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AN ACOUSTIC SURVEY OF THE SEA FLOOR SOUTH OF DORSET AND ITS GEOLOGICAL INTERPRETATION

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With an appendix on the microfauna of certain samples

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(*Communicated by W. F. Whittard, F.R.S.—Received* 3 *February* 1961)

[Plates 15 to 18]

CONTENTS

An area of sea floor from the Dorset coast southward to about 50° 30′ N, and between 2° 2′ and 2° 27′ W has been surveyed in detail using asdic equipment for recording relief, and a gravity corer and free-swimming divers for obtaining samples. Neighbouring areas were examined in less detail. The asdic provides an acoustic picture of the sea floor, and enables outcrops and faults to be mapped. Supplementary information was obtained from Admiralty surveys.

The submerged part of the Isle of Purbeck Anticline is shown to be an elongated dome with Corallian rocks exposed in its core at Lulworth Bank. The dome is intersected by many sub-parallel faults trending about 15° east of north. Except along the steep monoclinal northern limb dips are low, seldom more than 3° or 4°. Minor folds are superimposed on the main structure. In the east they lie nearly east and west, while in the west, where the Purbeck Anticline yields place to the Weymouth Anticline, a north-westerly trend is dominant.

South of the Purbeck Anticline lies a broad and gentle syncline in Jurassic and Lower Cretaceous rocks which is named the Shambles Syncline. It is overlain unconformably by Upper Cretaceous rocks.

I. Introduction

A geological map has been made of the ground between the Isle of Portland and Durlston Head, Dorset, and southwards to the junction of the Jurassic and Cretaceous rocks, with the aid of asdic equipment, an acoustic underwater equivalent of the Plan-Position

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Indicator (P.P.I.) Radar used on land. The geological value of this equipment was first noted by Chesterman, Clynick & Stride (1958). The area was chosen because it fulfilled three conditions: first, reconnaissance had shown that much of the floor was rock which gave good acoustic records; secondly, it was bordered by land so that structures to be discovered could be tied in with those already known; and thirdly, a knowledge of the seaward continuation of the structures would increase understanding of the region as a whole.

King (1954) produced a general map of the English Channel based on rock samples and bottom notations on Admiralty Charts and Falcon (1948, unpublished) correctly interpreted some of the major elements of submarine relief from Portland to Selsey Bill in terms of the geology of the adjacent land. The present work commenced in 1953 when Stride and his colleagues, using an echo sounder, recognized small-scale folding in the submerged eastern part of the Weymouth Anticline. In 1958 (Stride 1960) the echo ranging equipment on R.R.S. *Discovery II* showed that it was possible to map both fold and fault patterns from Lulworth Bank to St Alban's Ledge and to tie these in with the geology of the nearby land. The detailed survey was made by the present authors during 12 days at sea in R.R.S. *Discovery II* in the following year. The present paper was written jointly, but one of us (A.H.S.) concentrated on plotting acoustic data while the other (D.T.D.) studied the samples of rock obtained from the sea floor.

II. Apparatus and methods

Information about the shape and composition of the sea floor was obtained by echo sounding and echo ranging (asdic) equipment and numerous samples of the floor were taken. The echo sounder operated at 10 kc/s to give a profile of the sea floor with maximum discrimination of about half a fathom, and also revealed subsurface interfaces in Corallian Beds and in the Oxford and Kimmeridge Clays. The asdic equipment has been fully described by Tucker & Stubbs (1961). It operates at 36 kc/s with a pulse length of 1 ms, and a pulse-repetition rate of 1/s. The transducer is fitted to the ship's starboard side 13 ft. below water-level and stabilized for the roll of the ship so that it maintains a constant orientation with reference to the horizon, the desired position being selected by remote control. The transducer was usually set so that the axis of the main lobe lay between 3° and 5° below the horizontal. The principal lobe of the acoustic beam is a vertical fan, 11° by 1·8°, normal to the length of the ship. Four side lobes reach the sea floor at lesser ranges than the main lobe and one of these is approximately vertical, providing a profile of the floor. The system is shown diagrammatically in figure 1. Suitable features on the sea floor, such as rock outcrops, return strong echoes which are recorded on paper at their appropriate ranges. As the ship steams forward, and the process is repeated, echoes from each successive pulse are recorded alongside the last and build up an acoustic plan of the sea floor as shown in figures 8 to 12, plates 16 to 18. The maximum range is 800 yards. In the present work the slant range, measured on the record, was regarded as true range. The greatest error thus introduced is about 15 yards at the near side of the main beam, and is less than errors arising in determining the ship's position.

Decca Navigator Equipment was used for most position fixing. In Weymouth Bay the sounding lines were fixed by means of sextants and station pointers, and at diving stations

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a single sextant was used to fix the anchored motorboat. In Kimmeridge Bay fixing was done with a damped compass.

In Weymouth Bay, sounding lines about $\frac{1}{4}$ mile apart were run as two series with either northerly or north-easterly courses. On each line run over the shoal half a mile south of Redcliff Point the bedding was revealed by a strongly reflecting horizon dipping northwards and clearly traceable to an apparent depth of 25 ft. below the sea floor (figure 7).

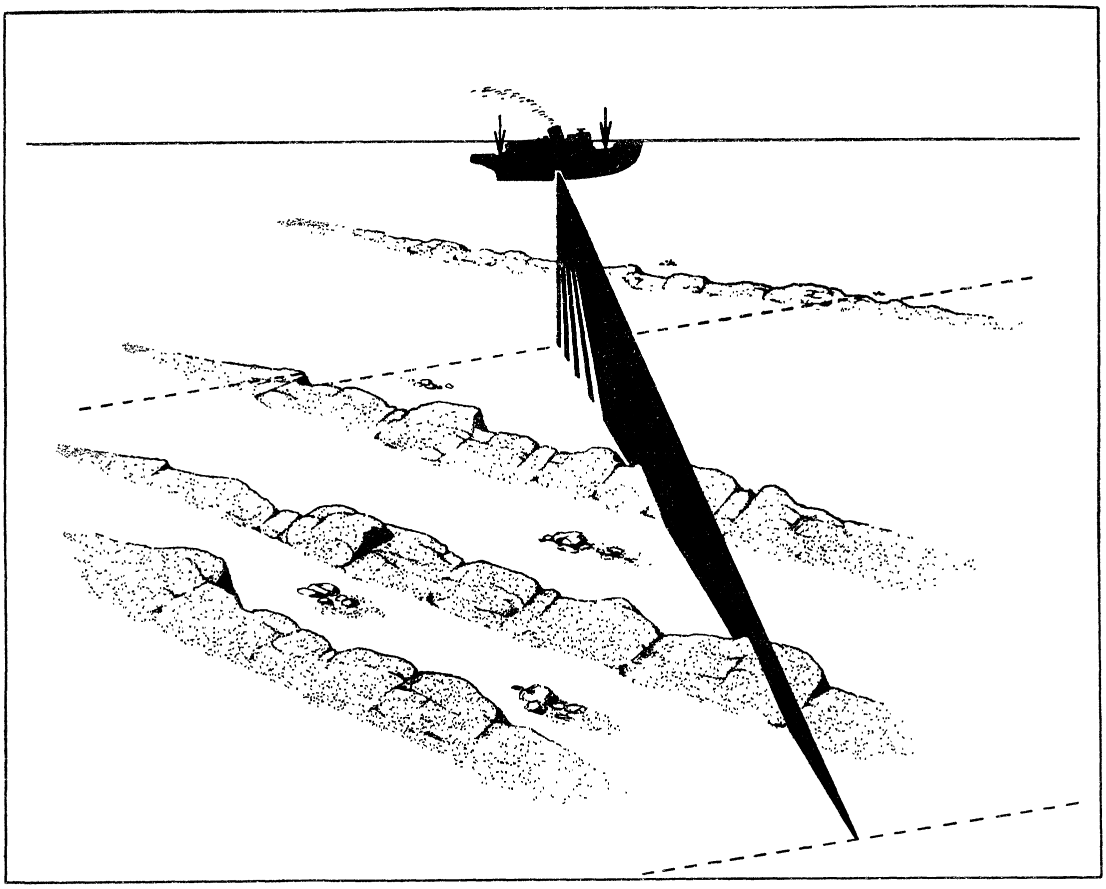

FIGURE 1. Diagram showing the mode of operation of the asdic installed in R.R.S. *Discovery II* and used extensively in the mapping described in this paper. The subsidiary and main acoustic beams are shown in solid black, and the broken lines delimit the area of sea floor being surveyed. For further explanation see p. 300.

These, and all other clearly defined interfaces, have been plotted as apparent dip directions on figure 3. An estimate of the apparent dip was made by determining the slope of the interfaces, and correcting for the greater velocity of the compressional waves in the Upper Jurassic clays than in the water. The absence of subsurface dips around Ringstead Ledge is probably due to an apron of detached blocks, lying at the foot of the outcrops, which would act as an efficient reflector for the incident sound. Elsewhere in Weymouth Bay the cover of gravel and stones inhibits sound penetration.

The ground between Portland and Durlston Head was almost completely examined by echo ranging equipment and the echo sounder was run continuously. In order to simplify navigation the courses chosen were approximately parallel to the coast and to the Decca

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position lines. At the end of the first leg the ship returned along the same course to examine acoustically the ground on the opposite side. It then sailed along a second course so spaced from the first that the outer limits of the asdic records overlapped a little, two courses being slightly less than 1600 yards apart. The advantage of this pattern is that errors of positioning can be readily detected since features of relief should occur at the same geographical location on runs along the same course.

The ship generally moved through calm water at about seven knots, at which speed water noise was insignificant. When noise was increased by sea waves useful acoustic records were obtained by steaming slower, but work was stopped when the surface water became so aerated as to act as a sound barrier.

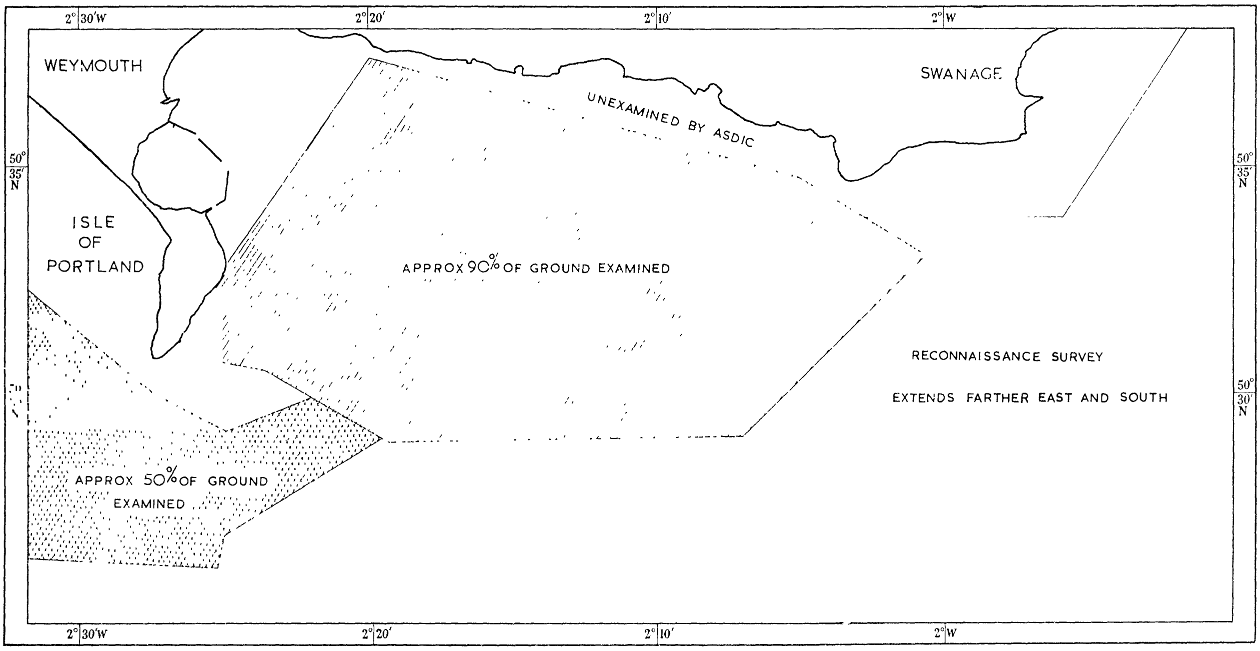

FIGURE 2. Sketch map of the area described in the paper showing (shaded) the extent of ground examined by detailed asdic survey. This is an indication of the reliability of different parts of figures 3, 4 and 6, in which it was not feasible to show the actual lines surveyed by asdic.

All distances are stated in nautical units (10 cables = 1 nautical mile or minute of latitude = 6080 ft.). Latitude and longitude are stated in degrees, minutes and decimal points of a minute. Bearings refer to the true compass.

The ship's position was determined by means of Decca Navigator Equipment at quarter-hour intervals and at other times necessary to define the courses. In deriving the course from the navigational data it was assumed that the courses were either straight lines or smooth curves and that the speed over the ground was constant, or varying progressively as the ship was affected by wind and currents. The accepted courses pass through the majority of the points fixed, and within a cable of the remainder. The discrepancies were due partly to human error, and partly to the variable errors inherent in the Decca system. The maximum value for these errors in the area is stated to be half a cable.

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In order to follow a desired course a ship must compensate for any lateral thrust applied by wind or tidal streams and so will move crab-wise over the ground. Under these conditions the acoustic beam of the asdic on R.R.S. *Discovery II*, which is fixed at right angles to her length, was no longer normal to the course made good, but deviated from the normal by an amount equal to the angle of set, that is, the angle between the course and the ship's head. Angles of set of 5° were common, 10° rare and 20° occurred once. One result was to reduce the width of the belt of sea floor which was examined, although this effect was trifling for angles up to about 10°. More serious were the spurious orientations recorded for features on the floor, because a feature parallel to the axis of the beam will always appear on an asdic record as if it were normal to the ship's course. Angles of set were recorded and orientations corrected in plotting the results.

In the analysis of the asdic records search was made for marker beds which could be recognized on adjacent records and where possible traced to the coast so as to associate patterns on the records with the geology of the land. On the east side of Portland, the scarp of Portland Stone is a prominent feature of the relief. There is a well-marked boundary approximately at the top of the Kimmeridge Clay, where soft rocks give way to harder layers of the Portland Sand, and in the middle part of the Kimmeridge Clay a number of stone bands give clear outcrops on asdic records. Information from the asdic records was supplemented by large- and small-scale features of relief known from Admiralty surveys. These features can display the geological structure closely, as on land, and also proved valuable in places where asdic records could not be made.

The sampling from aboard ship was done by a free-fall corer weighing 8 cwt. as used by Hill & King (1953, p. 11). The coring tubes were up to 3 ft. in length and of 2 in. internal diameter; flap valves and cutters were inserted in their lower ends. At critical places, up to five attempts were made to obtain a sample with the corer. We took 125 core samples in this way from R.R.S. *Discovery II* and in addition made use of thirty-six samples which had been taken in 1953. Free divers equipped with aqualungs worked thirty-nine stations in Weymouth Bay. The Portland and Purbeck rocks were difficult to sample by means of the corer, presumably because of the hardness and brittleness of the rocks. Chalk and Greensand cores were up to 3 in. long and a penetration of about 1 ft. was obtained in Jurassic clays.

Numerous samples were taken in Weymouth Bay because of the complex structures and the cover of superficial materials, and on Lulworth Bank because it was not otherwise possible to follow marker beds. Four lines of samples were extended southwards as far as the Chalk.

The final stage of the field work was done by divers near the northern shores of Weymouth and Kimmeridge Bays, in order to examine ground not covered by asdic. At Weymouth, effort was concentrated on taking samples, while at Kimmeridge measurements of dip were made. The divers were equipped with rubber exposure suits and aqualungs. Since they were not geologists they were instructed as to the observations which were required and at Weymouth the men were closely questioned by the authors after each dive. In the uppermost three fathoms the presence of thick seaweed made it difficult to approach the outcrops, and it was everywhere difficult to observe the dip of the Corallian. The divers reached a maximum depth of 12 fathoms.

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III. Geological description of the area

1. *Stratigraphy*

The rock formations which outcrop in the area are tabulated in table 1. In general, they are thickest in the Isle of Purbeck, and become progressively thinner towards the west. A full account of them will be found in Arkell (1947*a*).

Table 1

system	formation		approximate thickness (ft.) Weymouth area	Isle of Purbeck
Upper Cretaceous	Chalk		—	1300
Upper Cretaceous	Gault and Upper Greensand		120	160
Lower Cretaceous	Lower Greensand		—	195
Lower Cretaceous	Wealden Beds		—	2300
Upper Jurassic	Purbeck Beds		190	400
Upper Jurassic	Portland Beds	Portland Stone, Portland Sand	220	240
Upper Jurassic	Kimmeridge Clay		800	1840
Upper Jurassic	Corallian Beds	Ringstead Waxy Clay and Coral Bed 15; Sandsfoot Grits 25; Sandsfoot Clay 15–40; *Trigonia clavellata* Beds 23; Osmington Oolite Series 65; Bencliff Grit 10–15; Nothe Clay 40; Nothe Grits and *Trigonia hudlestoni* Bed 35	240	320
Upper Jurassic	Oxford Clay		600	650

The *Lower Greensand* has not been recognized on the sea floor; several samples could, lithologically, be either Wealden Beds or Lower Greensand. These two formations have been grouped together on the maps as Lower Cretaceous.

The *Wealden Beds* are thickest at Swanage, and persist westward along the coast to Durdle Door (02° 16·5′ W), where about 340 ft. are present. At sea they have only been identified in three cores (4044/1 to 4046/1), by the presence of unmistakable mottled clay, in the centre of the Shambles Syncline. Farther east, Wealden lithology is suggested by three bottom notations on Admiralty Chart 2615, one of 'red mud' and two of 'orange mud', near 50° 26′ N, 1° 47′ W. South and south-east of St Alban's Head several cores of grey marl are probably Wealden in date; the microfauna of one of them (4123/1) was examined, but proved inconclusive.

The *Purbeck Beds* extend westwards to Durdle Door on the coast, and reappear to the south in the Shambles Syncline and on the Isle of Portland. On our maps the base of the Purbeck Beds corresponds to the base of the Marls with Gypsum. The underlying Caps, Broken Beds and Cypris Freestones (Arkell 1947*a*, p. 124) could not be separated from the Portland Stone on the sea floor.

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The *Portland Beds* comprise the Portland Stone, overlying Portland Sand which includes clay, sand and sandstone. The boundary with the underlying Kimmeridge Clay has been subject to differences of opinion (Arkell 1947*a*, p. 90). In submarine geology the only boundary line which can be recognized is at the lowest sandstone, the Blacknore Sandstone at Portland and the Massive Bed in the Isle of Purbeck. No satisfactory core samples of Portland Stone were obtained, but the outcrop can frequently be recognized by its strong relief on the sea floor.

The *Kimmeridge Clay* is the thickest formation in the area. At Kimmeridge Bay (02° 08′ W) the thickness is about 1840 ft.* while between Wyke Regis (50° 35·5′ N) and Portland it is about 800 ft. A number of samples of Kimmeridge Clay were characteristic dark, bituminous shale, and some contained diagnostic fossils. Others were clays and were identified by Foraminifera. The middle part of the formation includes several thin beds of hard, impure limestone, which stand proud of the sea floor and hence were easily picked out by asdic.

Corallian Beds. The Ringstead Coral Bed, a few inches thick, has not been identified on the sea floor, and it is impossible to distinguish between the Ringstead Waxy Clay and the Kimmeridge Clay, so the top of the Corallian Beds has been drawn at the top of the Sandsfoot Grits on our maps.

