THE GEOLOGY AND PALAEONTOLOGY OF THE JURASSIC ROCKS OF EATHIE (CROMARTY)

by

CHARLES D. WATERSTON, B.Sc.

Van's Dunlop Scholar

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INTRODUCTION

Among the many notable geological features of north-east Scotland, one of the most interesting is the occurrence of isolated exposures of Jurassic rocks on the eastern seaboard of Sutherland and Ross-shire. The largest of these exposures occurs in the Brora-Helmsdale region where rocks of Liassic, Great Estuarine, Marine Callovian, Oxfordian, Corallian and Kimmeridgian ages occur. Of these the Kimmeridgian is of greatest extent, its estimated thickness being 1500 feet (Bailey and Weir, 1932). Seven of Salfeld's (1913) fossil zones have been identified - with varying degrees of certainty - in the Kimmeridgian beds, which are made up mainly of black shales interbedded with boulder bed.

Only one other exposure of Kimmeridgian rocks is seen in the Moray Firth area. This occurs at Eathie, thirty miles to the south-west, the smallest and southernmost of the Jurassic exposures of eastern Scotland, where rocks of the Rasenia cymodoce and Rasenia mutabilis zones are found. These rocks are the subject of the present thesis.

Eathie Haven lies on the small sandy bay, called the Boat Hard, which interrupts the rocky eastern shore of the Black Isle three miles south of Cromarty (see Fig. 1). It was once a prosperous fishing station, but is now marked by two small buildings /

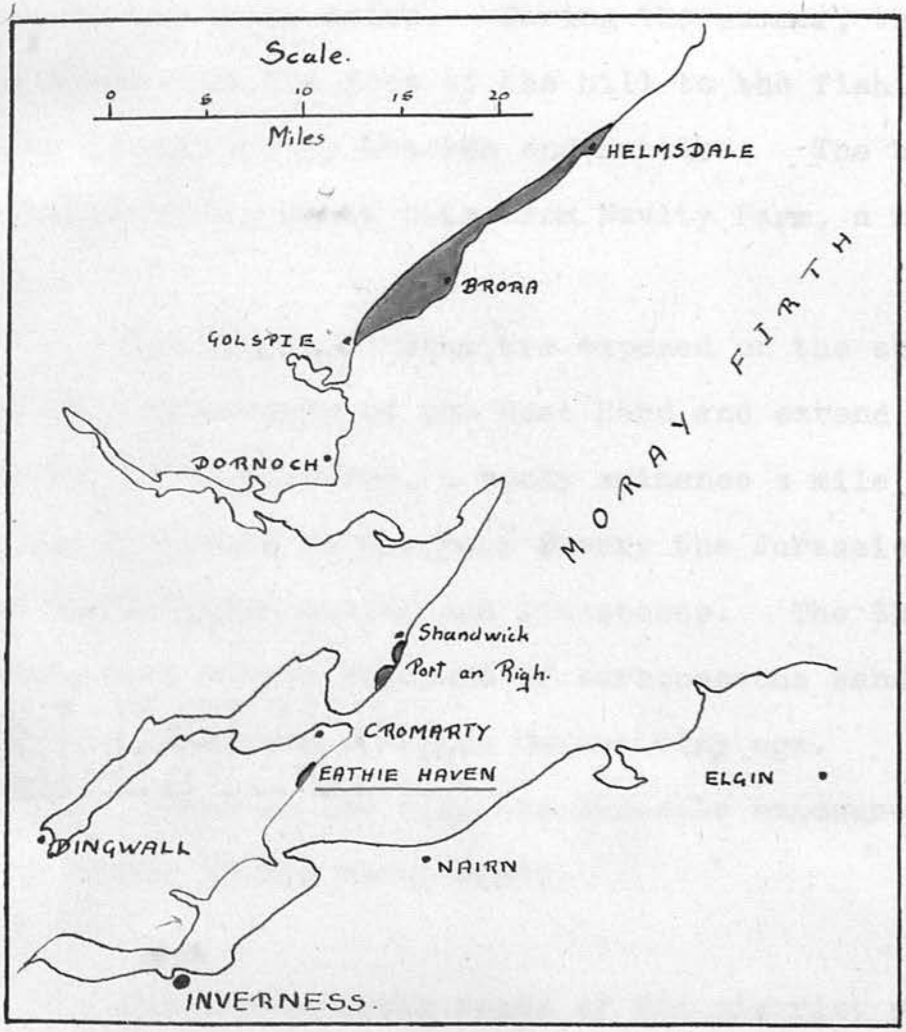


Fig. 1

Sketch Map to show the distribution of Mesozoic rocks in N.E. Scotland.

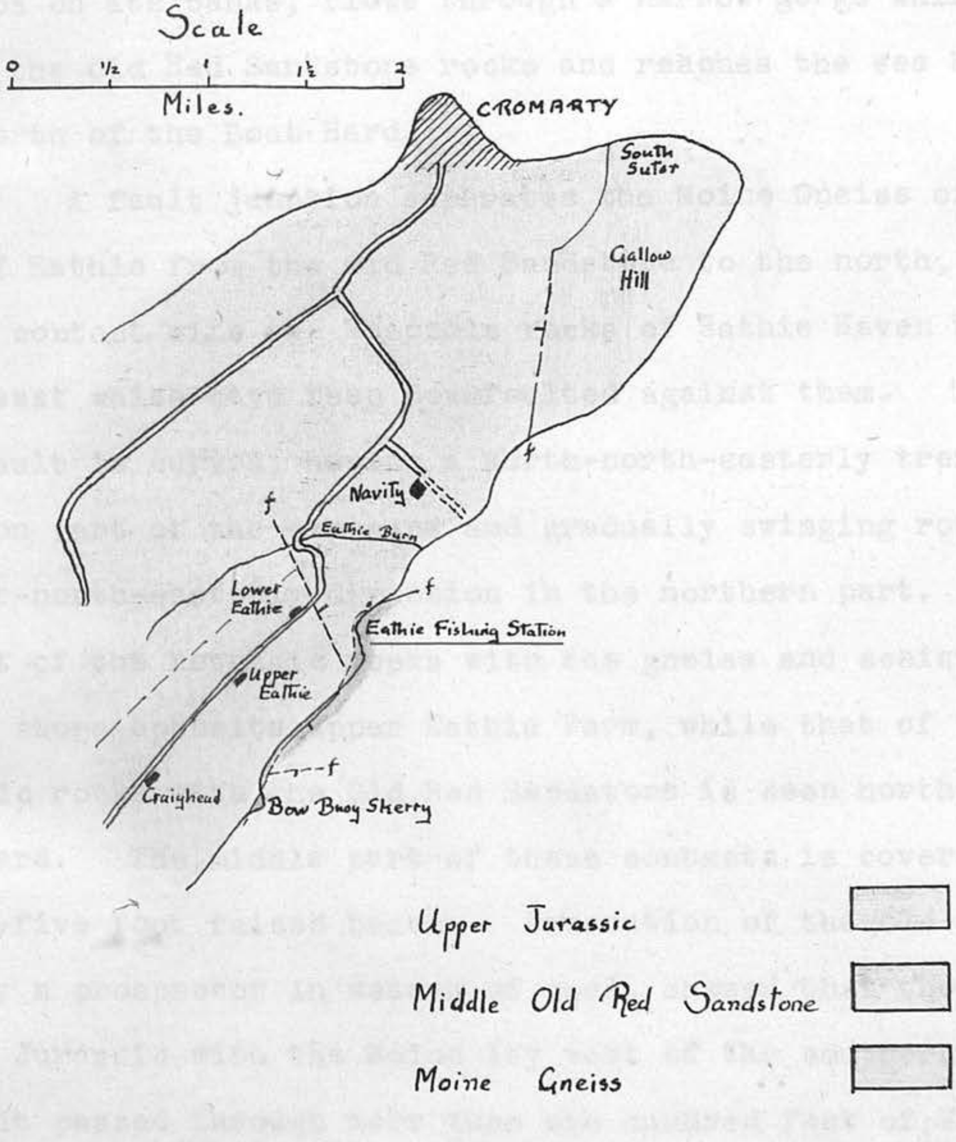
buildings which are occupied during the summer months only. From the shore the eastern slopes of the Hill of Eathie rise steeply to a height of six hundred feet making difficult direct access to the rocks below. During the summer, the old road, which winds down the face of the hill to the fishing station, is made impassable by bracken and nettles. The haven can then be reached by the shore path from Navity Farm, a mile to the north.

