THE GEOLOGY OF THE WESTERN APPROACHES OF THE ENGLISH CHANNEL

II. GEOLOGICAL INTERPRETATION AIDED BY BOOMER AND SPARKER RECORDS

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[Plates 24 to 29]

CONTENTS

A geological map of about 1700 square miles of the sea-bed south of the Cornish coast between Bolt Head and Fowey was prepared by coring and dredging for rock samples; a boomer-sparker survey was then selected in relation to the supposed geology to fix more precisely the geological boundaries and to ascertain the geological structure of the rocks underlying the sea-bed, in this case to a depth of about 400 ft.

The acoustic apparatus is described; the records are interpreted according to mathematical analysis and the probable limits of inaccuracy assessed.

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91 rock samples are described lithologically and the microfossils identified in all productive cases to give the stratigraphical ages. In some samples radiometric determinations have been made of the ages of the metamorphism of 'gneisses' and slates. All contacts are unconformable between the following major divisions: Metamorphic Complex, ?Devonian, New Red Sandstone, Upper Cretaceous, Eocene; the base of the Lias is unknown but these rocks form an inlier and are unconformably surrounded by the Upper Cretaceous. Pre-Santonian, Santonian, Campanian, Lower and Upper Maestrichtian are recognized; Danian appears conformable to the Maestrichtian but is included in the Tertiary although it is unconformably succeeded by Eocene; there is presumptive evidence of ?Oligocene in one cored sample.

True-scale sections drawn along the course of the ship using corrected apparent dips and applying different velocities to different rock-types gave the following approximate thicknesses: New Red Sandstone, 3100 ft.; Lower Jurassic, greater than 640 ft. (base not seen); Upper Cretaceous, 1225 ft., comprising Pre-Santonian 75 ft., Santonian 175 ft., Campanian 375 ft., Maestrichtian 600 ft.; Danian, 375 ft.; Eocene, greater than 430 ft. (top not seen).

In this particular combined experiment the boomer-sparker equipment has proved invaluable in correcting geological boundaries, in determining geological structure which with present coring methods at sea is almost impossible to detect, and in providing reasonably reliable figures of the thickness of major stratigraphical divisions. These two geological and geophysical investigations are mutually complementary and, with much greater energy output than was used in 1960, the promise is great for the determination of geological structure many thousands of feet below the sea-bed.

I. INTRODUCTION

The conditions of sedimentation which obtain on the sea-floor of the Western Approaches of the English Channel are such that about 60 % success can be achieved in collecting rock-samples at selected stations using the Stetson-Hill corer. Bare rock not infrequently forms the bottom, more commonly it supports a few inches of loose sediment, and under either of these circumstances a short core collected from rock *in situ* can be expected to be recovered. There are, however, expanses of the sea-bed which are covered by coarse, subangular, rocky detritus, by gravel, or by thick sands, which for one reason or another defeat attempts to penetrate them, and rock-cores are unobtainable by the methods that have been employed up-to-date. Such obscuring mantles of loose sediment become more widespread the farther west coring proceeds until, presumably, nowhere will rock-cores be collected from these areas of the continental shelf. At the time of writing cores have successfully been raised as far west as longitude 8° W., between latitudes $48\frac{1}{2}^\circ$ to $50\frac{1}{2}^\circ$ N. (Curry, Martini, Smith & Whittard 1962, fig. 1).

Proceeding at the same time as the coring work on the continental shelf, and primarily at Woods Hole Oceanographic Institution, were studies in methods of acoustic surveying which led, among other developments, to the design of the Continuous Seismic Profiler (C.S.P.) which incorporates either the sparker or the boomer. These are electronic devices for putting into sea-water repetitive sound pulses having a broad spectrum. Low frequencies in the spectrum of these pulses are not so rapidly attenuated in sub-bottom rocks as are the high frequency pulses of echo-sounding; they therefore possess greater penetration and enable the geological structure to be determined down to a depth of a few hundred feet.* By assuming the velocity of sound in water as known, and by measuring the travel

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* In 1961, using energy greater by a factor of from 13 to 25 than in 1960, the depth of rock penetrated aboard *Chain* below 2200 fathoms of water was of the order of two-thirds of a mile. This record was obtained with a 13000 joule boomer; the pulse-energy of the boomer used in the English Channel in 1960 was 1000 joules.

times of arrivals at the hydrophone over paths that can be identified by interpreting the recordings, the system can be used for measuring, first, the velocity of seismic, usually P, waves in rocks or beds of sediment below the sea-floor and, secondly, the shape and attitude of these bodies. In the investigation here reported, the C.S.P. has been used solely for the latter purposes, and the velocity data for rocks exposed on the floor of the English Channel (Hill & King 1953, p. 15) have been utilized in the interpretation of our results.

The geological approach on the one hand and the geophysical on the other were co-ordinated in a specific problem, which was designed to ascertain whether the methods were complementary, and to what extent they proved of mutual assistance. Accordingly, through the help of Dr T. F. Gaskell, a meeting at sea in September 1960 was arranged with R.V. *Chain* from Woods Hole and R.V. *Sarsia* from Plymouth. A course was chosen which traversed an area where the presence of a wide variety of rocks had already been proved by coring; this ran about 52 miles southwards from near Looe Island (see figure 6, facing p. 322), then returned northwards and a few miles to the east for another 30 miles; the course so selected traversed much of the sea-bed where Hill & King (1953, p. 4) had laid seven different stations for seismic refraction shooting, and a comparison could thus be made between some of their results and those presented here. The boomer and sparker were used aboard *Chain* and some parts of the unique and clear record which was obtained are reproduced on plates 24 to 29.

Hersey and others from Woods Hole devised the apparatus and took the record; Curry determined the Foraminifera and Ostracoda, and Martini the nannoplankton in the Cretaceous and Tertiary rocks; Whittard, assisted by Mr I. H. Ford, obtained the cores and described rocks older than the Cretaceous; accounts were supplied of metamorphic types by Professor F. C. Phillips, of Jurassic macrofossils by Professor D. T. Donovan, of Jurassic microfossils by Dr C. G. Adams and of X-ray mineral analyses by Mr R. Bradshaw; Mr N. F. Hughes examined ?Devonian slates for microflora; radiometric age-determinations have been communicated by Mr N. H. Dodson; Curry and Whittard prepared the stratigraphical analysis; all authors contributed to the interpretation of the records and to the geological conclusions to be drawn from the joint investigations.

II. Description of apparatus

The Continuous Seismic Profiler described here (Knott & Hersey 1956; Hoskins & Knott 1961; Hersey 1963) and the Seismic Profiler of Ewing & Tirey (1961) were similarly named because each provides automatic correlation of trains of waves from successive sound pulses in regular sequence. These trains of waves are so processed as to present a profile of the sea-bottom and of discontinuities in the sea-floor, the profile being built up continuously as the operating ship proceeds. The C.S.P. is a system of instruments having the essential elements of any echo-location system, namely a source of radiation, a receiver and a recorder for measuring time of travel.

The sound-source of the C.S.P. is triggered synchronously with the sweep of the recorder and emits a short pulse of high pressure, followed immediately by one or more lesser pulses. Reflected pulses from the sea-bed and below are received by an omnidirectional hydrophone. The electrical output of the hydrophone is amplified and then filtered to remove high frequencies, and the signals associated with successive pulses are recorded as variations in darkness in the line produced by the sweep-action of the recorder. The emitted pulse-sequence is referred to as a 'wave-train', which expression is used also to refer to its corresponding reflected pulses, to the resulting electrical variations which are fed to the recorder, and finally to the sequence of variations in darkness which result from the electrical variations.

The recorder displays the signals associated with successive wave-trains side by side. By this device, long familiar in echo-sounding, successive reflected pulses ('echoes') from the same reflector can be correlated in noise or other interfering signals. The records of the successive echoes from a single reflector form a characteristic pattern. Such a succession of echoes (or the pattern which they produce) is known as an 'echo-sequence'. When echoes are being received from a continuous surface, such as the sea-bed or a rock interface, the echo-sequences from individual reflectors merge to produce a continuous dark line (or, rather, several close-set parallel lines) in the record. An essential feature of the system is the repetition of the emitted pulse-sequence at a rate which ensures that the travel-time of a wanted echo does not change between successive pulses by a large fraction of the duration of the echo itself.

The C.S.P. employs a Precision Graphic Recorder (P.G.R.) (Knott & Hersey 1956), identical in principle with that which Marti (1922) invented for echo-sounding. The P.G.R., adapted from a facsimile recorder developed by the Alden Products Company, records electrochemically on a paper impregnated with a solution which reacts with the positive electrode to deposit iron oxides on the paper when a current passes through it. The electrical signal may be rectified either with a full-wave or with a half-wave rectifier. In the former case, both positive and negative signals are recorded; in the latter, one set, either positive or negative, is suppressed. The deposit is darker the larger the current between minimum and saturation levels, which set in at values of current which are inversely related to the sweep-speed of the recording stylus. When the recording current has been adjusted correctly to fall between minimum and saturation, and when the recording paper is uniformly wetted, then the amplitude of different parts of the wave-train can be compared reliably. The darkness of recording, however, is not a reliable means of comparing amplitudes unless both conditions are met; often on board ship this combination is unattainable.

Ability to correlate corresponding events on successive sweeps is greatly enhanced if the sweep of the P.G.R. is fast enough to resolve individual positive and negative signals. Obviously, the ratio of the sweep-speed of the recorder to the wave-period will be determining. Under favourable circumstances, the zero crossings of the echo-sequences are clearly displayed as white lines between dark bands of the positive and negative peaks, thus providing information about the phase-relation between successive wave-trains. For slower sweep-speeds the zero crossing may be obscured and phase correlation lost. By using a half-wave rectifier either the positive or the negative peaks are recorded, the set not recorded forming white bands in an echo-sequence; phase information is then retained to considerably slower sweep-speeds. Waves having periods of about 0·005 s have been resolved at sweep-speeds of 18 cm/s, but this is by no means an extreme. If phasal relations cannot be displayed owing to slow sweep-speed or short wave-period, full-wave rectification should be used to achieve the best results. Half-wave rectification was employed throughout the present study. A sample of part of the record is shown with a wave-train traced from a sweep of the oscilloscope observed to correspond with the sweep of the P.G.R. (figure 1).

Echoes recorded from reflectors buried by sediment or from within the crust of the Earth have originated mostly from high-order explosions, and their spectrum is well known to be poorer in high frequencies than that of the explosion itself. This observation suggests that

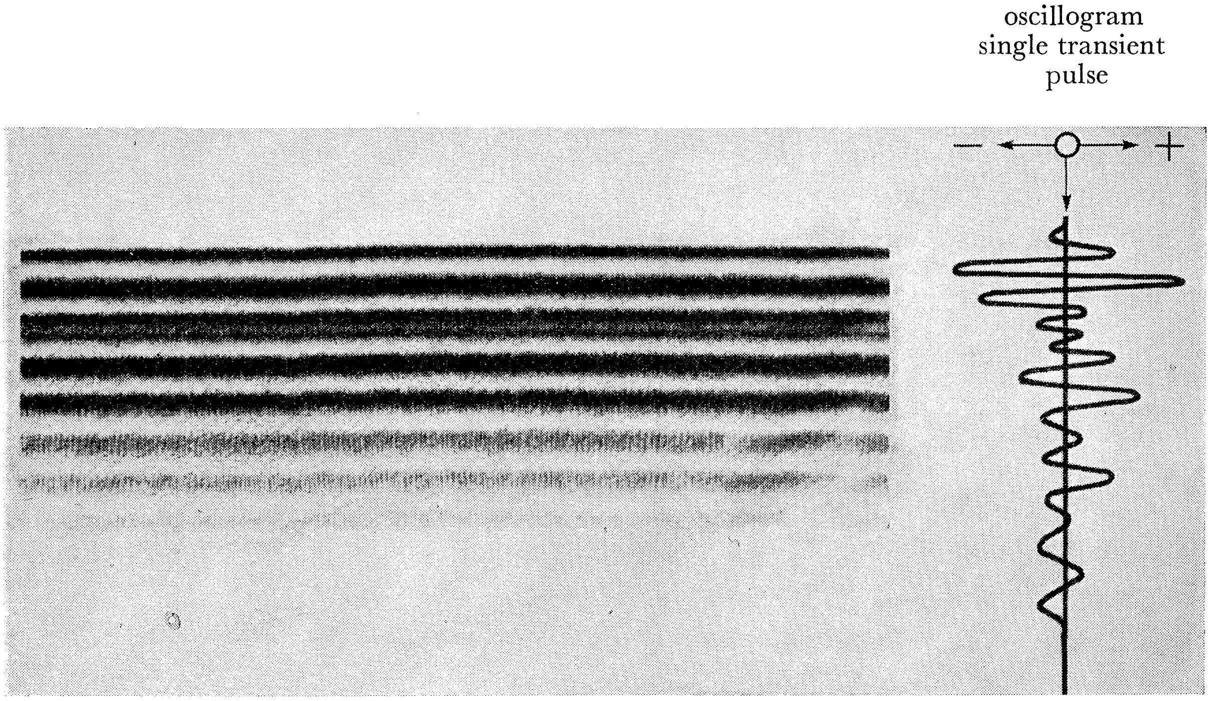


Figure 1. A P.G.R. record of successive printings of identical wave-trains compared with an oscillogram of a single wave-train. The dark bands on the P.G.R. record correspond to positive excursions of the wave-train.

high frequencies, as compared with low ones, are more highly absorbed in sediments and rocks. For example, Hersey & Ewing (1949) demonstrated that frequencies higher than the octave 400 to 800 c/s are not found in the spectrum of echoes of explosions that followed the echo from the sea-bed. These low frequency echoes were interpreted as coming from rocks buried under sediment in the deep sea, an interpretation which has been strengthened by the results of more recent studies of seismic refraction. For many years the band from 30 to 150 c/s has been used in seismic exploration for oil because only thus can echoes be recorded from strata many thousands of feet below the surface. Signals at frequencies above 600 c/s must, it seems, have been reflected from the sea-floor or have been generated by sources external to the C.S.P., such as waves or the ship's machinery. They serve only to obscure the information in wanted echoes and have been removed by filtration (see pp. 317, 323).

III. INTERPRETATION OF RECORDS AND CALCULATIONS

To interpret the P.G.R. record in terms of geological structure the record must first be analyzed seismically, identifying wave-trains on the record with travel-paths between source and receiver. The types of travel-path employed in this study are shown schematically in figure 2. The travel-time along the direct path *S–H* was always shortest. It was followed in order by the reflexion *S–B–H* from the sea-bed; and by reflexions like *S–SB–H* from reflectors below. To identify the wave-train associated with one of these paths the characteristics of the source, the recorder, and the consequences of the placement of source and receiver near the water's surface must be considered.

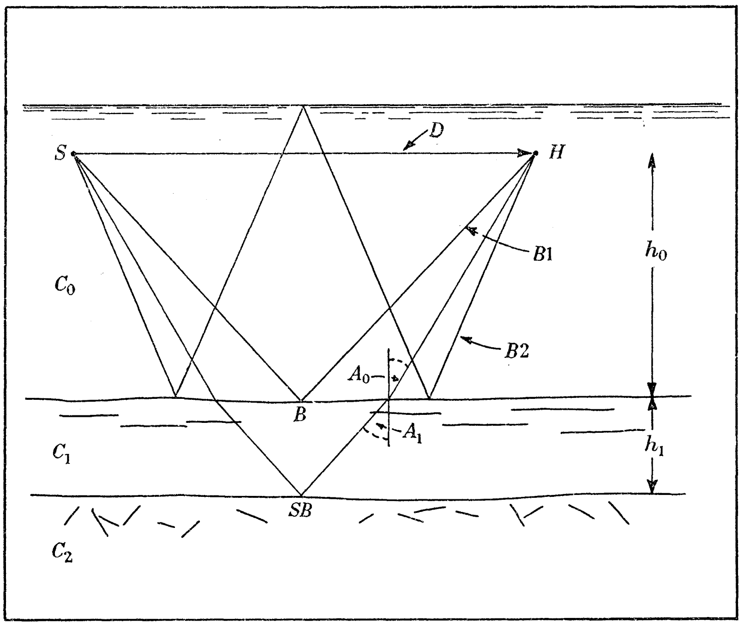
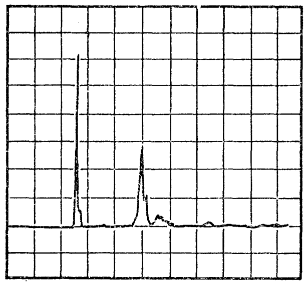


FIGURE 2. Schematic diagram of sound-travel between source and receiver. h_0, Depth of water; h_1, depth of reflecting rock interface below sea-floor; *H*, hydrophone; *S*, energy-source; *D*, distance between energy-source and hydrophone; C_0, velocity in water; C_1, C_2, velocities in upper and lower strata; *SH*, direct path (travel time T_D); *SBH*, bottom reflexion (*B* 1 with travel-time T_0); *SSBH*, sub-bottom reflexion (travel-time T_1); *B* 2, two sea-bed reflexions and an intervening surface reflexion.

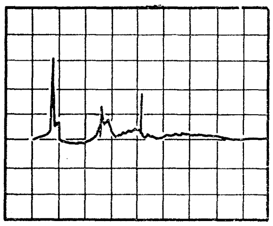
The P.G.R. recordings obtained during this survey were all half-wave rectified. Hence, sequences of light and dark bands are to be taken as alternate positive and negative excursions of the wave-form (not as envelopes of oscillations). Further, the pressure variations from a single pulse of either sparker or boomer are complex (see figure 3), and reflexions from the sea's surface near source and receiver further complicate the wave received at the hydrophone for a single pulse (see figure 4).

Thus, the wave-train over one of the paths of figure 2 truly represents 2 to 4 separate paths. These multi-paths are made nearly the same length by placing source and receiver both near the surface. If their depths are identical, constructive interference strengthens the wave. If, further, the surface-reflexion delay can be adjusted so that the surface-reflected pulse is in phase with the transmitted pulse (see figure 4) then even more enhancement is possible. In any arrangement the direct arrival and each reflexion will consist of sparker



abscissae — 1×10^{-3} s/div
ordinates — $0{\cdot}35 \times 10^{5}$ dynes/cm^2
separation — 4 m

boomer



abscissae — 2×10^{-3} s/div
ordinates — $0{\cdot}7 \times 10^{5}$ dynes/cm^2
separation — 6 ft.

FIGURE 3. Wave-form of sparker and boomer observed at short range; surface-reflected portion arbitrarily removed.

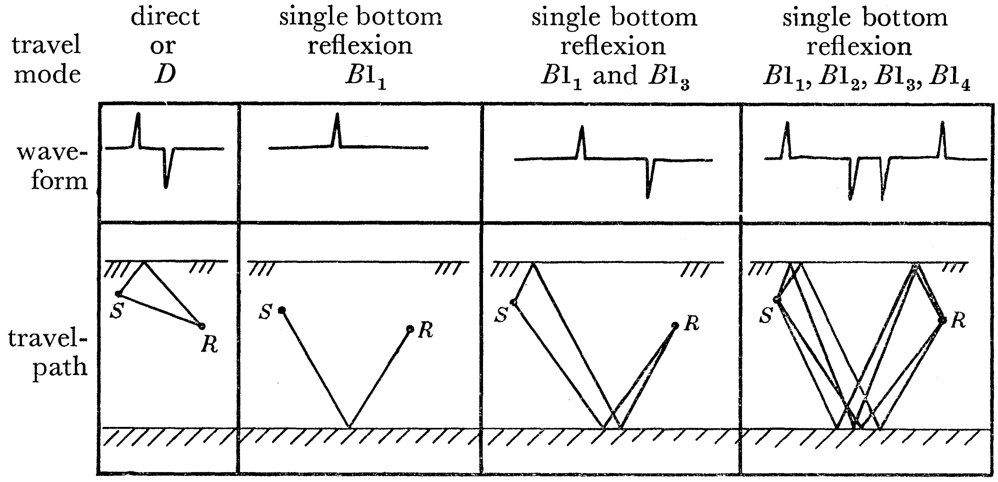


FIGURE 4. Typical modifications to wave-form of a pulse by multi-path travel from source (S) to receiver (R) for a single bottom reflexion.

several excursions of the wave-form, that is, dark and light bands on the record. In this study the direct arrival and the reflexion from the sea-bed were always much stronger than those from buried strata. As a result, the recording of the intense parts of these first two wave-trains commonly saturated the recorder, and weaker decaying oscillations from them show on the record sometimes superimposed on, and obscuring, later reflexions (see figure 5). Figure 5, a representative recording, is suitably coded to identify the various wave-trains with the corresponding principal travel-paths discussed above.

Figure 5 shows also the arrival *B*2 received after two reflexions from the bottom (and an intervening surface reflexion). Throughout this study *B*2 formed an obvious uniform echo-sequence and was easily recognizable. Over uneven topography or in regions of complex structure multiple echoes similar to *B*2 may be mistaken for deeper reflectors. However, seldom were reflexions traceable beyond *B*2; hence multiples of this sort are not a bothersome problem here. In places there were several reflecting surfaces, probably due to thin strata whose echoes appear to be superimposed to form a long complex echo-sequence, in which individual reflexions cannot always be resolved. In such instances we have had to be content with measuring apparent dip and approximate location (see figure 7, plate 24).

