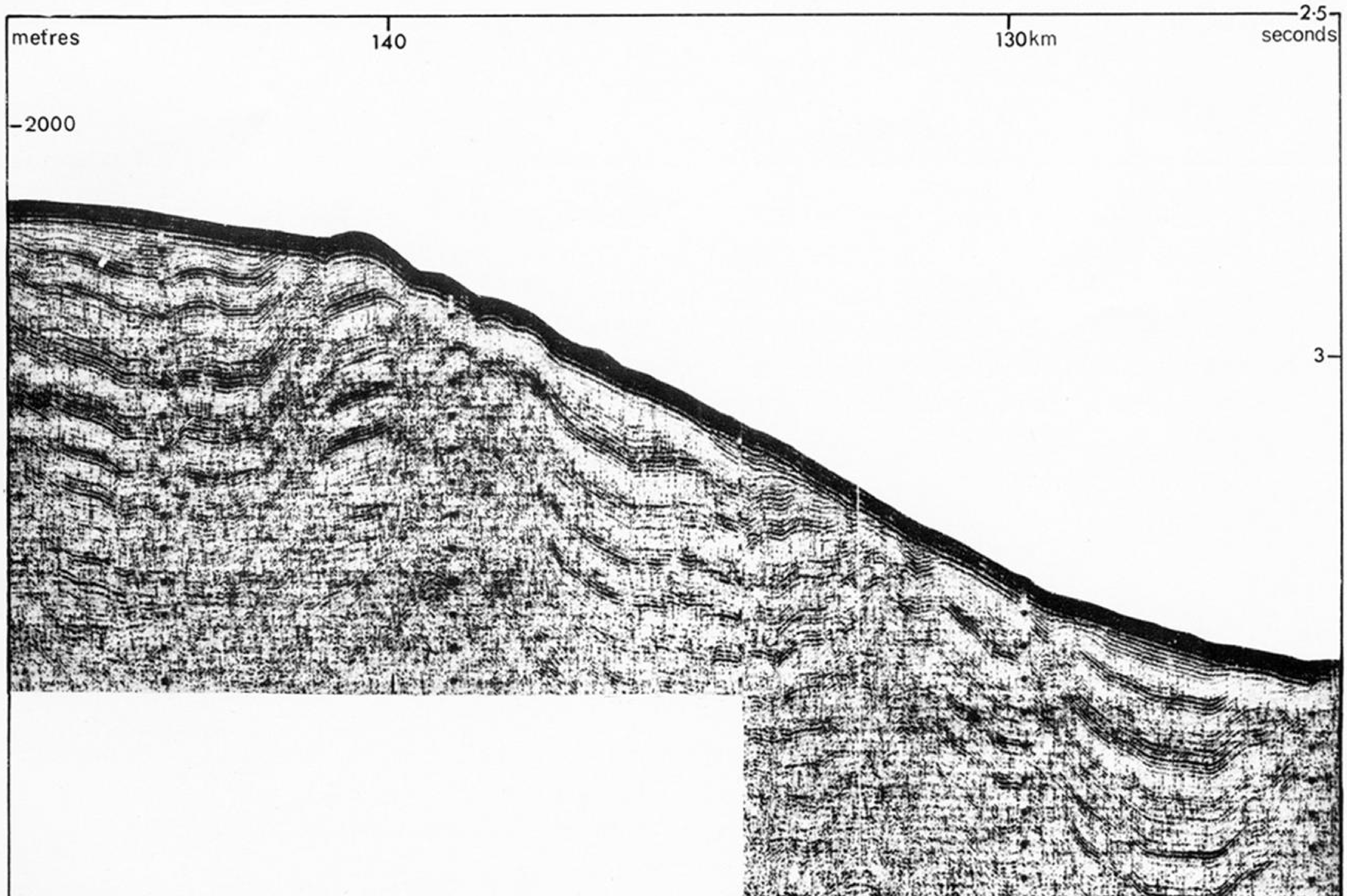
26

Figures 25 and 26. For legends see facing page.

Figure 24. Line drawings of continuous reflexion Arcer profiles ⑬ Oviedo, ⑭ La Coruna, ⑮ Finisterre and ⑯ Lisbon, shown as tentative geological sections of the continental margin around Iberia (figure 27). Unconformities are shown by blue lines and fault planes by red lines. Abbreviation: Cr. = Cretaceous.