The Jurassic rocks are exposed on the shore for a third of a mile north of the Boat Hard and extend in a narrow strip to Bow Buoy Skerry, a rocky eminence a mile south of it. From the Boat Hard to Bow Buoy Skerry the Jurassic rocks are Lower Kimmeridgian shales and limestones. The Skerry itself, however, is a minute exposure of carbonaceous sandstone and arenaceous limestone of Upper Oxford Clay age.

Except at low tide the Jurassic exposure is covered by the waters of the Moray Firth.

The pre-Mesozoic rocks of the district are metamorphic rocks which extend northwards from Rosemarkie and probably belong to the Moine Series. Red and yellow sandstones of Upper Middle Old Red Sandstone age flank the hills formed by the metamorphic rocks - Hill of Eathie, Gallow Hill, and the Sutors of Cromarty - and /

Fig. 2.



Sketch Map to show the geological setting
of the Mesozoic rocks of Eathie Haven.

and extend in a broad syncline over the western part of the Black Isle. The Eathie Burn, famed in the writings of Hugh Miller (1841) for his discovery of the Old Red Sandstone fish-bed which outcrops on its banks, flows through a narrow gorge which it has cut in the Old Red Sandstone rocks and reaches the sea half a mile north of the Boat Hard.

A fault junction separates the Moine Gneiss of the Hill of Eathie from the Old Red Sandstone to the north, and both are in contact with the Mesozoic rocks of Eathie Haven to the south-east which have been downfaulted against them. The boundary fault is curved, having a north-north-easterly trend in the southern part of the exposure and gradually swinging round to an east-north-easterly direction in the northern part. The contact of the Mesozoic rocks with the gneiss and schist is seen on the shore opposite Upper Eathie Farm, while that of the Mesozoic rocks with the Old Red Sandstone is seen north of the Boat Hard. The middle part of these contacts is covered by the twenty-five foot raised beach. Excavation of the old shafts sunk by a prospector in search of coal, showed that the boundary of the Jurassic with the Moine lay west of the southern shaft since it passed through more than one hundred feet of Kimmeridgian shales and limestones without striking the metamorphic rocks. The /

The northern shaft, sunk near the fisherman's bothy, lies close to the line of junction, Old Red Sandstone being encountered near the surface.

HISTORY OF PREVIOUS RESEARCH

A full account of previous research on the Mesozoic rocks of the east of Scotland was written by Judd in 1873. In his account of the history of research in the Brora district Judd remarks:-

> "The coal-beds of Brora were certainly known as early as the year 1529, as is proved by an ancient Sutherland charter, which was brought under my notice by the Rev. J.M. Joass. This charter is quoted in the 'Origines Parochiales Scotiae' (vol. ii, pt. ii, p. 727)".

The earliest account of the working of the coal at Brora is contained in the 'Genealogy of the Earls of Sutherland' written by Robert Gordon in 1630.

It is not surprising, therefore, that the rocks of the Black Isle - only thirty miles south-west of the Brora coalfield - first aroused the interest of prospectors as a possible source of coal. In the 'Agriculture of Ross and Cromarty' (1810) Sir George Steuart Mackenzie wrote:-

> "Coal, the most important of all economic minerals, has not yet been properly sought for, although there are indications of the existence of this substance, sufficient to warrant fair trials, in almost every part of the Black Isle and eastern parts of Ross-shire".

In the same year two shafts were sunk in the Jurassic rocks at Eathie in the hope of striking coal seams. This attempt, however, proved unsuccessful, and geological interest in the locality was not re-awakened until sixteen years later.

In /

In 1826 the results of Sir Roderick Murchison's survey of the Jurassic strata of Sutherland, Ross and Cromarty were presented to the Geological Society of London. In his survey Murchison noted the occurrence of Jurassic rocks at Eathie which he correlated with the Liassic deposits of England.

H.E. Strickland (1840) was concerned only with the sandstone dykes which penetrate the Jurassic rocks, but he adopted Murchison's suggestion that the country rocks were of Liassic age.

The popular writings of Hugh Miller, however, made famous this supposed Lias of Eathie. In his early work 'The Old Red Sandstone' he refers to the Jurassic of Eathie, and in his subsequent volumes many interesting observations are recorded concerning the great Liassic 'burial-ground' exposed only four miles south of his native town, Cromarty. More complete references are found in 'The Fossiliferous Deposits of Scotland' (1854), 'Testimony of the Rocks' (1857), 'My Schools and Schoolmasters' (1857, 7th edit.), and 'Sketch-Book of Popular Geology' (1859). Although the occurrence of sandstone dykes forms the subject of an appendix to the 'Sketch-Book of Popular Geology', Miller's chief interest lay in the collection and description of the fauna and flora. A description of the fossil flora forms much of the final chapter of 'Testimony of the Rocks'.

Judd /

Judd (1873) records:-

> "The Rev. W. Symonds stated in 1860 that a collection of Eathie and Shandwick fossils, on being submitted to some able Cotteswold palaeontologists, were pronounced by them to be of Upper Oolitic and not of Liassic age".

The Liassic age of the strata was again questioned ten years later when J. Phillips (1870), examining a collection of fossils made by Lieut. Patterson from Eathie and Shandwick, proposed an Upper Oxfordian age for the deposits.