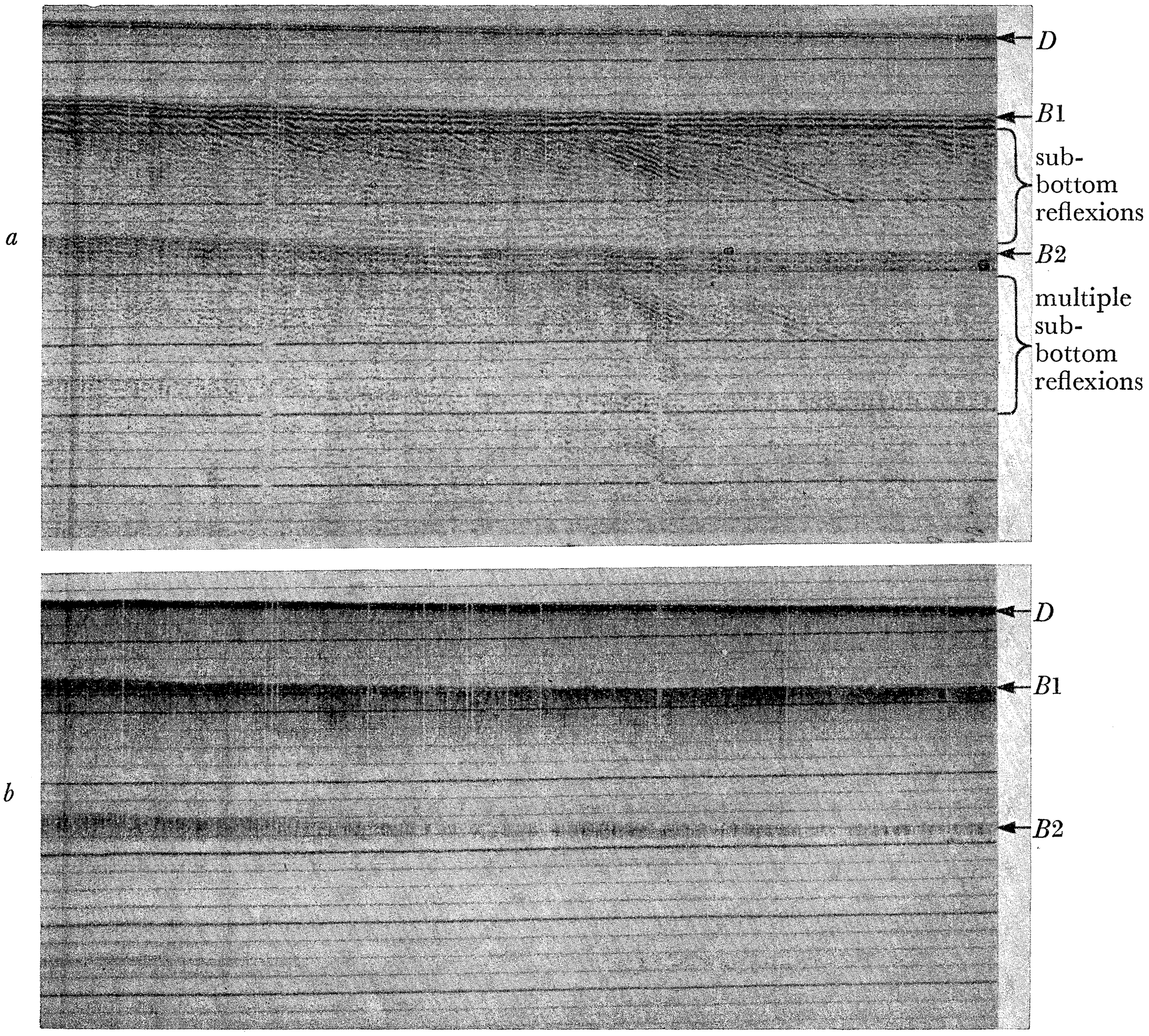
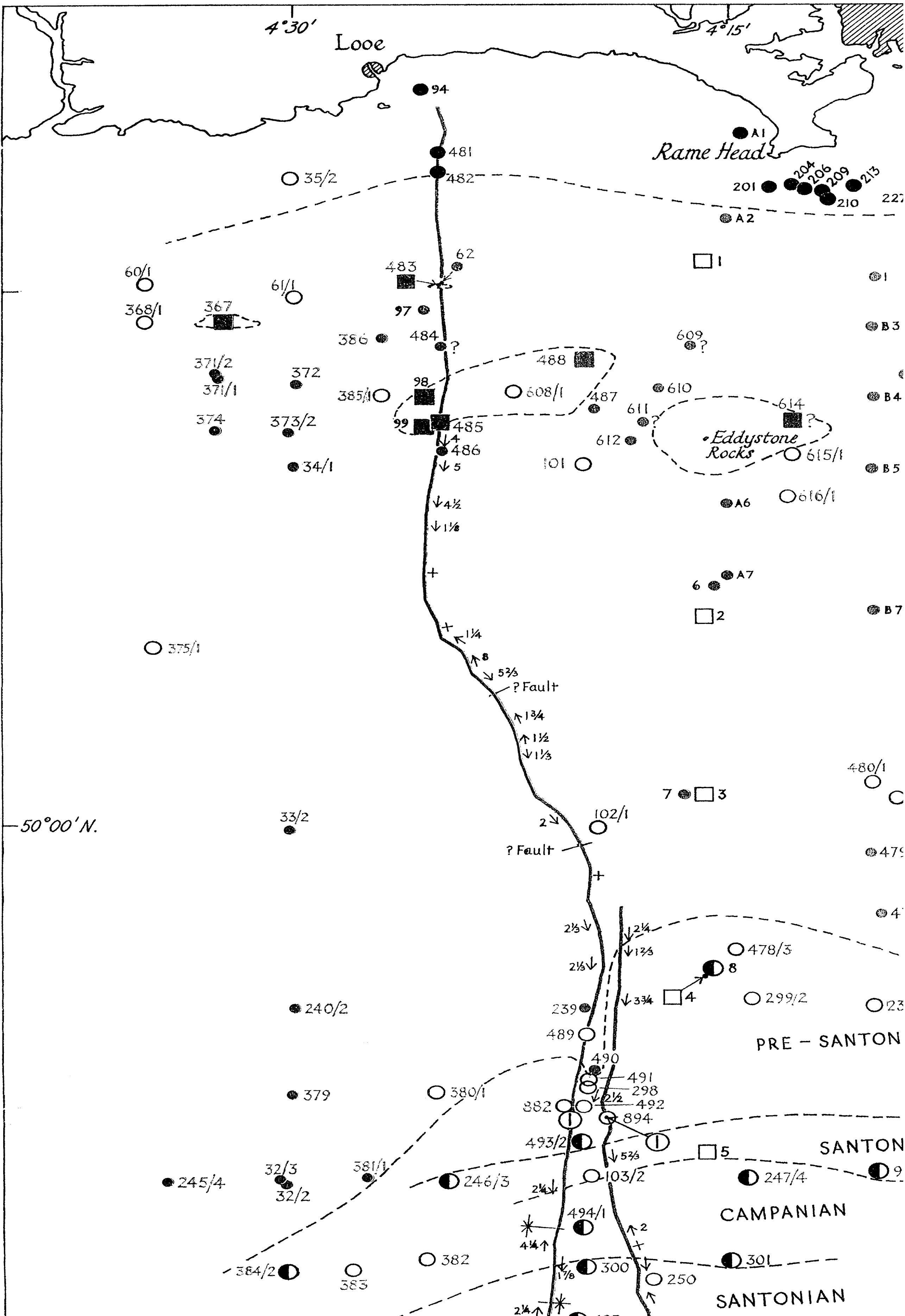


FIGURE 5. A representative P.G.R. recording identifying wave-trains with travel-paths of figure 2. *a*, Low frequency filter band; *b*, high frequency filter band.


4°30′
4°15′
Looe
Rame Head
Eddystone Rocks
50°00′N.
94
A1
481
482
35/2
201
204
206
209
210
213
227
A2
483
62
1
60/1
61/1
368/1
367
97
386
484
?
609
B3
371/2
371/1
372
488
98
385/1
608/1
487
610
B4
374
373/2
99
485
611
614
612
101
615/1
486
34/1
B5
A6
616/1
A7
6
2
B7
375/1
? Fault
480/1
7
3
33/2
102/1
? Fault
479
240/2
239
489
478/3
8
4
299/2
23
PRE – SANTON
490
491
298
379
380/1
882
492
894
493/2
5
SANTON
245/4
32/3
32/2
381/1
246/3
103/2
247/4
494/1
CAMPANIAN
300
301
384/2
383
382
250
SANTONIAN
4
5
4½
1⅛
1¼
8
5⅔
1¾
1½
1⅓
2
2⅓
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4¼
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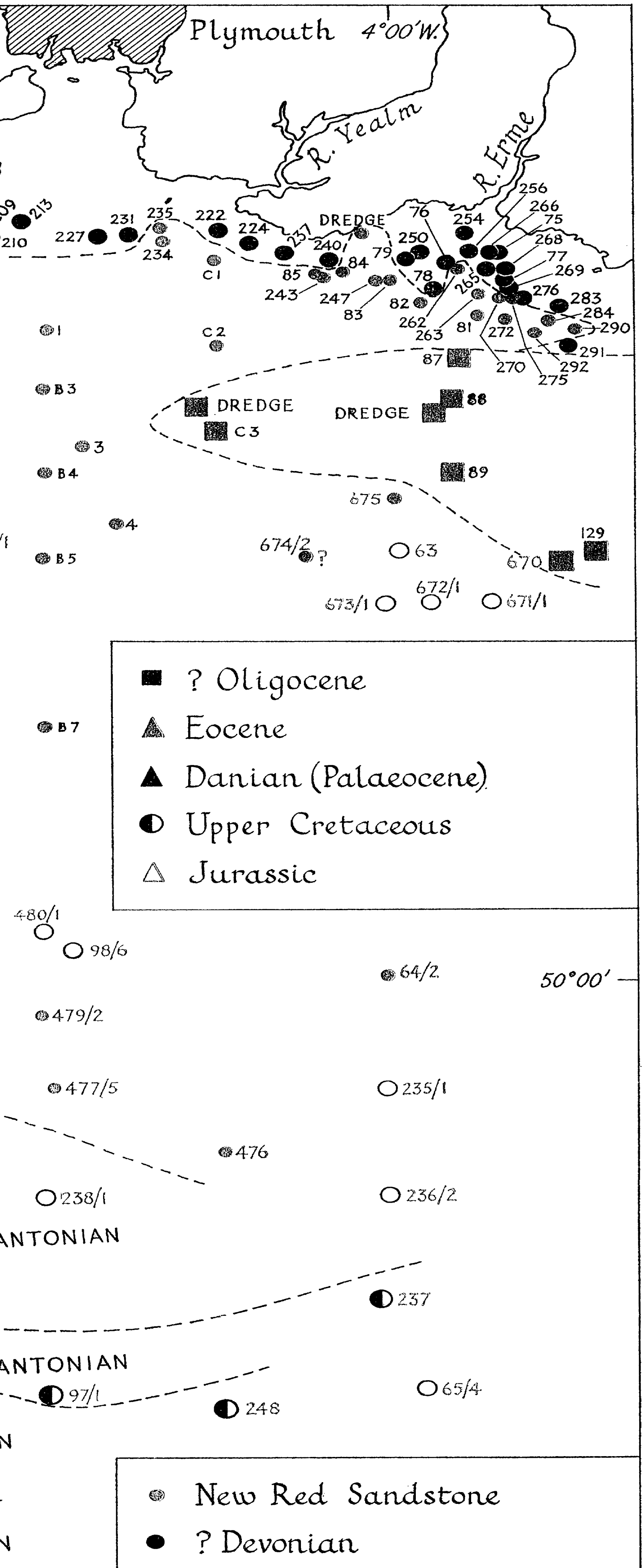
2¼
2


Plymouth
4°00′W.
R. Yealm
R. Erme
DREDGE
DREDGE
DREDGE
50°00′
ANTONIAN
ANTONIAN
? Oligocene
Eocene
Danian (Palaeocene)
Upper Cretaceous
Jurassic
New Red Sandstone
? Devonian
213
210
227
231
235
234
222
224
237
240
84
85
243
247
83
C1
C2
C3
76
254
250
79
78
82
262
263
265
81
256
266
75
268
77
269
276
283
284
290
291
292
272
270
275
87
88
89
675
674/2 ?
63
670
129
673/1
672/1
671/1
1
B3
3
B4
4
B5
B7
480/1
98/6
64/2
479/2
477/5
235/1
476
238/1
236/2
237
97/1
248
65/4

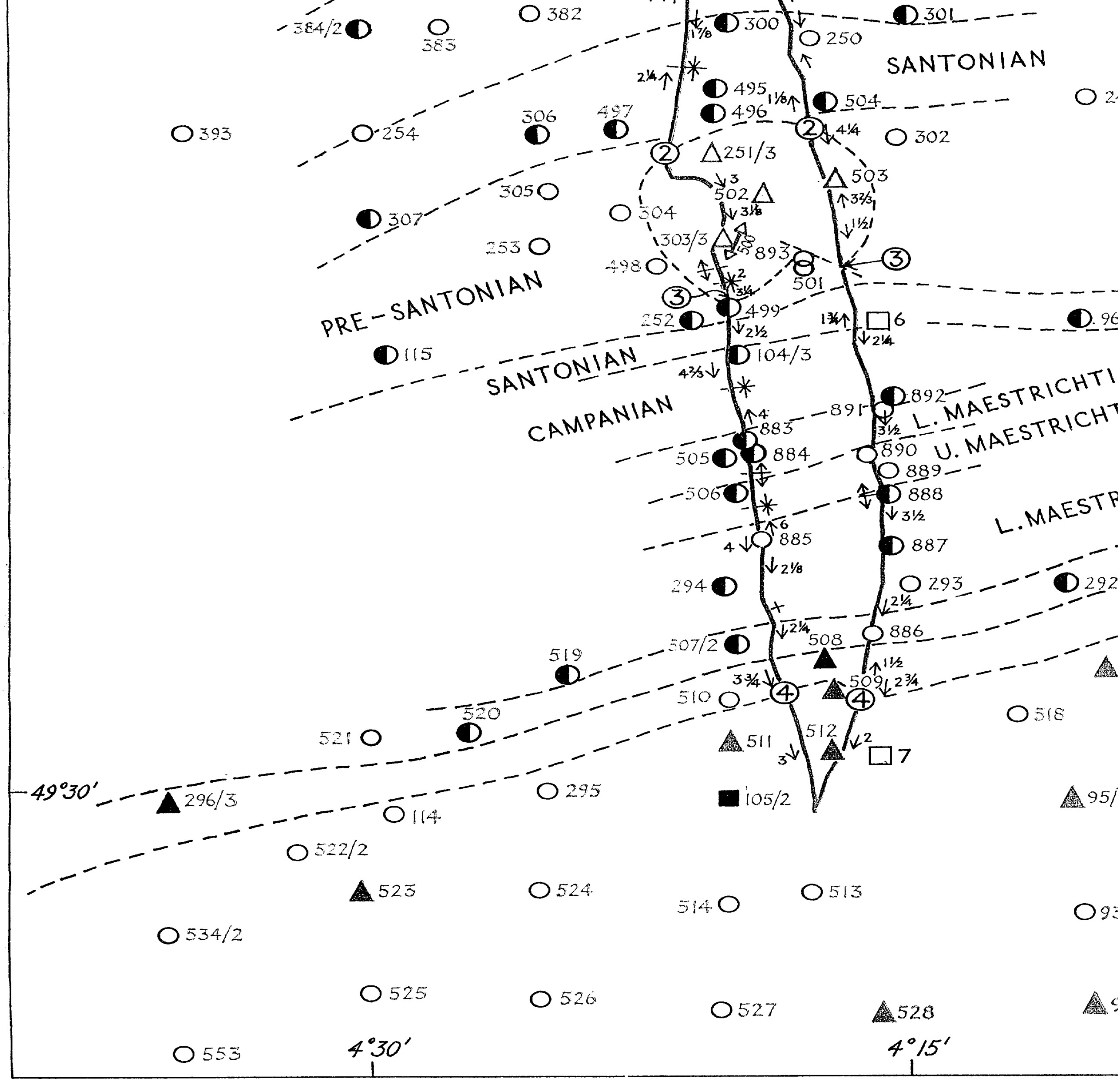
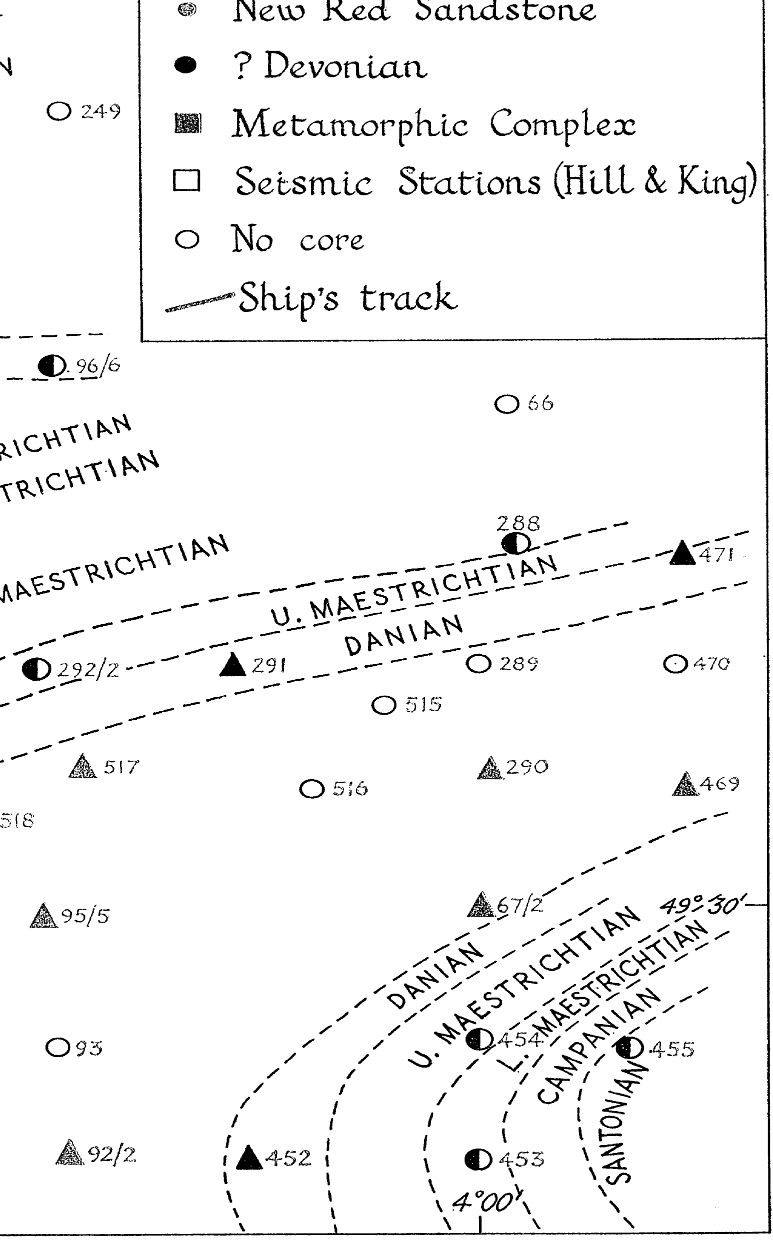


FIGURE 6. Marine geological map south of the Plymouth–Looe coastli
and dredge stations, the southern (left) and northern (right) cou
the directions and corrected angles of apparent dips as determi
records. Core and dredge stations numbered in red refer to th
numbered in black copied from Hill & King (1953, p. 12) anc
A, B or C from Holme (1953, p. 7). ① to ④ refer to the four r
page 348. Stations SB 484, 609, 611, 674/2 (New Red Sandstor
Complex) carry a query on the map; samples obtained at these st
text because the evidence of their probable geological age rests or
in those attributed to New Red Sandstone, and on rough groun
and broken core-barrels which are possibly indicative of Metam



coastline showing distribution of core
nt) courses taken by R.V. *Chain*, and
etermined from the boomer-sparker
to those taken by us; core stations
2) and those in black prefaced with
four marker horizons mentioned on
ndstone) and SB 614 (Metamorphic
these stations are not described in the
rests on red smears on the core-cutter
ground as shown by echo-soundings
Metamorphic Complex.

(*Facing p.* 322)

DESCRIPTION OF PLATES 24 TO 29

Reproductions of parts of the boomer-sparker record. The horizontal lines running through the record are produced by a series of marker pips spaced 0·0125 s apart. If the velocity of sound in sea-water is assumed to be 4950 ft./s, a reflector situated at a distance of 2475 ft. will produce an echo after a lapse of 1 s. The time-interval between successive pips (0·0125 s) thus represents a reflector distance of approximately 5 fm., and the lines may be regarded as 5-fm. markers. The velocities will be much higher in rocks and the lines will then represent greater intervals of depth. *D*, travel-time between energy-source and hydrophone; *B*1, sea-bed reflexion; *B*2, second sea-bed reflexion. Between *B*1 and *B*2 are reflexions from strata below the sea-bed, and the depth of penetration is approximately proportional to the energy output. The vertical exaggeration on the records is about six times, and the exact amount depends on the sound-velocities in different rocks and on the ship's true speed.

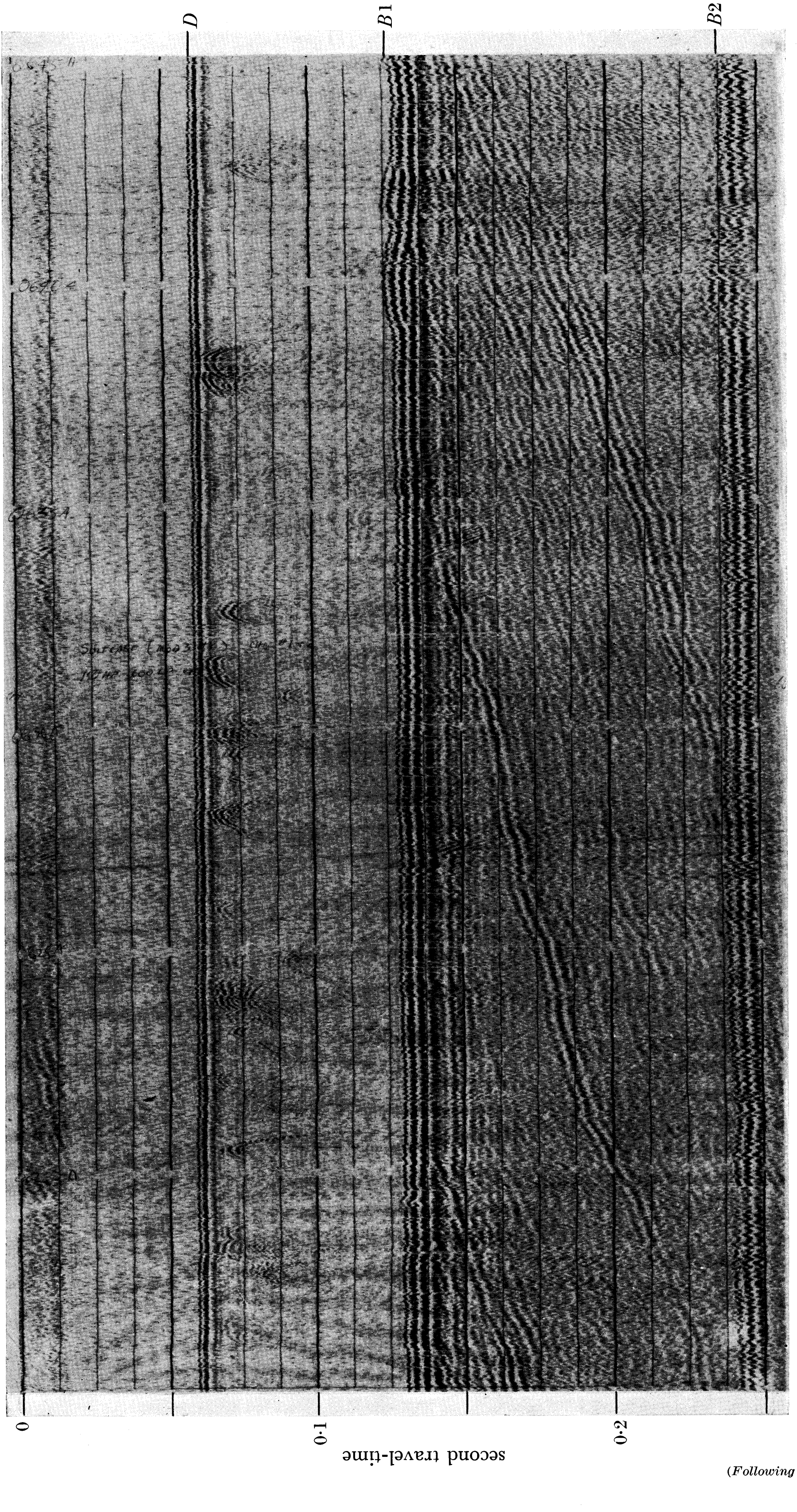


FIGURE 7. Northern run between latitudes 49° 33′ 35″ and 49° 35′ 48″, selected as a good record showing strong reflexions from simply dipping Upper Cretaceous strata. The corrected apparent dip is $2\frac{1}{4}$°.