In Weymouth Bay and on Lulworth Bank the Corallian Beds are lithologically identical with the exposures on the coast. From 8 to 12 miles south of Weymouth, fine sand and clay was taken at five core stations (4108/1–4112/2). Sample 4111/1 is proved by Foraminifera to be of Corallian age, probably equivalent to the Osmington Oolite Series, and the other four samples are lithologically similar. It may be that the Osmington Oolite series has changed facies and become sandy, or alternatively the beds could be Sandsfoot Grits and Clay.

The *Oxford Clay* is the oldest rock to crop out on the sea floor which we have examined. The thickness of 600 ft. at Weymouth is the most recent estimate (House 1958, p. 17). Recent boreholes by B.P. Exploration Company have proved a greater thickness beneath Kimmeridge.

2. *The eastern end of the Weymouth Anticline* (*figure* 3)

Weymouth Bay has been difficult ground to work out because of its unsuitability for examination by asdic, and the presence of complex structures. Fold axes were revealed by subsurface dips on echo-sounder records, but since the survey lines were not close enough for a unique interpretation, use was made of the relief given on a detailed Admiralty survey (E. 8437, scale 1:18,250) and numerous samples were taken. Rock outcrops are common only near the northern shore and even there they are partly covered by large boulders. An echo-sounder record of the anticline half a mile south of Redcliff Point is shown in figure 7.

The main anticlinal crest has a south-easterly trend. Towards its nose the topographic expression of the Corallian Beds appears to die out, probably as a result of low dip, and also because below 11 fathoms soundings are recorded to the nearest fathom only, whereas in shallower water they are stated to the nearest foot. Several echo-sounder traverses define

* Arkell (1947*a*, p. 64) has 1650 ft. Consideration of the original (1936–37) and new (1959) borehole records shows that the base was probably taken too high in the original interpretation.

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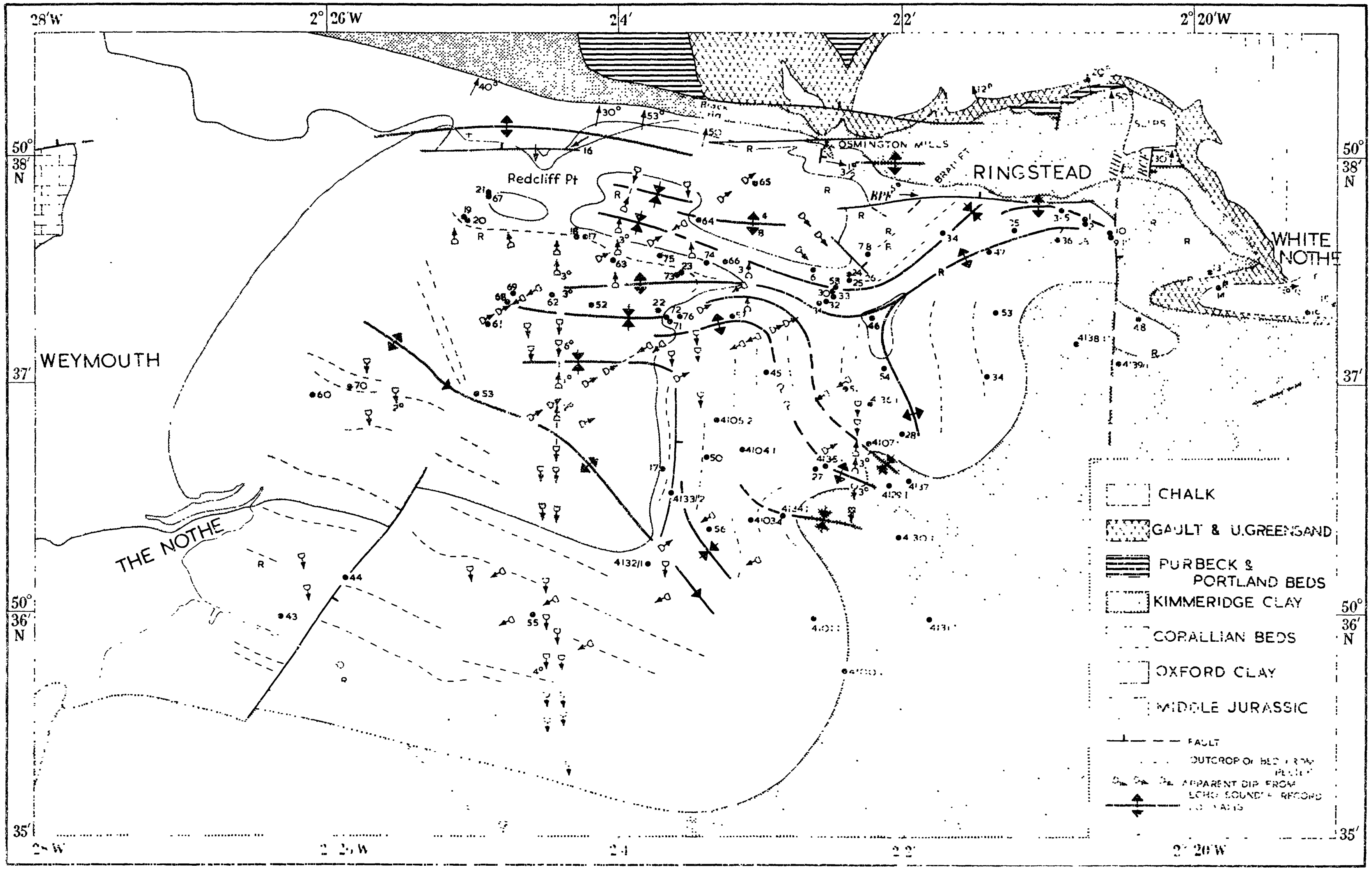

FIGURE 3. Geological map of the eastern end of the Weymouth Anticline. Scale approximately $1\frac{1}{2}$ in. to 1 mile. Land geology east of 2° 23·5′ W after Arkell (1951, fig. 4) by permission of the Council of the Geologists' Association. Black disks mark sampling stations; for details see Appendix I. *R* = rock floor notation on Admiralty Chart 2255. – – – = relief features from Admiralty surveys E 7874, E 8257 and E 8437. *BCF* = Burning Cliff Fault, *BPF* = Bran Point Fault, *HHF* = postulated Holworth House Fault.

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the position of the axis and its north-westward continuation is indicated by converging ridges in the Oxford Clay. Between this axis and the northern shore of Weymouth Bay there are a number of smaller folds which strike dominantly east and west. Traced eastwards these folds diverge either side of an inlier of Oxford Clay proved at station 46. One group swings north-east and ends against the Bran Point Fault, which can be traced on the foreshore at low tide (Arkell 1936*a*, fig. 1). The other group appears to swing sharply to the south and then to a south-easterly direction. Thus, the minor folds are deflected to the north and south of a broad synclinal area which marks the westernmost extent of the foresyncline of the Purbeck monocline, which passes out to sea between Bat's Head and White Nothe (Arkell 1947*a*, p. 286). A tongue of Upper Cretaceous rocks preserved in the trough of this fold is proved by stations 14 and 4138/1, flanked by Kimmeridge Clay at 13 and 4139/1.

A fault is assumed to account for a rapid deepening, with an abrupt change eastward to a flat sand floor, at 02° 20·5′ W. It lines up well with the fault near South Holworth Cottages postulated by Strahan but rejected by Arkell (1947*a*, p. 285).

3. *The Isle of Purbeck Anticline* (*figure* 4)

The Isle of Purbeck Anticline lies, *en échelon*, to the east and south of the Weymouth Anticline. On land the steep or overturned northern limb extends from Swanage westward to Bat's Head on the coast at 2° 17·45′ W, and part of the flat crest is preserved north of St Alban's Head (50° 34·5′ N, 02° 03′ W) (Strahan 1898, p. 214 ff.). Our work on the submerged portion has shown that the structure is an elongated, asymmetrical dome, bounded on the south by the Shambles Syncline. South of Swanage, Jurassic rocks plunge eastward below Wealden Beds, and between here and the Isle of Wight asdic reconnaissance lines have not detected any reappearance of the Jurassic rocks.

The map reproduced in figure 4 is drawn chiefly from asdic records, supplemented by scarp and dip slope features recognized on Admiralty surveys of Lulworth Bank (E. 8437) and of the ledge south of St Alban's Head (E. 8891), and core samples. The superficial cover is thickest at the Shambles and at Adamant Shoal (50° 33′ N, 02° 18′ W), which was proved by coring and dredging to be composed of gravel and shells. There is little ambiguity about the southern side of the structure because a number of marker beds can be recognized on asdic records and correlated with the relief as shown in figure 9. St Alban's Ledge is capped by Portland Stone, and the foot of the scarp is assumed to mark the base of the Portland Sand. A 'deep' has been eroded in the uppermost Kimmeridge Clay, and to the left the stone bands crop out and swing through a few degrees. The lower boundary of the Kimmeridge Clay around Lulworth Bank is placed just beyond the outermost ridge of Corallian rocks.

The outermost ridge on the north side of Lulworth Bank is presumed to be Sandsfoot Grits, and within it samples show that a large area is occupied by Osmington Oolite. The inner ridge is made of Bencliff Grit (station 4034/3) so that the hollow in the middle of the Bank must be floored by Nothe Clay (4064/1). An asdic record of faulted outcrops of Corallian Beds on Lulworth Bank is shown in figure 10

The dip of the Portland Beds along the southern limb of the fold is low, increasing from about 2° at the western end to a maximum of about 4° south-west of St Alban's Head

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as calculated from width of outcrop and assumed thickness. Along the northern side of Lulworth Bank the dip must be greater, as shown by the narrower outcrop and smaller displacements of it by faults, while on the coast at Durdle Door (02° 16·5′ W), the dip is 80° in the Portland Stone. The presence of Lower Kimmeridge Clay at station 4039/1, about two-thirds of the way from the lower to the upper boundary of the clay, shows that much of the steepening takes place in a narrow zone close to the coast.

On Lulworth Bank east-west strikes are dominant except at the western end where there is an anticlinal crest trending north-west which may continue for some distance along the southern side of the Bank. It cannot be traced through to any of the similarly orientated folds at the eastern end of the Weymouth Anticline, because the intervening ground is covered with superficial deposits.

East of Lulworth Bank fragments of roughly concentric outcrops within the Kimmeridge Clay mark the position of a dome, the featureless ground in the centre being interpreted as horizontal strata. On account of the absence of a shoal it is considered unlikely that there is a Corallian inlier here. The nearest bottom sample was of Lower Kimmeridge Clay at station 42.

In the eastern part of the Purbeck Anticline there are two subsidiary crests. The northern one, passing through Broad Bench (02° 8·7′ W), is well known through having been the site of exploratory oil wells. Eastwards it is lost inland in unexposed Kimmeridge Clay, and may or may not be continuous with the crest passing through Swyre Head (Strahan 1920, p. 29). The second anticline runs into the coast near Chapman's Pool (02° 3·7′ W) and is separated from the first by a shallow syncline with an amplitude of about 120 ft. East of St Alban's Head an anticlinal crest coincides approximately with the coast from 2° 00′ W to 1° 57′ W, and cannot certainly be linked with either of the anticlines west of the headland.

The acoustic survey has revealed a pattern of subparallel faults over the greater part of the Purbeck Anticline. Typical asdic records of the fault system are reproduced as figures 8 and 10. The faults could not be traced across the nose of the anticline in the Kimmeridge Clay between Lulworth Bank and St Alban's Head, where they are parallel to the outcrops, or across the steep northern limb. Other gaps in the pattern on figure 4 are due to the cover of superficial deposits. The direction of the majority of the faults is between 10° and 20° east of north, and they may share a common cause with the major joints in the Portland Stone on the Isle of Portland, which lie north-north-east and south-south-west (Arkell 1947*a*, p. 118). On the coast between Broad Bench and Chapman's Pool faults of this orientation have throws ranging from 6 in. to 45 ft. (Strahan 1898, p. 51) in Kimmeridge Clay, and farther east there is a throw of 80 ft. in Portland and Purbeck Beds. Along the southern limb of the Purbeck Anticline the displacements of the outcrop of the Portland Beds show that the greatest throws are of the order of 50 ft.

In the eastern part of the Purbeck Anticline, where the plunge is easterly, the majority of faults throw down to the west. They correspond to the tensional cross-faults described by de Sitter (1956, pp. 206–8). To the west lies a region of predominant easterly downthrows, the change from westerly downthrows occurring at about 2° 9′ W on the southern limb, and at about 2° 7′ W on the coast. This change of throw lies several miles east of the present axial culmination at Lulworth Bank.

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Seismic lines, undertaken by Seismograph Services Ltd in 1959–60 on behalf of British Petroleum Ltd who have kindly shown us the results, are in agreement with our mapping of the Purbeck Anticline, and confirm the positions of the minor folds south of Kimmeridge.

4. *The Shambles Syncline* (*figure* 5)

South of the Purbeck Anticline lies the structure which we call the Shambles Syncline, of which a fragment remains above sea level forming the Isle of Portland. The progressive easterly swing of the dip from the north to the south of the Isle, noticed by Strahan (1898, p. 112), is due to the south-easterly plunge of the syncline.

The northern limb of the syncline is well located by asdic records and relief features. East of The Shambles the outcrop of Portland Beds is marked by a belt of 15 fathom soundings (Admiralty Chart 2610). The Shambles itself we believe to be a sandbank because the Admiralty Charts and surveys record only sand, shingle and broken shells on its surface and there are sand waves along the southern side. Two ridges at the eastern end, however, are oriented differently from the rest of the bank. The southern and larger one is assumed to be the Portland Stone, while the northern one is a resistant bed in the Portland Sand.

The swing of the strike through north-south to the south-easterly direction of the southern limb of the fold is shown on a number of scattered asdic records, and by the relief. Immediately west of Portland Bill a deep hole, with soundings of over 40 fathoms, has been eroded in the Upper Kimmeridge Clay, and to the west a shoal marked by the 10 fathom contour is probably formed by the stone bands in the middle part of the Kimmeridge Clay. Southwards from Portland Bill a belt of ridges on the asdic records is assumed to mark the outcrop of the Portland Sand, as it lies east of featureless ground interpreted as the highest and stoneless part of the Kimmeridge Clay. A core from station 4148/1 is shown by the microfauna to belong probably to the Pavlovia Zones at the top of the Clay, and immediately east of this station is a ridge which may be the Blacknore Sandstone, at the base of the Portland Sand. The geological lines have been continued to the southern edge of the map (figure 5) parallel to the outcrops shown on asdic records, and the southern limb may be traced farther south-eastward (figure 6) to King's core station no. 118, which we interpret as Portland Stone. About $1\frac{1}{2}$ miles farther south-east again Chalk was encountered (station 4085/1). Kimmeridge Clay has been proved at a series of stations westwards to 4113/1 and its lower boundary is drawn between this station and 4112/1, which is lithologically identical with the sample from 4111/1, proved to be of Corallian age by its microfauna.

The outcrop of the Purbeck Beds is probably indicated by the flattening of the bottom a short distance south-east of Portland Bill. Cores 4077/1 and 4081/1 are ostracod limestones and are, with little doubt, of Purbeck age. East of the area covered by figure 5, a slight ridge shown by the 20 fathom contour on Admiralty Chart 2615 at about 50° 28′ N, 2° 12′ W is probably an expression of the Middle Purbeck limestones (Lower and Upper Building Stones).

The extension of the Wealden Beds into the area of figure 5 is not proved. Core 4082/1 consists of grey and faintly pink marl with lignite and pebbles of Purbeck Limestone, but it appears to have been disturbed and contains no diagnostic microfauna. Core 4083/1

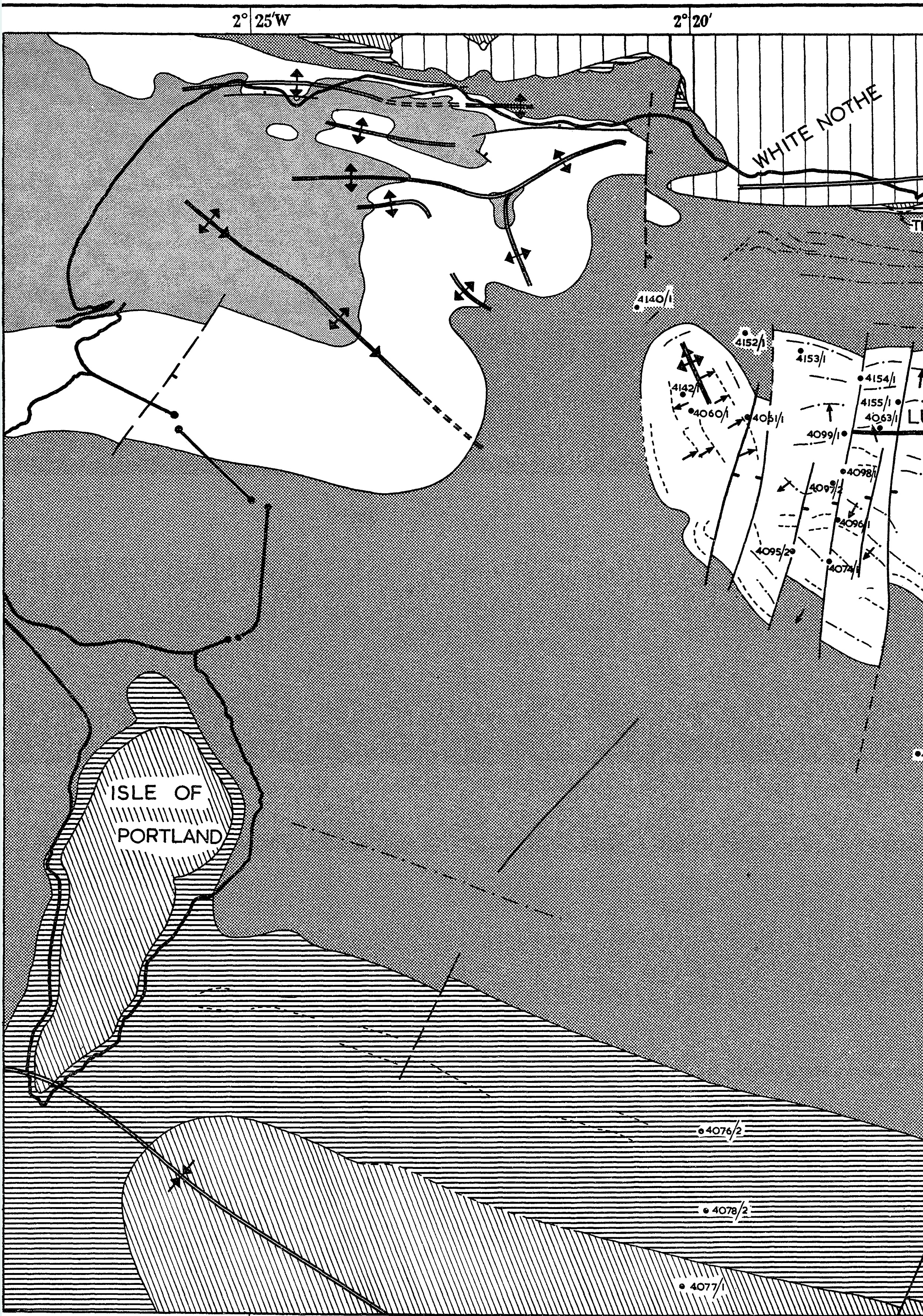

FIGURE 4. Geological map of the sea floor between Portland and S
see Appendix I. Abbreviations for horizons in the Kimmeridge Cl