Only three years were to elapse before J.W. Judd (1873) presented the first part of his masterly paper on the Secondary Rocks of Scotland before the Geological Society. This survey includes an account of the physical relations of the Jurassic strata at Eathie, and a list of the fossils obtained from them. Judd confirmed the Upper Oolitic age of the deposits and correlated them with the Middle and Lower Kimmeridge of England.

In 1889 the younger Hugh Miller's mapping of the Cromarty district was published by the Geological Survey on a scale of one inch to one mile (Sheet 94). Sub-division of the Jurassic, however, was not attempted on this map.

The important monograph by Seward and Bancroft on 'Jurassic Plants from Cromarty and Sutherland' (1913) was the next contribution to the growing knowledge of the Kimmeridge of Eathie. Seward and Bancroft recorded numerous plant genera and species /

species and described some new species from this locality.

S.S. Buckman (1922-23) concluded from a study of some ammonites from the black shales of Eathie that the beds are Lower Kimmeridgian and he placed them in the Amoeboceras (spinous) hemera of his 'Rasenian' age.

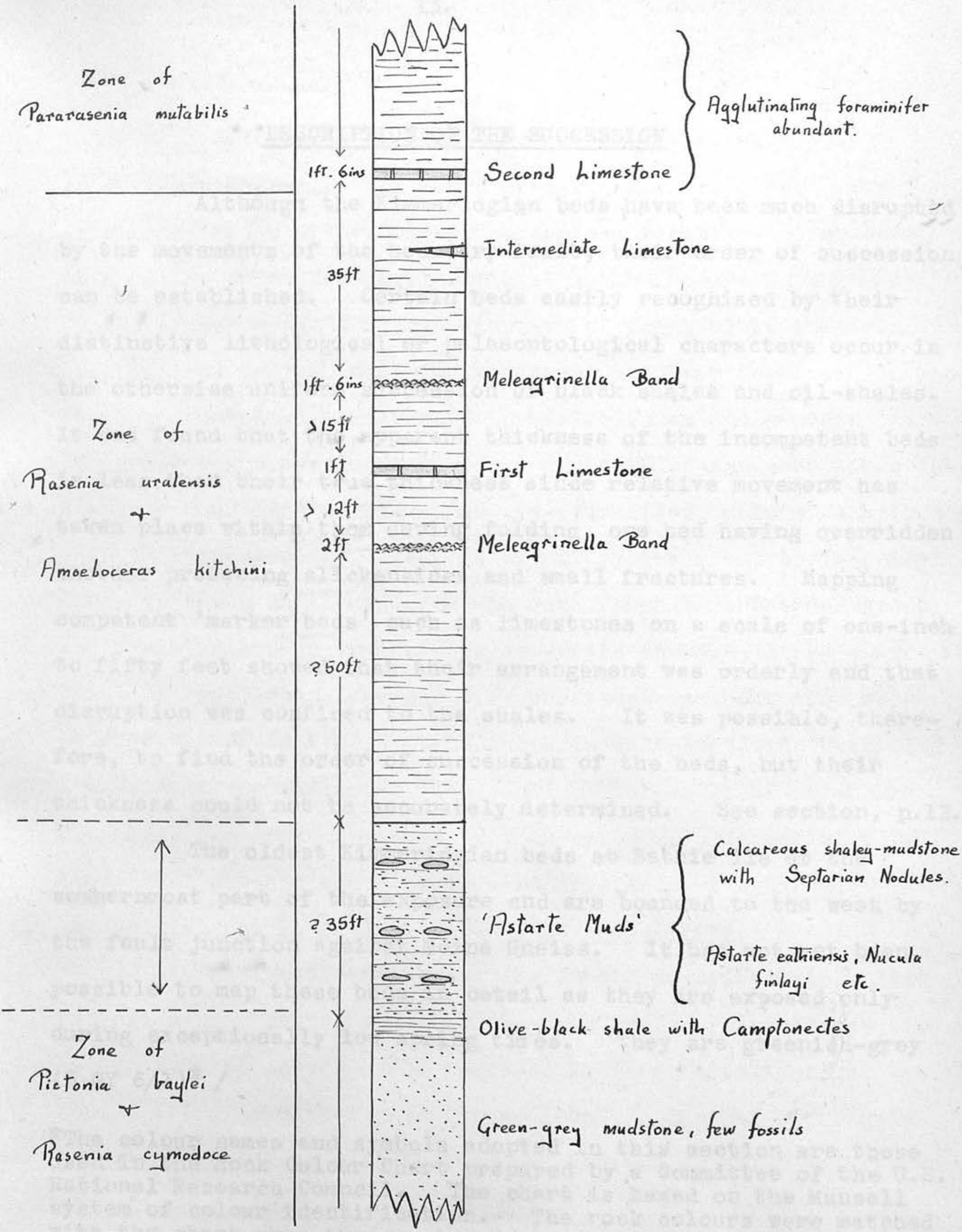
Two years later the Geological Survey published the memoir on the 'Geology of the Country around Golspie, Sutherlandshire' (1925) which contained a description of the Mesozoic rocks of East Sutherland and Ross by G.W. Lee. Twenty invertebrate species were identified in the Survey collection from Eathie, the ammonites being named by Buckman, Kitchin, and Pringle. Lee referred the bulk of the strata to the Rasenia cymodoce zone of Salfeld, pointing out that a few specimens indicated that part of the overlying Rasenia mutabilis zone is also represented. Lee's conclusions were repeated in 'A synopsis of the Mesozoic Rocks of Scotland' which he wrote in collaboration with J. Pringle in 1932.

In 1936 the Geological Survey published 'Scotland: The Northern Highlands' by J. Phemister, a volume in the series 'British Regional Geology'. Phemister gives a brief account of the Kimmeridgian of Eathie. He also mentions the Jurassic rocks of Bow Buoy Skerry which he correlates with the Studley-Horton beds of Oxfordshire, assigning them to the Lower Corallian.

This /

This thesis is based on the observations, map, and collections made at Eathie during sixteen weeks of field work. As stated in the introduction, the Jurassic rocks are exposed only at low tide, and consequently the time available each day at the exposure is limited. During July and August in 1947 the physical relations of the Kimmeridgian rocks were studied and the stratigraphical succession determined. A month at Easter 1948 was occupied in collecting fossils from the Kimmeridgian and Corallian rocks. The last visit was made in July 1948 when the sandstone injections and country rocks of the locality were mapped. Three days of this visit to the north were spent in examining the Jurassic exposures of the Brora-Helmsdale district of East Sutherlandshire, where structures referred to seismic phenomena were the subject of a detailed paper by Bailey and Weir in 1932.

IDEALISED SECTION OF THE STRATA AT EATHIE, CROMARTY.