(*Following figure* 6)

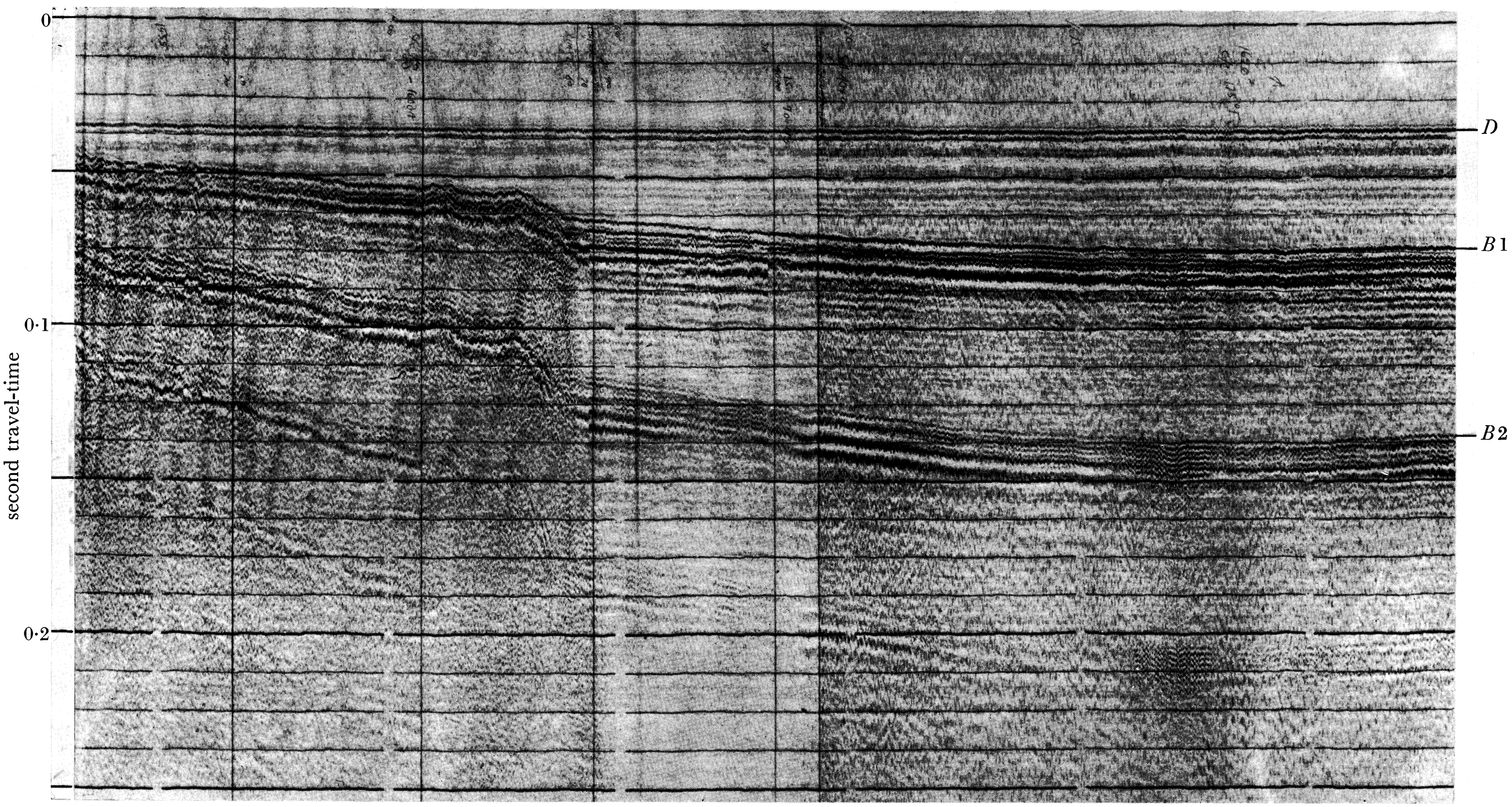


FIGURE 8. Southern run between latitudes 50° 19′ 12″ and 50° 17′ 00″, showing the irregular topography and structural complexity of the Devonian slates abruptly truncated by the nearly level sea-bed produced by the almost flat and unconformable New Red Sandstone. The first ($B1$) and second ($B2$) sea-bed reflexions are lettered on the right of the record, but on the left four reflexions, and a fifth weak one, are visible.

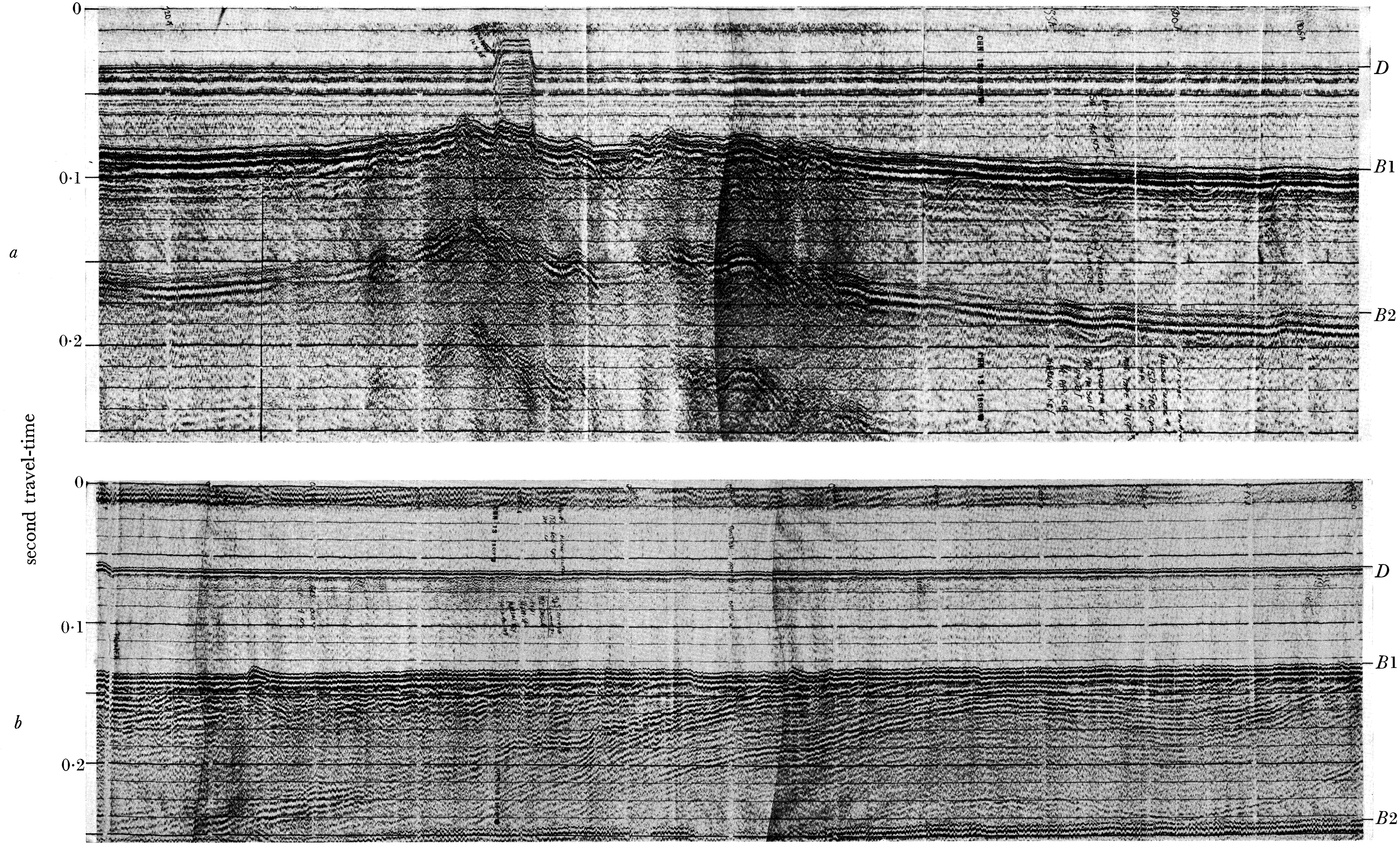


FIGURE 9. The curved vertical line running approximately through the centre of each figure marks the overlap between two photographs.

a. Southern run between latitudes 50° 13′ 35″ and 50° 09′ 20″, showing irregular topography formed by the Metamorphic Complex succeeded to left and right by the much gentler topography of the New Red Sandstone. Note within the Metamorphic Complex the inverted isosceles-triangular area with horizontal material at the top; this may represent unconsolidated sediment, or New Red Sandstone, or both; there is a suggestion that the lateral sides of this triangular area are faulted. Note also that on the right side of the figure the New Red Sandstone is gently folded.

b. Northern run between latitudes 49° 29′ 26″ and 49° 34′ 00″ showing, on the right, folded Upper Cretaceous and Danian with corrected dips on the anticline of $2\frac{3}{4}$° and $1\frac{1}{2}$° and, on the left, the slightly ruckled Eocene inclined at an average angle of 2°. The contact between the Eocene and Danian is unconformable, and it cuts the sea-bed at latitude 49° 32′ 06″ near the position of the curved line marking the photographic overlap. Corresponds to marker position ④ on map (see figure 6). A comparable record was obtained on the southern run, and the unconformity there crossed the ship's course at latitude 49° 32′ 16″.

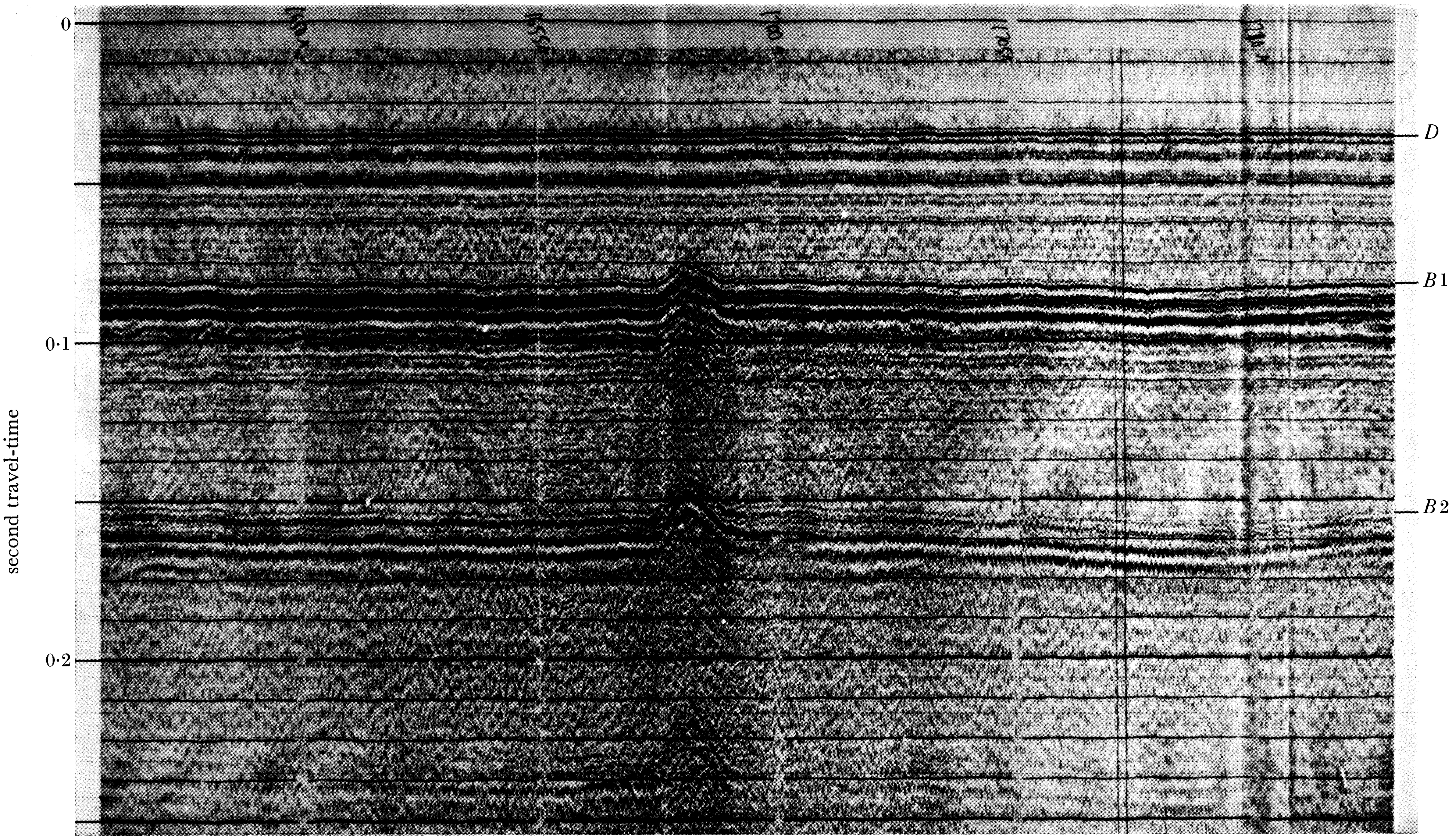


FIGURE 10. Southern run between latitudes 50° 16′ 06″ and 50° 14′ 00″. The sea-bed irregularity, and accompanying details of the record, within what was known to be a sea-bed made of New Red Sandstone was first detected on the boomer record; it was thought to be an inlier of Metamorphic Complex, which supposition was proved correct by subsequent coring (SB 483).

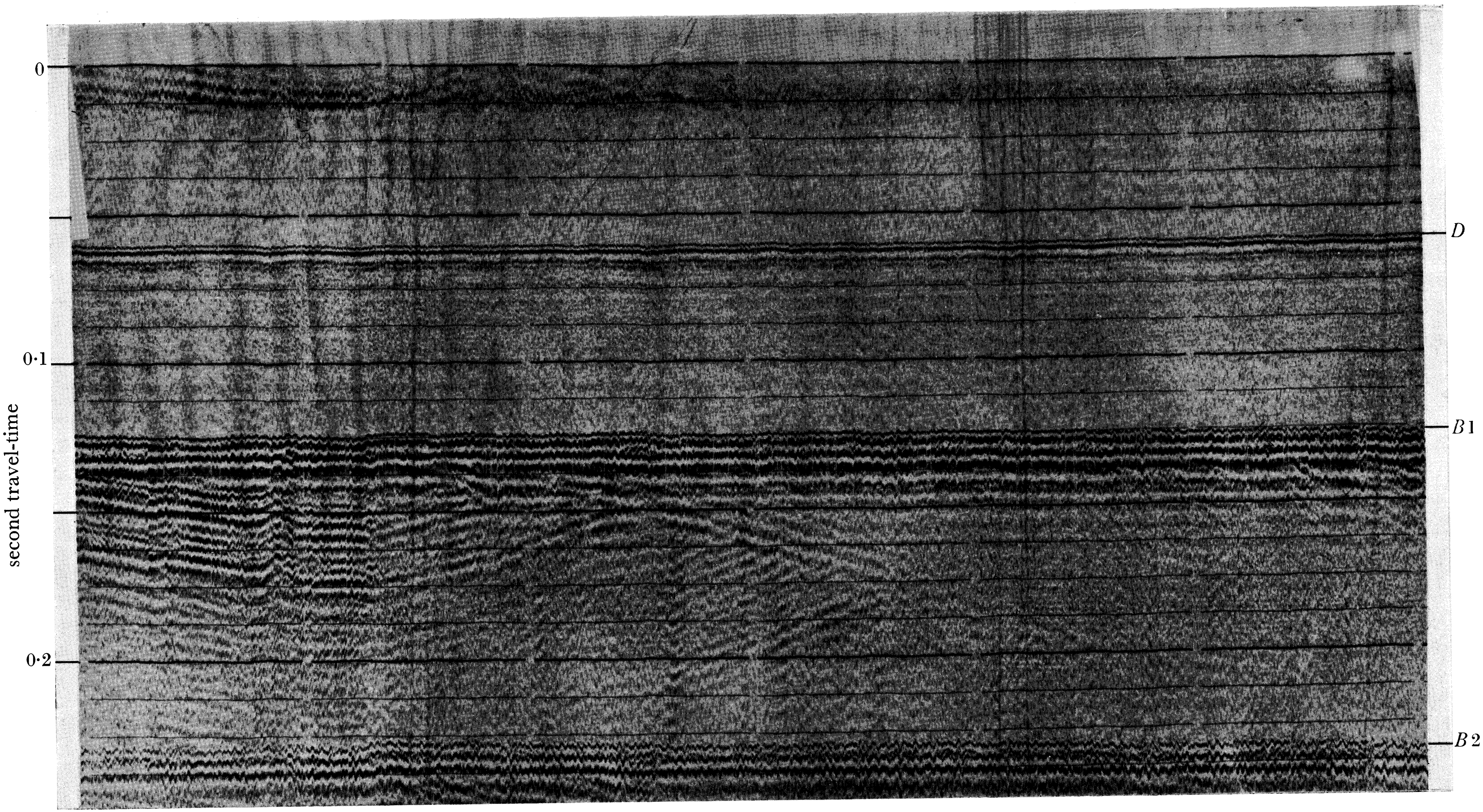


Figure 11. Southern run between latitudes 49° 41′ 45″ and 49° 39′ 26″, showing the unconformable contact between Upper Cretaceous on the right dipping at $2\frac{1}{2}$° and folded Lias on the left initially dipping at $3\frac{1}{4}$°; the Lias is commonly characterized on the records by closely-set dark and white bands. Corresponds to marker position ③ on map (see figure 6).

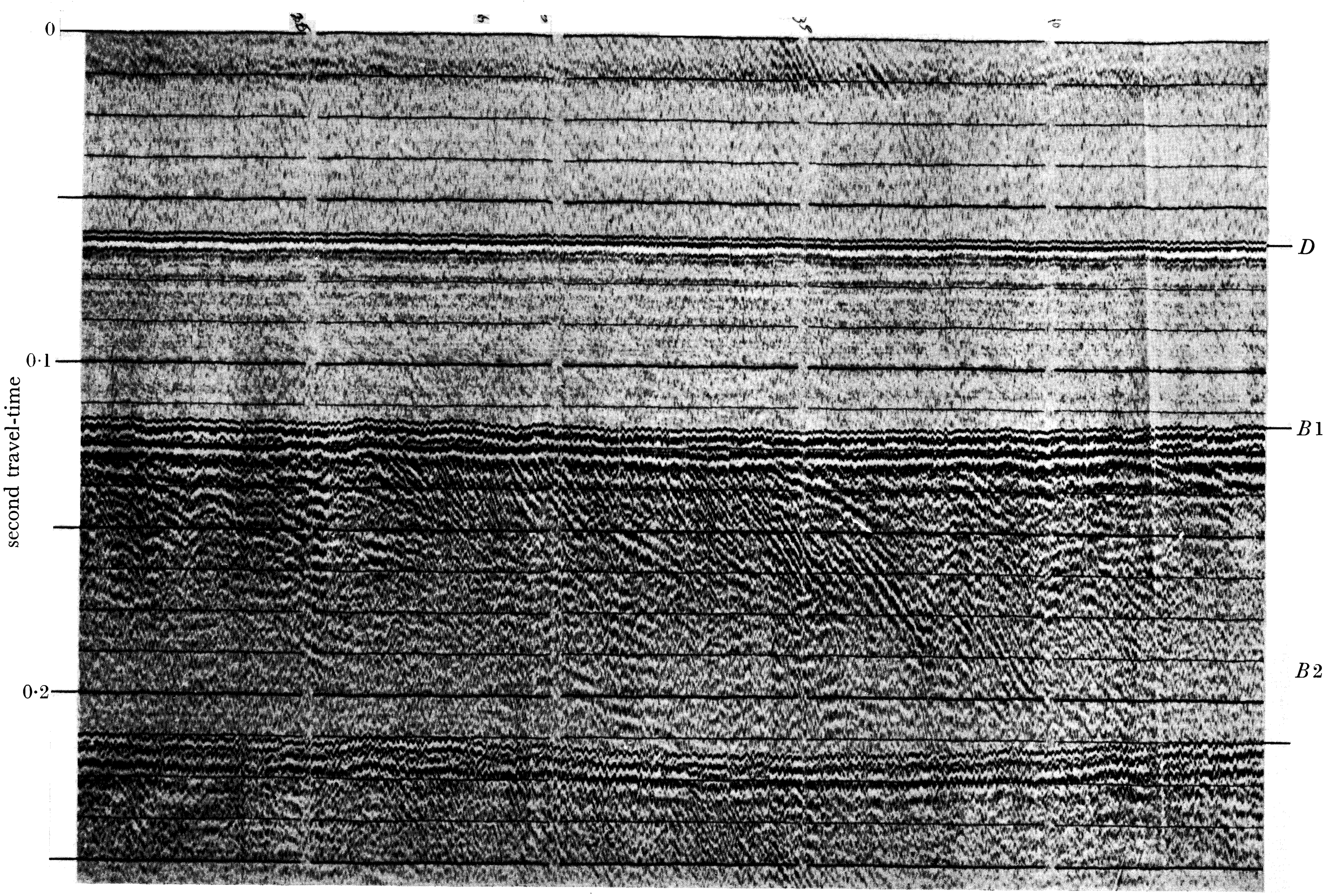


FIGURE 12. Southern run between latitudes 49° 52′ 30″ and 49° 50′ 48″, showing the peculiar 'false-bedded' pattern which is attributed to the presence of discordant layers at shallow depth below the sea-bed. So far as is known the rocks are of Cretaceous age but locally they may form no more than a thin coverage to the underlying New Red Sandstone. Corresponds to marker position ① on map (see figure 6).