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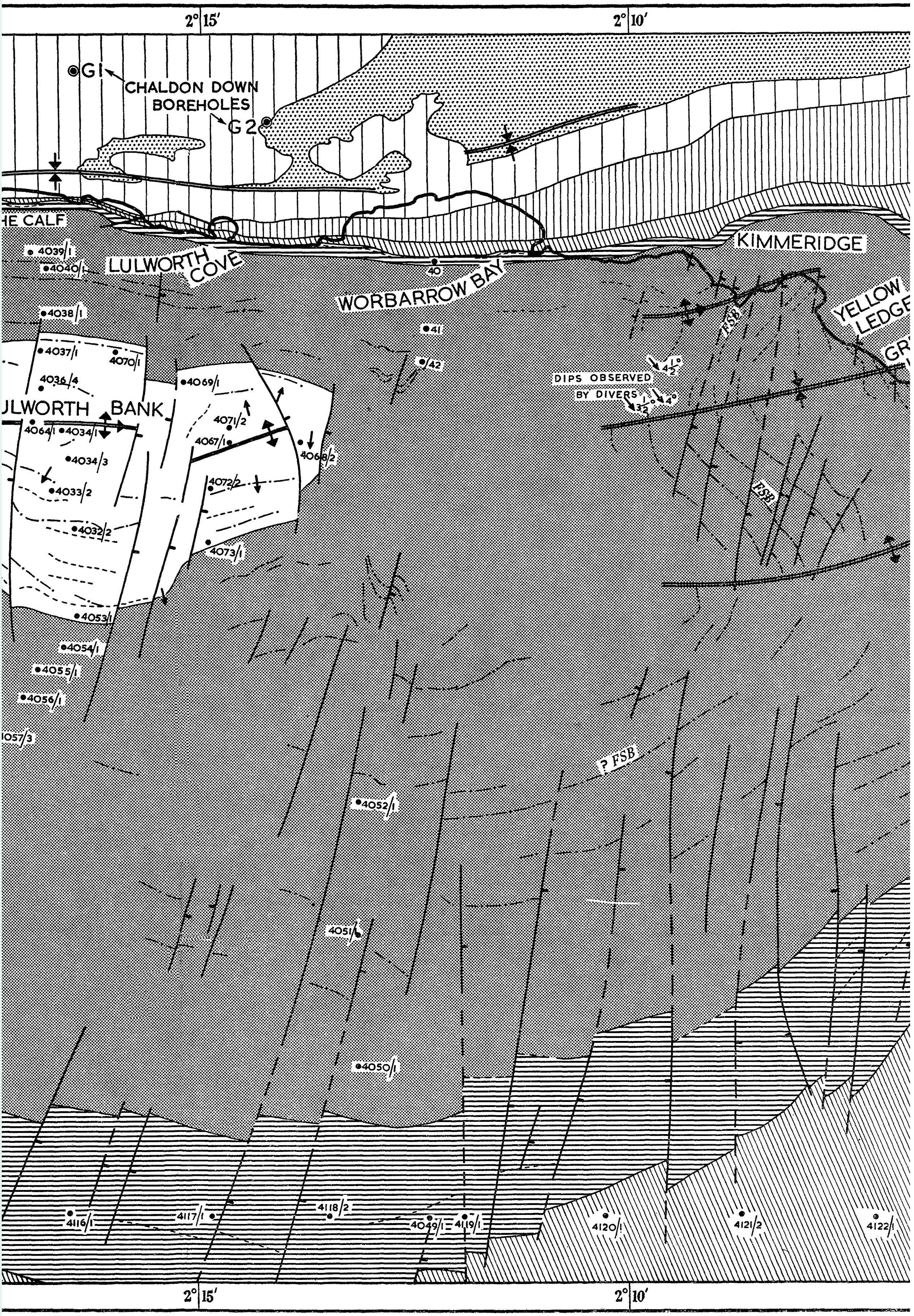

St Alban's Head. Scale approximately 1 in. to 1 mile. Black disks mark sampling stations; for det
Clay: *BS* = Basalt Stone; *FSB* = The Flats Stone Band; *FSSB* = Freshwater Steps Stone Band.

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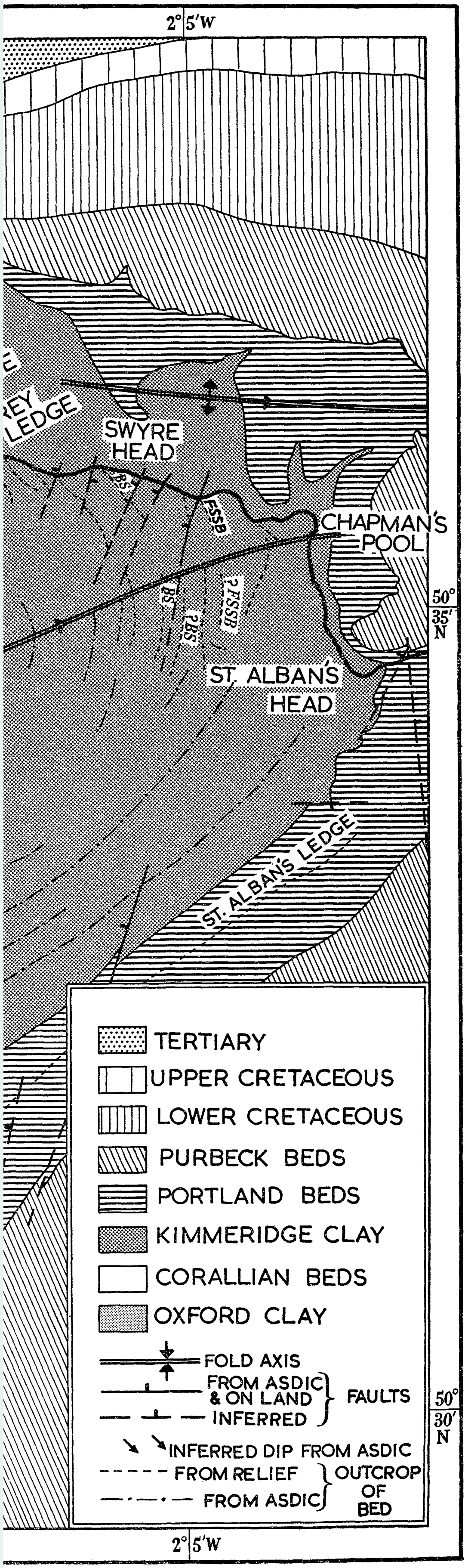

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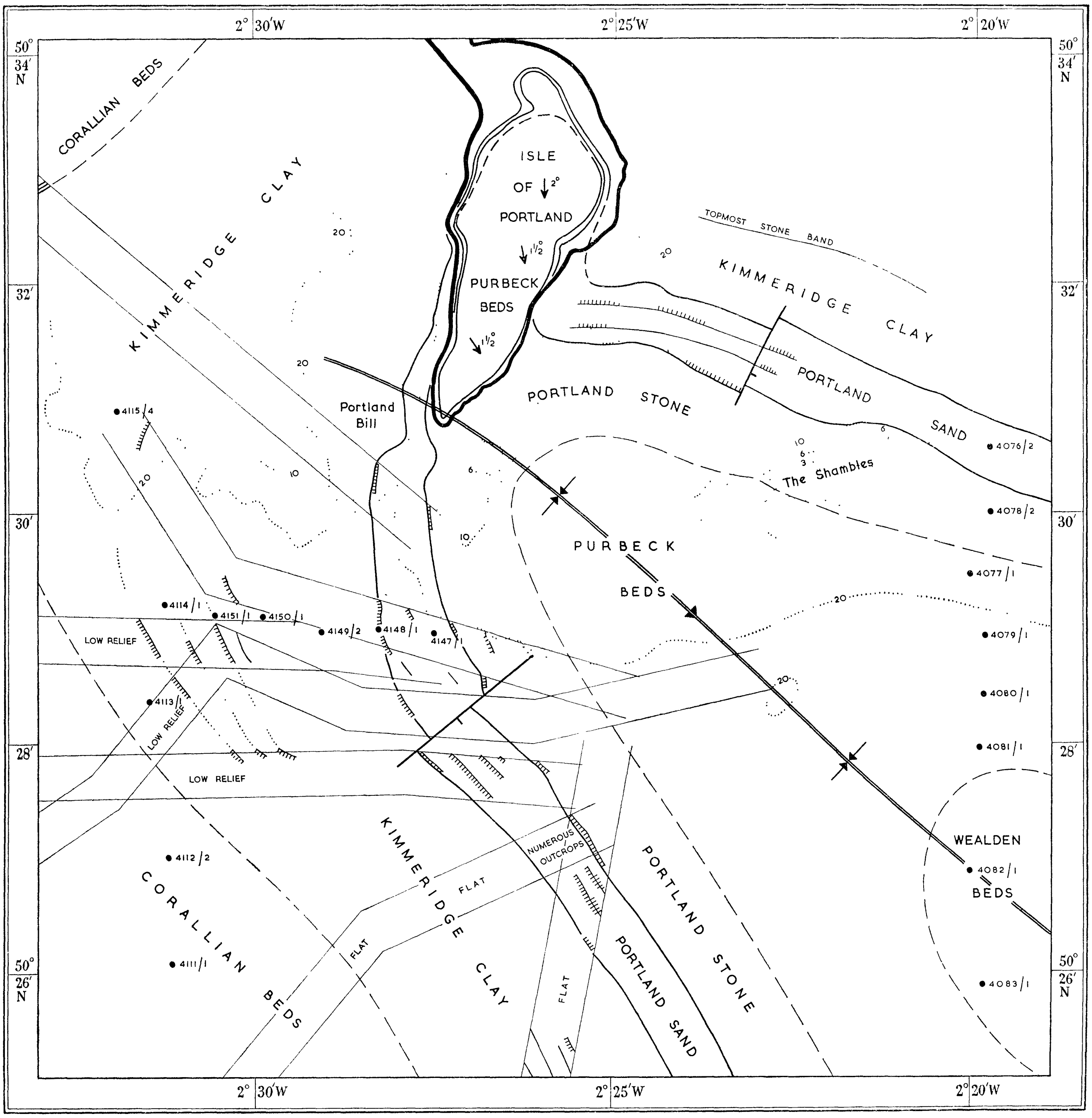

FIGURE 5. Geological map of the western end of the Shambles Syncline. Scale approximately $\frac{3}{4}$ in. to 1 mile. Black disks mark sampling stations; for details see Appendix I. Thin parallel lines delimit the strips covered by asdic surveys; between Portland Bill and The Shambles survey lines were closely spaced and have been omitted. Prominent outcrops are shown by lines with hachures on the scarp side. Symbols for faults and fold axes are the same as in figure 3. Submarine contours in fathoms.

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is coarse grey sand with much carbonaceous matter, and can be closely matched in the Wealden Beds of Dorset. Farther east at 2° 13′ W (figure 6) Wealden mottled clays and marls were proved at three core stations (4044/1 to 4046/1) which mark the centre of the syncline.

The outcrop of Corallian Beds south-south-west of Portland Bill (stations 4108/1 to 4112/1) probably indicates the existence of an anticline to the south-west of the Shambles Syncline, but the position of the axis was not determined. This structure may prove to be the westward continuation of the inlier of Jurassic and Wealden rocks at about 50° 18′ N, 1° 10′ W to 2° 05′ W discovered by King (1954, p. 87, pl. 4). Two asdic runs over King's inlier showed east-west strikes and apparent dips to the north.

5. *The Upper Cretaceous Unconformity*

(*a*) *The northern area*

The westward overstep of the Upper Cretaceous rocks along the Dorset coast is well known, but may be briefly summarized. At Swanage there appears to be complete conformity throughout the Upper Jurassic and Cretaceous, and this continues westwards to Worbarrow Bay (Arkell 1947*a*, p. 247). Two and a half miles farther west, at Lulworth Cove, Strahan (1898, p. 129) recorded a 'strong line of erosion', and Arkell (1947*a*, p. 296) referred to a possible angular discordance to 10° to 15°, at the base of the Gault, but the critical part of the section is not well exposed, and a local northward reduction in dip confuses the picture. However, in the Chaldon Down G2 borehole, about 1 mile to the north-north-east, Gault rests on Kimmeridge Clay (Lees & Taitt 1946, p. 259), and there must be an angular discordance at the base of the Gault of at least 8° between Lulworth Cove and the borehole.

At Durdle Door, 1 mile west of Lulworth Cove, Arkell (1938, pp. 28, 29) calculated that about 300 ft. of Wealden Beds had been removed before the deposition of the Gault, although Strahan (1898, p. 130) was of the opinion that 'the squeezing and thrusting of the strata have been here even more intense and...measurement is altogether untrustworthy'. Nevertheless, only 1 mile north of Durdle Door the Chaldon Down G1 borehole proved Gault resting on Lower Purbeck Beds (Lees & Taitt 1946).

West of Durdle Door the coast is formed of vertical or overturned Chalk, and there are offshore reefs of Portland Stone, apparently dipping about 80° north. In view of squeezing and strike-faulting it is unsafe to draw any conclusions as to the original relationships of the beds. The westernmost outcrop of Portland Stone is The Calf whence a submerged ridge can be traced an additional 200 yards westward on Admiralty Chart 2610. Beyond this point there is no evidence for the outcrop of Portland Stone and an asdic record (figures 12, 13, plate 18) south of White Nothe is interpreted as showing Gault resting unconformably upon Kimmeridge Clay as it does on land north-west of White Nothe (figure 3).

(*b*) *The southern area*

The Cretaceous outcrop which forms the southern limit of the Jurassic rocks was defined approximately by King (1954, pl. 4) and has been located more precisely on four lines of core stations worked by R.R.S. *Discovery II*. The chief modification of King's

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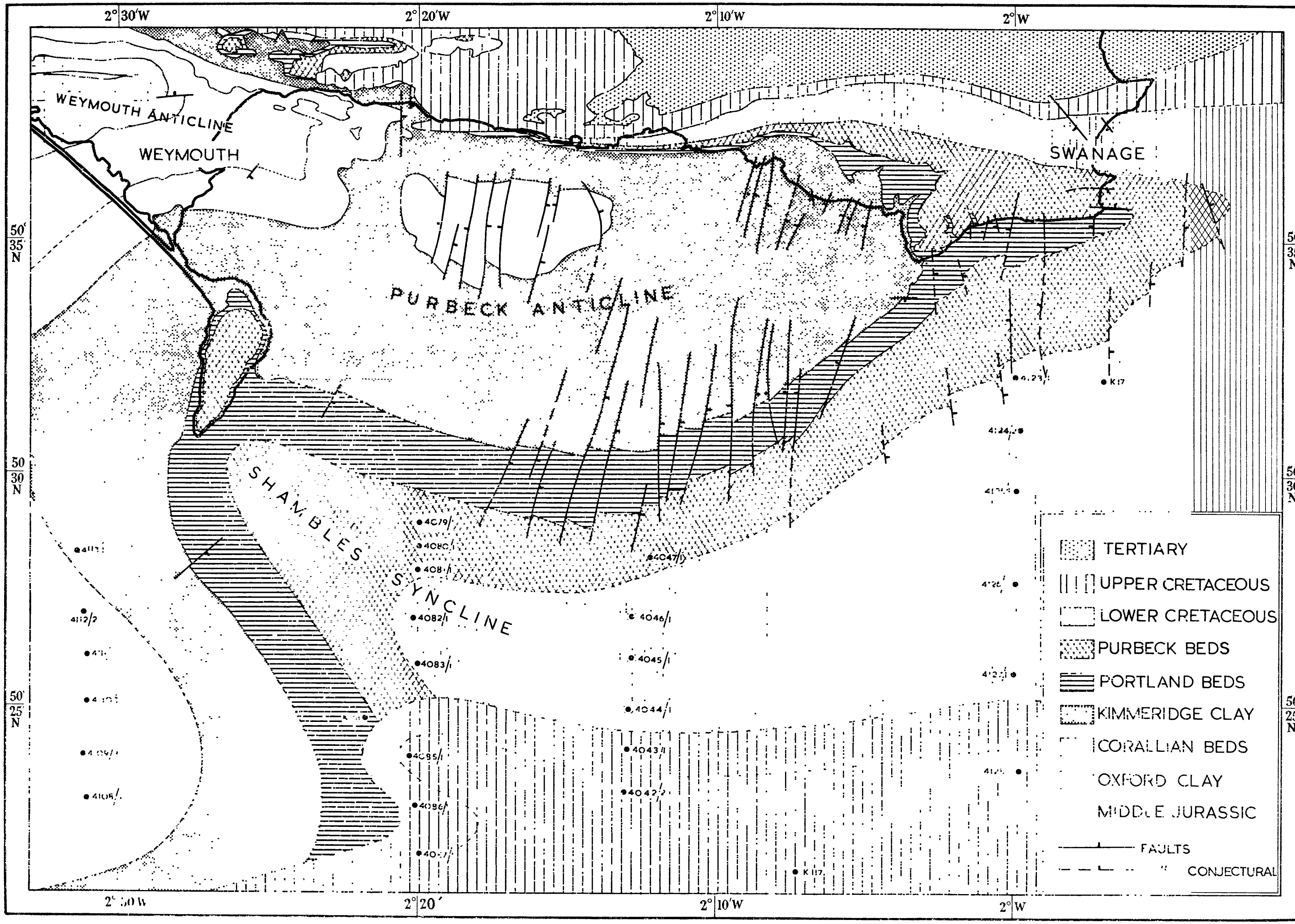

FIGURE 6. Geological map of the sea floor south of east Dorset. Scale approximately $\frac{1}{3}$ in. to 1 mile. Partly reduced from larger scale maps (figures 3 to 5 of this paper). Black disks mark sampling stations, shown only south of 50° 29′ N and east of 2° 00′ W. Encircled disks mark stations at which Wealden Beds were proved. Broken lines denote uncertain geological boundaries. The broken line within the southern outcrop of the Upper Cretaceous marks the junction of the Upper Greensand with the Chalk.

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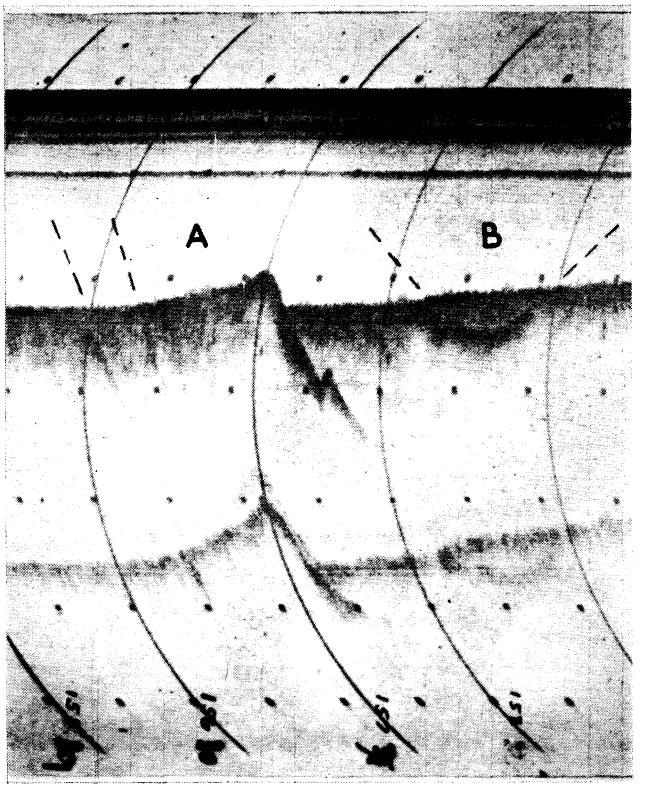

FIGURE 7. Echo-sounder profile $\frac{3}{4}$ mile long of the sea floor near the north shore of Weymouth Bay. The ridge *A* is formed by a bed of nodules in the Oxford Clay which can be traced to a depth of 25 ft. below the sea floor as a strongly reflecting surface. Another reflecting surface shows the presence of a syncline at *B*.