DESCRIPTION OF THE SUCCESSION

Although the Kimmeridgian beds have been much disrupted by the movements of the boundary fault, their order of succession can be established. Certain beds easily recognised by their distinctive lithological or palaeontological characters occur in the otherwise uniform succession of black shales and oil-shales. It was found that the apparent thickness of the incompetent beds is less than their true thickness since relative movement has taken place within them during folding, one bed having overridden another producing slickensides and small fractures. Mapping competent 'marker beds' such as limestones on a scale of one-inch to fifty feet showed that their arrangement was orderly and that disruption was confined to the shales. It was possible, therefore, to find the order of succession of the beds, but their thickness could not be accurately determined. See section, p.12.

The oldest Kimmeridgian beds at Eathie lie at the southernmost part of the exposure and are bounded to the west by the fault junction against Moine Gneiss. It has not yet been possible to map these beds in detail as they are exposed only during exceptionally low spring tides. They are greenish-grey (5 GY 6/1)* /

*The colour names and symbols adopted in this section are those used in the Rock Colour Chart prepared by a Committee of the U.S. National Research Council. The chart is based on the Munsell system of colour identification. The rock colours were matched with the chart when the specimens were perfectly dry.

(5 GY 6/1) calcareous mudstones interbedded with hard grey (5 GY 7/1) limestones and bands of calcareous nodules. The limestones break with a marked conchoidal fracture and weather to a yellow crust. Cone-in-cone structure occurs in the mudstones a quarter of a mile south-west of Point 33 in the main section (see map). Here the structure has been developed in the sediments 9 inches above and 9 inches below an undisturbed bedded limestone four inches thick, for a distance of six feet along the strike. The axes of the cones are approximately 20 millimeters apart; their average height is 50 millimeters, and their apical angle is about 50°. Fossils are much rarer in these mudstones and limestones than in the younger strata above.

The green-grey muds are succeeded by about five feet of olive-black (5 Y 3/1) shale which is characterised by the abundance of Camptonectes, the small, thin shells of which are flattened and often replaced by iron pyrites. In addition to ammonites, the bed contains crushed specimens of Astarte eathiensis, Nucula finlayi and Buchia concentrica.

The immediately overlying strata comprise thirty feet of medium-grey shaley mudstone in which bands of calcareous septarian nodules occur. The mudstone is very fossiliferous, the shells lying haphazardly in the sediment. The bed is rich in Astarte eathiensis. It is the only horizon at which Gastropods have /

have been found, the largest and most common of which is Amberleya. A bed two feet thick near the base of the 'Astarte muds' which has been hardened by impregnation with calcium carbonate, yielded many perfectly preserved fossils. The ammonites obtained from this bed include Amoeboceras kitchini, Rasenia spp. of the uralensis group, and Prorasenia spp.

Except for some 'marker beds' the remaining 120 feet of the succession is made up of olive black (5 Y 2/1) shales and oil-shales. The shales are fairly coarse-grained. The oil-shale has a low kerogen content, but the occurrence of marcasite nodules indicates that sulphur is abundant. The shales contain much plant material, and where branches or stems are found the casts are surrounded by a thin layer of bright coal. The shales are richly fossiliferous throughout. The surfaces of many of the bedding planes are covered with flattened shells, the nacreous layer of which is often well preserved. Ammonites such as Amoeboceras kitchini, A. beaugrandi and Rasenia spp. are abundant, and belemnites are embedded in the shales at all angles. Crushed specimens of the fine ribbed Pararasenia cf. mutabilis are found in the black shales at the top of the succession. The most common lamellibranch is Buchia concentrica which is found throughout the succession. Ostrea cf. roemeri and O. cf. bononiae /

bononiae are also abundant. Small round fish scales with concentric striae occur throughout the shales, and occasionally aggregates of fish bones are found. Micro-separation shows that siliceous foraminifera and radiolaria are also preserved in large numbers in the black shales. Astarte, Nucula and Gastropods have not been found in any horizon above the 'Astarte muds'.

The marker beds are of two kinds: shelly horizons in the shale, and bedded limestones. Approximately fifty feet above the 'Astarte muds' there is a shaley bed two feet in thickness which is crowded with the left valves of Meleagrinella leeana. Calcareous nodules found in this bed contain unflattened casts of the shell, but specimens from the shale are crushed.

About twelve feet above the lower Meleagrinella band is the First Limestone. This is a tough, bituminous, arenaceous limestone one foot thick and light olive-grey (5 Y 5/2) in colour, which weathers to a moderate yellowish-brown (10 YR 5/4). It is rich in the crushed remains of the same species occurring in the black shales and oil shales.

A second Meleagrinella band one foot six inches thick occurs approximately fifteen feet above the First Limestone.

In the southern part of the main section there is a limestone wedging out northwards forty feet above the First Limestone /

Limestone. It is one foot thick and dark bluish-grey in colour weathering to a light olive-grey crust. It is less fossiliferous than the First Limestone and contains less sandy material.

The Second Limestone is fifty feet above the first. It is a bedded arenaceous limestone dark grey (N 3) in colour, weathering to a light olive grey (5 Y 6/1). It grades through grey calcareous flaggy beds into the black shale below. It is less fossiliferous than the First Limestone, but contains many crushed specimens of Pararasenia cf. mutabilis. Micro-sections show that it is crowded with a small, sphericle, agglutinating foraminiferon (? Psammosphaera) which is also found in the black shales above.

The complete succession, although interrupted by minor faulting, is exposed south of the Boat Hard. The relation of the rocks north of the bay with the southern succession is more obscure. It seems probable, however, that the 'Inshore Limestone' which outcrops nearest the beach in the northern exposure is the northerly extension of the First Limestone of the southern exposure. The Inshore Limestone strikes in a north-easterly direction from the Boat Hard. Its outcrop was traced for one hundred yards before it was lost beneath shore drift. It is nine inches thick, and is vertical for most of its length, but in places it has a steep south-easterly dip. The evidence that this /

this limestone is the northerly extension of the First Limestone is not confined to the lithological and faunal similarity between the limestones, but includes the field relations which they bear to other marker beds. In the southern exposure a shelly Meleagrinella band occurs twelve feet below the First Limestone and another fifteen feet above it. Meleagrinella bands also occur at the same horizons above and below the Inshore Limestone. Astarte eathiensis was found in the basal black shales exposed north of the Boat Hard which suggests that the 'Astarte muds' extend northward from the southern exposure below the twenty-five foot raised beach, but that the muds have been largely cut off by the boundary fault against the Old Red Sandstone. Fragments of the northern extension of the Second Limestone are exposed.

A plant bed was found in the southern part of the northern exposure in the black shales below the Inshore Limestone (Points 18 and 19 on the map). This is a lenticular shaped bed thirty feet long, its maximum thickness being two feet. It is composed of a mass of land-plant fragments hardened by a calcite cement. In micro-section the cellular structure of the plants is clearly seen and the different plant tissues can be determined.