The proof that echo-sequences recorded after $B1$ (except $B2$–Bn) are from reflecting surfaces below the bottom and not from reflectors arranged in some appropriate pattern over the sea-bed lies ultimately in the comparison of the records with the evidence provided by cored samples. However, the differential attenuation of sound in rock and sediment provides supporting proof. The reflexions were recorded on a two-channel P.G.R., the two channels being fed through band-pass filters set at 150 to 600 c/s and 600 to 1200 c/s. The structure so evident in the low frequency channel is not visible at the high frequencies, suggesting that this structure has been revealed by waves which have passed through a medium which attenuates high frequencies, that is, presumably, through rock or sediment (figure 5).

The experimental procedure was to stream alongside the stern of the ship the sparker or boomer, and a hydrophone was trailed approximately 100 ft. astern. The sparker and boomer mountings were between about 6 and 10 ft. long, and they were maintained at a similar distance beneath the surface of the water. The depth of water ranged from 100 to 330 ft.; the rock interfaces were assumed to be horizontal and thus the geometry adopted is that shown in figure 2.

Consider a wave travelling from S to SB. Then, from figure 2:

$$\frac{D}{2} = h_0 \tan A_0 + h_1 \tan A_1,$$

$$\frac{T_1}{2} = \frac{h_0}{C_0} \sec A_0 + \frac{h_1}{C_1} \sec A_1.$$

From Snell's Law:

$$\sin A_1 = \frac{C_1}{C_0} \sin A_0.$$

Let

$$n = \frac{C_1}{C_0},$$

and

$$s = \sin A_0.$$

Then

$$\frac{D}{2s} = \frac{h_0}{\sqrt{(1-s^2)}} + \frac{nh_1}{\sqrt{(1-n^2s^2)}},$$

and

$$\frac{T_1}{2} = \frac{h_0}{C_0\sqrt{(1-s^2)}} + \frac{h_1}{C_1\sqrt{(1-n^2s^2)}}.$$

Now, since

$$D = C_0 T_D,$$

and

$$h_0 = \frac{C_0}{2} \sqrt{(T_0^2 - T_D^2)},$$

we have, solving for h_1,

$$h_1 = \frac{C_1}{2} \sqrt{(1-n^2s^2)} \left\{ T_1 - \sqrt{\left(\frac{T_0^2 - T_D^2}{1-s^2} \right)} \right\},$$

$$h_1 = \frac{C_0^2}{2C_1} \sqrt{(1-n^2s^2)} \left\{ \frac{T_D}{s} - \sqrt{\left(\frac{T_0^2 - T_D^2}{1-s^2} \right)} \right\},$$

two simultaneous equations in h_1 and s.

Tables were then built on an IBM 1620 Data Processing System which effectively solved these equations. In the calculations, travel-times are in milliseconds, C_0 and C_1 were taken respectively as 1·505 and 2·204 m/ms, and h_1 is given in metres. One set of tables gives values for s, and for either T_D or T_1. Other sets of tables give values for $t_s = \sqrt{(T_0^2 - T_D^2)}$;

t_s, so defined, is the travel-time corresponding to h_0, that is, $t_s = h_0 2/C_0$. The procedure is (i) to determine t_s from its table of values; (ii) to select the appropriate T_D table, and also the T_1 table which contains the determined value of T_1; (iii) to place these two sheets alongside and follow down the columns headed with the determined travel-times until for some value of s the values of h_1 coincide, or nearly coincide.

The value of h_1 gives the vertical thickness of sediment and/or rock above the reflecting layer but, since in the mathematical solution the rock-surface was assumed horizontal, the value is an approximation for inclined strata. An analysis of the error introduced by this approximation shows that for actual (true) dips of 10° or less the calculated (apparent) dip would differ from the true dip by less than 3 %. This error is much smaller than the possible error due to an incorrect estimate of the speed of sound through rocks of varying physical characters. As the C.S.P. has not been used on this survey to determine dips greater than about 10°, the possible error due to this approximation has been disregarded.

Other possible errors in determinations of thickness and dip of rocks due to an incorrect estimate of C_1 may be substantial. To a first approximation, any error in C_1 will produce a directly proportional error in h_1. The velocity of C_1 assumed in this paper (2·204 m/ms; 7230 ft./s) is near the mean of Class 1 of Hill & King (1953, p. 15), later modified in Day *et al.* (1956, p. 32), which has a range of 5600 to 8210 ft./s. It will be noted that if the actual velocity falls within this range, errors of greater than 10 % in C_1 (and hence also in h_1) are still possible.

The vertical distance below the sea-floor of the stratum at any particular position on the record having been calculated, the distance away at which the stratum intersects the sea-bed is measured, and the apparent angle of dip in the direction of the ship's course is corrected using the computer tables (see above). It is these corrected dips that have been included on the map (figure 6), while the reproductions of parts of the boomer-sparker record (plates 24 to 29) show uncorrected dips.

IV. Descriptions and age-determinations of cored samples

The area which was selected for geological description lies approximately between longitudes 4° 00′ and 4° 30′ W., and is bounded by the coast between the mouth of the River Erme and Looe in Cornwall, and by latitude 49° 26′ N. (figure 6). Here the stratigraphy was already known in broad outline from the evidence supplied by 95 cores; a course followed along 4° 20′ crosses over Metamorphic Complex as well as ?Devonian slates, New Red Sandstone, Lower Jurassic (Lias), Upper Cretaceous (Chalk) and Older Tertiary strata; accordingly, widely different lithological types were 'sampled' by the boomer and sparker in the chosen area and, furthermore, Hill & King (1953) had worked a line of refraction shooting stations near to 4° 20′. After the boomer records had been studied, 34 additional cores at new stations were recovered approximately along the same meridian in order to try to produce on a larger scale a more detailed geological map of the Upper Cretaceous; after a true-scale geological section was drawn, 6 more cores were collected in order to ascertain whether rocks older than the Cretaceous cropped out on the sea-bed at predicted places.

Cores have been numbered consecutively throughout the survey, which commenced in 1957, and are prefaced by SB, S for R.V. *Sarsia* and B for Bristol. Where more than one attempt was required to obtain a sample, the registration number is followed by a diagonal line or solidus, and this by the number of the attempt. In each of the following descriptions, which are arranged numerically under major stratigraphical headings, after the registration number follow the Decca Navigator readings (R = red, G = green, P = purple in that order), the latitude (north), the longitude (west), and the depth of water. Samples are preserved in the collections of the Geology Department, University of Bristol.

(*a*) *Metamorphic Complex*

In the vicinity of Plymouth, metamorphic rocks are found in two petrologically distinct regions; first, to the east on the mainland in the Start area and also offshore and, secondly, to the south and west in the Eddystone Rocks, the Hand Deeps and other sea-bed outcrops (see figure 6). The rocks of cores SB 367, 483 and 485 are closely related petrographically to the garnetiferous 'gneiss' of the Eddystone Rocks (Reid 1907, p. 50) and show significant differences from any rocks exposed on the mainland, either in The Lizard or in the Start Point area. On the other hand, SB 670 resembles the green schists of the Start area (Tilley 1923, pp. 180–5). There are structural differences, also, between these two metamorphic regions. In the Start schists, axes of major folding and a well-marked lineation trend almost east–west, plunging slightly south of west at low angles. In the Eddystone-Hand Deeps areas, judging from the attitude of the exposed rocks and of bathymetric charts constructed from echo-soundings (Phillips 1964, figs. 2, 3), the structural trend runs more nearly north–south. The significance of this marked change in the schistosity is not as yet explained.

Using the potassium-argon method of dating, Mr Dodson (personal communication) has found that the dates when the two suites received their metamorphism are significantly different, the Eddystone suite being about 60 My older. Metamorphosed rocks selected from the mainland on Start Point and Bolt Head gave a range 290 to 310 My, as compared with figures for the Eddystone metamorphic suite of 351 My (Dodson, unpublished) and 375 ± 17 My (Miller & Green 1961, p. 1176). All these figures have been determined on minerals which have recrystallized through metamorphism, and they do not therefore provide evidence of the date when the original rocks were formed, other than the inference that they must be older.

SB 367. R: A 10·2; G: E 41·6. 50° 14·2′; 4° 32·45′. 28 fm.

Garnetiferous quartz-muscovite-biotite schist. Some fresh orthoclase occurs and apatite is rather abundant in large crystals.

SB 483. G: D 44·7; P: B 59·0. 50° 14·63′; 4° 24·9′. 30 fm.

Garnetiferous quartz-muscovite-biotite schist. Compared with SB 367 orthoclase is more abundant but cloudy, and biotite is less frequent. There is some cataclasis; quartz shows strain shadows and partial granulation, while micas are bent and distorted.

SB 485. G: D 46·1; P: B 51·65. 50° 11·35′; 4° 25′. 24 fm.

Quartz-muscovite-biotite schist with some garnet. Perthitic orthoclase and an acid plagioclase contain abundant well-developed flakes of white mica. Apatite is common, and a characteristic component is a number of yellowish pseudomorphs in chloritic and micaceous minerals, which have the appearance of 'pinite' after cordierite.

SB 488. G: D 35·6; P: B 50·9. 50° 13·1′; 4° 20′. 31 fm.
Quartz-muscovite-biotite schist, rich in quartz but biotite is infrequent; schistosity is nearly vertical.

SB 670. R: A 10·75; G: A 43·85. 50° 09·9′; 3° 55·1′. 28 fm.
Chlorite-albite schist with veins of carbonate; some cataclasis present.

(*b*) *?Devonian*

Many cores of slate have now been collected offshore from the coasts of Devon and Cornwall, but in none have macrofossils been seen. The stratigraphical ages of these rocks have not been established and, although it is probable that many are of Devonian age, the possibility that some appertain to the Carboniferous cannot be disregarded.

The two samples mentioned below were examined for palynological data; organic matter is present in both, especially SB 482, but there is nothing identifiable.

SB 481. G: D 44·0; P: B 70·0. 50° 18·9′; 4° 25′. 14 fm.
A blocky-weathering, resistant, fine-grained sandstone and siltstone, interbedded with thinly banded, micaceous, medium to dark-grey slate; where weathered chemically, the sandstone is speckled with interstitial limonitic clay-body which is seldom more than $\frac{1}{4}$ mm across. A more precise age than ?Devonian is not determinable.

SB 482. G: D 44·1; P: B 68·4. 50° 18·35′; 4° 25′. 25 fm.
Silvery-grey slate showing a vertical cleavage; the rock cannot reasonably be correlated with any subdivision of the Devonian seen on the mainland.

(*c*) *New Red Sandstone*

The attribution of the samples to the New Red Sandstone raises no stratigraphical problems, but in the absence of macrofossils and microfossils it is impossible to relegate a particular sample either to the Permian or to the Trias. That Permian rocks occur in the west country has only recently been proved by a potassium-argon determination of the Killerton Park lava, near Exeter, which gave 279 ± 6 My, that is, a Lower Permian age (Miller *et al.* 1962, p. 395). These so-called Exeter Traps are associated with breccias, conglomerates, sandstones, siltstones, shales and mudstones, but similar lithologies found elsewhere in the west country do not necessarily imply a Permian, in preference to a Trias, age, because the physiographical conditions, which obtained at the very different times when these Permian and Trias rocks were deposited, were generally similar and gave origin to similar sediments. The samples have accordingly been classified in the New Red Sandstone.

SB 32/3. R: C 3·61; G: F 37·73; P: A 60·54. 49° 50′; 4° 30·6′. 47 fm.
Light-brown, blocky mudstone, slightly mottled pale-green, which provided no microfossils on treatment with acid. The sample may be of the age of the Keuper Marl but the colour is not typical.

SB 33/2. R: B 7·50; G: E 46·2; P: A 68·38. 49° 59·8′; 4° 30·2′. 42 fm.
Brick-red, micaceous mudstone, rarely mottled pale-green, which shows affinity with the Keuper Marl.

SB 34. R: A 14·75; G: E 38·76; P: B 52·61. 50° 10·1′; 4° 30′. 37 fm.

Reddish-brown and grey, banded rock which has the grain-size of a coarse sandstone but which is predominantly composed of flattened pellets of shale and soft, weathered, volcanic material; occasionally angular quartz occurs and the matrix is argillaceous.

SB 62. R: A 7.57; G: D 44·55. 50° 15·2′; 4° 24·9′. 34 fm.

Pinkish-red, mottled cream and also darker red, coarse-grained 'gritty' rock; angular, pale-green fragments weathered to a clay mineral may originally have been igneous. Matrix is argillaceous and the flattened pellets are up to 4 mm across.

SB 64/2. R: B 14·1; G: C 30·12; P: A 50·55. 50° 00·1′; 4° 00·2′. 43 fm.

Light-brown, micaceous, blocky mudstone, closely similar to SB 32/3, and possibly Keuper Marl.

SB 239. R: B 19·7; G: E 32·7. 49° 54·8′; 4° 20·05′. 43 fm.

Pinkish-brown, slightly micaceous, rarely pale-green mottled, mudstone, possibly Keuper Marl.

SB 240/2. R: B 17·5; G: F 32·4. 49° 54·8′; 4° 30·1′. 45 fm.

Brick-red and grey, micaceous, argillaceous sand-rock, in which the sand grains are exceptionally well rounded and indicative of an aeolian origin; some felspar, chlorite and illite present.

SB 245/4. R: C 2·35; G: F 44·7. 49° 49·8′; 4° 34·4′. 47 fm.

Brick-red and greenish-grey shaly mudstone, in which pale chlorite may be concentrated in the lighter bands, and in the predominating red bands a colourless biaxially negative mineral with a low 2 V and R.I. 1·575, at present unidentified.

SB 371/1. R: A 12·0; G: E 42·7. 50° 12·55′; 4° 32·6′. 33 fm.

Brick-red breccia with angular fragments at least 30 mm across of quartz-veined micaceous quartzite. The matrix comprises flat and angular pieces of quartz, quartzite and slate, a few millimetres in size and covered by pellicles of ferruginous clay.

SB 371/2. R: A 11·9; G: E 42·9. 50° 12·7′; 4° 32·7′. 33 fm.

A finer-grained rock than SB 371/1; the matrix is more argillaceous, but flat and angular pieces of slate and quartzite, up to 15 mm across, are jumbled together without preferred orientation.

SB 372. R: A 11·7; G: E 37·4. 50° 12·4′; 4° 30′. 34 fm.

Brick-red, argillaceous rock with many flat and angular fragments of slate, quartzite and vein-quartz, up to about 15 mm in size.

SB 373/2. R: A 13·45; G: E 38·4. 50° 11′; 4° 30·2′. 35 fm.

Brick-red, argillaceous rock, speckled with an almost white clay mineral and 'books' of dark-brown biotite up to 2 mm in diameter, associated with quartz-grains and flattened pellets. The biotite books are surrounded by a soft white mineral of the montmorillonite group, perhaps saponite.

SB 374. R: A 13·8; G: E 43·4. 50° 11·1′; 4° 32·6′. 36 fm.

Brick-red, argillaceous rock with flattened, small fragments; directly comparable with SB 372.

SB 379. R: B 22·25; G: F 34·9. 49° 52·4′; 4° 30·2′. 44 fm.

Reddish-brown, micaceous, blocky mudstone similar to SB 64/2 but more red; possibly Keuper Marl.

SB 381/2. R: C 4·0; G: F 32·5. 49° 50·1′; 4° 27·6′. 45 fm.
Brownish, micaceous, blocky mudstone, darker than SB 239, with occasional resinous quartz-grains; possibly Keuper Marl.

SB 386. R: A 9·7; G: E 31·0. 50° 13·7′; 4° 27′. 32 fm.
Brick-red breccia which contains subangular fragments of slate, siltstone, quartzite and vein-quartz set in a ferruginous clay matrix.

SB 476. R: B 23·0; G: C 42·8. 49° 55·95′; 4° 04·9′. 41 fm.
Reddish-brown, micaceous, blocky mudstone with rare quartz-grains; almost the same colour as SB 379. The sample also shows an irregular mass of pale greenish-grey argillaceous rock which, however, is much more sandy.

SB 477/5. R: B 16·5; G: D 30·6. 49° 57·45′; 4° 09·8′. 40 fm.
Fine-grained, pale yellowish-grey sandstone containing angular pieces of greenish-grey shale; in the cored sample, associated with reddish-brown mudstone; possibly Keuper Marl.

SB 479/2. R: B 12·25; G: C 47·1. 49° 59·2′; 4° 10·2′. 39 fm.
Brick-red, micaceous mudstone similar to SB 379; possibly Keuper Marl.

SB 486. G: D 46·7; P: B 49·8. 50° 10·45′; 4° 24·9′. 37 fm.
Cream-coloured, argillaceous rock with much white mica and many flat, usually angular, fragments mostly converted into a white clay mineral; quartz-grains present but rare. Some layers are brick-red but otherwise they are physically comparable with the 'leached' white rock.

SB 487. G: D 35·6; P: A 77·5. 50° 11·7′; 4° 19·7′. 34 fm.
Pinkish-red, coarse-grained rock with many flat and subangular fragments of paler reddish-cream slate, also some rounded quartz-grains, set in a red argillaceous matrix.

SB 610. G: D 30·7; P: A 76·5. 50° 12·3′; 4° 17·4′. 34 fm.
A markedly speckled rock with innumerable silvery-grey, angular, micaceous, slaty fragments, which lie subparallel and contrast strongly with the reddish matrix.

SB 612. G: D 33·4; P: A 74·5. 50° 10·8′; 4° 18·4′. 32 fm.
Brick-red, white-speckled breccia containing angular fragments, up to 30 mm in length, comprising predominantly quartzite, vein-quartz, micaceous schists, and weathered igneous rocks; the ferruginous clayey matrix is micaceous, and contains white and dark micas.

SB 613. G: C 39·0; P: A 74·75. 50° 13·5′; 4° 12·8′. 30 fm.
Brick-red, argillaceous rock with many flat angular pieces of slate, of which a relatively small number is silvery-grey in colour and similar to the fragments in SB 610.

SB 675. R: A 7·1; G: B 32·9. 50° 11·4′; 3° 59·9′. 32 fm.
Brick-red breccia cemented with barytes and includes many subangular fragments of vein-quartz and micaceous schists.

(*d*) *Jurassic*

Three of the samples yield definitive palaeontological evidence of a Lower Lias age, and there is strong presumptive evidence in a fourth; the other core resembles pale shales either of the Tea Green Marls or Cotham Beds, but the precise age cannot be determined as no microfossils have been isolated. Accordingly, in this the most westerly inlier of Jurassic rocks recognized in the English Channel or Bristol Channel, no Jurassic strata younger than the Lower Lias have yet been found.

SB 251/3. R: C 19·6; G: E 43·9. 49° 44·6′; 4° 20·5′. 46 fm.

Light-grey, slightly greenish, yellowish rusty-weathering, calcareous shale which provided no microfossils. The locality is situated at the northern end of the Jurassic inlier and, on the boomer record, the shales show an apparent dip of not less than 3° in a south-south-easterly direction underneath the Lower Lias of SB 502, which lies $1\frac{1}{3}$ miles away to the south-east. Lithologically the sample has affinities with the Tea Green Marls of the topmost Keuper Marls and with the Cotham Beds of the Rhaetic, rather than with the Lias.

SB 303/3. R: D 0·9; G: E 46·3. 49° 42·6′; 4° 20·2′. 47 fm.

Light-grey, yellowish-grey weathering, calcareous mudstone with calcareous nodules between 1 and 5 mm across. The Foraminifera include *Bolivina* sp., *Dentalina* cf. *vetusta* d'Orbigny, ?*Discorbis* sp., *Eoguttulina liassica* (Strickland), *Frondicularia* cf. *sulcata* Bornemann, *Lenticulina* cf. *varians* Bornemann, *Lingulina tenera* Bornemann, *Marginulina prima* d'Orbigny, *Planularia* cf. *protracta* (Bornemann), *Pseudoglandulina tenuis* (Bornemann), *Spirillina infima* (Strickland) and *Vaginulina* sp. Dr Adams has reported that this assemblage is characteristic of the Lower Jurassic of Britain. It is, however, poor in diagnostic fossils. Of the most commonly occurring species, *Spirillina infima* and *Eoguttulina liassica* are long-ranged forms, whilst *Bolivina* sp. is different from all previously described species from Britain—it is not *B. rhumbleri* Franke. All the species listed in the fauna occur in the Lias, and *Frondicularia sulcata* and *Lingulina tenera* are restricted to this formation. Typical Upper Lias Foraminifera are absent and the general appearance of this assemblage suggests a position in the upper part of the Lower Lias. The sample yielded no calcareous nannoplankton.

SB 500. Dredge shot at R: D 1·5 and G: E 46·0, and hauled at R: D 0·0 and G: E 45·1; dredge shot at 49° 42·9′ and 4° 20′, and hauled at 49° 42·3′ and 4° 19·3′.

Grey and brownish-grey, calcareous shale with much gypsum on bedding planes. One fragment bears the ammonite *Arnioceras* sp., indicative of a Sinemurian age, Semicostatum–Obtusum Zones. There are also a number of pieces of 'beef', and the lithology agrees well with that of the 'Shales with Beef' subdivision of the Lias (Lang, Spath & Richardson 1923, pp. 88–98). The 'Shales with Beef' correspond to parts of the Semicostatum and Turneri Zones. The coccolithophorid assemblage includes about four undescribed forms, some related to *Zygodiscus*, but the main elements are *Schizosphaerella punctulata* Deflandre & Dangeard and *Parhabdolithus marthae* Deflandre. In the present state of knowledge of these fossils a more precise determination than Lias is not possible.

SB 502. R: C 23·25; G: E 42·3. 49° 43·6′; 4° 19′. 47 fm.

Dark-grey, calcareous shale, with innumerable crystalline rosettes of gypsum. Macrofossils include *Arnioceras semicostatum* (Young and Bird), *Oxytoma inaequivalve* (Sowerby) and an unidentified bivalve. The ammonite indicates a Lower Lias age, Sinemurian Stage, Semicostatum, Turneri or Obtusum Zone, while *O. inaequivalve* ranges throughout the Sinemurian and extends higher. The coccolithophorids again include undescribed forms of *Zygodiscus*, *Schizosphaerella punctulata*, *Parhabdolithus marthae* and *Zygolithus erectus* Deflandre, of Liassic age. The microfossils include calcitic casts of minute lamellibranchs and gastropods, but no Foraminifera were recognized.

SB 503. R: C 22·9; G: E 39·55. 49° 44′; 4° 17′. 46 fm.

Light brownish-grey, calcareous shale with gypsum rosettes, generally similar to SB 502 but rock is paler in colour. The coccolithophorids include forms listed in SB 500 and SB 502, and they point to a Liassic age; a similar stratigraphical assignment is favoured from the evidence afforded by the Foraminifera which include *Dentalina* cf. *pseudocommunis* (Franke), *Dentalina* sp., *Vaginulina contracta* (Terquem), *Lenticulina minuta* (Bornemann), *Frondicularia* sp. nov., *Lingulina tenera* and *Eoguttulina liassica*.