(*Facing p.* 314)

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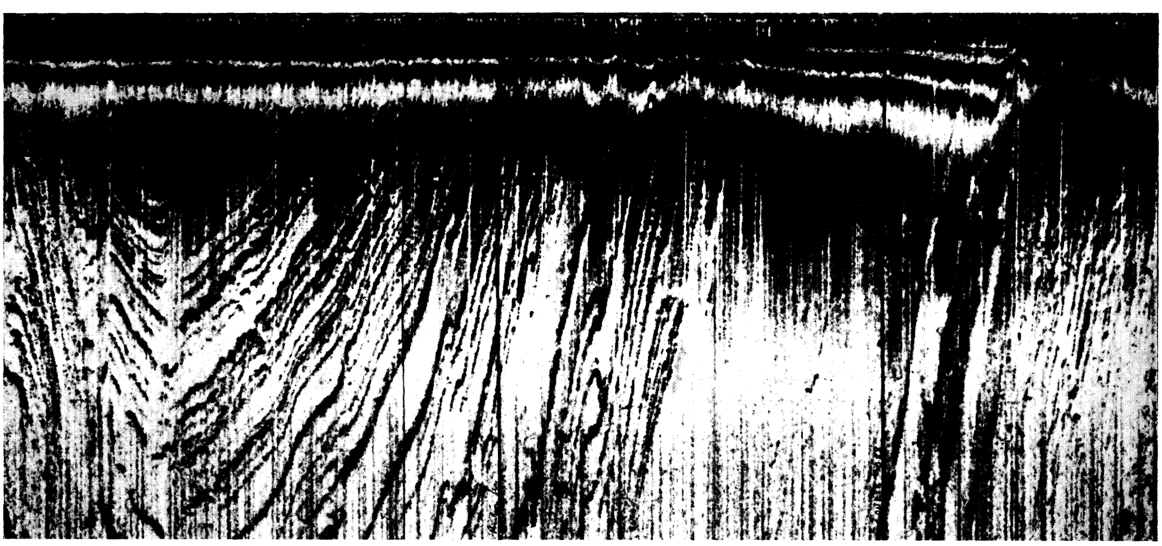
FIGURE 8. An asdic record approximately 2700 yards × 800 yards showing faults in Kimmeridge Clay $1\frac{1}{2}$ miles south of Broad Bench. The beds dip gently towards the bottom of the figure, and the direction of downthrow of the faults can, therefore, be deduced from the lateral displacements of marker beds.



Kimmeridge Clay Portland Beds

FIGURE 9. An asdic record approximately 4000 yards × 800 yards of rocky floor about 3 miles south-west of St Alban's Head, showing the pattern of outcrops which has been used to define the southern limb of the Purbeck Anticline. The record shows, from left to right, Kimmeridge Clay with resistant beds, featureless uppermost Kimmeridge Clay, and Portland Beds forming a ridge. Narrow dark bands represent scarp edges of beds as in figure 8. The distortion of the scale greatly exaggerates the curvature of the outcrops in the Kimmeridge Clay at the left-hand side of the figure.

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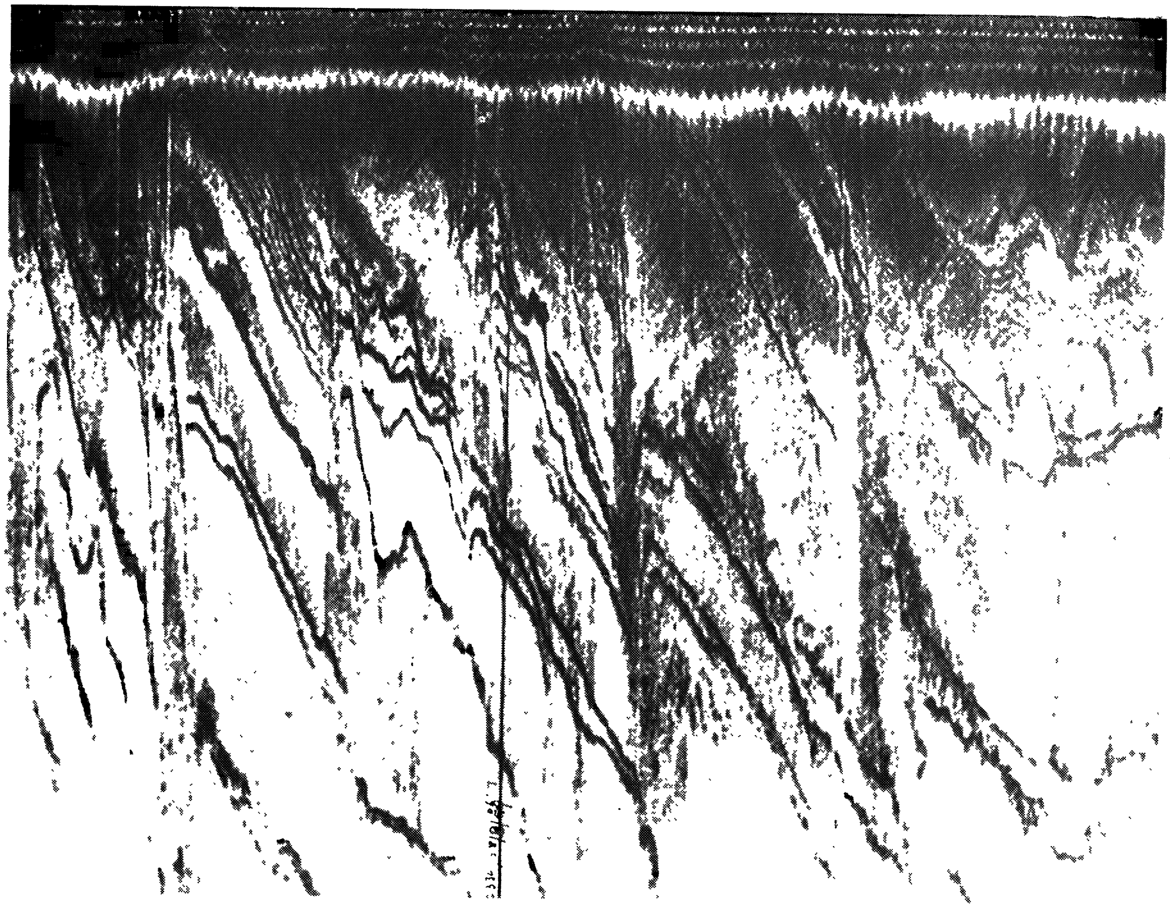

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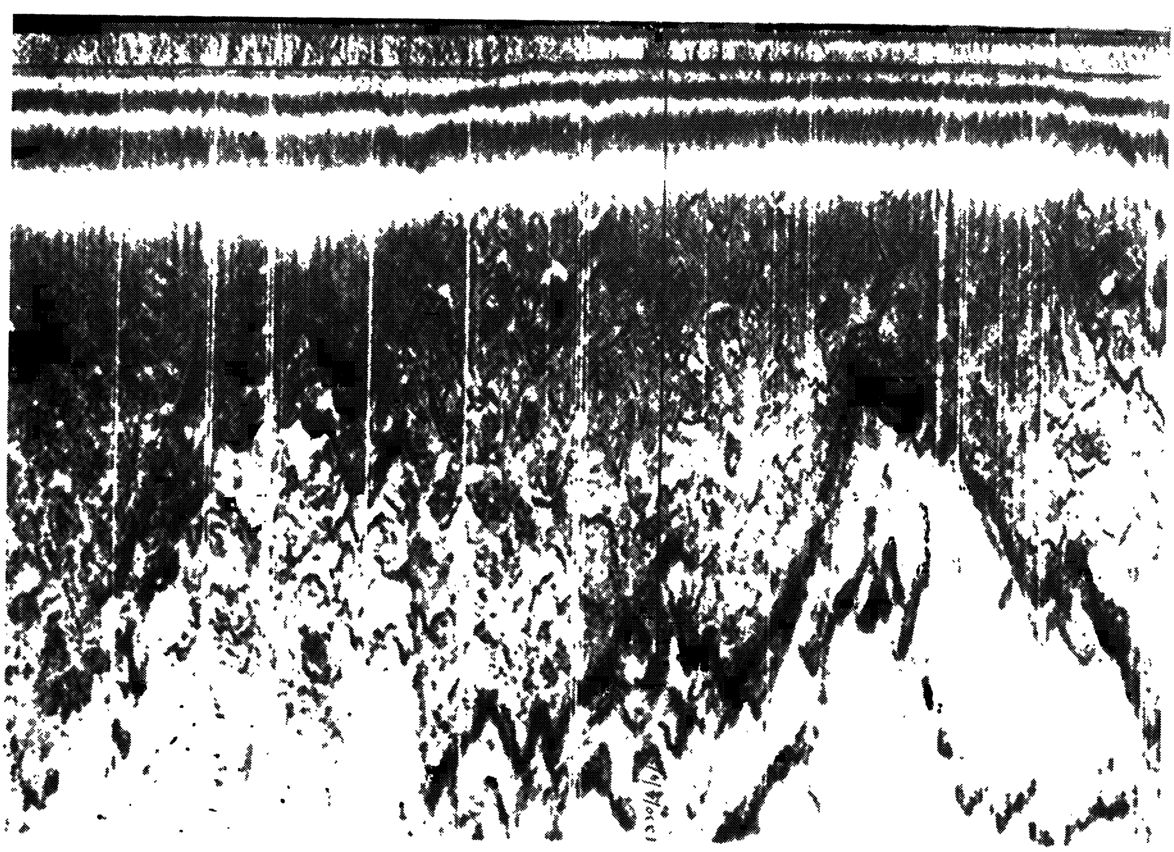

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FIGURES 10 AND 11. For description see p. 315.

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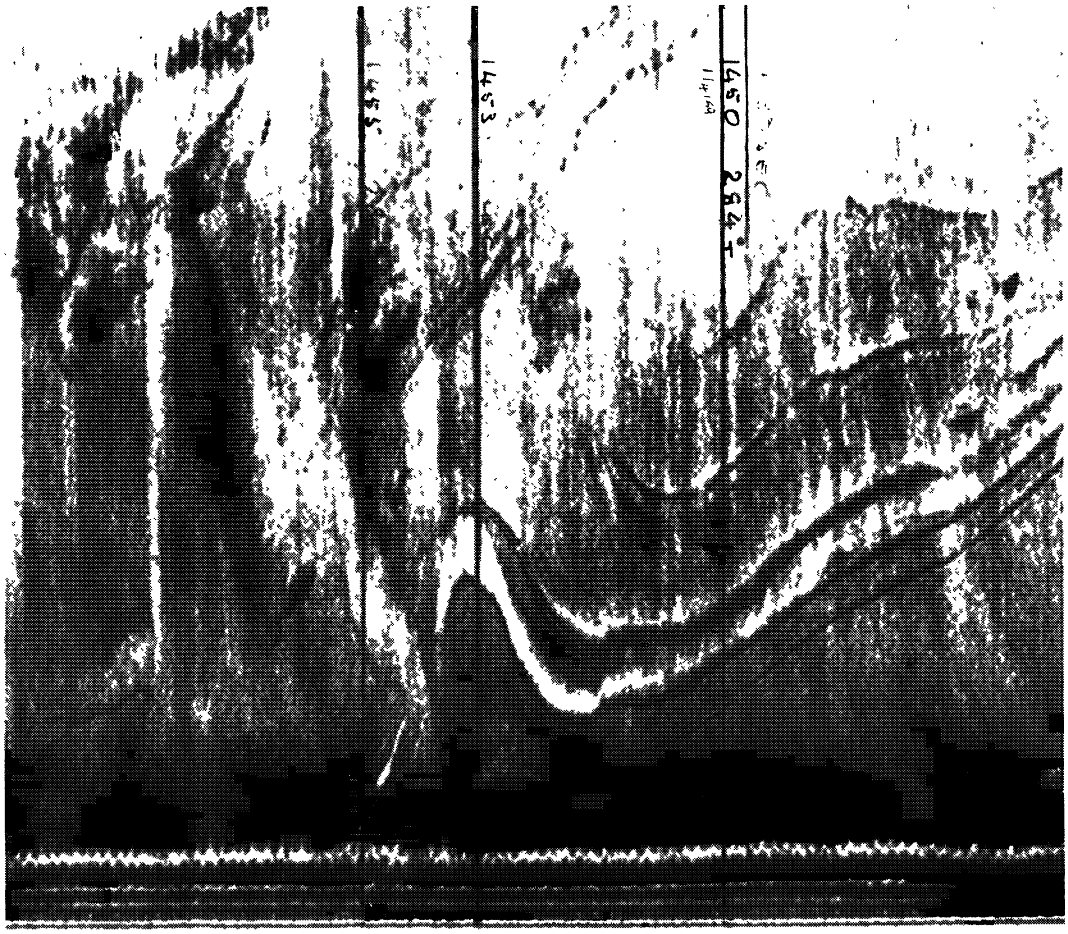

FIGURE 12

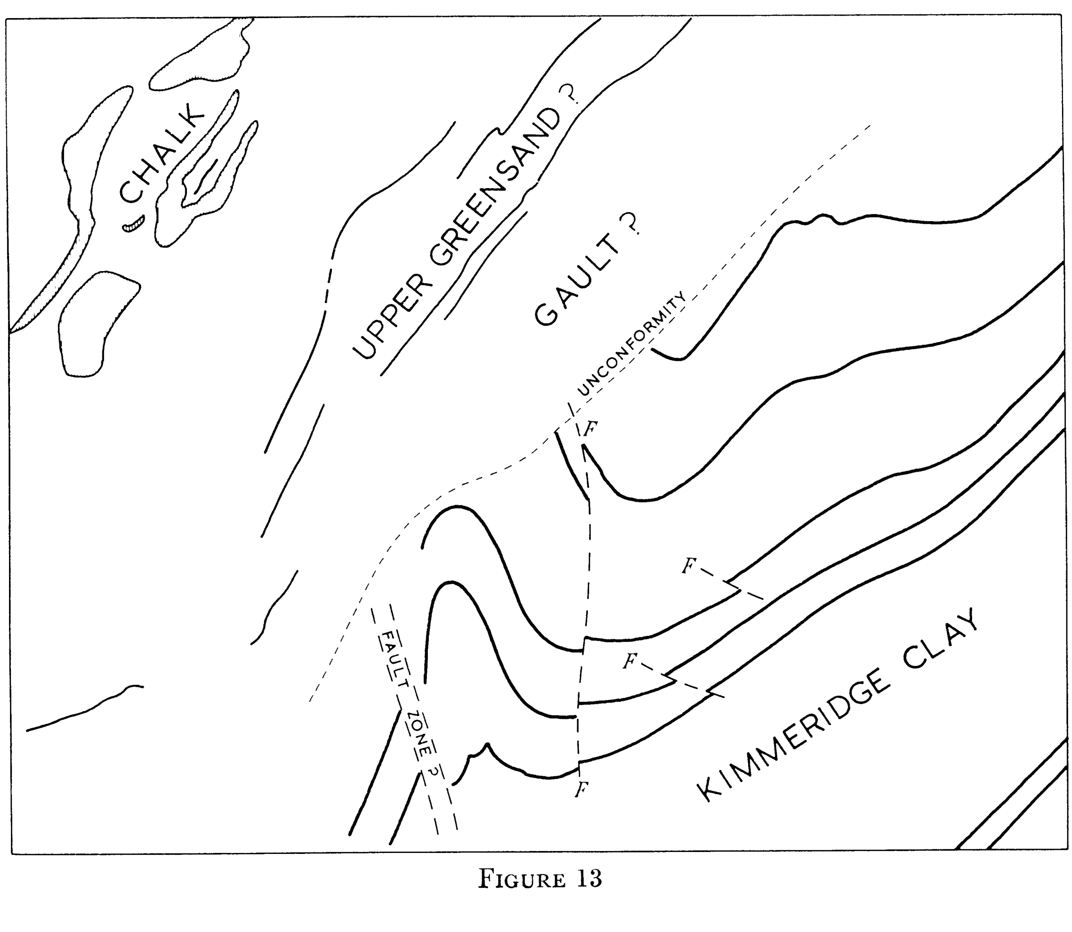

FIGURE 13

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line is due to a minor fold, or perhaps a fault, shown by the presence of Chalk at station 4085/1, north of glauconitic sand, presumed to be Upper Greensand, at stations 4086/1 and 4087/1. The Gault, Upper Greensand and Chalk have been assumed to be conformable throughout the southern part of figure 6, as they are in Dorset.

Westward overstep of Upper Cretaceous on to progressively older rocks was shown by King (1954). We cannot say whether Lower Greensand is present in the eastern part of our area, because samples from stations 4124/2 to 4127/1 could not be identified precisely. On the next line of cores, at 2° 13′ W, Upper Cretaceous rocks probably lie directly upon Wealden Beds, as Wealden mottled clays were found at station 4044/1 only $1\frac{3}{4}$ miles north of Chalk at 4042/2. There is almost certainly Gault (4043/1) and Upper Greensand in between, leaving little room for Lower Greensand, although a narrow outcrop could be present if the dip were increased in sympathy with the minor fold already mentioned. The regional dip can hardly be more than 1° or 2° to the south.

There is little evidence for strike directions in the vicinity of the minor fold, and this part of the map must be regarded as very generalized. Overstep of Upper Cretaceous on to Portland Beds is indicated by a core of shelly limestone (K118), taken by King and identified by the present authors as Portland Stone, about $1\frac{1}{4}$ miles north-west of the Chalk at station 4085/1. The further overstep on to the Kimmeridge Clay, shown on figure 6, is conjectural, but is likely on account of the presence of the anticline of Jurassic rocks, exposing Corallian Beds in the core, already described (p. 313).

The axis of the small syncline affecting Upper Cretaceous rocks thus lies on Jurassic rocks of the southern limb of the Shambles Syncline, in like manner, but on a larger scale, to the Spring Bottom Syncline which overlies north-dipping Upper Jurassic and Lower Cretaceous rocks near Osmington (Arkell 1951).

On the westernmost line of stations (2° 31′ W) angular pebbles of Chalk were recovered at station 4089/1 (4 miles south of the margin of figure 6), presumed Upper Greensand at 4091/1 (2 miles farther north), and Corallian Beds at 4108/1, the ground in between the last two stations mentioned being masked by an impenetrable cover of gravel.

Description of plates 17 and 18

Figure 10. An acoustic map 4000 yards × 800 yards obtained by echo ranging (asdic) equipment of faulted Corallian Beds on Lulworth Bank. The dark bands represent the edges of beds facing the ship and broader light areas are the gentle dip slopes. The dip is towards the bottom left-hand corner of the figure.

Figure 11. An asdic record 3200 yards × 800 yards about 4 miles south-east of Portland Bill showing the appearance characteristic of low-dipping Purbeck Beds. The zig-zag pattern is probably due to two intersecting sets of joints.

Figure 12. An asdic record showing the unconformable relationship of the Gault to the Kimmeridge Clay due south of White Nothe. The area represented is approximately 3400 yards × 800 yards, and the scale exaggeration normal to the ship's course is about × 3·7. This record is printed with the ship's course along the lower edge so that the orientation is approximately the same as for the maps in the text.

Figure 13. Diagram to show the interpretation of the asdic record reproduced in figure 12. *F* – – – *F* denotes a fault.