TECTONICS /

TECTONICS

The Jurassic strata of Eathie lie within the zone of the Great Glen Fault and are therefore very much disrupted. Although the main wrench movements of the fault finished before the Upper Carboniferous (Kennedy, 1946), the fracture which down-faults the Kimmeridgian beds against the pre-Mesozoic strata is a later normal fault along the same line of weakness.

The Kimmeridge beds are cut by small faults in two directions. The section near the Southern Shaft is disturbed by a fault running obliquely across the shore at some 30° east of north having a downthrow on the seaward side of about 30 feet. A parallel fault zone may be present further north causing a lateral displacement of the Second Limestone seawards, and of the First Limestone from beneath the twenty-five foot raised beach to the exposure south of the Boat Hard. Small faults, most of them too small to map, make up the second group. They cross the strata at some 75° east of north.

The strike of the beds is in the form of an arc running practically north and south in the southern part of the exposure but changing to a north-easterly trend to the north. The general dip of the Jurassic beds in the area is some 20' east. The large boundary fault has distorted the beds at their contact with /

with the pre-Mesozoic rocks however, and the dip is greater than 20' over most of the exposure. The dip gradually increases towards the fault until at the contact the beds are vertical. The small fault which cuts the strata obliquely has also distorted the beds, dragging them into highly inclined positions.

Incompetent shales and competent limestones in the succession have further complicated the folding. Relative movement has taken place within the shale, one bed overriding another with the production of slickensides and small fractures, and a consequent abbreviation of the apparent thickness of the strata.

THE SANDSTONE INJECTIONS

The occurrence of sandstone injections at Eathie forms one of a number of features found in the Kimmeridgian rocks of the North-east of Scotland which have puzzled geologists for many years. These features were the subject of a detailed paper by Bailey and Weir (1932), who related the phenomena found in the Brora-Helmsdale district to submarine faulting during the Kimmeridgian. According to their interpretation the area was shaken by frequent earthquakes causing landslips from a submarine fault scarp "which spread into graded boulder beds in a manner indicating the co-operation of tunamis". Fault movements produced chasm-breccias along the fault, and earthquakes caused by these movements fissured the Jurassic rocks. Bailey and Weir (p. 458) relate what they have seen along the Ord Fault with other localities thus:-

> "The Helmsdale movement can be brought into relation "with the general contemporaneous history of Britain, more particularly with the fissuring of Kimmeridgian at Ethie on the Moray Firth and the development of the Camasunary Fault in Skye".

The present investigation is supplementary to the work of Bailey and Weir, being a further enquiry into one aspect of their more comprehensive study.

Previous /

Previous Opinion

Though the sandstone dykes of Eathie had been noted by Sir Roderick Murchison while in the company of Sedgwick in 1827, they were carefully described for the first time by H.E. Strickland in 1840. Strickland gives a description of the form and substance of the dykes, illustrating his paper with a cross section of the exposure which shows the relation of the sandstone dykes to the bituminous shales. He mentions "two dykes which are parallel with the stratification of the Lias shale", as well as others which are in no part of their course parallel to the strata which they penetrate. His opinion concerning the origin of these dykes is expressed in these words:-

> "The sedimentary structure of this rock forbids us to refer it to igneous injection from below, and notwithstanding the complete resemblance of these intrusive masses to ordinary plutonic dykes, we have no resource left but to refer them to aqueous deposition, filling up fissures which had been previously formed in the Lias shale".

Strickland suggests that tensional fissures might have been opened by the upheaval due to the emplacement of the syenitic and granitic rocks found on the East coast of Ross-shire.

Hugh Miller (1859) again described the dykes - in which he had found a poorly preserved fossil - and accepted Strickland's interpretation of their origin. He writes (p. 308):

"Let /

> "Let us but imagine - that the Lias, already existing in its present consolidated state, opened into yawning rents and fissures - as the earth opened in Calabria during the great earthquake, - and that the loose sand and calcareous matter which formed the sea-bottom at that time, borne downwards by the rushing water, suddenly filled up these rents, ere the yielding matrix had time to loose any of its steepness of side or sharpness of edge, which it could not have failed to do had the process been a slow one. The sandstone dykes, apparently Oolitic, mark, it is probable, the first operations of those upheaving agencies to which we owe the granitic wall, and which ere they had accomplished their work, may have been active during occasional intervals for a series of ages".

Judd (1872-73) summarised the observations made on the dykes and added that "at Eathie some of the most important of these pseudo-dykes run along the axes of the anticlinal folds of the contorted strata".* He agreed with Strickland and Miller that they had been filled from above, but differed from them in considering that at the time of formation of the fissures

> "the shales were already covered by beds of soft and unconsolidated sand, and that as the fissures gradually opened, the sand as gradually found its way down into the interstices".

Although later workers have described the Eathie beds, none has been directly concerned with the sandstone injections until Bailey and Weir visited the locality. In their paper of 1932 a brief description of the dykes at Eathie was given.

Description /

* Judd was mistaken in interpreting the steeply dipping Kimmeridgian strata as sharply folded. Some of the most important injections however, do follow the strike of the beds.

Description

Field Relations

Three types of injection are described:

1. Dyke-like injections which cut across the strike of the strata and are usually much branched.
2. Sill-like injections running parallel to the strike of the strata, being longer and less branched than the first type.
3. Vein injections forming complexes in association with the limestones.

Sandstone injections are found penetrating the Kimmeridgian shales throughout their exposure at Eathie. The injections were mapped by the writer on a scale of 1 inch : 50 feet and it was found that they followed two general trends one in which the strike of the injections approximates to the NE-SW strike of the shales in which they occur, a second, in which the injections strike across the shales at an angle of some 75 degrees east of north.

The cross-cutting injections are vertical and of the classic 'Kintradwell' type (Murchison, 1827). They vary in thickness from mere stringers of one or two inches across (e.g. at point 9)* to the widest injection of this type at Eathie which is three feet broad (point 30). They may be as much as 150 ft. long /

*The figures in brackets refer to numbered positions on the map. (Rear cover pocket).

long, but many minor changes of trend occur, and normally they form a complex of ramifying branches (See plates II & III).

The strike injections are developed on a much larger scale, than the cross-cutting type. The largest injection at Eathie - which runs along the high water mark in the central part of the exposure - is of this type. It varies from three to five feet in thickness and is over 200 yards in length, (See Plate V). The usual thickness of this type of injection is one or two feet, but the length varies greatly. Lengths of 100 yards or more, however, are not exceptional. This type of injection is not subject to the sudden changes in strike or the abundant branching seen in the discordant injections, but follows the strike of the shale with little or no divergence. Occasionally branching does take place (e.g. points 12 and 15) but in no case is this branching of the complex character seen in the cross-cutting injections. Not only do they conform to the strike of the shale, but in large measure they conform to the dip also. Near the high-water mark the shales dip at high angles, and are sometimes vertical. The strike injections which penetrate these shales have thus assumed a dyke-like attitude. Near low water mark however, the shales have a gentle dip of about 20 degrees and the injections found in these rocks are in the form of extensive, slightly dipping, concordant sheets which, as they simulate /

simulate the habit of intrusive igneous sills, should be termed "sandstone sills". Strickland in describing these "sills" remarks:

> "I have been more exact in describing this locality, because the identity of the specimens here exhibited with ordinary stratified sandstone is so perfect, that the clearest evidence was necessary to prove that they had been inserted into fissures of the Lias subsequently to its deposition".