(*e*) *Upper Cretaceous* (*excluding Danian*)

The stratigraphical ages of the Upper Cretaceous samples have been determined by using such microfossils as the Foraminifera, and the coccolithophorids and related forms generally known as the calcareous nannoplankton. Foraminifera are more definitive stratigraphically of pre-Maestrichtian deposits than are the nannoplankton, due particularly to lack of information about the latter; both groups can be more certainly applied to the Maestrichtian.

Among the coccolithophorids, some of the common but smaller forms of *Coccolithus* are difficult to distinguish without the electron-microscope, but those from the Cretaceous differ from the Tertiary ones in the thickness of the plates and construction of the central area, as discussed by Bramlette & Martini (1964). In the fossil lists the Cretaceous forms are recorded as *Coccolithus* sp. C, and the Tertiary ones as *Coccolithus* sp. T.*

The subdivision of the Upper Cretaceous into its several Stages has been variously interpreted, and it is the interpretation of Hiltermann & Koch (1960) which is adopted here.

(i) *Post-Albian to Pre-Santonian* (table 1).

Included in this group are three samples whose ages seem better determined by Foraminifera than by nannoplankton. Until a few years ago *Nannoconus* was believed to have become extinct at the end of the Lower Cretaceous but, in 1960, Deflandre & Deflandre-Rigaud described a *Nannoconus* assemblage from the Upper Santonian of the Paris Basin which is different from Lower Cretaceous assemblages, and is presumably not reworked. No evidence of reworking has been found in the cored samples referred to Pre-Santonian or Santonian ages, and *Nannoconus* appears to have its upper stratigraphical range at, or near, the top of the Santonian.

SB 115. R: D 1·67; G: F 45·13. 49° 40′; 4° 29·6′. 48 fm.

Hard and cream-coloured chalk bored by Recent molluscs and worms; contains abundant organic debris, with few ill-preserved, heavily mineralized, Cretaceous Foraminifera, but a small number of Cretaceous genera such as *Stensioeina*, *Gavelinopsis*,

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* Although *Coccolithus pelagicus* (Wallich) occurs in many Cretaceous and Palaeogene samples, it is omitted from the lists, because it is obviously a contaminant from Neogene or Recent times.

Palmula, *Praebulimina* are unmineralized and are possibly contaminants from Recent sand. The fauna (table 1) is not significant stratigraphically; possibly a Pre-Santonian record, of the Coniacian or Turonian.

Table 1. Microfossil assemblages suggesting a Post-Albian to Pre-Santonian age

A. Foraminifera	115	252	493/2	499
Arenobulimina	*f*	*f*	—	*c*
?*Ataxogyroidina variabilis* (d'Orb.)	—	—	—	*r*
?*Eggerellina*	*r*	—	—	—
Eouvigerina cretacea (Heron-Allen & Earland)	—	—	—	*c*
gracilis (Egger)	—	—	—	*c*
stormi Brotzen	—	R	—	—
Gavelinella costata Brotzen	R	—	—	A
pertusa (Marsson)	—	—	—	R
'*Globigerina*' *portsdownensis* Williams-Mitchell	—	—	*c*	—
Gyroidinoides nitidus (Reuss)	—	—	—	*c*
sp. indet.	*c*	*f*	—	—
Hagenowella	—	—	—	*r*
Lenticulina	—	—	*r*	—
Loxostomum eleyi (Cushman)	—	*f*	—	*c*
Marssonella trochus (d'Orb.)	—	—	F	F
Praebulimina	—	*f*	—	*c*
Pseudovalvulineria	—	—	*a*	—
Reussella cushmani Brotzen	—	—	—	*c*
Rotalipora turonica Brotzen	—	—	*c*	—
Tritaxia tricarinata Reuss	—	—	—	*f*
Valvulineria lenticula (Reuss)	—	—	—	*f*
B. Nannoplankton				
Arkhangelskiella sp.	*r*	—	—	—
Coccolithus sp. C	*f*	*r*	*f*	*f*
Coccolithus? sp. 35	—	—	R	F
Lucianorhabdus cayeuxi Deflandre	—	*r*	—	—
Nannoconus multicadus Deflandre & Deflandre-Rigaud	—	—	*r*	*r*
sp.	*f*	*f*	*f*	*c*
Rhabdolithus anthophorus Deflandre	—	R	—	—
Rhabdolithus? sp. 9	R	—	—	R
Stephanolition sp.	—	—	*r*	—
Tetralithus obscurus Deflandre	—	—	—	*r*
Zygodiscus sp. 19	—	—	—	F
Zygrhablithus intercisus (Deflandre)	R	*r*	R	F
turriseiffeli (Deflandre)	*r*	*r*	*r*	*r*

a Abundant; *c*, common; *f*, frequent; *r*, rare; *rr*, very rare. Roman capitals signify cf. determinations. This notation will be used in tables 1 to 7. Nannofossil numbered species have now been allocated specific names, see Bramlette, M. N. & Martini, E., 1964, *Micropaleontology*, **10**, 292.

SB 252. R: D 4·4; G: F 31·2. 49° 40·8′; 4° 21′. 45 fm.

Hard greyish chalk with much organic debris derived from echinoderms, *Inoceramus* and Bryozoa. Foraminifera rare, and one small *Porosphaera* was isolated. *Eouvigerina stormi*, with which two specimens are compared (table 1), ranges through Turonian-Coniacian, and *Loxostomum eleyi* through the Senonian; Santonian and Campanian foraminiferal indicators are conspicuously absent; SB 252 is probably to be referred to the Coniacian.

SB 493/2. R: C 4·5; G: E 37·0. 49° 51·2′; 4° 20·1′. 44 fm.

Hard greyish chalk with many organic fragments such as abundant *Inoceramus* prisms and rare mineralized Foraminifera. One example of the brachiopod *Orbirhynchia wiesti* (Quenstedt) was extracted from the core and identified by Dr D. V. Ager, who gave the range as Upper Cenomanian to Lower Turonian; this is confirmed by the presence among the Foraminifera of *Rotalipora turonica* (range Upper Cenomanian–Lower Turonian) and *Pseudovalvulineria*, the latter having been recorded by Jefferies (1962, p. 627) as abundant at certain levels in the *Actinocamax plenus* Marls.

SB 499. R: D 4·5; G: E 47·4. 49° 41·1′; 4° 20′. 47 fm.

Soft, pale-grey chalk with plentiful organic fragments of Bryozoa, *Inoceramus* prisms and echinoderms, of fine sand and silt grades; some well-preserved Foraminifera, phosphatic fragments and glauconite. The listed Foraminifera (table 1) are indicative of either a Coniacian or Santonian age, but a correlation with the Coniacian is preferred because marker species of the Santonian are absent.

(ii) *Santonian* (table 2).

Among the Foraminifera, *Gavelinella pseudoexcolata* and *Gavelinella* sp.1 are characteristic of the Santonian; the earliest *Bolivinoides* to occur in England, *B. strigillatus*, also makes its first appearance, as does the first *Orbignyna.*

SB 96/6. R: D 12·0; G: E 33·65. 49° 40·8′; 4° 10·2′. 46 fm.

The discovery of *Bolivinoides strigillatus* indicates that the Chalk is considerably younger than Coniacian; probably appertains to Upper Santonian or Lower Campanian.

SB 97. R: C 11·73; G: D 40·02. 49° 50·2′; 4° 9·95′. 43 fm.

A core was not obtained but a chalky smear was taken from the outside of the core-cutter. The foraminiferal assemblage is meagre but consistent with a Santonian age; the sample yielded no significant calcareous nannofossils.

SB 237/2. R: C 12·2; G: C 41·45. 49° 52·5′; 4° 0·4′. 41 fm.

A smear with many fragments of hard cream chalk was taken from the core-cutter. Foraminifera are moderately common, mineralized and ill-preserved, but they are consistent with derivation from one horizon; it is assumed that the sample was collected from Chalk in place. Stratigraphical indication is probably Santonian.

SB 246/3. R: C 5·2; G: E 45·85. 49° 49·8′; 4° 24·8′. 45 fm.

The nannoplankton point to a Santonian age but the Foraminifera, although uncommon and poorly preserved, suggest either Upper Santonian or Campanian.

SB 300. R: C 12·85; G: E 40·3. 49° 47·5′; 4° 20′. 43 fm.

Only a smear of hard cream chalk was recovered; the Foraminifera, which are common but ill-preserved, indicate an Upper Santonian or, less probably, a Lower Campanian age.

SB 306. R: C 16·5; G: F 33·4. 49° 45′; 4° 25·3′. 47 fm.

The Foraminifera are too rare and ill-preserved to be of stratigraphical significance, but the nannoplankton are probably Santonian.

SB 307. R: C 18·5; G: F 43·0. 49° 43·1′; 4° 30′. 48 fm.

Abundant fragments of hard chalk contain microfossils suggestive of derivation from one horizon (Santonian) and the sample is accepted as having come from in place.

SB 455. R: F 12·2; G: E 32·0. 49° 27·2′; 3° 56·3′. 46 fm.

Soft white chalk rich in organic material, particularly in well-preserved Foraminifera, of Upper Santonian or, less certainly, Lower Campanian age. Of interest is a single

TABLE 2. MICROFOSSIL ASSEMBLAGES SUGGESTING A SANTONIAN AGE

A. Foraminifera	96/6	97	237/2	246/3	300	306	307	455	495	496	504
Arenobulimina	*f*	—	*r*	—	*f*	*f*	*r*	*c*	*c*	—	*f*
Bolivinoides decoratus (Jones)	—	—	—	R	—	—	—	—	—	—	—
delicatulus Cushman	—	—	—	C	—	—	—	—	—	—	—
strigillatus (Chapman)	*r*	—	—	—	*r*	—	—	*f*	—	—	—
Cibicides	—	—	—	—	—	—	*r*	*f*	*r*	—	—
Eggerellina	*f*	—	—	—	*r*	—	—	—	*f*	—	—
Eouvigerina cretacea (Heron-Allen & Earland)	—	—	—	*f*	*c*	—	*c*	*c*	*c*	—	—
Eponides lunata Brotzen	—	—	—	—	R	—	—	—	—	—	—
Gaudryina	—	—	—	—	*f*	—	—	—	*r*	—	—
Gavelinopsis	—	—	*f*	—	A	—	—	C	—	—	—
Gavelinella of *clementiana* group	—	—	—	*r*	—	—	—	—	—	—	—
costata Brotzen	R	—	R	R	*f*	—	*f*	—	*r*	*rr*	C
pseudoexcolata (Kalinin)	*c*	R	*f*	—	*a*	—	R	*c*	*a*	*f*	—
sp. 1.	*r*	—	*f*	*r*	*a*	*f*	*c*	*a*	*a*	—	—
Globorotalites michelinianus (d'Orb.)	*f*	—	F	—	*a*	—	—	*a*	*c*	—	—
multiseptus (Brotzen)	—	—	—	C	—	—	—	—	—	—	—
sp. indet.	—	*rr*	—	—	—	—	—	—	—	—	—
Globotruncana linneiana (d'Orb.)	—	—	—	—	—	—	*f*	*c*	—	—	—
sp. indet.	—	*r*	—	—	—	—	—	—	*f*	—	—
Globulina	—	—	—	—	*r*	—	*r*	—	—	—	—
Gyroidinoides nitidus (Reuss)	—	—	—	—	*f*	—	—	*f*	*c*	—	—
sp. indet.	*f*	*rr*	—	—	—	*f*	*c*	—	—	—	*f*
Hagenowella elevata (d'Orb.)	—	—	—	—	—	—	—	*f*	—	—	—
Heterostomella	—	—	—	—	—	—	—	—	—	—	*r*
Lagena sulcatiformis Pożaryska & Urbanek	—	—	—	—	R	—	—	—	—	—	—
sp. indet.	—	—	—	—	—	—	—	*r*	*r*	—	—
Lenticulina pseudovortex Marie	—	—	—	—	—	—	—	R	—	—	—
sp. indet.	—	—	*r*	*r*	*r*	—	*r*	*f*	*r*	—	—
Marssonella trochus (d'Orb.)	—	—	—	—	—	—	—	*c*	—	*rr*	—
sp. indet.	*f*	—	—	—	*f*	*r*	*f*	—	*r*	—	—
Orbignyna ovata Hagenow	—	—	—	—	—	—	—	*r*	—	—	—
Planoglobulina	—	—	—	—	—	—	—	*r*	—	—	—
Planomalina	—	—	—	—	*r*	—	*f*	—	—	—	—
Praebulimina ventricosa (Brotzen)	—	—	—	—	*c*	—	—	—	*a*	—	—
sp.	—	—	—	*c*	—	—	*c*	*c*	—	—	*r*
Reussella buliminoides Brotzen	—	RR	C	—	—	—	—	—	—	—	—
cushmani Brotzen	*c*	—	*c*	—	*c*	—	—	*a*	*c*	—	—
Spiroplectammina	—	—	—	—	—	—	*f*	*f*	*r*	—	—
Stensioeina pommerana Brotzen	A	—	—	—	A	—	—	*a*	—	—	—
sp. indet.	—	—	*f*	*f*	—	—	—	—	—	—	—
Tritaxia tricarinata Reuss	R	—	—	—	—	—	—	C	R	—	—
sp. indet.	—	—	—	—	*c*	—	—	—	—	—	—
Valvulineria lenticula (Reuss)	—	—	—	—	R	—	—	—	*c*	—	—
B. Nannoplankton											
Arkhangelskiella cymbiformis Vekshina	F	—	—	—	R	F	R	F	R	—	R
parca Stradner	—	—	—	R	—	—	—	—	—	—	—
Braarudosphaera bigelowi (Gran & Braarud)	—	—	—	R	R	—	—	R	—	R	R
Coccolithus sp. C	*f*	R	*f*	*f*	*f*	*f*	*r*	*f*	*r*	*f*	*f*
Coccolithus? sp. 35	—	—	—	—	—	R	—	R	R	—	R
Discolithina numerosa (Gorka)	F	—	—	R	—	—	—	—	R	—	—
Lucianorhabdus cayeuxi Deflandre	*r*	—	*r*	*r*	*r*	*f*	*r*	*f*	*r*	*f*	*r*
Microrhabdulus decoratus Deflandre	*r*	—	—	—	—	—	—	*r*	—	—	—
Micula staurophora (Gardet)	—	—	—	—	—	*r*	—	*r*	—	—	—
Nannoconus spp.	*r*	—	*r*	*r*	*r*	*f*	*r*	*r*	*r*	*f*	*r*
Rhabdolithus anthophorus Deflandre	—	—	F	R	R	—	—	—	R	R	—
Rhabdolithus? sp. 9	*f*	—	*r*	*r*	*r*	*f*	*r*	*f*	*r*	*f*	*r*
Tetralithus gothicus Deflandre	—	—	—	R	—	—	—	R	—	—	—
obscurus Deflandre	*r*	—	—	—	—	—	—	—	—	*r*	—
Zygodiscus sp. 19	R	—	R	—	R	F	F	R	R	R	R
Zygrhablithus intercisus (Deflandre)	*f*	—	*r*	*r*	—	*f*	*r*	*f*	—	*r*	*r*
turriseiffeli (Deflandre)	*f*	—	*f*	*f*	—	*f*	*f*	*c*	*r*	*f*	*r*

specimen of *Planoglobulina* sp., a genus common in the Senonian of the U.S.A. but previously unrecorded from England.

SB 495. R: C 16·3; G: E 42·4. 49° 46′; 4° 20·3′. 45 fm.

Hard white chalk which yielded a Santonian fauna.

SB 496. R: C 17·5; G: E 42·7. 49° 45·5′; 4° 20·4′. 45 fm.

Large white smear, uncontaminated by Recent sand, with abundant fragments of chalk; Santonian age.

SB 504. R: C 18·9; G: E 38·1. 49° 45·6′; 4° 17·2′. 46 fm.

Hard chalk with meagre fossils but age is either Santonian, or possibly Coniacian.

(iii) *Campanian* (table 3)

Of the Foraminifera, *Bolivinoides decoratus* replaces *B. strigillatus* early in the Campanian, and *Gavelinopsis voltziana* and *Praebulimina laevis* are abundant. Species of *Pullenia* and *Pseudouvigerina* appear for the first time.

Among the nannoplankton, all but *Coccolithus* sp. C are rare, *Nannoconus* is now absent, and *Arkhangelskiella* cf. *parca* and *Rhabdolithus* cf. *anthophorus* are smaller and more delicate than those found in the succeeding Lower Maestrichtian strata.

SB 104/4. R: D 7·25; G: F 30·0. 49° 40′; 4° 19·8′. 48 fm.

A smear of chalk from the core-cutter which, however, yielded sufficient Foraminifera suggestive of an Upper Santonian or Lower Campanian age, either zone of *Offaster pillula* or *Actinocamax quadratus*; the nannoplankton incline to a Campanian age.

SB 247/4. R: C 9·75; G: D 46·95. 49° 50′; 4° 14·4′. 45 fm.

The foraminiferal evidence is inconclusive but probably Campanian is the verdict from the nannoplankton.

SB 248. R: C 15·9; G: D 33·15. 49° 49′; 4° 04·9′. 43 fm.

Intensely hard, pale-cream chalk showing surfaces with a pale-grey skin; the sample may have been taken from a loose pebble. The Campanian age is not in doubt.

SB 301. R: C 15·1; G: E 32·85. 49° 47·6′; 4° 15′. 43 fm.

A white smear with abundant fragments of hard chalk. *Bolivinoides* cf. *decoratus* and *Gavelinopsis* cf. *plana*, supported by the nannofossils, are reasonable indices of the Campanian.

SB 892/2. R: D 12·32; G: E 43·25. 49° 39′; 4° 15·5′. 47·5 fm.

Hard white chalk heavily bored by Recent organisms. *Pseudovalvulineria* cf. *glabra* and *Bolivinoides*, intermediate between *B. strigillatus* and *B. decoratus*, are typical of the *Actinocamax quadratus* Zone, Lower Campanian.

(iv) *Lower Maestrichtian* (table 4)

At, or near, the base of the Maestrichtian appear new gavelinellids, such as *Gavelinella incerta*, *G. ekblomi*, *Gavelinopsis plana*, *G. involutiformis*; new species of *Bolivinoides*, especially *B. giganteus*, and *Bolivina incrassata*, *Tappanina selmensis*, *Coleites* are also stratigraphically significant.

The assemblages of nannoplankton are comparable with those from the Gulpen Chalk of Holland (Zone B, and lower part of Zone C), the Ripley Formation of Alabama, and part of the Abiod Formation of Tunisia. *Arkhangelskiella parca*, *Lucianorhabdus cayeuxi*, *Rhabdolithus anthophorus* and *Tetralithus obscurus* are significant forms in the Lower Maestrichtian assemblages because they do not persist into the Upper Maestrichtian.

SB 288. R: E 6·7; G: D 41·9. 49° 37·3′; 3° 59·3′. 47 fm.

Hard white chalk with many echinoderm fragments and well-preserved Foraminifera.

SB 294. R: D 19·4; G: E 36·2. 49° 34·6′; 4° 20·2′. 46 fm.

Hard white chalk which formed a smear on the core-cutter, but the Foraminifera and nannofossils all indicate derivation from the Maestrichtian and it is therefore assumed that the sample was taken from in place.

TABLE 3. MICROFOSSIL ASSEMBLAGES SUGGESTING A CAMPANIAN AGE

A. Foraminifera	104/4	247/4	248	301	892/2
Arenobulimina	—	—	*r*	—	*f*
Bolivinoides decoratus (Jones)	—	—	—	RR	—
intermediate between *decoratus* and *strigillatus*	—	—	—	—	*a*
strigillatus (Chapman)	F	—	—	—	—
? *Eggerellina*	—	—	*r*	—	—
Eouvigerina	—	—	—	—	*r*
Gavelinella costata Brotzen	—	—	—	—	R
pseudoexcolata (Kalinin)	F	—	—	—	—
sp. 1	—	—	—	—	*c*
Gavelinopsis plana (Schijfsma)	—	—	—	RR	—
voltziana (d'Orb.)	C	—	R	—	—
Globorotalites michelinianus (d'Orb.)	—	—	—	—	*f*
multiseptus (Brotzen)	F	—	—	—	—
Gyroidinoides	*r*	—	*r*	—	*r*
Lenticulina	—	—	—	—	*r*
Orbignyna	—	—	*r*	—	—
? *Osangularia*	*f*	—	—	—	—
Praebulimina	*f*	—	—	—	*r*
Pseudovalvulineria glabra Goel	—	—	—	—	C
Stensioeina	*f*	*rr*	*r*	*rr*	*r*
B. Nannoplankton					
Arkhangelskiella cymbiformis Vekshina	*r*	*r*	—	—	unexamined
parca Stradner	R	R	R	R	
Coccolithus sp. C	*f*	*f*	*f*	*f*	
Lucianorhabdus cayeuxi Deflandre	*r*	*r*	*r*	*r*	
Rhabdolithus anthophorus Deflandre	—	—	F	R	
Rhabdolithus? sp. 9	—	*r*	*r*	*r*	
Tetralithus obscurus Deflandre	*r*	—	—	—	
Zygrhablithus intercisus (Deflandre)	RR	—	—	—	
turriseiffeli (Deflandre)	*r*	—	—	—	

SB 453. R: F 13·1; G: E 38·3. 49° 25′; 4° 00′. 48 fm.

Soft white chalk with rich assemblages of well-preserved Bryozoa, Foraminifera and nannofossils. The general aspect of the foraminiferal list is that of the *Belemnitella mucronata* Zone which spans from the Upper Campanian to the Lower Maestrichtian; however, *Tappanina selmensis* has not been found below the *Ostrea lunata* Zone and *Gavelinella* cf. *lundegreni* only occurs rarely in the *mucronata* Zone, and is much commoner in Lower Campanian samples. This somewhat conflicting evidence is resolved by the presence of typical Lower Maestrichtian nannoplankton.

SB 505. R: D 11·8; G: F 32·6. 49° 37·8′; 4° 20·1′. 45 fm.

Soft white chalk especially rich in the foraminifer *Stensioeina*.

SB 519. R: D 20·6; G: F 43·7. 49° 32·6′; 4° 24·5′. 49 fm.