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IV. Geological structure and history

The coastal geology north of the area newly investigated is dominated by the steep or overturned northern limb of the Purbeck Anticline, which may be termed the Purbeck Monocline. This monocline, which owes its present form to Tertiary earth movements, extends from the coast north of Swanage westward to Bat's Head (2° 17·45′ W) where it passes out to sea, and dies out rapidly south-west of White Nothe. As it does so another major structure, which may be termed the Ridgeway Monocline,* comes in about $2\frac{1}{4}$ miles to the north, forming the steep, faulted northern limb of an otherwise gentle structure, the Weymouth Anticline. Our survey has located the southern limb of the Purbeck Anticline, which is shown to be a strongly asymmetrical structure, essentially similar to the Weymouth Anticline and to many others in south-eastern England; the Portsdown, Peasemarsh and Kingsclere Anticlines may be mentioned for comparison.

The western end of the Purbeck Anticline passes into the Weymouth Anticline. Our work has shown that there is no single anticlinal crest continuous from one fold to the other, as has been supposed (Arkell 1936*b*, fig. 5; Chatwin 1948, pl. 1), but that to the south of the overlap of the two monoclines lie several minor folds with a north-westerly trend. Farther south, there is a corresponding swing in the axis of the Shambles Syncline. These north-westerly folds form an exception to the general east and west trend of minor as well as major folds in south-east Dorset. North-westerly trend is also shown by minor folds affecting the base of the Tertiary between Dorchester and Bere Regis (Geological Survey One-Inch Sheet 328) in a corresponding position north of the overlap of the monoclines, and farther north the broad, gentle north-westerly anticline passing through Sandford Orcas and Milborne Port (White 1923, p. 5) provides an analogue of the Corallian anticline south of the Shambles Syncline.

Thus the north-westerly folds are localized to the north and south of the overlap of the Ridgeway and Purbeck Monoclines, and there is a strong presumption that they are genetically connected with the displacement of the monoclinal zone. In this context, the Burning Cliff Fault west of White Nothe (p. 307, figure 3) assumes a new importance, for it may be part of the system of tear faults which must occur where one monocline is replaced *en échelon* by another.

An alternative interpretation of the two fold directions in the area is that they belong to two sets of structures of different origin, one having been superimposed on the other. The east and west trend is shown by a number of asymmetrical folds affecting Cretaceous and Lower Tertiary rocks in south-eastern England. The north-west and south-east trend is less conspicuous. It is shown by a group of gentle folds in the Jurassic rocks between Swindon (Wilts.) and Aylesbury (Bucks.), believed to be of Upper Wealden or Lower Aptian age (Arkell 1947*b*, pp. 134–41). These folds do not affect the Upper Cretaceous, but have been detected beneath it by means of the residual gravity anomalies (Falcon & Tarrant 1951, pl. 14, and Arkell in discussion, pp. 168–9). Nearer to the Dorset area a similar trend is shown by the western end of the Portsdown Anticline, and by folds affecting the base of the Oligocene in south-west Hampshire (White 1921, fig. 30). Across the Channel it is found in Tertiary structures in north-western France.

* The Chaldon and Ridgeway Fold and Overthrust of Strahan (1895, p. 555); Abbotsbury-Ridgeway-Chaldon Fault Zone of Arkell (1947*a*, p. 249).

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Two periods of folding have been generally recognized in south-eastern Dorset: the 'Intra-Cretaceous Disturbances' (Strahan 1895, p. 559), which took place before the deposition of the Gault, and the Tertiary folding, usually dated as Miocene. We interpret the Shambles Syncline as an intra-Cretaceous structure, and nearer the coast pre-Gault earth movements are demonstrated by the discordant relationship of the Upper Cretaceous to the Kimmeridge Clay due south of White Nothe (figure 12, plate 18), as well as by the well-known unconformity in the Ringstead–Osmington area on land. In the eastern part of the area, where there is no unconformity at the base of the Upper Cretaceous, intra-Cretaceous movements cannot be proved, but it seems reasonable to suppose that the minor folds in the Jurassic rocks of the Purbeck Anticline are of intra-Cretaceous date. The age of the fault pattern which covers much of the Purbeck Anticline is likewise unproved, but by analogy with the dip-faults of similar orientation in the Ringstead area it should be intra-Cretaceous.

A full discussion of the tectonic history of south-eastern Dorset is outside the scope of this paper. There is evidence for episodes of earth movement additional to the two principal ones mentioned in the last paragraph. If the Lower Purbeck Broken Beds are due to penecontemporaneous slumping, as implied by O. T. Jones (in discussion of Arkell 1938, p. 54), the Purbeck Anticline had already started to rise in late Jurassic times. Elevation and denudation during the Upper Cretaceous, perhaps along the Weymouth Anticline, has been deduced from the presence of Upper Greensand and older rocks in the Chalk Rock of Winterbourne Abbas (Robbie 1950), and renewed activity early in the Eocene is shown by the occurrence of pebbles of Upper Greensand and Jurassic chert in the Bagshot Beds on Warmwell Heath (Arkell 1947*a*, p. 230) about 4 miles north of the Purbeck Monocline. In fact, the monoclines mark a structurally active zone along which earth movements recurred time after time. Major faults in the Upper Palaeozoic basement, such as have been assumed to account for the Kingsclere and Isle of Wight Monoclines (for example, White 1949, p. 21, fig. 2), may have been the underlying cause.

The success of geological work at sea depends on the co-operation of many people, of whom only a few can be mentioned individually. We are especially indebted to Mr A. R. Stubbs for maintenance of the acoustic equipment at sea and for valuable discussion. The Master and officers of R.R.S. *Discovery II* undertook navigation in difficult waters, and thus made possible the successful completion of the work. Members of the Cambridge and Guildford Sub-aqua Clubs carried out the diving at Weymouth and Kimmeridge, respectively, and Mr K. G. Burridge was in charge of the motor boat used at Weymouth. The identification of some of the core samples has been made from a study of the contained microfossils by Dr A. J. Lloyd, who contributes an appendix. Mr N. L. Falcon, F.R.S., Chief Geologist of the British Petroleum Co. Ltd., has provided unpublished information, and the same company has generously given a grant to cover much of the expense of the diving.

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References

Arkell, W. J. 1936*a* The Corallian Beds of Dorset. *Proc. Dorset nat. Hist. Fld. Cl.* **57**, 59–93.

Arkell, W. J. 1936*b* The tectonics of the Purbeck and Ridgeway Faults in Dorset. *Geol. Mag.* **73**, 56–73, 97–118.

Arkell, W. J. 1938 Three tectonic problems of the Lulworth district: studies on the middle limb of the Purbeck fold. *Quart. J. Geol. Soc. Lond.* **94**, 1–53.

Arkell, W. J. 1947*a* The geology of the country around Weymouth, Swanage, Corfe and Lulworth. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

Arkell, W. J. 1947*b* *The geology of Oxford.* Oxford University Press.

Arkell, W. J. 1951 The structure of Spring Bottom Ridge, and the origin of the mud-slides, Osmington, Dorset. *Proc. Geol. Assoc., Lond.* **62**, 21–30.

Chatwin, C. P. 1948 British regional geology. The Hampshire Basin and adjoining areas. Second edition. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

Chesterman, W. D., Clynick, P. R. & Stride, A. H. 1958 An acoustic aid to sea bed survey. *Acustica*, **8**, 285–290.

De Sitter, L. U. 1956 *Structural geology.* London: McGraw Hill.

Falcon, N. L. 1948 Geology of the sea floor between Portland and Selsey. *B.P. Geological Division, Record no. U.K.* 138 (unpublished).

Falcon, N. L. & Tarrant, L. H. 1951 The gravitational and magnetic exploration of parts of the Mesozoic-covered areas of south-central England. *Quart. J. Geol. Soc. Lond.* **106**, 141–170.

Hill, M. N. & King, W. B. R. 1953 Seismic prospecting in the English Channel and its geological interpretation. *Quart. J. Geol. Soc. Lond.* **109**, 1–19.

House, M. R. 1958 The Dorset coast from Poole to the Chesil Beach. *Geol. Assoc. Guide* no. 22. Colchester: Benham.

King, W. B. R. 1954 The geological history of the English Channel. *Quart. J. Geol. Soc. Lond.* **110**, 77–101.

Lees, G. M. & Taitt, A. H. 1946 The geological results of the search for oilfields in Great Britain. *Quart. J. Geol. Soc. Lond.* **101**, 255–317.

Robbie, J. A. 1950 The Chalk Rock at Winterbourne Abbas, Dorset. *Geol. Mag.* **87**, 209–213.

Strahan, A. 1895 On overthrusts of Tertiary date in Dorset. *Quart. J. Geol. Soc. Lond.* **51**, 549–562.

Strahan, A. 1898 The geology of the Isle of Purbeck and Weymouth. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

Strahan, A. 1920 Special reports on the mineral resources of Great Britain. VII. Mineral oil, Kimmeridge oil-shale, lignites, jets, cannel-coals, natural gas. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

Stride, A. H. 1960 Recognition of folds and faults on rock surfaces beneath the sea. *Nature, Lond.* **185**, 837.

Tucker, M. J. & Stubbs, A. R. 1961 A narrow beam echo-ranger for fishery and geological investigations. *Brit. J. appl. Phys.* **12**, 103–110.

White, H. J. O. 1921 A short account of the geology of the Isle of Wight. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

White, H. J. O. 1923 The geology of the country south and east of Shaftesbury. *Mem. Geol. Surv. U.K.* London: H.M. Stationery Office.

White, P. H. N. 1949 Gravity data obtained in Great Britain by the Anglo-American Oil Company Limited. *Quart. J. Geol. Soc. Lond.* **104**, 339–364.

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Appendix I. Station lists

Rock specimens at stations 1 to 42 were obtained by free-swimming divers, at the remaining stations by a gravity corer. Unsuccessful stations are not listed.

† Indicates divers' samples which were not broken off outcrops in place.

* Indicates that a report on the sample will be found in appendix II.

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
1	50° 37·72′	2° 20·72′	† grey, brown-weathering calcareous, fairly coarse sandstone, with shelly fragments; rare white ooliths	Corallian: Sandsfoot Grits
2	50° 37·68′	2° 20·70′	† hard, grey, shelly limestone	Corallian Beds
3	50° 37·74′	2° 20·83′	† whitish oolite with streak of fine-grained limestone	Corallian: Osmington Oolite Series
4	50° 37·74′	2° 20·83′	grey marly limestone with shell fragments	Corallian Beds
5	50° 37·74′	2° 20·83′	grey, brown-weathering, shelly, fine-grained calcareous sandstone	Corallian: ? Sandsfoot Grits
6	50° 37·48′	2° 22·65′	grey, brown-weathering, calcareous sandstone	Corallian: possibly Bencliff Grit
7	50° 37·56′	2° 22·25′	† (*A*) pale-grey, rather fine-grained calcareous sandstone, the calcitic matrix optically continuous † (*B*) pale-grey clay † (*C*) grey clayey sand	Corallian: Bencliff Grit
8	50° 37·56′	2° 22·25′	† hard, grey, shelly limestone; some resemblance to 2 and 4	Corallian Beds
9	50° 37·64′	2° 20·56′	† pale yellow-grey, brown-weathering limestone; many hair-like grey laminae show in cross-section	Corallian Beds
10	50° 37·67′	2° 20·56′	† grey limestone, oolitic in patches	Corallian: Osmington Oolite Series
11	50° 37·63′	2° 20·56′	white-speckled, greenish-grey and grey limestone, with thick shells preserved in crystalline calcite; similar to *Trigonia clavellata* Beds	Corallian: *Trigonia clavellata* Beds
13	50° 37·48′	2° 19·88′	dark-grey bituminous shale, with numerous white-shelled lamellibranchs	Kimmeridge Clay
14	50° 37·42′	2° 19·80′	† chalk with *Inoceramus* fragments	Chalk
15	50° 37·35′	2° 19·00′	chalk, one piece with flint in place; both pieces show slickensliding	Chalk
16	50° 37·32′	2° 19·18′	chalk	Chalk
17	50° 37·63′	2° 24·20′	dense, hard, grey nodule, slightly calcareous, with red-brown weathered skin	Red Nodule Beds, Oxford Clay (17–18)
18	50° 37·64′	2° 24·28′	same as 17	
19	50° 37·73′	2° 25·04′	pale-grey calcareous clay with specks of gypsum	uncertain
20	50° 37·72′	2° 25·02′	same as 17	Red Nodule Beds, Oxford Clay
21	50° 37·86′	2° 24·86′	† grey, calcareous sandstone, with fragments of *Chlamys fibrosa* (J. Sowerby)	Corallian Beds: ? Nothe Grits
22	50° 37·32′	2° 23·71′	same as 17	Red Nodule Beds, Oxford Clay (22–23)
23	50° 37·48′	2° 23·55′	same as 17	
24	50° 37·47′	2° 22·36′	grey calcareous clay	uncertain
25	50° 37·46′	2° 22·35′	† grey, brown-weathering calcareous sandstone; shelly fragments. *Chlamys fibrosa* (J. Sowerby)	Corallian Beds
26	50° 37·46′	2° 22·35′	† grey, brown-weathering calcareous fine-grained sandstone, with calcitic matrix optically continuous; similar to, though not identical with, 7*A*	Corallian: Bencliff Grit
28	50° 37·77′	2° 22·00′	pale yellow-grey limestone with ooliths or grains and shelly fragments	Corallian: Osmington Oolite or *Trigonia clavellata* Beds
30	50° 37·41′	2° 22·46′	† (*A*) bluish-grey and whitish, brown-weathering oolite	Corallian: Osmington Oolite Series
			† (*B*) grey, brown-weathering highly calcareous sandstone	Corallian Beds
31	50° 37·36′	2° 22·56′	† white oolite	Corallian: Osmington Oolite Series (31–34)
32	50° 37·37′	2° 22·52′	† whitish oolite	
33	50° 37·39′	2° 22·48′	† brown-weathering, fine-grained oolite	
34	50° 37·66′	2° 21·72′	† grey, brown-weathering oolitic limestone grey, calcareous clay	

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APPENDIX I (*cont.*)

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
35	50° 37·67′	2° 21·23′	brown-weathering oolite	Corallian: Osmington Oolite Series (35–38)
36	50° 37·64′	2° 20·88′	† (*A*) pale-grey compact limestone, with white ooliths and fragments of shells † (*B*) grey, crystalline limestone with pyrite and fragments of shells	
37	50° 37·64′	2° 20·88′	brown-weathering oolite	
38	50° 37·64′	2° 20·88′	whitish to blue-grey oolite	
39	50° 37·01′	2° 21·42′	grey, brown-weathering, highly calcareous, rather coarse-grained sandstone, with shelly fragments and rare ooliths	Corallian: Sandsfoot Grits
40	50° 36·82′ (approx.)	2° 12·40′ (approx.)	(*A*) grey, fine-grained compact limestone (*B*) grey, crystalline, shelly limestone with ?*Ostrea*, leaving silty residue on solution in dilute HCl. Joined on to type (*A*) in one specimen	Portland Sand
41	50° 36·32′ (approx.)	2° 12·40′ (approx.)	dark, fine-grained crystalline limestone; silty residue on solution in dilute HCl; (a small piece only, bounded on two faces by calcite veins)	uncertain
42	50° 36·07′ (approx.)	2° 12·40′ (approx.)	medium-grey marl with ammonites: *Aulacostephanus* or *Rasenioides*, finely ribbed species	Lower Kimmeridge Clay: Mutabilis or Pseudomutabilis Zone
			Samples taken in 1952 *and* 1953	
43	50° 35·96′	2° 26·33′	highly calcareous clayey sand, with rare glauconitic grains	Corallian Beds
44	50° 36·12′	2° 25·84′	brownish-grey clay with abundant mica and gypsum	uncertain
45	50° 37·05′	2° 22·95′	grey, silty clay, with numerous shells and shelly fragments; contains rounded pieces of sandstone with white matrix; the core also includes a bed (?) of fine-grained calcareous sandstone	Corallian Beds
46	50° 37·29′	2° 22·20′	* pale-grey calcareous clay or marl	Oxford Clay: near the top according to the microfauna
47	50° 37·58′	2° 21·39′	brown-weathering, grey oolite; grey marl	Corallian: Osmington Oolite Series
48	50 37·28′	2° 20·34′	* brown, calcareous sand, with green grains; highly micaceous; grey micaceous clay with patches rich in ostracods, and small shell fragments; highly carbonaceous sand	microfauna indicates Corallian: Nothe Grits or Clay, with contamination from a nearby Cenomanian outcrop
49	50° 36·62′	2° 23·66′	grey, clayey sand, slightly calcareous, with pyritic patches, and fossil wood	Corallian: probably Nothe Grits
50	50° 36·65′	2° 23·36′	fine-grained, grey, calcareous clayey sand or sandstone, with mica-flakes and shell fragments	Corallian: Nothe or Sandsfoot Grits?
51	50° 36·99′	2° 22·40′	* Grey calcareous clay; gypsum present, rare mica	Corallian: Nothe Grits suggested on evidence of the microfauna
52	50° 37·38′	2° 24·14′	pale-grey calcareous clay; gypsum present in small spheres; pyritic streaks (?plant remains); *Cardioceras* (*Scarburgiceras*) *praecordatum* Douvillé: *Dicroloma trifidum* (Phillips)	Oxford Clay: Mariae Zone, upper part (Praecordatum Subzone)
53	50° 37·28′	2° 21·34′	fine-grained, grey calcareous sandstone; pyrite in small grains and aggregates	Corallian Beds?
54	50° 37·05′	2° 22·12′	grey, brown-weathering, clayey and calcareous fine sand, also clay, interbedded. Shelly fragments	Corallian: Nothe Grits
55	50° 35·96′	2° 24·51′	pale-grey calcareous clay	uncertain
56	50° 36·36′	2° 23·33′	blue, sandy clay	uncertain
57	50° 37·31′	2° 23·17′	pale-grey slightly calcareous clay, with mica and disseminated pyrite; shell (? oyster)	uncertain
58	50° 37·40′	2° 22·45′	grey, calcareous clay, with much comminuted shelly material; gypsum present in small spheres. *Cardioceras* sp. ind., *Gryphaea* sp. ind.	Oxford Clay or a Corallian Clay
59	50° 36·97′	2° 24·94′	grey, brown-mottled slightly calcareous clay	Oxford Clay
60	50° 36·93′	2° 26·09′	pale-grey, slightly calcareous clay with shell (?oyster) fragments; gypsum specks	uncertain
61	50° 37·25′	2° 24·88′	pale-grey, slightly calcareous clay; abundant comminuted shelly material and black streaks (?plant); *Kosmoceras* (cf. *K. tidmoorense* Arkell)	Oxford Clay: Athleta or Lamberti Zone
62	50° 37·38′	2° 24·40′	clay identical with that from 61; ammonite fragment (?*Cardioceras*)	Oxford Clay or a Corallian Clay

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

Appendix I (*cont.*)