This evidence is provided both macroscopically and microscopically, but in one case the field relationships alone are sufficient to prove that it is a subsequent injection. The intrusion is in the form of a transgressive sill one foot thick, which is seen in strike section (see Plate VI). It follows one horizon in the shale for 100 ft. and during the next 30 ft. it transgresses into higher zones of the shale until it reaches the base of the Upper Limestone, with which it remains in contact as far as it can be traced out to sea (see Plate VII). Where it is transgressing the shales its dip is 29°, but in contact with the limestone it is only 20°.

The discordant and concordant character may be combined in one injection. The injection at points (6) and (7) is a discordant sandstone dyke 9 inches thick; at point (8), however, the strike turns through 40° and approximates to that of the shale. Here the dyke is no longer vertical but dips with the shales: in /

in this case the dip is steeper than that of the shales. Another example is at point (21) where a vertical dyke cutting through the shales has branched on either side; these branches strike with the shales and have a dip of 33°.

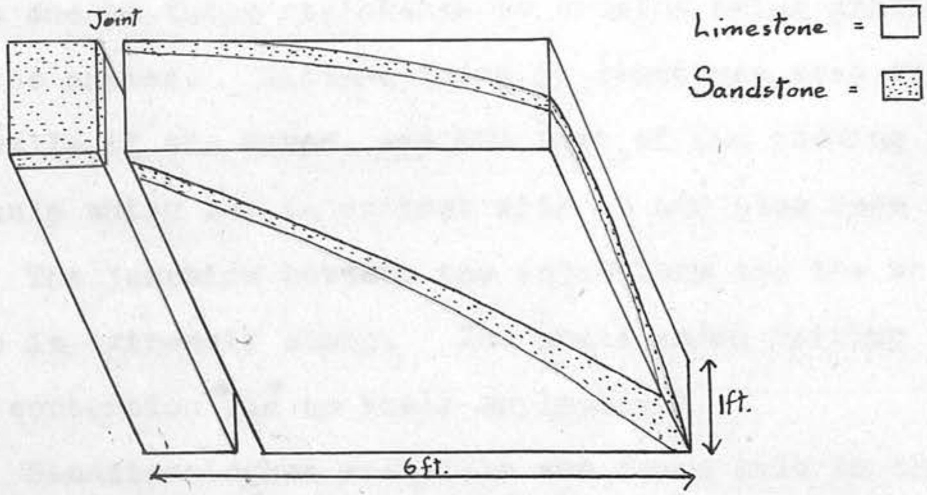
In addition to the major injections the area is penetrated by many small sandstone veins too small to be shown on the map. In the limestones, in which they form 'net-veining', these veins are especially abundant and complex.

An example of this association is found at point E. Here a thin sill-like sandstone vein occurs near the top of the Second Limestone. In some places it now forms a covering skin on the limestone due to the denudation of the formerly overlying limestone. The vein sends downwards numerous small stringers into the upper layers of the limestone. At this point the limestone is ten feet from the nearest major injection - a sandstone sill one foot in thickness.

Another small complex occurs in the Intermediate Limestone at point (31). Here a transgressive vein, three inches thick, was seen to penetrate the limestone. As it reached higher levels of the limestone its dip increased until after crossing a joint in the limestone it formed a vertical face (fig. 3).

Fig. 3.

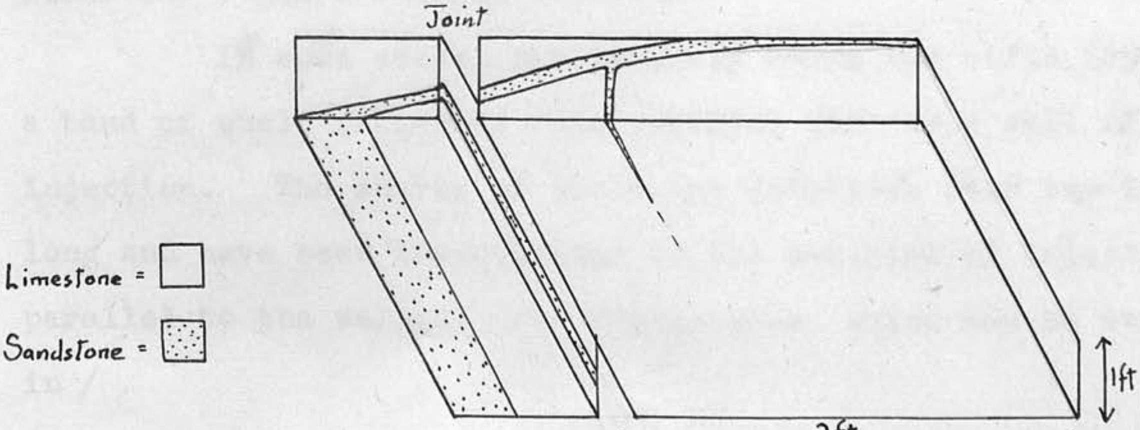
Transgressive sandstone vein penetrating the Intermediate Limestone.



A similar example was seen in the First Limestone between points (55) and (56) associated with another small vein one inch in thickness. Vertical branches were seen penetrating the limestone; one of these is illustrated in fig. 4 which also shows how a joint developed in the limestone at this point has affected the vein as well as the limestone.

Fig. 4

Sandstone veining in the First Limestone.



In many cases the dykes stand up to a height of one or more feet due to their resistance to erosion being greater than that of the shales. Slickensiding is sometimes seen on the exposed walls of the dykes, and the cast of the bedding planes of the shale which was in contact with it has also been seen.

The junction between the injections and the shale or limestone is extremely sharp. The shale shows neither lamination nor contortion due to their emplacement.

Sandstone dykes and sills are found only in the Kimmeridgean. They do not cross the faults which form the boundary between the Jurassic and the Old Red Sandstone or the Rosemarkie Metamorphics, nor are they found in the Corallian which is exposed north-east of Learny Point.

Macroscopic Description

The substance of the injections is a hard massive sandstone interrupted only by a system of transverse jointing. Bedding planes could not be detected. Throughout dykes and sills alike the texture remains constant.

In some cases, particularly among the sills (Spec. P.93), a band of shale fragments runs parallel with each wall of the injection. The shards of shale are sometimes over two inches long and have been incorporated in the material of injections parallel to the walls. The shard-bands, which may be two inches in /

in thickness, are separated from the wall by about half an inch of sandstone. The shale inclusions are soft and brittle and do not appear to have undergone alteration. One dyke, three inches thick, contains shale fragments two inches long which lie at all angles to the walls of the dyke and are not confined to definite bands.