Table 4. Microfossil assemblages suggesting a Lower Maestrichtian age

A. Foraminifera	288	294	453	505	519	883	884	887	888/2
Arenobulimina	—	—	*r*	—	—	—	—	—	—
Astacolus	—	—	—	*r*	—	—	—	—	—
Bolivina incrassata Reuss	—	—	—	—	—	*r*	—	*r*	—
plaita Carsey	—	—	*c*	C	—	*c*	R	—	—
Bolivinoides decoratus (Jones)	—	—	*f*	—	—	—	—	—	—
delicatulus Cushman	—	—	—	R	—	—	—	—	—
draco (Marsson)	—	—	—	R	—	—	—	—	—
giganteus Hilterman & Koch	—	R	—	—	—	—	—	—	—
oedumi (Brotzen)	—	—	—	F	—	R	R	—	—
Bulimina strobila Marie	—	—	F	—	—	—	—	—	R
Cibicides beaumontianus (d'Orb.)	—	—	*f*	—	—	—	—	—	R
? *Conorbina*	—	—	—	*c*	—	—	—	—	—
Dorothia pupa (Reuss)	—	—	—	*r*	—	—	—	—	—
Eggerellina	—	—	*r*	—	—	—	—	—	—
Eouvigerina cretacea (Heron-Allen & Earland)	—	—	*c*	—	—	—	—	—	—
gracilis (Egger)	—	—	—	—	—	*r*	—	—	—
Eponides biconvexa Marie	—	R	*f*	F	R	F	—	—	*r*
lunata Brotzen	F	—	—	—	—	—	—	—	—
Gavelinella incerta Hofker	—	*r*	—	—	*c*	—	—	F	—
ekblomi (Brotzen)	—	R	—	F	—	—	—	—	—
lundegreni (Brotzen)	—	—	A	—	—	—	—	—	—
pertusa (Marsson)	—	—	*f*	*f*	*f*	*f*	—	—	R
Gavelinopsis complanata (Reuss)	—	—	—	—	—	C	—	—	—
involutiformis Hofker	*a*	*f*	—	—	—	—	—	—	—
plana (Schijfsma)	F	R	—	—	F	A	F	F	A
voltziana (d'Orb.)	—	—	*a*	*c*	*c*	*c*	*a*	*c*	*a*
Globorotalites multiseptus (Brotzen)	—	—	*a*	—	—	—	—	—	—
Globotruncana arca (Cushman)	—	—	*f*	—	—	—	—	—	—
linneiana (d'Orb.)	—	—	*c*	—	—	—	—	—	—
Guttulina	—	—	*r*	—	—	—	—	—	—
Gyroidinoides nitidus (Reuss)	—	—	*c*	—	—	—	—	—	—
octocameratus (Cushman & Hanna)	—	—	—	*c*	*r*	*f*	—	—	*r*
Heterohelix	*c*	—	—	—	—	—	—	—	—
Heterostomella rugosa (d'Orb.)	—	—	*f*	*r*	—	*f*	—	—	—
Lagena sulcatiformis Pożaryska & Urbanek	—	—	F	R	—	—	—	—	—
Lenticulina pseudovortex Marie	—	—	*f*	—	—	—	—	—	—
subangulata (Reuss)	—	—	*r*	R	—	—	—	—	—
trilobata (d'Orb.)	—	—	R	—	—	—	—	—	—
Marginulina bullata (Reuss)	—	—	*r*	—	—	—	—	—	—
Marssonella	*r*	—	*c*	—	—	*f*	*f*	—	—
Orbignyna	—	—	*r*	—	—	—	—	—	—
Osangularia	—	—	—	—	—	*f*	—	—	—
Planomalina	—	—	*c*	*f*	—	*f*	—	—	—
Praebulimina laevis (Beissel)	R	*f*	F	*f*	*c*	*c*	*f*	*f*	R
Pseudouvigerina cristata (Marsson)	—	—	*f*	*r*	—	*f*	—	—	—
Pullenia quaternaria (Reuss)	—	—	*f*	—	—	R	—	—	—
Pyrulina	—	—	*r*	—	—	—	—	—	—
Reussella prolixa (Cushman & Parker)	*c*	*c*	—	*c*	*r*	*f*	—	—	—
Rugoglobigerina	—	—	*f*	—	—	—	—	—	—
Spiroplectammina laevis (Roemer)	—	—	F	C	—	C	R	—	—
Stensioeina pommerana Brotzen	—	—	*a*	*a*	—	*a*	F	R	F
Tappanina selmensis (Cushman)	*r*	—	*f*	*f*	—	F	—	—	—
Tritaxia	—	—	*r*	—	—	—	—	—	—
Valvulineria	—	—	*f*	*r*	—	*f*	—	—	—

Table 4 (*cont.*)

B. Nannoplankton	288	294	453	505	519
Arkhangelskiella cymbiformis Vekshina	*c*	*f*	*f*	*c*	*c*
parca Stradner	*r*	*f*	*r*	*f*	*f*
Braarudosphaera bigelowi (Gran & Braarud)	*r*	*r*	*f*	*r*	*r*
Coccolithus sp. C	*c*	*c*	*c*	*c*	*c*
Coccolithus? sp. 32	*r*	—	—	—	—
sp. 35	—	—	*r*	—	*r*
Discolithina numerosa (Gorka)	F	—	C	R	C
Kamptnerius magnificus Deflandre	—	*r*	*r*	—	—
Lithraphidites sp. 36	*f*	—	—	—	—
Lucianorhabdus cayeuxi Deflandre	*r*	*c*	*c*	*c*	*c*
Marthasterites inconspicuus Deflandre	*r*	—	—	—	—
Microrhabdulus decoratus Deflandre	*r*	*f*	*r*	*r*	*r*
sp. 40	*r*	*r*	—	—	—
Micula staurophora (Gardet)	*f*	*r*	*f*	*f*	*c*
Rhabdolithus anthophorus Deflandre	—	—	*f*	*f*	*f*
Rhabdolithus? sp. 8	—	—	*r*	*r*	—
sp. 9	—	*r*	—	*r*	—
Tetralithus obscurus Deflandre	*r*	*f*	*f*	*f*	*r*
Zygodiscus sp. 22	*r*	*r*	—	*r*	—
Zygrhablithus intercisus (Deflandre)	*c*	*r*	*r*	*f*	*f*
turriseiffeli (Deflandre)	*c*	*r*	*c*	—	*f*

samples
883, 884, 887, 888/2
unexamined
for
nannofossils

SB 883. R: D 11·93; G: F 31·75; P: A 52·00. 49° 38′; 4° 19·5′. 47 fm.

Hard white chalk with common Foraminifera and *Inoceramus* prisms.

SB 884. R: D 12·28; G: F 31·70; P: A 51·97. 49° 37·8′; 4° 19·4′. 47 fm.

SB 887. R: D 20·78; G: E 46·75; P: A 50·90. 49° 35·5′; 4° 15·5′. 47 fm.

Hard white chalk with rare Foraminifera probably of Lower Maestrichtian age.

SB 888/2. R: D 17·85; G: E 45·45; P: A 50·98. 49° 36·8′; 4° 15·6′. 48 fm.

Fragments of hard white chalk were recovered from the tube of the corer; the small number of Foraminifera that was isolated indicates probably an Upper Campanian or a Lower Maestrichtian age.

(v) *Upper Maestrichtian* (table 5)

Among the Foraminifera, *Racemiguembelina fructicosa* is especially characteristic and appears to be confined to the Upper Maestrichtian of north-western Europe. Strata of comparable age occur in the typical development of the Maestrichtian in Holland (ENCI Quarry), in the Prairie Bluff Formation of Alabama, and in the Argiles el Haria of Tunisia. The nannofossil assemblages are rich in variety and are commonly better preserved than in other Cretaceous cored samples; *Tetralithus murus* has been observed in SB 292/2 and 507, a species which seems to be present only in uppermost Maestrichtian deposits of Europe, North America and North Africa.

SB 292/2. R: E 2·75; G: E 40·5. 49° 34·9′; 4° 10·8′. 47 fm.

A smear taken from a core-cutter, which provided a foraminiferal assemblage consistent with having come from a sample of Maestrichtian chalk; for this reason, the smear is believed to have come from rock *in situ*.

SB 454. R: F 7·0; G: E 36·2. 49° 27·3′; 4° 00′. 48 fm.

Soft cream chalk rich in fragments of Bryozoa, and in Foraminifera and nannoplankton.

TABLE 5. MICROFOSSIL ASSEMBLAGES SUGGESTING AN UPPER MAESTRICHTIAN AGE

A. Foraminifera	292/2	454	506	507/2	520
Alabamina	R	*r*	*r*	—	—
Anomalinoides	—	*f*	—	*f*	—
Arenobulimina	—	*f*	*f*	*f*	—
Astacolus compressus (d.Orb.)	—	R	R	—	—
Bolivina incrassata Reuss	—	*c*	*c*	*c*	—
plaita Carsey	*r*	C	*r*	—	—
Bolivinoides delicatulus Cushman	—	R	—	—	—
giganteus Hiltermann & Koch	—	F	*r*	*r*	—
Cibicides	—	*r*	*r*	—	—
Coleites	—	—	—	—	*r*
Discorbis koeneni (Brotzen)	—	R	—	—	—
Eggerellina gibbosa var. *conica* Marie	—	—	*r*	—	—
Eponides biconvexa Marie	—	R	F	—	—
toulmini Brotzen	—	*f*	—	—	—
Gavelinella ekblomi (Brotzen)	—	*f*	*f*	*f*	—
incerta Hofker	—	*c*	*f*	*c*	—
pertusa (Marsson)	*r*	*c*	*f*	*r*	*r*
Gavelinopsis involutiformis Hofker	*c*	*a*	*a*	—	—
plana (Schijfsma)	C	F	F	F	—
voltziana (d'Orb.)	—	—	—	*a*	*c*
Globulina	*r*	*r*	—	—	—
Globotruncana arca (Cushman)	R	*c*	*r*	F	—
stuarti (de Lapp.)	—	R	—	—	—
Guembelitria	—	*f*	—	*c*	—
Gyroidinoides octocameratus (Cushman & Hanna)	—	*f*	—	*f*	—
Heterohelix	*f*	*f*	*r*	*f*	—
Lagena sulcatiformis Pożaryska & Urbanek	—	—	*r*	—	—
Orbignyna ovata Hagenow	—	—	—	*r*	—
rimosa (Marsson)	—	*f*	F	F	—
Planomalina	—	*f*	—	*f*	—
Praebulimina laevis (Beissel)	F	*f*	*r*	*a*	*r*
Pseudouvigerina cimbrica Brotzen	F	*c*	—	*f*	—
cristata (Marsson)	—	—	*c*	—	—
Pullenia	*r*	—	—	—	—
Racemiguembelina fructicosa (Egger)	—	*f*	*f*	*c*	—
Reussella prolixa (Cushman & Parker)	*c*	*c*	*a*	*a*	—
Rugoglobigerina	—	*c*	—	*r*	—
Spiroplectammina laevis (Roemer)	—	F	R	A	—
Stensioeina esnehensis Nakady	—	—	—	F	—
Tappanina selmensis (Cushman)	—	R	—	*f*	—
B. Nannoplankton					
Arkhangelskiella cymbiformis Vekshina	*c*	*c*	*c*	*a*	*f*
Braarudosphaera bigelowi (Gran & Braarud)	*r*	*f*	*r*	*f*	*r*
Coccolithus sp. C	*f*	*c*	*c*	*c*	*f*
gallicus (Stradner)	—	*r*	—	*f*	—
Discolithina numerosa (Gorka)	F	F	F	F	F
Kamptnerius magnificus Deflandre	—	*r*	—	—	—
Lithraphidites sp. 36	*f*	*f*	*f*	*f*	*f*
Microrhabdulus sp. 40	*f*	*f*	*f*	*c*	*f*
Micula staurophora (Gardet)	*f*	*f*	*f*	*f*	*r*
Rhabdolithus decorus Deflandre	*r*	*r*	—	—	—
Rhabdolithus? sp. 8	—	—	—	*r*	—
sp. 9	*r*	*r*	*r*	*r*	—
Tetralithus murus Martini	*r*	—	—	*r*	—
Zygodiscus sp. 19	—	*r*	—	—	—
sp. 20	—	—	—	*r*	—
sp. 22	*r*	*r*	—	*r*	*r*
Zygrhablithus intercisus (Deflandre)	*c*	*c*	*c*	*c*	*f*
turriseiffeli (Deflandre)	*f*	*c*	*c*	*c*	*f*

SB 506. R: D 14·5; G: F 33·2. 49° 36·8′; 4° 19·8′. 49 fm.

Soft white chalk with abundant microfossils.

SB 507/2. R: D 23·7; G: F 37·1. 49° 33′; 4° 19·8′. 49 fm.

Soft white chalk with abundant microfossils.

SB 520. R: D 21·8; G: G 30·9. 49° 31·3′; 4° 27·3′. 50 fm.

Hard white chalk which has not yielded many Foraminifera or nannofossils, but *Coleites* has not been recorded in Europe from rocks older than Maestrichtian.

(vi) *Upper Cretaceous, undivided*

Three smears taken from core-cutters contain chalky fragments almost certainly of Upper Cretaceous age, but none of the microfossils identified are diagnostic of Stages.

SB 384/2. R: C 8·9; G: F 39·5. 49° 47·4′; 4° 30·25′. 44 fm.

A white smear yielded fragments of intensely hard yellowish chalk. Ill-preserved and mineralized Foraminifera include *Gyroidinoides*, *Gavelinella* and *Praebulimina*; among nannofossils, *Coccolithus* sp. C is frequent and *Zygrhablithus turriseiffeli* very rare.

SB 494. R: C 10·1; G: E 39·5. 49° 48·4′; 4° 20·1′. 44 fm.

Only *Coccolithus* sp. C was identified with certainty.

SB 497/2. R: C 17·0; G: F 30·0. 49° 45·1′; 4° 23·1′. 45 fm.

Fragments of hard, white, yellow and brown limestone are probably Upper Cretaceous in age as they yielded *Coccolithus* sp. C.

(*f*) *Palaeocene* (*including Danian*)

According to the classical interpretation the Danian is the highest subdivision of the Cretaceous rocks, and the Montian comprises the lowest of the Palaeogene. However, it is now held that the Tuffeau de Ciply, which many authors regard as the lower part of the Montian of Mons, is of the same age as at least some part of the type Danian; while the Calcaire Grossier de Mons, which overlies the Tuffeau de Ciply without apparent discordance, may also be Danian (Voigt 1960; Hofker 1961; Marlière 1962; Rasmussen 1962).

Danian (table 6)

Among the nannofossils, of special significance with regard to a Danian age are frequent *Cribosphaerella danica* and *Coccolithus helis*; rare *Cyclococcolithus*? sp. 17 and *Thoracosphaera* sp. 31 provide evidence in support. Of interest are very rare *Goniolithus fluckigeri* which have not previously been recorded from beds older than Middle Eocene.

SB 291. R: E 7·1; G: E 34·9. 49° 34·7′; 4° 05·9′. 47 fm.

A hard, white, chalky limestone which contains a large number of foraminiferal species known from the Maestrichtian and Danian. Typically Maestrichtian species, such as *Globotruncana* spp., *Racemiguembelina fructicosa*, *Bolivinoides giganteus*, are absent; on the other hand, *Globigerina pseudobulloides*, which is confined to the Danian, and *G. triloculinoides*, which first appears there, are present. Other species known from the Danian, but not the Maestrichtian, of Denmark are *Eponides frankei*, *Karreria fallax*, *Bolivinopsis scanica*, *Bulimina plena* and *Pyramidina curvisuturata*. Some of these species range into post-Danian beds but there is nothing in the sample which suggests a post-Danian age. A similar fauna comes from the Upper Danian of Östra Torp, Scania, Sweden (Brotzen 1940, 1959).

SB 296/3. R: D 19·75; G: G 44·8. 49° 29·7′; 4° 35·6′. 50 fm.

A smear with abundant fragments of pale greyish-buff limestone was examined only for foraminifers, which yielded *Rotalia* sp. cf. *tuberculifera* similar to specimens obtained from SB 452 and SB 471, both of which samples on other evidence are placed in the Danian.

TABLE 6. MICROFOSSIL ASSEMBLAGES SUGGESTING A DANIAN AGE

A. Foraminifera	291	296/3	452	471	508
Angulogerina	—	—	*c*	—	*c*
Alabamina midwayensis Brotzen	R	—	F	—	—
Anomalinoides danicus (Brotzen)	*a*	—	—	—	—
nobilis Brotzen	—	—	*c*	—	—
Bolivinoides	*r*	—	—	—	—
Bolivinopsis scanica Brotzen	*r*	—	—	R	—
Bulimina plena Brotzen	*f*	—	—	—	—
Chiloguembelina	—	—	*r*	*f*	—
Cibicides	—	—	*c*	*a*	—
Cibicidoides proprius Brotzen	*r*	—	—	—	—
Coleites danicus Brotzen	—	—	—	R	—
reticulosus (Plummer)	*c*	—	—	—	—
Discorbis conula (Brotzen)	—	—	—	—	*r*
koeneni (Brotzen)	—	—	*f*	—	—
Epistominella alata (Marsson)	F	—	—	—	—
meeternae (Visser)	—	—	C	—	A
Eponides frankei (Brotzen)	*c*	—	—	—	—
toulmini Brotzen	*f*	R	*c*	*f*	*a*
Gavelinella ekblomi (Brotzen)	*r*	—	*f*	*f*	—
Gavelinopsis plana (Schijfsma)	—	—	F	—	C
voltziana (d'Orb.)	—	—	C	—	A
sp.	*a*	*f*	*a*	—	—
Globigerina pseudobulloides Plummer	*a*	—	F	*c*	RR
triloculinoides Plummer	*f*	—	—	—	—
Globigerinoides daubjergensis (Bronnimann)	R	—	—	—	—
Gyroidinoides	*c*	—	*c*	*c*	*c*
Karreria fallax (Rzehak)	*f*	—	—	—	—
Lagena	*f*	—	—	—	—
Lenticulina	*f*	—	—	—	*f*
Marssonella	*f*	—	—	—	—
Mississippina binkhorsti (Reuss)	*r*	—	—	—	—
? *Nonion* sp.	—	—	*f*	*r*	*c*
Osangularia lens Brotzen	A	—	—	—	—
Polymorphinidae	*f*	—	—	—	*f*
Pseudouvigerina cristata (Marsson)	*f*	—	—	—	—
Pullenia	*r*	—	—	—	—
Pyramidina curvisuturata (Brotzen)	*a*	—	—	—	*a*
Reussella paleocenica (Brotzen)	R	—	C	*a*	C
Rotalia sp. ? *tuberculifera* Reuss	—	R	C	F	C
Spiroplectammina	*c*	—	—	*r*	—
Tappanina selmensis (Cushman)	*c*	—	*c*	—	*r*
B. Nannoplankton					
Coccolithus helis Stradner	*r*	—	*r*	—	—
sp. T	*f*	*r*	*c*	*r*	*r*
Cribrosphaerella danica Brotzen	*r*	—	*r*	—	—
Cyclococcolithus? sp. 17	*r*	—	—	—	—
Goniolithus fluckigeri Deflandre	—	—	*r*	—	—
Thoracosphaera imperforata Kamptner	—	—	R	—	—
sp. 31	*r*	—	—	*r*	—
Zygolithus concinnus Martini	RR	—	—	—	—

SB 452. R: F 7·0; G: E 44·3. 49° 25′; 4° 05·5′. 48 fm.

Soft cream limestone which crushed readily to yield a fine calcareous sand composed mainly of calcite crystals. Many microfossils, among which the foraminifers are mostly very small. The fauna includes a few *Globigerina*, probably *G. pseudobulloides*; the Danian sees the first appearance of *Globigerina*, and *G. pseudobulloides* is confined to the Danian.

SB 471. R: E 13·0; G: D 37·5. 49° 37′; 3° 55′. 45 fm.

Hard, pale-buff limestone which breaks down into a mass of crystalline calcareous fragments of fine sand grade.

SB 508. R: E 1·3; G: F 33·5. 49° 33′; 4° 17·3′. 49 fm.

Soft, pale-cream limestone composed of irregular calcite crystals frequently overgrowing organic fragments. This sample, as in previous cases, contains foraminifers known from Upper Maestrichtian and Danian horizons, but yielded no forms specific to the Maestrichtian nor indicators of an age later than Danian. *Epistominella* cf. *meeternae* is common in the Tuffeau de S. Symphorien, and also occurs in the Tuffeau de Ciply, of Belgium; the former is top Maestrichtian or Lower Danian, and the latter is Danian.

(*g*) *Eocene* (table 7)

The most abundant element in the fossil assemblages are the Foraminifera and stratigraphical dating of the samples is founded on them. Unfortunately, no identifiable specimens of the main groups of importance for dating in the Eocene, viz. the nummulites, *Discocyclina* and its allies, and the globigerinids, have been found in the samples next to be described. The analysis is founded mainly on the occurrence of fragmentary remains of *Alveolina* and *Orbitolites*, and of certain species of *Rotalia* and its allies. Two species of *Halkyardia* have been recovered and *H. ovata* appears to be specially significant for dating; in south-western France it occurs only at Bartonian (perhaps also Auversian) horizons. As a whole the samples are characterized by the abundance of miliolids and the dominance of *Pararotalia lithothamnica* and *Rotalia complanata*. The ostracods have been named as closely as possible; they are classified on internal features and well-preserved material is lacking in our samples. The nannofossils are surprisingly poorly represented and are of no stratigraphical value.

SB 67/2b. R: F 0·6; G: E 33·27. 49° 39′; 4° 00′. 49 fm.

A smear from the outer surface of a core-cutter contained only slight contamination by Recent material and was sampled probably from rock *in situ*. The Foraminifera point to a Middle or Upper Eocene age, but smears from the same general locality (SB 67/3 and 67/4) contain *Sphaerogypsina*, which elsewhere outside our map is associated with *Orbitolites* and *Alveolina*, and have accordingly been assigned to a Lutetian or Auversian age (Middle or lower Upper Eocene).

SB 92/2. R: F 2·1; G: F 32·08. 49° 25·1′; 4° 10′. 50 fm.