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
63	50° 37·56′	2° 24·00′	pale-grey slightly calcareous clay, with gypsum specks; similar to that from 61 and 62; ammonite and lamellibranch fragments (?*Quenstedtoceras*, *Kosmoceras*)	Oxford Clay
64	50° 37·73′	2° 23·42′	pale-grey, slightly calcareous clay; gypsum specks, shelly fragments	uncertain
65	50° 37·87′	2° 23·02′	identical with clay from 64; lamellibranch and ammonite fragments: Perisphinctid of Oxfordian type, *Cardioceras* (*Scarburgiceras*) sp., cf. *mirabile* Arkell	Oxford Clay: Mariae Zone
66	50° 37·53′	2° 23·21′	pale-grey, slightly calcareous clay, with black streaks (similar to those in sample from 61); mica, minute pyrite grains. Lamellibranchs. *Cardioceras* (?*Scarburgiceras*) sp. ind.	Oxford Clay or a Corallian Clay
67	50° 37·82′	2° 24·85′	pale-grey, calcareous clay, with gypsum specks; lamellibranch, gastropod, and ammonite fragments: *Quenstedtoceras*	Oxford Clay
68	50° 37·34′	2° 24·74′	pale-grey, calcareous clay with comminuted shell. *Cardioceras* (s.l.) sp., lamellibranchs	Oxford Clay
69	50° 37·38′	2° 24·07′	similar to sample from 68. *Quenstedtoceras* sp. ind., lamellibranchs, *Dicroloma trifidum* (Phillips)	Oxford Clay
70	50° 36·98′	2° 25·84′	grey, calcareous clay with mica and gypsum. *Cardioceras* (*Scarburgiceras*) sp. juv. (cf. *praecordatum* Douvillé)	Oxford Clay: Mariae Zone
71	50° 37·27′	2° 23·60′	grey, brittle, rubbly sandstone	?Corallian Beds
72	50° 37·29′	2° 23·64′	similar to sample from 71	?Corallian Beds
73	50° 37·45′	2° 23·57′	grey clay	uncertain
74	50° 37·53′	2° 23·38′	grey clay	uncertain
75	50° 37·39′	2° 23·66′	grey clay	uncertain
76	50° 37·31′	2° 23·58′	grey clay	uncertain
			Samples taken from R.R.S. Discovery II *in* 1959	
4031/1	50° 34·52′	2° 16·59′	grey shale or siltstone; grey fine-grained sandstone seams, sparsely glauconitic	Corallian Beds
4032/2	50° 34·83′	2° 16·42′	white oolite	Corallian: Osmington Oolite Series
4033/2	50° 35·12′	2° 16·74′	soft grey limestone with lamellibranch fragments; grey marly clay	Corallian: possibly Osmington Oolite Series
4034/1	50° 35·56′	2° 16·59′	brown-weathering, white, porous sandstone (fragment, probably of a pebble)	Corallian: probably Bencliff Grit
4034/3	50° 35·36′	2° 16·53′	white sandstone with disseminated pyrite; weathered orange-brown	Corallian: probably Bencliff Grit
4036/4	50° 35·89′	2° 16·88′	hard, grey, shelly and sandy oolite	Corallian: Osmington Oolite or *Trigonia clavellata* Beds; the latter perhaps more probable
4037/1	50° 36·15′	2° 16·89′	grey, pyritic, micaceous clay; black rods	uncertain
4038/1	50° 36·44′	2° 16·82′	pale-grey, pyritic and micaceous, strongly calcareous clay	uncertain
4039/1	50° 36·87′	2° 17·01′	dark-grey shale, bituminous, abundant white shelly fragments. *Protocardia*, small cardioceratid ammonites	Lower Kimmeridge Clay
4040/1	50° 36·78′	2° 16·78′	dark-grey shale. *Amoeboceras*, aptychus	Lower Kimmeridge Clay
4042/2	50° 23·14′	2° 13·13′	cream-coloured chalk	Chalk
4043/1	50° 24·09′	2° 12·95′	clayey, slightly glauconitic and micaceous silt or very fine sand; not calcareous; no diagnostic fossils	Upper Greensand, Lower Greensand or Wealden Beds
4044/1	50° 24·90′	2° 12·89′	core of red, brown and pale-grey marl with sand grains; fragments of coarse argillaceous sandstone	Wealden Beds
4045/1	50° 26·04′	2° 12·81′	ochre-yellow fine sand; pale-grey sand; mottled grey and purple-pink clay	Wealden Beds
4046/1	50° 26·90′	2° 12·83′	mottled pink and grey clay	Wealden Beds
4047/1	50° 28·20′	2° 12·19′	grey marl with ostracods	Purbeck Beds or Wealden Beds
4049/2	50° 29·74′	2° 12·33′	crystalline limestone with shell-fragments and worm tubes or borings; occasional green grains; (loose pieces only: no core)	Portland Stone
4050/1	50° 30·86′	2° 13·14′	medium-grey plastic clay, slightly calcareous	uncertain
4051/1	50° 31·83′	2° 13·13′	grey calcareous clay or marl, in places speckled with gypsum	Kimmeridge Clay (by comparison with 4052)
4052/1	50° 32·82′	2° 13·12′	medium grey bituminous shale (not calcareous); *Protocardia*, fish scales, ?*Discina*, aptychus; in places speckled with gypsum like 4051	Kimmeridge Clay

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Appendix I (*cont.*)

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
4053/1	50° 34·18′	2° 16·39′	grey clay (not calcareous); fine mica flakes	uncertain
4054/1	50° 33·94′	2° 16·60′	(*A*) pale-grey marly clay, with fine flakes of mica (*B*) fine-grained ?siltstone or marl with abundant carbonaceous specks; much mica	uncertain uncertain
4055/1	50° 33·78′	2° 16·95′	pale-grey marly clay, with fine flakes of mica as 4054 *A*; rare ostracods	uncertain
4056/1	50° 33·56′	2° 17·09′	dark shaly clay (not calcareous); fragment of 'Rasenid' ammonite, shells	Kimmeridge Clay
4060/1	50° 35·79′	2° 20·00′	pale-grey calcareous clay with abundant small flakes of mica identical with 4054*A*, 4055	uncertain
4061/1	50° 35·74′	2° 19·35′	pale-grey, micaceous, sandy calcareous clay	uncertain
4063/1	50° 35·64′	2° 17·83′	grey-brown oolite with shell fragments and rare sand grains	Corallian: Osmington Oolite or *Trigonia clavellata* Beds
4064/1	50° 35·63′	2° 16·98′	* pale-grey sandy calcareous clay; pyrite rods present	Corallian: probably Nothe Clay according to the microfauna
4067/1	50° 35·48′	2° 14·61′	brown-weathering (?grey) oolite, passing into grey compact limestone, with scattered ooliths	Corallian: Osmington Oolite or *Trigonia clavellata* Beds
4068/2	50° 35·47′	2° 13·74′	grey calcareous clay; oolite fragments	?Corallian: Osmington Oolite Series
4069/1	50° 35·91′	2° 15·15′	fine yellow sand with abundant limonitic material; small unweathered patches are grey and show quartz grains in apparently clayey matrix, probably with pyrite	Corallian Beds: could be Sandsfoot Grits, with which it is almost identical lithologically
4070/1	50° 36·15′	2° 15·97′	grey slightly calcareous clay, fine disseminated mica and pyrite	uncertain
4071/2	50° 35·68′	2° 14·61′	oolitic limestone and oolite debris, weathering brown	Corallian: Osmington Oolite Series
4072/2	50° 35·13′	2° 14·81′	sandstone with disseminated limonite and grey streaks (identical with 4142)	Corallian: Sandsfoot Grits?
4073/1	50° 34·72′	2° 14·86′	grey, slightly calcareous, argillaceous sandstone, *Ostrea* fragments	Corallian: probably Sandsfoot Grits
4074/1	50° 34·69′	2° 18·43′	fine-grained sandstone with limonite, similar to 4072/2; thin grey streaks; buff, weathering brown	Corallian: Sandsfoot Grits?
4076/1	50° 30·50′	2° 19·90′	fine-grained, brown-grey sand	Portland Sand
4076/2	50° 30·56′	2° 19·87′	(*A*) grey clay speckled with gypsum; calcareous (*B*) pebbles of granular limestone with shell fragments showing beekitisation	Portland Beds
4077/1	50° 29·45′	2° 20·11′	crystalline limestone; granular limestone with numerous ostracods; faint bituminous smell when struck; (probably pieces of pebbles only)	Purbeck Beds
4078/1	50° 29·97′	2° 19·95′	fine-grained granular limestone; shelly fragments and worm-tubes or borings	probably Portland Stone
4078/2	50° 30·00′	2° 19·83′	(same as 4078/1)	probably Portland Stone
4079/1	50° 28·92′	2° 19·89′	pale-grey calcareous speckled clay; similar to 4076/2 *A*	uncertain
4080/1	50° 28·43′	2° 19·93′	traces of pale-grey calcareous clay on corer (no sample)	uncertain
4081/1	50° 27·94′	2° 20·00′	limestone packed with broken shell fragments, greenish when wet; ostracods	Purbeck Beds
4082/1	50° 26·88′	2° 20·11′	* hard, grey marl with pyrite crystal aggregates, and carbonized wood; numerous pebbles, apparently of Purbeck Limestone, which may be in place; it is difficult to exclude contamination; no microfauna; abundant ferruginous bodies	probably either Wealden Beds or Sandsfoot beds
4083/1	50° 25·89′	2° 19·97′	medium to coarse grey sand with much carbonaceous material	Wealden Beds or Lower Greensand
4084/1	50° 24·90′	2° 20·10′	traces of grey clay on corer (no sample)	uncertain
4084/2	50° 24·89′	2° 19·95′	traces of sand on corer (no sample)	uncertain
4085/1	50° 23·90′	2° 20·25′	fine-grained cream limestone with ostracods, *Inoceramus*; grey limestone with glauconite, sponge spicules	Chalk
4086/1	50° 22·84′	2° 20·05′	glauconitic and micaceous grey sand	Wealden Beds, Lower Greensand or Upper Greensand
4087/2	50° 21·80′	2° 19·92′	glauconitic white sand	probably Upper Greensand
4089/1	50° 16·88′	2° 30·72′	pebbles of hard cream limestone; ostracods, irregular echinoid spines	?Chalk
4091/1	50° 18·98′	2° 31·20′	fine-grained, pale, brown-weathering calcareous sandstone	?Upper Greensand

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Appendix I (*cont.*)

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
4095/2	50° 34·76′	2° 18·85′	pale-grey calcareous clay; fine mica, a little pyrite; lamellibranchs and gastropods	?Corallian Beds
4096/1	50° 35·00′	2° 18·36′	brown-weathering, whitish-grey oolite	Corallian: Osmington Oolite Series
4097/2	50° 35·26′	2° 18·39′	grey fine-grained compact limestone	uncertain
4098/1	50° 35·33′	2° 18·28′	oolite identical with 4096	Corallian: Osmington Oolite Series
4099/1	50° 35·63′	2° 18·28′	grey sandy limestone with ooliths and shelly fragments	Corallian Beds
4100/1	50° 35·72′	2° 22·38′	traces of grey calcareous clay on corer (no sample)	uncertain
4101/1	50° 35·95′	2° 22·60′	grey highly calcareous micaceous clay with plant remains; pale-yellow fine sand interbedded	Corallian Beds
4103/2	50° 36·38′	2° 23·06′	crystalline shelly and oolitic limestone	Corallian: Osmington Oolite Series
4104/1	50° 36·71′	2° 23·09′	grey calcareous clay, speckled with gypsum	uncertain
4105/2	50° 36·83′	2° 23·28′	* grey, slightly calcareous clay, speckled with gypsum. *Lopha*, other lamellibranch fragments	Corallian Beds: the microfauna favours Nothe Grits but lithology indicates Nothe Clay
4107/1	50° 36·73′	2° 22·25′	* grey, finely micaceous silty clay, mottled with yellow-ochre colour; rare plant remains; not calcareous	Corallian: Sandsfoot Grits and Clay
4108/1	50° 22·94′	2° 31·02′	pale-yellow to ochreous fine sand; two chert pebbles and a fragment of glauconitic sandstone	Corallian Beds (by comparison with 4111)
4109/3	50° 23·92′	2° 31·19′	yellow-brown weathering clayey grey sand; fine-grained, ochreous, calcareous sandstone	Corallian Beds (by comparison with 4111)
4110/1	50° 25·05′	2° 31·10′	grey pebbly sand, with grey calcareous clay	Corallian Beds (by comparison with 4111)
4111/1	50° 26·02′	2° 31·09′	* pale-grey and yellowish, slightly clayey, pebbly sand; ooliths were present in the residue examined for microfauna	Corallian: probably Osmington Oolite Series according to the microfauna and lithology
4112/1	50° 27·08′	2° 30·92′	traces of grey clay on corer (no sample)	uncertain
4112/2	50° 26·97′	2° 31·14′	coarse, grey slightly clayey, pebbly sand; same as 4111	Corallian Beds (by comparison with 4111)
4113/1	50° 28·31′	2° 31·40′	dark-grey shale (not calcareous), abundant white shells and fragments; lamellibranchs, ammonites; speckled with gypsum	Kimmeridge Clay
4114/1	50° 29·15′	2° 31·18′	same as 4113. *Discina latissima* (J. Sowerby), *Protocardia* sp.	Kimmeridge Clay
4115/4	50° 30·87′	2° 31·85′	same as 4113; lamellibranchs, fish-scales	Kimmeridge Clay
4116/1	50° 29·77′	2° 16·54′	grey, fine-grained calcareous sandstone, shelly fragments	uncertain
4117/1	50° 29·75′	2° 14·87′	traces of fine-grained clayey sand on corer (no sample)	uncertain
4118/2	50° 29·75′	2° 13·47′	chert fragments on corer (no sample)	Portland Stone
4119/1	50° 29·75′	2° 11·91′	grey, fine-grained, sandy limestone with abundant lamellibranch shell-fragments	Portland Beds
4120/1	50° 29·75′	2° 10·26′	* grey calcareous clay, speckled with gypsum and fine hair-like carbonaceous fragments	Purbeck Beds according to the ostracods
4121/2	50° 29·75′	2° 08·68′	slightly calcareous, micaceous, clayey fine sand	uncertain
4122/1	50° 29·72′	2° 07·08′	grey calcareous clay with specks of gypsum and abundant white shell fragments; limestone with similar shell fragments and ostracods	? Purbeck Beds
4123/1	50° 32·06′	1° 59·91′	* (*A*) stiff grey clay (not calcareous) with scattered fine sand grains, (*B*) highly calcareous sandstone, the calcite cement in crystallographic continuity; black specks; whitish to honey colour	Middle Purbeck Beds according to the microfauna
4124/2	50° 30·94′	1° 59·72′	same as 4123*A*	Purbeck or Wealden Beds
4125/1	50° 29·63′	1° 59·87′	stiff pale-grey clay (not calcareous) with abundant gypsum; ochre-stained in patches	uncertain
4126/1	50° 27·63′	1° 59·89′	pale-grey, friable fine sand (not calcareous); some clay, small flakes of mica	Wealden Beds or Lower Greensand
4127/1	50° 25·74′	1° 59·93′	(*A*) grey soft sand (not calcareous) (*B*) pale brown-grey rock consisting of fine sand or silt grains in a clayey matrix, only faintly calcareous	Lower Cretaceous
4128/1	50° 23·64′	1° 59·79′	chalk and flint	Chalk
4129/1	50° 36·54′	2° 22·11′	* dark-grey shaly clay, not calcareous, specks of gypsum; white shell fragments; pyrite; some greensand but this could be due to contamination	Kimmeridge Clay; about Mutabilis Zone, according to the microfauna

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Appendix I (*cont.*)

Station no.	Lat. (N)	Long. (W)	Lithology	Stratigraphical horizon
4130/1	50° 36·32′	2° 22·03′	* pale-grey marl	Kimmeridge Clay: about Mutabilis Zone according to the microfauna
4131/1	50° 35·96′	2° 21·79′	pale-grey marl (identical with **4130**)	Kimmeridge Clay
4132/1	50° 36·19′	2° 23·77′	grey calcareous clay with 'brecciated' appearance, some fine sand; lumps of ?chalk or white calcareous siltstone; also yellow, friable sand, with parts of an echinoid spine which could be derived	uncertain
4133/2	50° 36·49′	2° 23·62′	yellow sand and clay with quartz-pebbles; a small sample of doubtful value	?debris from Corallian Beds
4134/1	50° 36·42′	2° 22·86′	yellow calcareous sand, shelly fragments; ooliths or worn calcareous grains	Corallian Beds
4135/1	50° 36·62′	2° 22·55′	yellow-weathering calcareous sandstone, dark grey-green when fresh, with dark grains of ?glauconite or phosphate; shelly fragments	Corallian: probably Sandsfoot Grits
4136/1	50° 36·89′	2° 22·23′	* grey calcareous micaceous clay, with specks of pyrite and carbonaceous matter; foraminifera; shelly fragments, gypsum specks	Corallian: Nothe Clay probable on the evidence of the microfauna
4137/1	50° 36·56′	2° 21·95′	grey pyritic, calcareous sand; rare green grains; a little mica; shelly fragments	?Corallian Beds or sandy Kimmeridge Clay
4138/1	50° 37·17′	2° 20·79′	* grey sand with mica and numerous glauconitic grains; faintly calcareous	Recent sediment derived from Upper Greensand and Lower Chalk
4139/1	50° 37·08′	2° 20·50′	dark-grey shaly clay (not calcareous); gypsum flecks, white shelly fragments; ammonite; a microconch with lappet of rasenid type	Lower Kimmeridge Clay
4140/1	50° 36·52′	2° 20·59′	* grey clayey sand (not calcareous); glauconitic grains	Kimmeridge Clay; Cymodoce Zone according to the microfauna
4141/1	50° 36·19′	2° 20·32′	pale-grey to yellow, fine-grained clayey sandstone (not calcareous); scattered glauconite	Corallian Beds
4142/1	50° 35·88′	2° 20·11′	grey and yellow, fine-grained calcareous sandstone; shell-fragments, small gastropod casts; identical with 4072/1, 4074/1	Corallian: Sandsfoot Grits from stratigraphical position
4148/1	50° 28·97′	2° 28·25′	* grey, slightly calcareous, clayey fine sand, with glauconite, mica and pyrite; similar to **4140**	Kimmeridge Clay; probably *Pavlovia* Zone according to the microfauna
4149/2	50° 29·00′	2° 28·95′	grey fine-grained sand, micaceous, sparsely glauconitic, clayey; probably same group as **4148**	probably Upper Kimmeridge Clay
4150/1	50° 29·08′	2° 29·82′	grey calcareous shaly clay, ?gypsum specks. *Discina latissima* (J. Sowerby), fish scale	Kimmeridge Clay
4151/1	50° 29·08′	2° 30·49′	grey, friable micaceous marl; smells bituminous when heated; soluble in dilute HCl but leaves dark residue; specks of gypsum; fish scale, black carbonaceous fragments, fish vertebrae?	uncertain
4152/1	50° 36·34′	2° 19·40′	highly calcareous grey clay, with ochreous stains. Rare carbonaceous fragments	?Kimmeridge Clay
4153/1	50° 36·20′	2° 18·76′	yellow sand and calcareous sandstone with shelly fragments; slightly glauconitic	Corallian Beds
4154/1	50° 36·01′	2° 18·08′	grey clayey fine sand, with carbonaceous specks; weathered yellow in patches	Corallian: ?Sandsfoot Grits
4155/1	50° 35·84′	2° 17·65′	strongly oolitic, grey marl; pyrite, black specks	Corallian: Osmington Oolite Series
Samples, collected by Professor W. B. R. King, now in the Geological Survey Museum				
K17 (MR 19939)	50° 32′	1° 57′	pale-grey fine sand	probably Lower Cretaceous
K 117 (MR 20000)	50° 21·75′	2° 07·25′	hard, white fine-grained limestone	Chalk. Similar to the Chalk Rock
K 118 (MR 20001)	50° 24·7′	2° 21·8′	grey, shelly limestone; worm tubes or burrows prominent	Portland Stone

(Numbers in brackets are registered numbers in the Geological Survey Museum.)