The sandstone is very hard and in hand specimen the detrital particles, set in a calcite cement, can be easily distinguished. The cement is so abundant that the rock effervesces on the application of cold dilute hydrochloric acid. Fracture faces of the sandstone exhibit lustre mottling.

Microscopic Description

Minerals present

1. Grains. The principal mineral is quartz which far exceeds in abundance any other kind of mineral fragment. It is present in the form of perfectly clear grains which, with few exceptions, are free from inclusions. Many of the quartz grains exhibit undulose extinction.

The mineral next in order of abundance is felspar, of which orthoclase and microcline are the most common varieties. Microperthite and plagioclase are also present. The plagioclase shows fairly coarse lamellar twinning; when symmetrical extinction occurs it is that of labradorite. In micro-section the felspar /

felspar appears clear, but many of the fragments have a superficial staining caused by pale brown decomposition products.

Flakes of muscovite and biotite occur sparingly, both minerals being present as fresh flakes. Fragments of a ferruginous chert are also present.

Examination of the heavy minerals shows that colourless zircon, greenish-brown tourmaline, and black iron ores are present. The proportion of heavy minerals in the rock however, is very small.

2. Cement. The cement is wholly made up of calcite which occurs as large optically continuous crystals enclosing many sand grains. There is no euhedral development, the boundaries of the cementing crystals being very irregular and interlocking. Characteristic rhombic cleavage is developed in many of the calcite crystals forming the cement, and in some places it appears as if pressure had been exerted on a dyke causing the calcite to glide along its cleavage.

Texture

The rock is made up of equidimensional grains having an average diameter of about 0.25 mm., although fragments as small as 0.01 mm. and as large as 1.0 mm. in diameter are not uncommon. The average length of the mica flakes is 0.5 mm. but their width is /

is only 0.05 mm. The texture is uniform throughout, no bedding planes or other sedimentary structures are present.

Most of the grains of quartz and felspar are approximately equidimensional and sub-angular in shape. Some of the quartz grains however are well rounded, whereas others are angular. A few of the orthoclase crystals still exhibit their original prismatic form.

The mica flakes and elongate shale or limestone inclusions are orientated with their long axes parallel to the walls of the injection, but no other parallelism in the arrangement of the grains is apparent in micro-section.

A highly characteristic feature of the rock is that each sand fragment appears in micro-section as an isolated grain set in the calcite cement. The grains appear to have acted as nuclei for the growth of the cement. The calcite has later recrystallised to form large anhedral crystals. In most cases the contact between the grains and the cement is sharp, but the solutions responsible for the deposition of the calcite cement have acted on some of the quartz grains, dissolving the silica and replacing it by calcite. Where replacement has occurred the boundaries of the quartz grains are ragged, the grains being penetrated by small tongues of calcite. Inclusions of shale and limestone have sharp boundaries since no reaction has taken place between them and the cement /

cement. The junction of the sandstone injections with the rocks through which they penetrate is also seen to be sharp and smooth in micro-section. (Plate VIII, fig. C).

The contact of a sandstone sill and the limestone forming the roof was examined; a small crack in the limestone was found to be filled with the injected material. Sand grains had penetrated into the wider parts of the fissure, while its narrow extension was filled by crystalline calcite alone.

Pressure has been applied to some of the injections after their consolidation, as occasionally the sand grains - quartz and felspar - have been cracked and the spaces between the fragments filled with the cement. In places also, as already noted, gliding appears to have taken place along the rhombic cleavages of the calcite cement. (Plate VIII, Fig. B).

Percentage of Cement in the Sandstone

The percentages by volume and by weight of the calcite in the sandstone dyke material were determined as these data may be of use for comparative purposes.

By Volume. The volumes occupied by the grains and the cement were determined using a Shand Mechanical Stage. Twenty-two traverses were made over four micro-sections, prepared from specimens taken from different injections. Fourty-four readings were /

TABLE I.

Specimen No.	P. 100		P. 94		P.101		B.I. 39	
	Grains	Cement	Grains	Cement	Grains	Cement	Grains	Cement
Distances in millimeters covered over Grains and Cement in Each Traverse	11.25 mm.	10.41 mm.	10.29 mm.	7.14 mm.	12.93 mm.	10.88 mm.	12.20 mm.	8.52 mm.
	11.94	9.54	9.38	8.39	10.43	7.91	12.74	8.05
	12.26	9.30	9.75	8.38	5.72	5.08	12.86	8.38
	13.33	8.31	9.13	6.67	6.19	5.21	12.78	8.05
	12.92	9.17			6.40	4.36	11.91	7.92
	12.47	9.74			11.88	9.90		
	13.59	9.12						
Totals	87.76	65.59	38.55	30.58	53.55	43.34	62.49	40.92
Percent. of cement in total	42.7%		45.7%		44.7%		39.6%	

Average Percentage of Cement = 43.2

were made (Table I). Calculation from these readings showed that the calcite occupies 43.2% of the total volume of the sandstone.

By Weight. Examination of thin sections of the sandstone showed that soluble carbonates were confined to the cement. In order to find the percentage by weight of the cement in the sandstone therefore, the loss of weight by a small sample of sandstone was determined when the carbonates were dissolved in warm dilute hydrochloric acid. The specimens of sandstone used were not composite powders representative of all injections, but were taken at random from the largest dyke. Two determinations were made, the results of which showed that the weight of cement was 38.9% of the total weight of the sandstone in the first experiment and 42.9% in the second.

Age and Origin of the Sandstone Injections

The writer did not obtain enough field evidence at Eathie to enable him to date with any accuracy the time of injection of the sand into the Kimmeridgian shales. That the shale was consolidated before the sand was injected is evident, as the latter has occupied fissures in the shale, consolidated fragments of which have been incorporated in the sandstone as inclusions.

Casts of the bedding planes of the shale, which are found /

found on some of the walls of the discordant dykes, show the same dip as do the shales to-day. This might suggest that the dykes were injected after the shale had been upturned. This suggestion however, assumes that the sand consolidated without further movement of the shale, or that if subsequent movement had taken place the consolidated sandstone and shale had moved as a unit; it ignores the possibility that movement of the shale might have occurred after injection had taken place, but while the sand was still mobile.

Additional field evidence, e.g. the occurrence of boulder beds, such as can be seen in the Helmsdale-Brora region, led Bailey and Weir (1932) to suggest that the fissuring of the lower Kimmeridgian shales of that area was of seismic origin due to movements of the Ord Fault in Kimmeridgian times. This may be brought into relation with the injection phenomena of Eathie, the origin of which would probably be contemporaneous with the Brora-Helmsdale occurrences.