Fragments of limestone washed from a smear on a core-cutter produced a meagre foraminiferal assemblage, among which the association of *Rotalia complanata* and *Pararotalia lithothamnica*, and the absence of *Rotalia trochidiformis*, *R. suessonensis* and *R. guerini*, suggests an Upper Eocene age; the occurrence of *Alveolina*, which appears

TABLE 7. MICROFOSSIL ASSEMBLAGES SUGGESTING AN EOCENE AGE

A. Foraminifera	67/2b	92/2	290	469	509	511	512	517	523	528
Alabamina	—	—	—	—	*c*	—	—	R	—	—
Alveolina sp.	—	*rr*	—	—	—	—	—	—	—	—
Articulina pseudosulcata Kaassch	—	—	—	—	—	—	—	R	—	—
terquemi Cushman	—	—	—	—	—	—	—	R	—	—
spp.	—	—	—	—	—	*f*	—	—	—	—
Asterigerina campanella (Gümbel)	—	—	—	—	—	*r*	—	—	—	—
Boldia	—	—	—	—	—	R	—	*f*	—	—
Bolivina	—	—	—	—	—	*r*	—	—	—	—
Buliminella	—	—	—	—	—	*r*	—	—	—	—
Cancris subconicus (Terq.)	—	—	—	R	—	—	—	—	—	—
Cibicides carinatus (Terq.)	—	—	—	C	—	A	—	—	—	*c*
productus (Terq.)	—	—	—	—	F	—	—	—	—	—
robustus Le Calvez	—	—	—	—	C	C	—	—	—	—
westi Howe	—	—	—	—	*c*	—	—	—	—	—
Clavulina parisiensis d'Orb.	—	—	—	—	—	—	—	*f*	—	—
Cycloloculina punctata (Terq.)	—	—	—	—	R	—	—	—	—	—
Discorbis magna Vialli	—	—	—	—	—	—	—	—	—	R
quadrata (Terq.)	—	—	—	—	—	*r*	—	—	—	—
spp.	—	—	—	—	—	*r*	—	*r*	—	*r*
Elphidium laeve (d'Orb.)	F	—	—	—	*a*	*c*	—	*a*	—	—
latidorsatum (Reuss)	—	—	—	—	—	—	—	—	—	R
subnodosum (Roemer)	—	—	—	—	—	—	—	—	—	*a*
Epistomaria semimarginata d'Orb.	R	RR	—	—	—	—	—	*f*	—	—
Eponides toulmini Brotzen	—	—	—	—	A	—	—	—	—	—
Globulina gibba d'Orb.	—	—	—	—	—	—	—	—	—	*f*
var. *myristiformis* (Will.)	—	—	—	—	—	—	—	*f*	—	*r*
Guttulina problema d'Orb.	—	—	—	—	—	—	—	—	—	C
sp. indet.	—	*r*	—	—	*f*	*r*	—	*f*	—	—
Gyroidina	—	—	—	—	—	*r*	—	—	—	—
Halkyardia minima (Liebus)	—	—	—	R	*a*	*r*	—	*r*	—	*f*
ovata (Halkyard)	—	—	—	—	*r*	—	—	*r*	—	—
Hauerina	—	—	—	—	—	—	—	—	*r*	—
Lenticulina	—	—	—	—	*f*	*r*	—	—	—	—
Miliola prisca (d'Orb.)	F	—	RR	C	R	*a*	A	*a*	*a*	—
saxorum Lamarck	F	—	RR	R	F	F	F	*f*	*c*	C
strigillata (d'Orb.)	—	—	—	—	—	F	—	—	—	—
Nummulites sp.	—	—	—	—	—	*f*	—	—	—	—
Orbitolites complanatus (*s.l.*) (Lamarck)	—	—	RR	—	—	—	—	R	*f*	—
Pararotalia armata (d'Orb.)	—	—	—	F	C	C	—	—	—	—
lithothamnica (Uhlig)	A	F	—	C	R	A	—	A	—	*a*
Peneroplis	—	—	—	—	—	*c*	—	*f*	—	—
Pyrgo bulloides (d'Orb.)	—	—	—	R	*f*	—	—	*f*	*a*	—
elongata (d'Orb.)	—	—	—	*r*	—	F	—	—	F	—
sp. indet.	R	—	—	—	—	—	*c*	—	*f*	*r*
Quinqueloculina costata d'Orb.	—	—	—	—	—	*c*	—	F	—	—
juleana d'Orb.	—	—	—	—	*a*	R	—	*c*	—	—
ludwigi Reuss	—	—	—	—	—	—	—	F	—	A
seminulum (Linné)	—	—	—	C	F	A	—	C	—	—
Reussella	*r*	—	—	—	*r*	*r*	—	*c*	—	*r*
Rotalia complanata d'Orb.	F	A	RR	F	—	*c*	—	A	C	C
sp. 1	—	—	—	—	—	*c*	—	—	—	—
Sigmomorphina	—	—	—	R	—	*r*	—	—	—	*r*
Spirolina cylindracea Lamarck	—	—	—	—	—	—	—	*f*	—	—
striata d'Orb.	—	—	—	—	—	—	—	*a*	—	—
Spiroloculina bicarinata d'Orb.	—	—	—	—	R	C	—	*f*	—	—
costigera Terq.	—	—	—	—	—	—	—	*f*	—	—
pertusa Terq.	—	—	—	—	—	—	—	C	—	—
tricarinata Terq.	—	—	—	—	C	*r*	—	*a*	—	—
Spiroplectammina sp. 1	—	—	—	—	*r*	*f*	—	F	—	F
Triloculina angularis d'Orb.	—	—	—	F	—	—	—	—	—	—
gibba d'Orb.	—	—	—	F	—	—	—	—	—	—
inflata d'Orb.	—	—	—	R	—	—	—	*r*	R	—
trigonula (Lamarck)	—	—	—	—	—	F	F	C	F	A
Valvulammina globularis (d'Orb.)	—	—	—	—	—	—	—	R	—	—
Valvulina terquemi Le Calvez	—	—	—	—	—	—	—	R	—	—
sp.	—	—	—	—	—	—	—	*r*	*f*	*f*

TABLE 7 (*cont.*)

B. Ostracoda	67/2b	92/2	290	469	509	511	512	517	523	528
Aulocytheridea mourloni Keij	—	—	—	—	C	—	—	—	—	—
Bairdoppilata gliberti Keij	—	—	—	*r*	*c*	—	—	*f*	—	—
Cytheretta costellata (Roemer)	—	—	—	—	—	—	—	*f*	—	—
crassivenia Apostolescu	—	—	—	—	R	—	—	—	—	—
Haplocytheridea perforata (Roemer)	—	—	—	—	—	—	—	—	—	*r*
heizelensis Keij	—	—	—	—	—	—	—	R	—	—
Hermanites paijenborchiana Keij	—	—	—	R	*r*	—	—	*r*	—	R
?*Kingmaina forbesiana* (Bosquet)	—	—	—	—	—	—	—	*r*	—	—
Krithe rutoti Keij	—	—	—	—	—	—	—	F	—	—
Leguminocythereis striatopunctata (Roemer)	—	—	—	—	—	—	—	*r*	—	—
Loxoconcha subovata (v. Muenster)	—	—	—	—	—	—	—	—	—	R
Monsmirabilia foveolata (Bosquet)	—	—	—	—	*r*	—	—	—	—	—
Pokorynella limbata (Bosquet)	—	—	—	—	—	—	—	—	—	R
Schizocythere tessellata (Bosquet)	—	—	—	—	R	—	—	R	—	—
Triginglymus angulatopora (Reuss)	—	—	—	—	—	—	—	—	—	*r*
C. Nannoplankton										
Coccolithus sp. T	—	—	—	*r*	*r*	—	—	*r*	*f*	*f*
Rhabdosphaera tenuis Bramlette & Sullivan	—	—	—	—	*rr*	—	—	—	—	—

not to be a contaminant, probably favours a correlation with the Auversian rather than the Bartonian.

SB 95/5. R: E 14·45; G: E 45·66. 49° 29·8′; 4° 10·5′. 50 fm.

A smear composed of Recent sand, which provided polished Foraminifera derived from the Eocene, and fragments of crystalline limestone with translucent specimens of ill-preserved *Pararotalia* and ?*Rotalia*; these latter suggest Eocene limestone, perhaps *in situ*.

SB 290. R: E 19·0; G: E 30·1. 49° 32·8′; 3° 59·8′. 49 fm.

Angular fragments of greenish-grey, hard limestone, rendered spongy by numerous moulds of molluscs and bryozoans, obviously originated from the same source. Broken rock-surfaces show abundant cross-sections of Foraminifera, including species of miliolids and rotalids, intermixed with grains of glauconite and quartz. The age is Middle or Upper Eocene as shown by *Orbitolites* and not contradicted by the remaining foraminifers. Among fossils not listed in table 7, *Turbinolia* ranges Eocene–Oligocene, but in the Anglo–Paris–Belgian Basin is restricted to Cuisian–Bartonian; *Diastoma* cf. *costellatum* (Lamarck) is indicative of Middle or Upper Eocene. Other occurrences are *Dentalium* and ?*Arca*.

SB 469. R: F 1·4; G: D 42·9. 49° 32·4′; 3° 55′. 45 fm.

Pale-buff, hard, glauconitic limestone composed for the most part of calcareous organic fragments of sand-grade, but with about 2% of quartz-grains up to 0·5 mm. The aspect of lithology and fauna is that of the group SB 509, 511, 517 but no fossils believed to be diagnostic have been recognized. Age is probable Middle or Upper Eocene.

SB 509. R: E 3·3; G: F 34·0. 49° 32·15′; 4° 17·1′. 50 fm.

Slightly indurated quartz-sand, with about 5% of glauconite and fairly abundant calcareous organic material of which the foraminifers and ostracods have been identified. The presence of *Halkyardia ovata* indicates Upper Eocene, probably Bartonian, age.

SB 511. R: E 3·5; G: F 39·15. 49° 31·1′; 4° 20′. 49 fm.

Glauconitic sandy limestone in which the microfossils are partly obscured by secondary calcification. The lithology and fauna closely resemble those of SB 509, though *H. ovata* has not been found; Upper Eocene, probably Bartonian. Six minute juveniles of *Nummulites*, probably a radiate species, were found, but could not be identified.

SB 512. R: E 6·0; G: F 35·4. 49° 30·9′; 4° 17·15′. 49 fm.

Greenish-buff, coarse-textured, glauconitic limestone which contains large quantities of miliolids; the constituent grains of the limestone are heavily overgrown and cemented with calcite, and this makes the identification of fossils almost impossible. There is a general resemblance between the fauna, so far as it can be identified, and that of SB 509 and 511; consequently, the age may be tentatively placed as Middle or Upper Eocene.

SB 517. R: E 8·65; G: E 41·25. 49° 32·8′; 4° 09·5′. 47 fm.

Soft buff limestone consisting of consolidated organic sand with abundant quartz-grains and not infrequent glauconite. Lithology and fauna are similar to those of SB 509 and 511. *Halkyardia ovata* indicates an Upper Eocene, probably Bartonian, age, though the presence of *Orbitolites* might suggest a slightly earlier date.

SB 523. R: E 3·3; G: G 38·6. 49° 27·7′; 4° 30·4′. 53 fm.

Soft, buff, coarse-textured limestone composed almost entirely of foraminiferal tests, with little interstitial matter. The main evidence with regard to age is provided by *Orbitolites complanatus* (*s.l.*), but the absence of *Rotalia trochidiformis*, *R. suessonensis* and *R. guerini* preferentially points to Upper Eocene. Lehmann (1961) has studied *O. complanatus* from the Middle or Upper Eocene of the Paris Basin, Cotentin and Loire-Inférieure, and has divided it into four species, but these are so finely drawn that the two specimens of *Orbitolites* from SB 523 cannot confidently be allocated to any one of Lehmann's new species.

SB 528. R: E 21·0; G: F 39·0. 49° 24·9′; 4° 15·7′. 52 fm.

Coarse-grained, buff limestone which contains but little glauconite. Among the foraminifers, *Discorbis magna* occurs in Bartonian and Oligocene deposits of Aquitaine and *Pararotalia lithothamnica* is exceptionally large and ornate, and suggests a late date; among the ostracods, *Pokornyella* is not known before the Upper Eocene and *Triginglymus angulatopora* is a Middle–Upper Eocene species. The stratigraphical age is thus claimed as Upper Eocene.

(*h*) ? *Oligocene*

SB 105/2. R: E 6·31; G: F 39·92. 49° 29·8′; 4° 20′. 51 fm.

Pale, buff-coloured, fine-textured limestone with fairly abundant sand grains and a little glauconite; set in the sandy limestone matrix are large numbers of waterworn macrofossils such as Bryozoa and fragments of oysters and echinoderms. The identified fossils include the following. Echinoids: an immature ?*Echinocyamus* and fragments possibly of *Scutella*. Cirripedes: one plate of *Balanus* sp. Ostracods: *Cytheretta* cf. *tenuiplicata* (Bosquet), ?*Pokornyella limbata* (Bosquet) and *Quadracythere* cf. *macropora* (Bosquet). Foraminifers: *Cibicides* sp., *Clavulina* sp., *Discorbis* sp., *Elphidium* sp.,

?*Halkyardia minima* (Liebus), *Pararotalia lithothamnica* (Uhlig), *Pyrgo* cf. *bulloides* (d'Orb.), *P.* cf. *elongata* (d'Orb.), *Rotalia* sp. 1, *Spiroplectammina* sp., *Triloculina* cf. *inflata* d'Orb., *T.* cf. *trigonula* (Lamarck) and *Valvulina* sp.

There are several lines of evidence which, although in each case is slight, as a whole support the conclusion that the sample is probably of Oligocene age. (i) *Balanus* is rare or absent before the base of the Barton Beds, after which it becomes abundant. (ii) Of the three ostracods, two were named originally from the Stampian of the Paris Basin, and the third from the Rupelian of Belgium (Stampian ≈ Rupelian; Middle Oligocene). *P. limbata* occurs also in the highest Eocene, and the other two ostracods range from Middle Oligocene to Miocene. (iii) *Discorbis* sp. is related to *D. bractifera* Le Calvez (Middle to Upper Eocene) but is stouter. (iv) *Rotalia* sp. 1 is similar to, and perhaps occupies the same ecological niche as, *R.* cf. *complanata* which occurs in Middle to Upper Eocene core-samples (table 7). *Discorbis* sp. and *Rotalia* sp. 1 are found in the Stampian at Gaas and Poyanne (Aquitaine), and at Lormandière (Rennes). *Discorbis* sp. is found in the Marnes à Huîtres (Lower Stampian, Paris Basin) and the Marnes vertes of Floirac (Middle or Lower Oligocene, Bordeaux). *Rotalia* sp. 1 is known in the Sable d'Étampes of Jeurs (Stampian, Paris Basin) and in the Unterer Meeressand of Weinheim (Rupelian, Germany). (v) *Pararotalia lithothamnica* is represented by large specimens with prominent umbilical plug and deep-set septal grooves on the ventral side; the grooves trifurcate at the margin, which is ornate ventrally and also sometimes dorsally. Such specimens characterize the late Upper Eocene and Oligocene; the species has not been found in the Middle Oligocene of the northern parts of France and Germany, but is present in rocks of this age in Aquitaine.

V. CORRELATION AND COMPARISON OF THE GEOLOGICAL AND GEOPHYSICAL METHODS AND RESULTS

Sampling of the rocky sea-bed within the area depicted in figure 6 was first achieved by dredging from the *Pourquoi-pas?* (Dangeard 1928) but 40 years ago navigational and palaeontological techniques were not so advanced as nowadays, while applied geophysical methods were not available to the oceanographer. The results of Hill & King (1953, pp. 12–13) and of Holme (1953, p. 7) are of much greater significance and reliability; their core-stations have been included on our map (figure 6).

On the basis of 95 core-stations a geological map was prepared in manuscript. Although these stations were selected, first, on a crude 10′ grid of latitude and longitude and, secondly, followed by closer-set stations in critical positions, yet the distribution which was the most significant geologically suggested that the best opportunity to co-ordinate geological and geophysical information lay along the meridian approximately running through Looe. Accordingly, a southward course followed by a much shorter northward course was run with the boomer and sparker; both pieces of acoustic equipment were used separately and on several occasions in order to try and assess if there was any difference in performance, but the boomer was used for the longer total time. Geologically, there was nothing to choose between the performance of either boomer or sparker; hereafter, for brevity, results will be attributed to the boomer.

Good working agreement was found to obtain regarding the inferred positions of the contacts between major geological divisions as determined, first, by coring and, secondly, more accurately by the boomer. In one instance, where the coverage by core-stations was completely inadequate, the boomer located the contact more than a mile away from its inferred position; however, where cores had been obtained at positions which determined contacts more accurately it was found that the discrepancy was about 100 yards. Our marine geological surveys are not claimed to be other than reconnaissances, particularly having regard to the large areas examined, and it should be borne in mind that in reconnaissance surveys on land inaccuracies of the same order of magnitude are commonplace.

(*a*) *Unconformities*

Apart from determining the positions of all the major geological contacts, the boomer gave evidence of the characteristics of those contacts such as are unobtainable by coring methods at present employed. Even if rotary coring of the rocky sea-bed is developed as a method of general applicability, in some respects the boomer will probably always supply more data, more quickly, about unconformable and also conformable contacts, although with regard to the sedimentary condition of the rocks on either side of these contacts the boomer will be much less informative.

After the boomer record was examined, 34 further core-stations were manned in 1961 in order to check on the positions of the stratal contacts as fixed by Decca, and to produce a more detailed map of the distribution of the subdivisions of the Chalk which the record showed to be repeated by folding. In no case where a core was obtained did it prove different from the prediction on the record, which confirms the reliability of the boomer technique.

The boomer established the existence of unconformable relationship between each of the major geological divisions—a condition which was indicated, but not proved, by an examination of the stratigraphy of the cored samples.

(*b*) *Boomer patterns characteristic of rock-types*

The New Red Sandstone provides a smooth and regular sea-bed but to the north the rocks abut against the ?Devonian slates, which are characterized by a rough sea-floor. The internal pattern of the boomer record of the slates suggests moderately tightly folded beds in marked contrast with the New Red Sandstone, where only minor folding and simple apparent dips can be detected (figure 8, plate 25). The New Red Sandstone also surrounds inliers of metamorphic rocks of the Eddystone–Hand Deeps complex, which protrude through the unconformable mantle (figure 9*a*, plate 26). Again, the internal pattern on the boomer record due to the metamorphic masses is strikingly different from the patterns of the New Red Sandstone and ?Devonian; presumably, many more reflective interfaces exist closer together and at variable angles. Indeed, the complex pattern is thought to be diagnostic of these metamorphic rocks, and when the record elsewhere picked out a small sea-bed irregularity, no more than 200 yards across and with a similar pattern (figure 10, plate 27), it was claimed to be a previously undetected inlier of metamorphic rocks, which subsequent coring in 1961 confirmed (SB 483). The metamorphic complex produces a sea-bed even more jagged than that of the ?Devonian slate; at one place on figure 9*a*, plate 26, a wedge-shaped mass may indicate infilling either by modern sediments or by the New Red Sandstone; in either explanation it is noteworthy that small-scale faulting appears laterally to define the valley. Deductions such as these from boomer record patterns are only significant regionally, and even within one region they should be regarded as suggestive rather than demonstrative.

The Lias constitutes one inlier within the Upper Cretaceous (figure 6). Whereas the unconformable contact is not clearly portrayed on the record at the northern end, at the southern end of the traverse the angular unconformity is beautifully displayed (figure 11, plate 28); the Lias and Chalk show corrected apparent dips respectively of $3\frac{1}{4}^\circ$ to the north and of $2\frac{1}{2}^\circ$ to the south. The internal pattern on the record of the Lias is again typical, because there are many, closely set, dark and white bands rhythmically repeated; these may represent reflexions from alternations of thin limestones and shales. The Lias is also folded; faults are more easy to detect than in any other major geological division crossed during the traverse, because a break in the continuity of the multiple black and white bands quickly becomes obvious on the record.

The boomer record of the Chalk produced no diagnostic pattern but occasionally some rock interfaces are strong reflectors (figure 7, plate 24 and figure 9*b*, plate 26). A rare structural detail occurs at two places opposite one another on the north and south arms of the traverse and, having regard to their position, probably along the strike; the detail is recognized as a manifestation of some peculiarity in the rocks themselves, and not as an artifact. The Chalk shows a prevailing low-angle dip, but in places the thickness of the rock between bedding-planes is crossed by much steeper black and white bands (figure 12, plate 29) to create an impression of 'false-bedding'. The two localities where the 'false-bedding' was recorded occur close to the Cretaceous and New Red Sandstone unconformable contact, and it is thought that this contact here lies at shallow depth below the sea-bed. The 'false-bedding' pattern may possibly arise through discordant stratigraphical successions.

There is no reason to claim an unconformity between the Upper Cretaceous and the Danian, which rocks are here included in the Palaeocene and classified with the Tertiary. A pronounced unconformity exists, however, between the Danian and Eocene, and this was clearly recorded in the southern and the northern runs (figure 9*b*, plate 26); the overall angle of dip is less in the Eocene than in the Danian and the Cretaceous, but the Eocene rocks are ruckled and make a strong angular discordance. Like the Cretaceous, the Eocene does not yield records which are individual to itself and by which it can be identified.

(*c*) *True-scale sections*

Wherever angles of dip were well defined on the boomer record they were corrected according to the method which has already been described (p. 324). These converted figures, which are predominantly apparent and not true angles, were added to the map (figure 6), from which were prepared geological sections on the scale of 1/15000; the sections from the southward and the northward runs were drawn alongside one another, and were thus directly comparable. Four geological marker horizons immediately became obvious and were cross-correlated, viz. (i) the unusual records simulating 'false-bedding' in the Chalk which may be represent patterns arising from unconformable strata; (ii) the Cretaceous/Lias unconformity on the northern margin of the Jurassic inlier; (iii) the same unconformity on the southern margin of the same inlier which, however, is replaced to the south-east by a fault; and (iv) the Danian/Eocene unconformity (see figure 6 where these marker horizons are numbered ① to ④). Minor structures can next be sorted out by reference to the four markers, viz. (i) two synclines and an intervening anticline correlate in the New Red Sandstone; (ii) an anticline and syncline are common to the Jurassic; and (iii) in the Upper Cretaceous the correlation of folds is more dubious because an extra fold is identified in the northern run.

The construction of the true-scale sections caused few surprises, but in two places the presumed base of the Upper Cretaceous just cleared the sea-bed before turning over on an anticline and returning to intersect the sea-bed, thus implying that rocks older than the Cretaceous cropped out at those positions. In 1963 a further six core-stations were selected in order to ascertain whether or not the sea-bed was composed of older rocks; in these six attempts only Upper Cretaceous and Danian cores were recovered. A re-examination of the true-scale sections was now necessary; it was found that an error of a fraction of a degree in the plotting of the apparent dips would result in the base of the Chalk remaining below the sea-bed, instead of above it in two places as the first construction showed. Having regard to the errors which are built into the final drawing of the geological section, such as the assumptions involved in the mathematical analysis (see p. 324), the inaccuracies which arise in plotting navigational positions on Decca charts, the technical difficulties of drawing geological lines on geological sections to an accuracy of a fraction of a degree—having regard to these, the geometry of the true-scale section fits to an astonishingly high degree of probability the known geological conditions.

(*d*) *Determination of thicknesses*

The thickness of the New Red Sandstone was determined from the true-scale geological sections as 2640 ft., but this measurement is directly related in the mathematical solution to an assumed velocity of 7230 ft./s (see p. 324). This thickness must therefore be corrected for the higher velocities in the New Red Sandstone and, adopting the mean of the velocity range for Class 2 rocks (Hill & King 1953, p. 15; Day, Hill, Laughton & Swallow 1956, p. 32), the figure for the thickness of the New Red Sandstone is thus modified to 3100 ft., which is in reasonable agreement with 2700 ft. deduced by Hill & King from seismic investigations (1953, p. 17, fig. 6). They also proposed a combined thickness of about 600 ft. for Cretaceous and Jurassic rocks, but here our measurements are in conflict because 1600 ft. has been calculated from the geological sections for the Cretaceous alone; Hill & King did not record Jurassic rocks *in situ* but in the inlier shown on figure 6 there is a minimum thickness of 640 ft. of Liassic strata; the total is therefore not less than say 2200 ft. It should be borne in mind when evaluating these calculations that the geology of the area under consideration is now known to be more complex than was the opinion a decade ago, but, as yet, there is no evidence in support of the statement 'that in this western Channel trough the Chalk may contain a number of intraformational non-sequences, and that it is nowhere more than a few hundred feet in thickness' (King 1954, p. 85). Donovan (1963, p. 8) has also questioned Hill & King's estimate of about 600 ft. for the combined Jurassic and Cretaceous rocks, and has suggested that they 'cannot be more than about 3000 feet thick'. Finally, at the southern end of the traverse a minimum thickness of 430 ft. of Tertiary strata can be determined directly from the boomer record.