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Appendix II. The microfaunas of some submarine samples from Weymouth Bay

By A. J. LLOYD

Introduction

In the summer of 1959 the present author was approached by Dr D. T. Donovan with a view of identifying, by means of micropalaeontological techniques, the horizons from which a number of otherwise uninformative samples were derived. These samples were obtained from the sea floor off the coast of Dorset in order to verify the structural conclusions drawn from an acoustic survey described in the main part of this publication. Two methods of sampling were employed:

(1) A small diameter, free-fall corer, operated from the surface, which penetrated a few inches into the sea floor and yielded a small sample.

(2) Collection by divers with only rudimentary geological experience.

Parts of sixteen samples were sent to me for examination. The dry sample was, in the first instance, soaked in 20 volume hydrogen peroxide, then boiled repeatedly in solutions of washing soda and/or caustic soda till disaggregation was complete. The dried residues were examined under a binocular microscope and the micro-organisms separated by hand.

Most of the samples yielded Foraminifera, Ostracoda and the dissociated parts of larger animals. In thirteen cases the samples could be assigned with certainty to stages of the Jurassic, and often to certain zones or beds. Of the remainder, two contained obviously mixed faunas, and the third was barren.

Validity of results

There were two quite independent sets of factors which had to be borne in mind when dating the assemblages, either of which could have led to misleading results.

The first source of error lies in the fact that not one of the samples was collected by a trained micropalaeontologist with due regard to normal precautions, and in many cases the collection site was never seen. As a result every sample contained a certain amount of Recent material and in some cases over 80% of the total fauna (in numbers of individuals) consisted of present-day Foraminifera and Ostracoda. In the case of the cored samples the force with which the corer struck the sea floor was sufficient to drive a certain amount of superficial material into the solid substratum to such a depth that nearly all the resultant sample was contaminated. This was of no great significance with regard to the Recent microfauna, which could always be distinguished with ease, but there remains the possibility that fossil Foraminifera derived from nearby submarine outcrops and present in the superficial layer might become intimately mixed with the fauna of the substratum. As the determination of age was based more on assemblages than index forms this could be a serious source of error.

The second inadequacy of this study is the lack of modern published accounts of Upper Jurassic and Lower Cretaceous microfaunas. There are just two accounts of marine microfaunas known to the present author. Barnard (1953) has dealt with Foraminifera from the Upper Oxford Clay, and Lloyd (1959) has described the Kimmeridgian arenaceous forms. As yet, there is no account of the ostracods. The predominantly fresh-water

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faunas of the Purbeck and Wealden Beds have been the subject of papers by F. W. Anderson and P. C. Sylvester-Bradley and are, in consequence, much better known.

The absence of published accounts is particularly serious as these Foraminifera are prone to facies control. For example, the Kimmeridgian faunas of the Bas Boulonnais have much closer affinities with those of the Dorset Corallian than they have with the Dorset Kimmeridge Clay.

These defects were made good, in part, by a reference collection of Dorset microfaunas built up by the present author over the past 8 years. The age determinations presented here are based on a comparison of assemblages from the submarine samples with those of the reference collection, but in no case could an exact match be made. The submarine samples were invariably poorer in numbers of species than their supposed equivalents from coastal outcrops. As there was no great difference between the weights of samples this was thought to be due to the restricted horizontal extent of a cored sample (coast samples were usually taken from an area of 10 to 15 in.^{2} on a bedding plane).

A second result of the lack of published accounts is that many stratigraphically important species either have not received taxonomic revision, or are new species whose manuscript names can not be mentioned here.

In the following notes the lithologies have received only passing mention. They can rarely be used as a guide to horizon (sample 46 is a notable exception), but often provide a useful check on the age indicated by the fauna. For location of samples and further notes on the lithologies see appendix I of this publication.

Description of the samples

When first received the samples were not accompanied by location data or notes as to relative positions. This meant that each sample had to be treated on its own merits, and adjacent members of a series could not be recognized as such. Subsequent discussions with Donovan showed that, for most part, the ages which had been determined were in agreement with the distribution of the samples.

In this section the samples are dealt with in numerical order, and are not grouped stratigraphically.

Sample 46

This is probably the most successful of the samples collected, from the micropalaeontological view. The Foraminifera are abundant, well preserved, and include all the forms to be expected at its horizon. The most common arenaceous forms are *Ammobaculites suprajurassicus* and *A. agglutinans* but *Haplophragmoides rotunda*, *Tolypammina* sp. and a small *Trochammina* also occur. In number of species the lagenids are dominant; *Lenticulina subalata* and the *L. munsteri*/*L. russiensis* group are equally common but *L. flaccida*, indicating an Oxfordian age, is well represented. Of the other lagenids, *Planularia pauperata*, *P. filosa*, '*Frondicularia*' *franconica* and *Dentalina gumbeli* are typically Oxfordian, while *Citharina harpa*, *Tristix triangularis* and nodosariids of the *N. radicula* group have a longer range. A notable feature of the fauna is the common occurrence of calcareous adherent forms, probably *Bullopora*. Finally, there are a few small specimens referable to '*Epistomina*'.

This assemblage is unquestionably Oxfordian and almost certainly Cordatum Zone in age. On the basis of the Foraminifera alone a high Oxford Clay age could be assumed

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but the residue contained a number of liver-red, ferruginous mudstone nodules. This confirms the age as Red Nodule Beds.

Sample 48

The Foraminifera of this sample can be divided into three distinct assemblages. Recent Foraminifera, mainly *Rotalia* and miliolids are as abundant as a Lower Corallian Beds assemblage which includes *Ammobaculites subaequale*, *Lenticulina subalata* and *L. flaccida*, *Citharina harpa*, '*Epistomina*' *ornata* and *Spirillina infima*. The third assemblage, with fewest specimens, consists of *Tritaxia macfadyeni*, *Gaudryina* sp. and a single *Rotalipora turonica*, clearly Upper Cenomanian in age.

This sample was probably taken in beds of Nothe Grits/Nothe Clay age, close to a submarine outcrop of Cenomanian if not, indeed, on the feather edge of the Cenomanian.

Sample 51

The fauna is dominated by equal numbers of large *Ammobaculites*, *A. subaequalis* and *A. coprolithiforme* both occurring, and *Lenticulina* with the *L. subalata* and the *L. munsteri*/*L. russiensis* groups. Less common are *L. flaccida*, *Haplophragmoides rotunda*, '*Frondicularia*' *franconica* and *Tristix triangularis*. Once again, a Cordatum Zone age is indicated, and in view of the common occurrence of arenaceous forms, a high level in the zone. This rather restricted assemblage is best matched with outcrop samples from the Nothe Grits.

Sample 4064/1

The arenaceous Foraminifera present include the large forms of *Ammobaculites* found through much of the Oxfordian. Large coiled forms close to *A. subaequalis* are more common than the small coiled *A. coprolithiforme* type, while the much smaller *A. agglutinans* and *A. minuta* also occur. The bulk of the fauna, however, consists of lagenids, with the usual Upper Jurassic species of *Lenticulina* predominating. Specimens that can be referred to the *L. subalata* and *L. munsteri*/*L. russiensis* groups make up over 70% of the fauna, but other lagenids are not uncommon. *Dentalina* is represented by three species—*D. gumbeli*, *D. bicornis* and *D. vetustissima*; *Marginulina* by slender forms close to *M. linearis*. Single specimens of *Citharina inconstans*, *Tristix suprajurassica* and *Spirillina infima* were also found.

The general character of the fauna places it in the Oxfordian Stage, but a more precise age is difficult to determine. On the one hand the comparative rarity of large arenaceous forms makes a low horizon unlikely, while on the other the absence of robust lagenids virtually rules out the Osmington Oolite. The delicate lagenids are forms found in the Nothe Clay (as well as elsewhere). The lithology of the sample would agree with a horizon high in the Nothe Clay or low in the Osmington Oolite Series.

Sample 4082/1

Completely barren of fossil micro-organisms. The nature of the sample suggests that it is a slumped clay that may not be *in situ*. The residue contains a number of ferruginous bodies and much fine silt, characters that have been seen in samples from the Sandsfoot beds.

Sample 4105/2

The bulk of the fauna consists of large arenaceous forms with *Ammobaculites subaequalis* rather more common than *A. coprolithiforme*, though smaller arenaceous forms, including *Proteonina difflugiformis* and *Reophax sterkii*, are represented by numerous specimens.

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Lenticulinids of the *L. subalata* and *L. munsteri*/*L. russiensis* groups are not uncommon while *Citharina harpa*, *C. inconstans*, a species of *Citharinella*, '*Frondicularia*' *franconica* and juvenile *Tristix* also occur.

Again an Oxfordian age is clearly indicated. The abundance of large *Ammobaculites* suggest a low horizon in the Corallian Beds and, as *A. subaequalis* is more common than *A. coprolithiforme*, Nothe Grits are more likely than Nothe Clay.

Sample 4107/1

Less than a dozen fossil Foraminifera were found in this sample, and of these the bulk could be referred to the *Lenticulina munsteri*/*L. russiensis* group. Single specimens were also found of *Ammobaculites agglutinans* and '*Epistomina*' *stelligera*.

The residue from this sample consists of silt-grade material with ferruginous flakes, a lithology often associated with poor microfaunas, so the restricted fauna recovered is not necessarily due to collection failure. Both fauna and lithology can be matched in coastal samples from the Sandsfoot beds.

Sample 4111/1

Arenaceous forms are common, with *A. coprolithiforme* more abundant than *A. subaequale*, but species of *Lenticulina* dominate the fauna. *L. subalata* and the *L. munsteri*/*L. russiensis* group are most common, but *L. matutina* also occurs. The other lagenids are forms with robust tests—*Citharina condita* and *Vaginulina jurassica*. *Spirillina infima* was also found.

This assemblage is clearly of Oxfordian age, and the robust lagenids suggest an Upper Oxfordian horizon. The residue was mainly of sand-grade material but ooliths were common. Taken together these indicate the Osmington Oolite as the probable source.

Sample 4120/1

No Foraminifera at all were found in this sample, but ostracods of a type usually regarded as non-marine are common. The two genera identified, represented by equal numbers of specimens, were *Candona*, which is most common in the Lower Purbeck Beds, and a smooth, nearly hook-less cypridean form close to *Langtonia*, which has zonal value in the Upper Purbeck. This contradiction in age may be due to contamination, but in any event a Purbeck age is obvious.

Sample 4123/1

The fossil micro-organisms of this sample could all be referred to one ostracod genus—*Ulwellia*, represented by numerous individuals. This, almost certainly, indicates a Middle Purbeck age for the sample.

Sample 4129/1

The characteristic feature of this assemblage is the total absence of arenaceous forms, and the presence of numerous lenticulinid species, each represented by many individuals. *Lenticulina subalata*, *L. munsteri* and *L. russiensis* occur throughout the Upper Jurassic, but when *L. polygona* and *L.* cf. *nautiloides* are also present, a Lower Kimmeridgian age is to be suspected. The occurrence of *Citharina inconstans* is not incompatible with this age determination.

The absence of arenaceous forms makes correlation with the Baylei or Cymodoce Zone unlikely, but the assemblage has been seen in outcrop samples of the Mutabilis Zone.

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Sample 4130/1

The restricted fauna comprised few elements. *Ammobaculites braunsteini* was represented by few individuals that could be matched more easily with Mutabilis Zone Kimmeridgian forms than with those from the Corallian Beds. The lenticulinids, belonging to the *L. subalata* and *L. munsteri*/*L. russiensis* groups, also included variants with a Kimmeridgian cast.

Sample 4136/1

The fauna bears a strong resemblance to that found in sample 4064/1. Arenaceous forms are dominant, *Ammobaculites subaequalis* and *A. coprolithiforme* being the most common, but a few individuals referrable to *A. deceptorius* were also found. Lenticulids of the *L. munsteri*/*L. russiensis* group are not infrequent and there are a few specimens of *Citharina harpa*. An Oxfordian age is clearly indicated with a Nothe Clay horizon most likely.

Sample 4138/1

This sample yielded many Recent Foraminifera but only a few fossil forms. Of these a small species of *Arenobulimina* is most common, similar to a form occurring in the Cenomanian (personal communication from Dr T. Barnard). The only other fossil form is a single specimen of a juvenile *Lenticulina* of indeterminable horizon.

Quite clearly this sample was taken entirely in a Recent sediment, but with some contamination from Mesozoic rocks. The occurrence of the arenobuliminid suggests that the closest solid outcrop, probably but not certainly submarine, was of Cenomanian age.

Sample 4140/1

Except for a few corroded and pyritized *Elphidium*, all the Foraminifera are fossil, with small arenaceous forms most abundant. These included many variants of a number of species: *Proteonina difflugiformis*, three species of *Reophax*—*R. scorpiurus*, *R. sterkii* and *R. helvetica*, several variants of *Ammobaculites agglutinans* and *A. deceptorius*, *Haplophragmoides latidorsatum*, *Textularia agglutinans* and *Trochammina squamata*. By contrast, calcareous forms are rare, including *Lenticulina subalata*, a citharinid of the *C. harpa* group and '*Epistomina*' *porcellanea*.

Such an assemblage, with its dominance of small arenaceous forms, is unusual in the Upper Jurassic, but all these elements can be found together in the Cymodoce Zone of the Kimmeridge Clay.

Sample 4148/1

The microfauna, of few elements, is almost entirely fossil. Most of the specimens can be referred to variants within the *Citharina harpa* plexus occurring towards the top of the Kimmeridge Clay. The other lagenids present support this. *Lenticulina subalata* is represented by large, coarsely ornamented forms and there are several specimens of a new, and as yet unpublished, species of *Saracenaria* that is restricted to the middle of the Rotunda Zone (in Arkell's 1956 sense).

Conclusions

When the present author began this investigation he felt that in view of the obvious risk of contamination it would be difficult to come to a completely satisfactory age-determination for more than a few particularly favourable samples. However, of the sixteen samples, thirteen yielded faunas in which, when the Recent material had been

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removed, a single assemblage was left whose age could be fixed within more or less narrow limits. Even more surprising was the fact that one of the remaining 'contaminated' samples, 48, yielded a fauna that could be separated into two distinct fossil assemblages, both of which gave potentially useful information. In no other case was there any reason to suspect a mixture of faunas from adjacent beds, though the possibility of this having happened cannot be entirely ruled out.

On the adverse side, the faunas obtained were usually much poorer both in individuals and number of species than samples collected by hand from similar horizons on the coast; and there remains the possibility that the sample was taken from a block of material not *in situ*. The first situation is thought to depend on the limited surface area sampled and could possibly be overcome by either using a multiple corer, or taking several samples at each station. The second source of error can usually be eliminated in areas where the structure is simple by considering the total picture derived from all the samples.

References

Arkell, W. J. 1956 *Jurassic geology of the world*. Edinburgh and London.

Barnard, T. 1953 Foraminifera from the Upper Oxford Clay of Redcliff Point, near Weymouth, England. *Proc. Geol. Assoc.* **64**, 183–97.

Lloyd, A. J. 1959 Arenaceous Foraminifera from the Type Kimeridgian (Upper Jurassic). *Palaeontology*, **1**, 298–320.

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Figure 4. Geological map of the sea floor between Portland and St Alban's Head. Scale approximately 1 in. to 1 mile. Black disks mark sampling stations; for details see Appendix I. Abbreviations for horizons in the Kimmeridge Clay: *BS* = Basalt Stone; *FSB* = The Flats Stone Band; *FSSB* = Freshwater Steps Stone Band.

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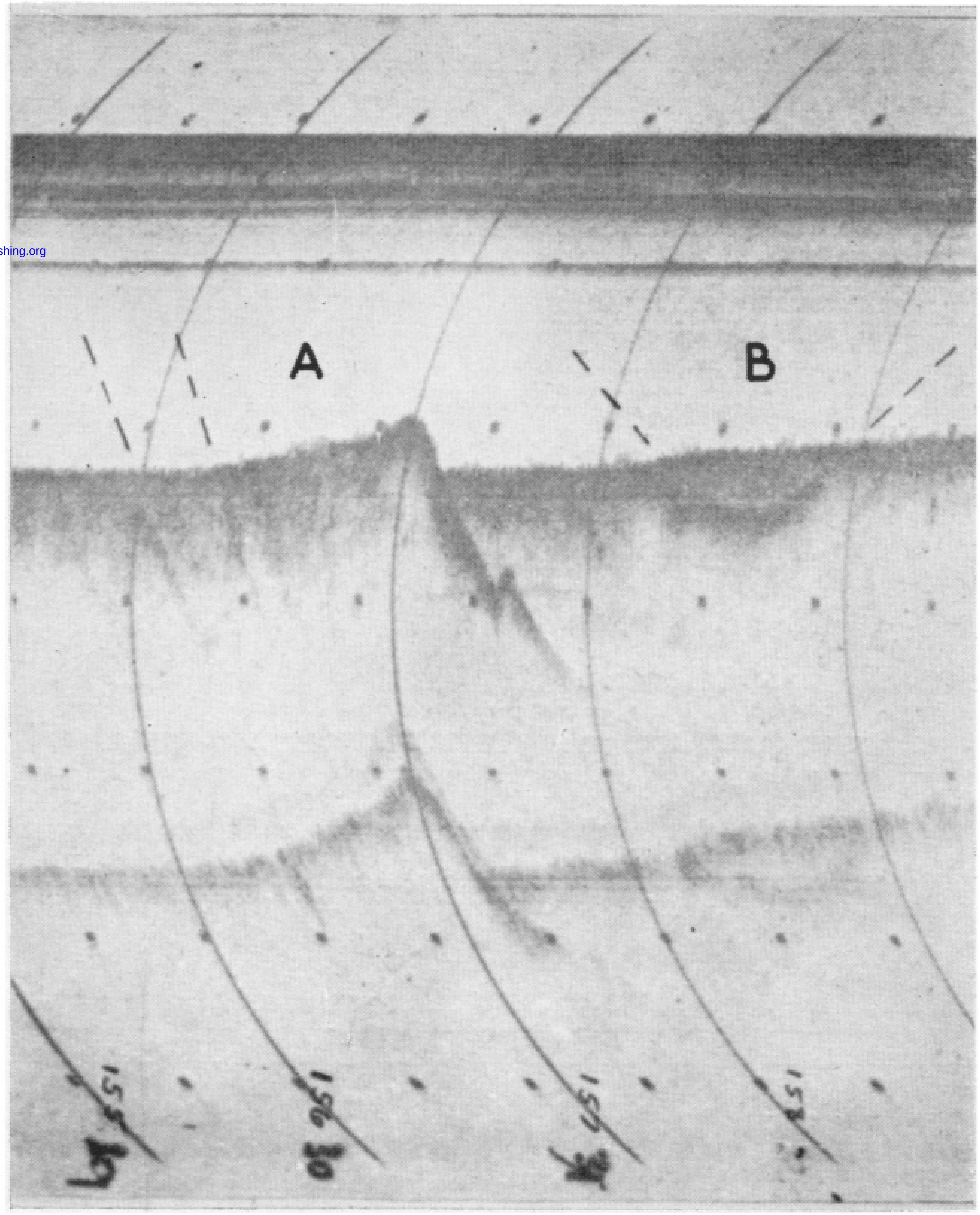

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FIGURE 7. Echo-sounder profile $\frac{3}{4}$ mile long of the sea floor near the north shore of Weymouth Bay. The ridge *A* is formed by a bed of nodules in the Oxford Clay which can be traced to a depth of 25 ft. below the sea floor as a strongly reflecting surface. Another reflecting surface shows the presence of a syncline at *B*.