28



29

Figures 28 and 29. For legends see facing page.

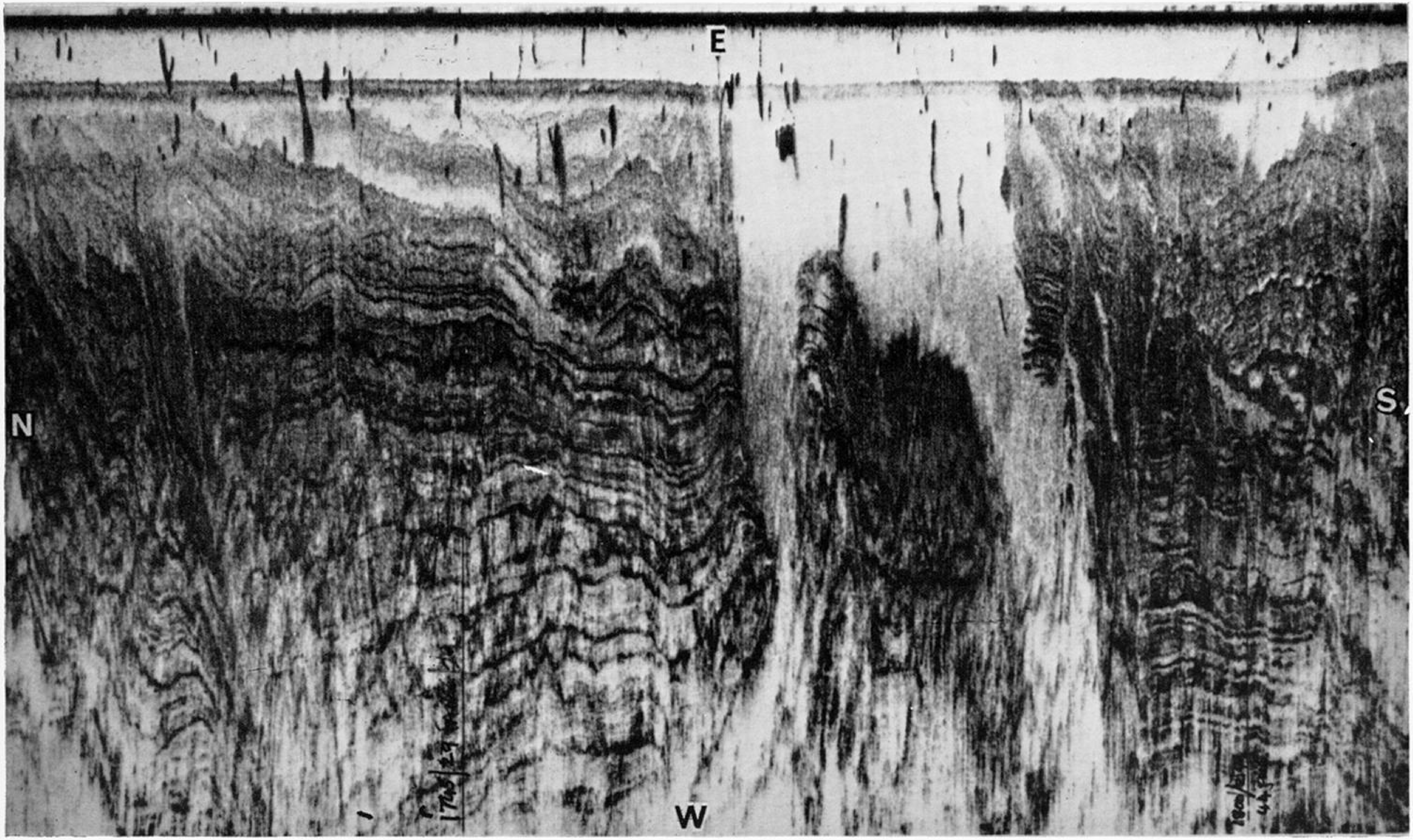


FIGURE 30. An acoustic map of 8 × 1 km of continental shelf located 25 km oceanward of the Jurassic rocks of western Portugal (black rectangle in figure 27) showing three large outcrops of sedimentary strata separated by relatively flat floors of sandy material. Adjacent beds of rock are of somewhat variable hardness such that the more resistant layers stand proud as scarps (narrow dark lines) and the gentle dip slopes (broader grey bands) face towards Portugal. The prominent black blobs in the upper part of the record are echoes from fish or plankton.