(*e*) *Folding in Upper Cretaceous and Danian*

Folding in the chalky rocks south of the Jurassic inlier had not been determined prior to 1960; when in 1960 the boomer was streamed on the southern run, clear records of folds were obtained. Similar recordings of folds were made on the northern run but here there were no cored samples with which stratigraphy could be matched with the folds. In 1963, core-stations were determined at those positions of the northern run where the several divisions of the chalky Upper Cretaceous and Danian were expected to be repeated by folding, as predicted from samples obtained from the vicinity of the southern run and from the boomer record. Unfortunately, cores were recovered only at four stations, but the foraminiferal assemblages gave the geological ages in each case in accordance with prediction. These additional data have made it reasonable to guess at the approximate thicknesses of the divisions of the Upper Cretaceous; they are Pre-Santonian greater than 75 ft.; Santonian 175 ft.; Campanian 375 ft.; Lower Maestrichtian 400 ft.; Upper Maestrichtian 200 ft. The Upper Cretaceous is therefore not less than 1225 ft. thick. The Danian has a minimum thickness of 375 ft.

VI. CONCLUSIONS

The boomer and sparker are important and powerful tools to be used for the elucidation of geological structure in marine geological surveys, but they are best applied after preliminary surveys have been made by the conventional methods of coring and dredging where deep structures are exposed or otherwise available for study at the sea-bed. In these circumstances traverses are run across the strike after the general distribution of rock-types and the approximate positions of geological boundaries have been determined. In this manner, junctions can be expected to show up on the P.G.R. in the vicinity of previously inferred positions and they can be given much greater significance. In deep water or where Recent sedimentary cover is too thick to be penetrated by available corers, often the C.S.P. can be used to guide the geologist to such outcrops as may exist. In any event, the C.S.P. will provide data for the determination of the geometrical shape of the structure. Ultimately, geological sampling is required for the fullest possible appreciation of the geological history and structure.

The greatest promise in the future in the operation of the C.S.P. and P.G.R. systems in the English Channel and its Western Approaches lies in the production of a boomer or sparker in which the pulse-energy is greater than 13000 joules. In 1960, the 1000-joule boomer used by us gave reflexions from depths below the sea-bed of 400 ft.; in 1961, the 13000-joule boomer used by Hersey emitted sound pulses which penetrated to about 3500 ft.; recently Moore & Curray (1963) have procured excellent results over a possible salt-dome upthrust with 9000 joules input energy to a sparker and penetration of rock to about 3000 ft. It can now be announced that at Woods Hole the sparker has recently been fortified and has an energy of 100000 joules per discharge; reflexions have been recorded in excess of a second of travel-time below the sea-bed. The boomer has also been improved and it has been used successfully to high pressures and, like the sparker, has given information to a depth of rock of the order of at least 1 mile. If this much improved high energy acoustic apparatus were available for use in the Western Approaches of the English

Channel then reflexions from rock interfaces underlying the Mesozoic and Tertiary succession in the English Channel could be recorded. The structure within this pre-Mesozoic basement should become known, and hence the determination of the structural relationship between Brittany and south-west England, linked by the sub-Channel, appears to be a goal within reach.

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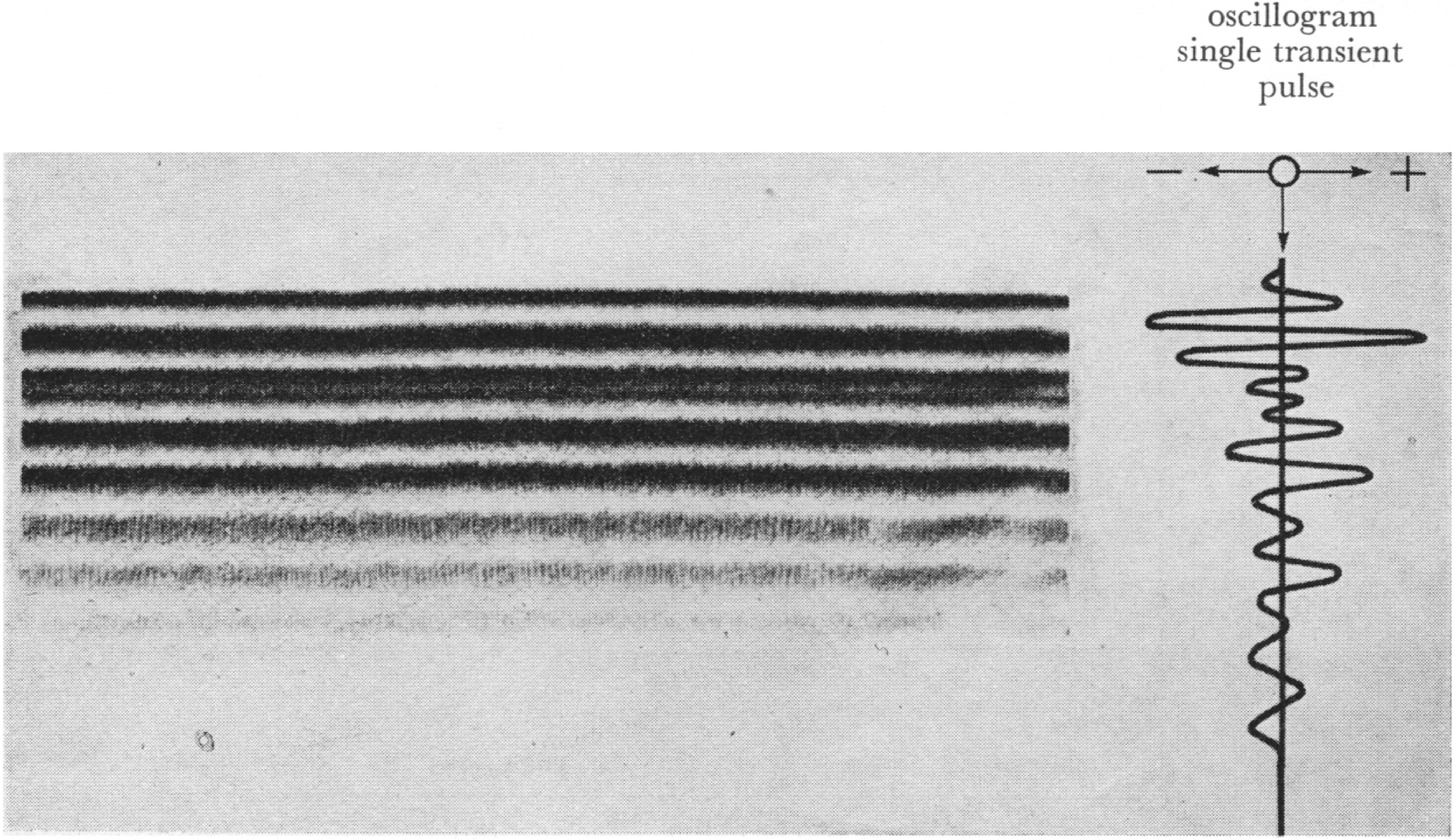

Figure 1. A P.G.R. record of successive printings of identical wave-trains compared with an oscillogram of a single wave-train. The dark bands on the P.G.R. record correspond to positive excursions of the wave-train.

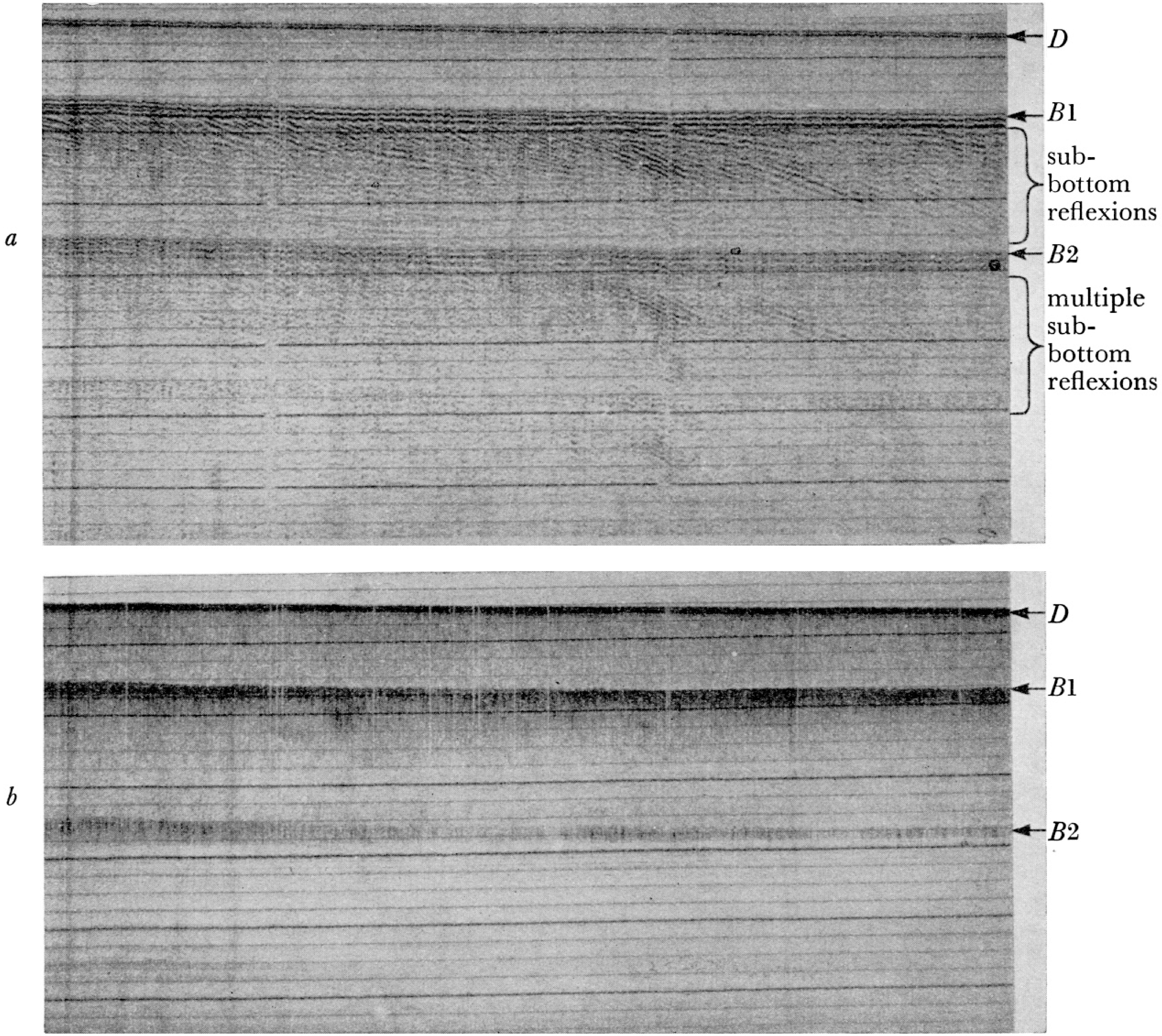

Figure 5. A representative P.G.R. recording identifying wave-trains with travel-paths of figure 2. *a*, Low frequency filter band; *b*, high frequency filter band.

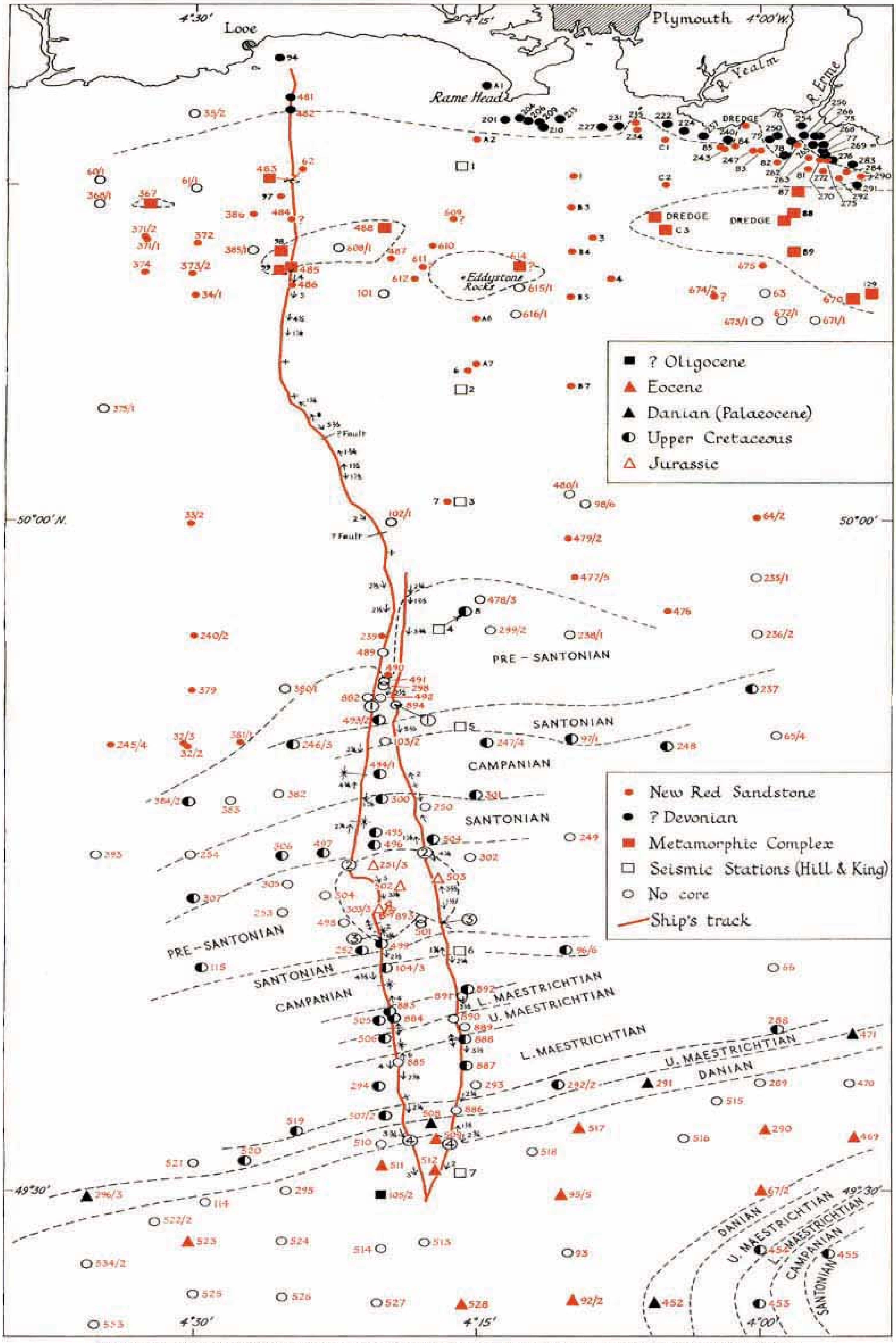

FIGURE 6. Marine geological map south of the Plymouth–Looe coastline showing distribution of core and dredge stations, the southern (left) and northern (right) courses taken by R.V. *Chain*, and the directions and corrected angles of apparent dips as determined from the boomer-sparker records. Core and dredge stations numbered in red refer to those taken by us; core stations numbered in black copied from Hill & King (1953, p. 12) and those in black prefaced with A, B or C from Holme (1953, p. 7). ① to ④ refer to the four marker horizons mentioned on page 348. Stations SB 484, 609, 611, 674/2 (New Red Sandstone) and SB 614 (Metamorphic Complex) carry a query on the map; samples obtained at these stations are not described in the text because the evidence of their probable geological age rests on red smears on the core-cutter in those attributed to New Red Sandstone, and on rough ground as shown by echo-soundings and broken core-barrels which are possibly indicative of Metamorphic Complex.

(Facing p. 322)

FIGURE 7. Northern run between latitudes 49° 33′ 35″ and 49° 35′ 48″, selected as a good record showing strong reflexions from simply dipping Upper Cretaceous strata. The corrected apparent dip is $2\frac{1}{4}$°.

Figure 8. Southern run between latitudes 50° 19′ 12″ and 50° 17′ 00″, showing the irregular topography and structural complexity of the Devonian slates abruptly truncated by the nearly level sea-bed produced by the almost flat and unconformable New Red Sandstone. The first ($B1$) and second ($B2$) sea-bed reflexions are lettered on the right of the record, but on the left four reflexions, and a fifth weak one, are visible.

FIGURE 9. The curved vertical line running approximately through the centre of each figure marks the overlap between two photographs.

a. Southern run between latitudes 50° 13′ 35″ and 50° 09′ 20″, showing irregular topography formed by the Metamorphic Complex succeeded to left and right by the much gentler topography of the New Red Sandstone. Note within the Metamorphic Complex the inverted isosceles-triangular area with horizontal material at the top; this may represent unconsolidated sediment, or New Red Sandstone, or both; there is a suggestion that the lateral sides of this triangular area are faulted. Note also that on the right side of the figure the New Red Sandstone is gently folded.

b. Northern run between latitudes 49° 29′ 26″ and 49° 34′ 00″ showing, on the right, folded Upper Cretaceous and Danian with corrected dips on the anticline of $2\frac{3}{4}^\circ$ and $1\frac{1}{2}^\circ$ and, on the left, the slightly ruckled Eocene inclined at an average angle of 2°. The contact between the Eocene and Danian is unconformable, and it cuts the sea-bed at latitude 49° 32′ 06″ near the position of the curved line marking the photographic overlap. Corresponds to marker position ④ on map (see figure 6). A comparable record was obtained on the southern run, and the unconformity there crossed the ship's course at latitude 49° 32′ 16″.

Figure 10. Southern run between latitudes 50° 16′ 06″ and 50° 14′ 00″. The sea-bed irregularity, and accompanying details of the record, within what was known to be a sea-bed made of New Red Sandstone was first detected on the boomer record; it was thought to be an inlier of Metamorphic Complex, which supposition was proved correct by subsequent coring (SB 483).

FIGURE 11. Southern run between latitudes 49° 41′ 45″ and 49° 39′ 26″, showing the unconformable contact between Upper Cretaceous on the right dipping at 2½° and folded Lias on the left initially dipping at 3¼°; the Lias is commonly characterized on the records by closely-set dark and white bands. Corresponds to marker position ③ on map (see figure 6).

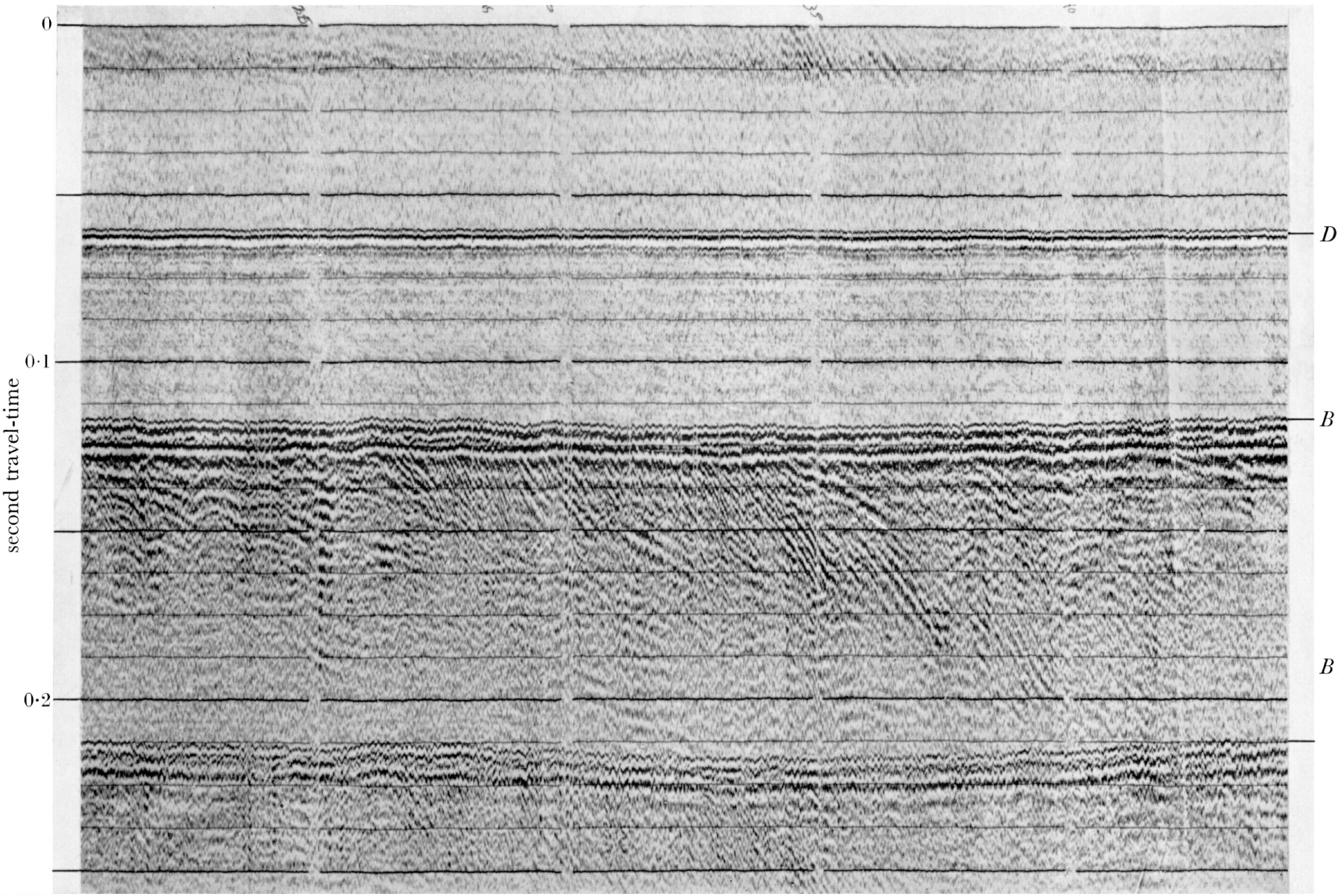

Figure 12. Southern run between latitudes 49° 52′ 30″ and 49° 50′ 48″, showing the peculiar ‘false-bedded’ pattern which is attributed to the presence of discordant layers at shallow depth below the sea-bed. So far as is known the rocks are of Cretaceous age but locally they may form no more than a thin coverage to the underlying New Red Sandstone. Corresponds to marker position ① on map (see figure 6).