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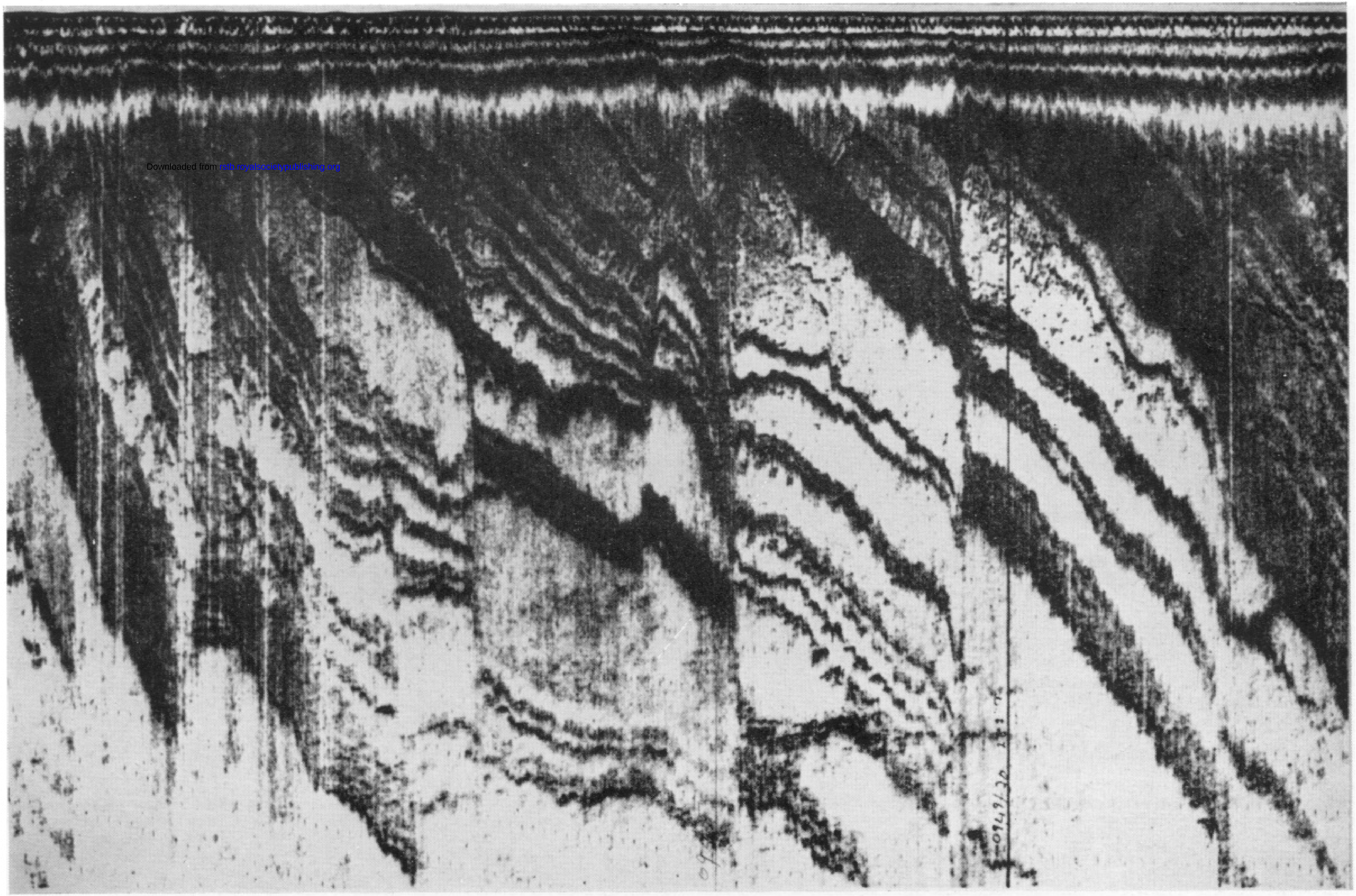

IGURE 8. An asdic record approximately 2700 yards × 800 yards showing faults in Kimmeridge Clay $1\frac{1}{2}$ miles south of Broad Bench. The beds dip gently towards the bottom of the figure, and the direction of downthrow of the faults can, therefore, be deduced from the lateral displacements of marker beds.

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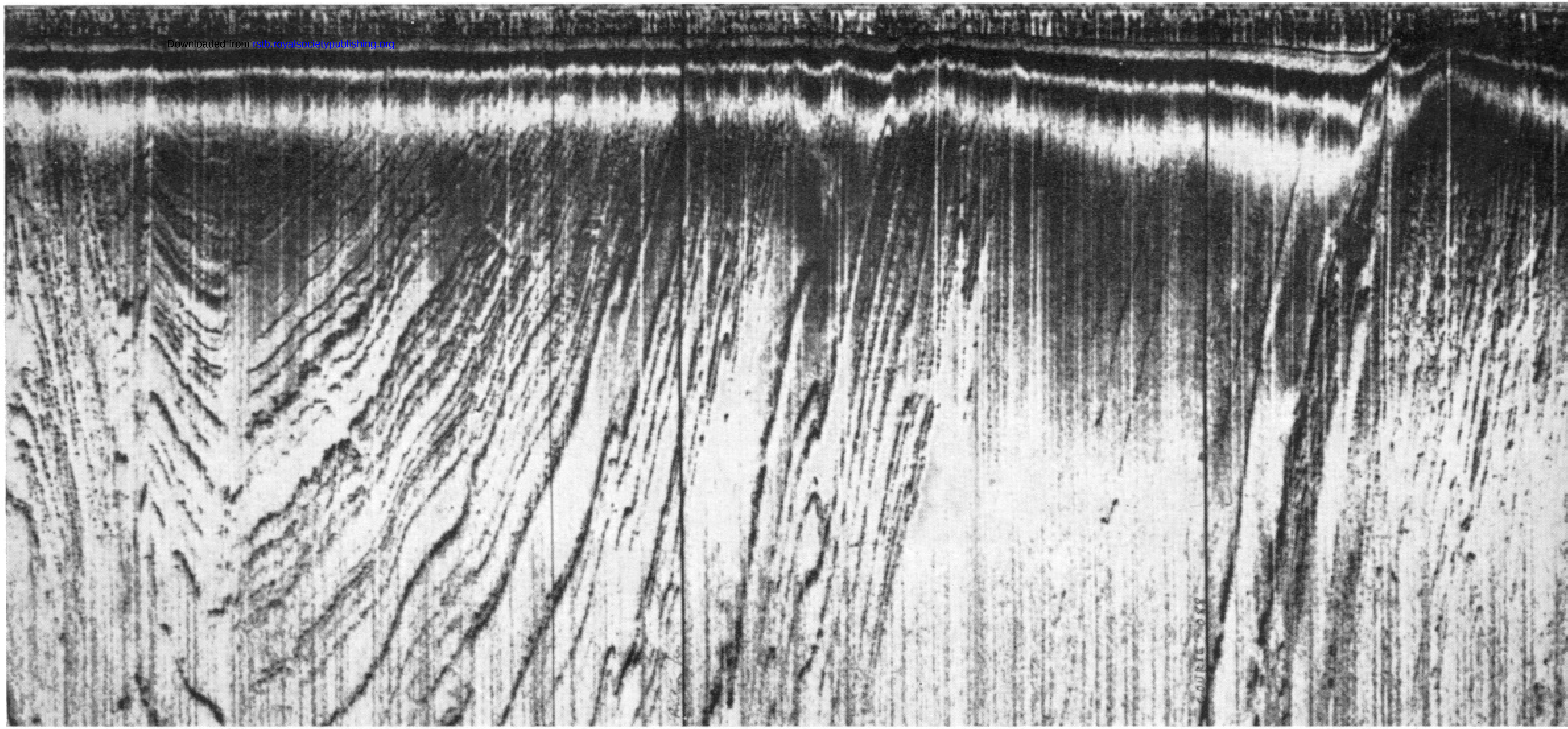

FIGURE 9. An asdic record approximately 4000 yards × 800 yards of rocky floor about 3 miles south-west of St Alban's Head, showing the pattern of outcrops which has been used to define the southern limb of the Purbeck Anticline. The record shows, from left to right, Kimmeridge Clay with resistant beds, featureless uppermost Kimmeridge Clay, and Portland Beds forming a ridge. Narrow dark bands represent scarp edges of beds as in figure 8. The distortion of the scale greatly exaggerates the curvature of the outcrops in the Kimmeridge Clay at the left-hand side of the figure.

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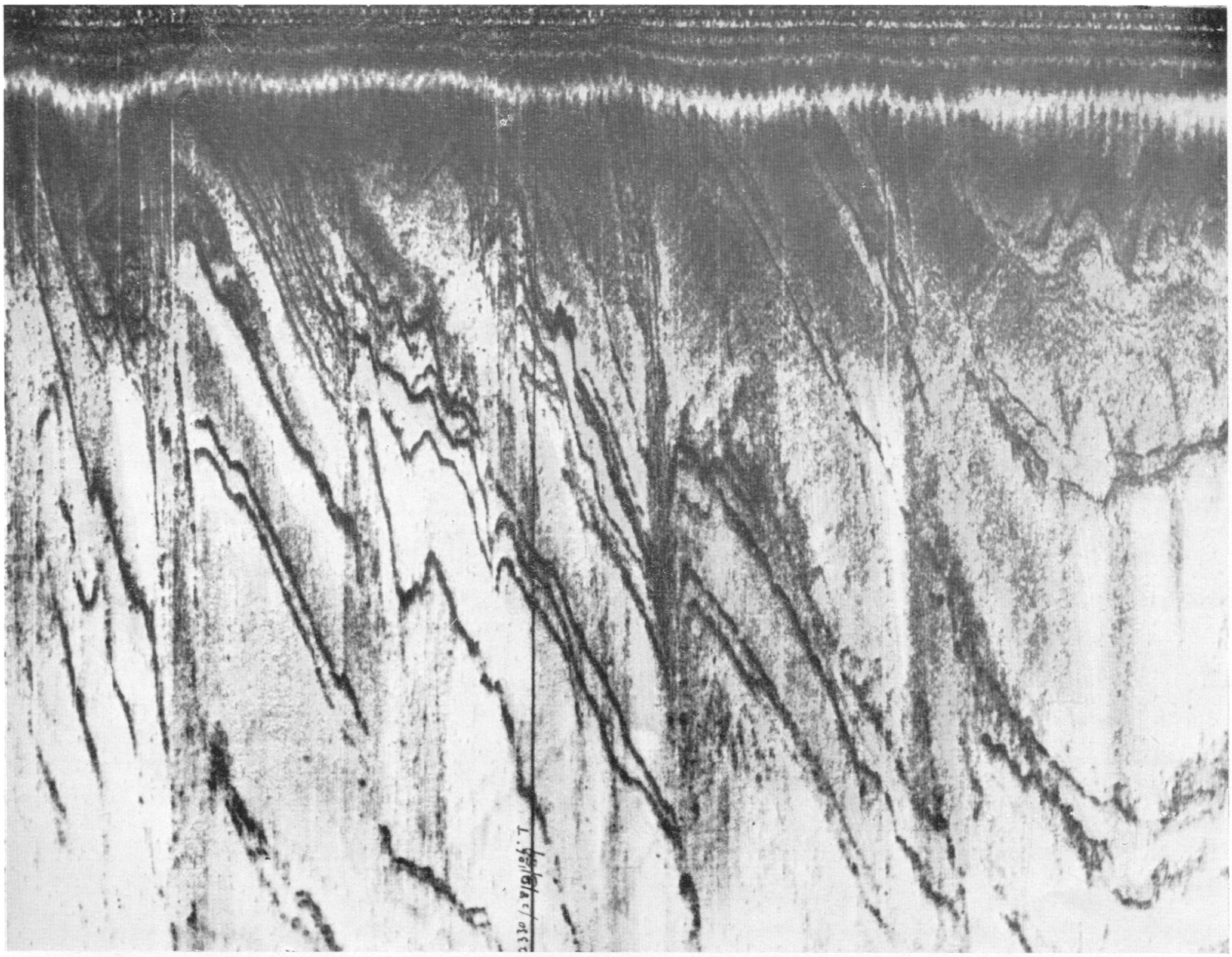

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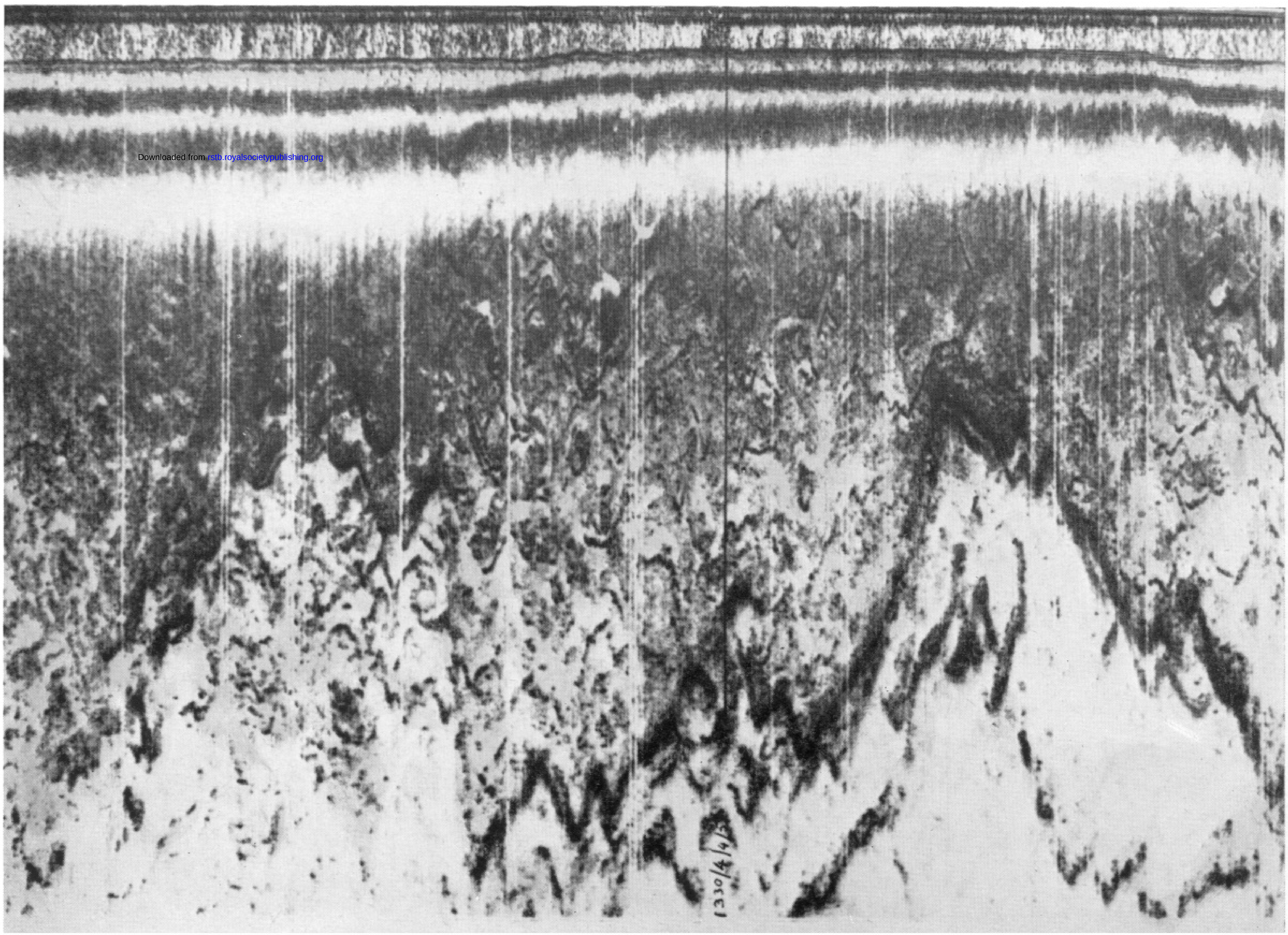

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FIGURES 10 AND 11. For description see p. 315.

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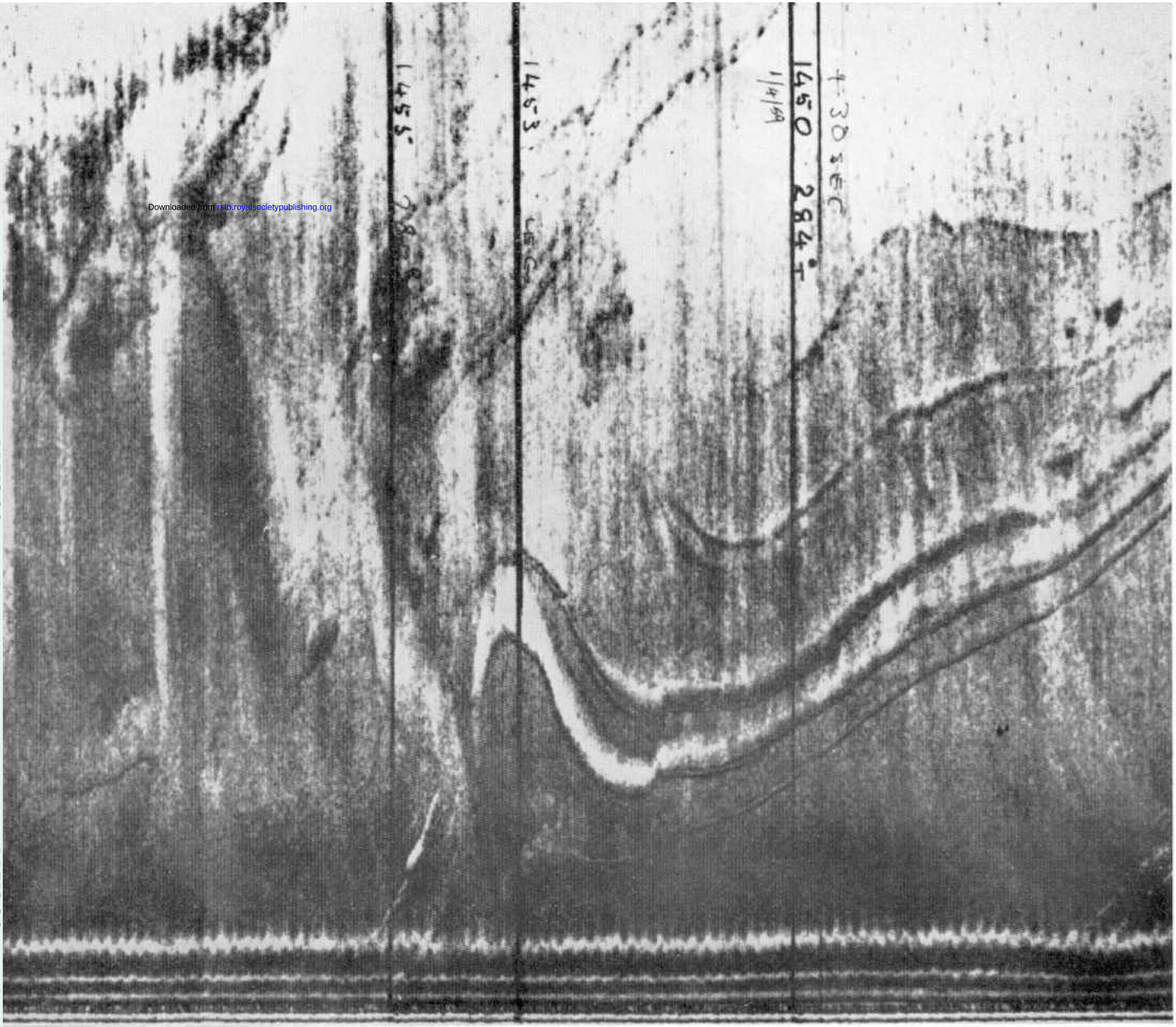

FIGURE 12

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