It seems most probable that the fissures into which sand penetrated were of seismic origin. Their field relations show that they do not occur haphazardly but are orientated in two directions which would be expected if they were the result of movements associated with earthquakes. The cause of the earthquakes may be found in dislocations along the Great Glen Fault /

Fault, the main movements of which were completed before Jurassic times (Kennedy, 1946 & 1948). This line of weakness continues to act as a source of tremors to-day, and in Mesozoic times these may well have been of a more violent nature.

Two hypotheses may be put forward regarding the mechanism by which sand was injected into the fissures in the shale: the first depending solely on the action of gravity on the sand forming the sea floor at the time of fissuring, the second depending on the mobility of water-laden sand or 'swimming-sand' which is akin to that possessed by an igneous rock-melt.

All previous workers concerned with the sandstone dykes of Eathie have supported the 'gravitational theory'. This supposes that, when the consolidated shales were fissured by earthquake action, the loose sand and calcareous matter which formed the sea floor at the time were "borne downwards by the rushing water"*, thus filling up the cracks, the loose sand being subsequently consolidated to form sandstone dykes. This hypothesis can account for most of the field evidence connected with the dyke-like injections. Fragments of shale or limestone would be torn from the walls of the fissure and the downward flow of the material would align these fragments with the mica flakes and other /

*Hugh Miller, 1859.

other elongate minerals parallel to the walls of the dyke. The larger fragments would be concentrated near the margins of the dyke since the material would be flowing more slowly at the sides than in the centre. The resulting unsorted texture of the sandstone would tend to be uniform owing to its rapid emplacement. That this has been the mode of origin of certain sandstone dykes cutting the upper part of the Kimmeridgian in the Helmsdale district has been proved by Bailey and Weir (1932, p. 452), where a dyke of shelly sandstone is in direct continuity with an overlying bed of like material.

> "It is almost certain that the sand of the dyke has been filled in from above at the time of formation of the bed with which it is united, because fifteen similar dykes occur in the shales closely underlying this particular sandstone bed, and while some can be traced into continuity with it, none seems to continue beyond it".

No direct evidence concerning the origin of the dykes is available at Eathie, since there is no overlying sandstone bed exposed which could have acted as a source for the injected sand. If a sandy bed does occur above the shales, it is hidden by the waters of the Moray Firth.

The gravitational hypothesis is not so adequate when applied to the origin of the sill-like injections which, as already noted, assume considerable proportions in the locality. Long tensional fissures having a very low dip would have to be produced /

produced in order that such injections should form. The fissures would have to be maintained for a sufficient period to enable the sand to flow into them and consolidate there. Such fissures might be produced if the rocks forming the sea floor were buckled in such a way that certain beds were arched up over the strata beneath them, or if the crest of an anticline was broken and the beds were sufficiently rigid to separate from one another. (Figs. 5 & 6).

Diagrammatic sections to illustrate hypotheses of formation of 'Sandstone Sills'.

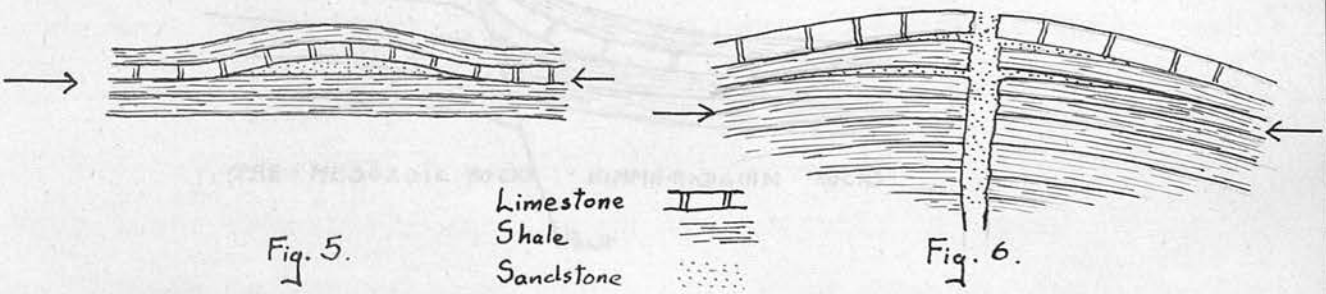


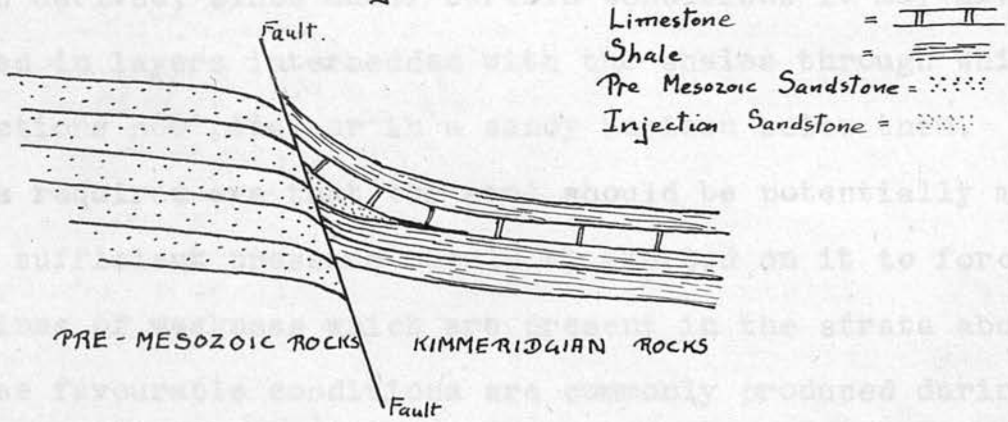
Fig. 5. Fig. 6.

It seems most unlikely that the strength and elasticity of the rocks would be sufficient for such a mechanism to operate so near the surface and on such a scale. Cracks would form in the roof rocks causing them to collapse, and owing to their greater specific gravity they would sink into the water-laden sand beneath, forcing it back into the vertical fissures. The compressional forces necessary to buckle the rocks would have thrown the /

the Kimmeridgian strata of the area into a series of sharp folds. Such folds, are not found.

Low-angled fissures might be produced by the vertical movement of a normal fault if the flexibility of the beds of the downthrown block differed widely - the upward drag exerted at the fault plane on the sinking strata separating the beds from one another. (Fig. 7).

Fig. 7.



Diagrammatic section to illustrate hypothesis of formation of 'Sandstone Sill'.

The conditions required for this occurrence are present at Eathie. The Jurassic rocks have been downfaulted against the older rocks of the area, and the rigidity of the limestones in the Kimmeridgian succession would be greater than that of the shales. Since the roof rocks of the cavity would be in a state of compression at their upper surfaces, tensional fissures could not be produced to allow the sand to enter it, and, in order that it should be filled /

filled, one end would have to be open to the surface. This hypothesis, like those already discussed, assumes that the strength of the limestone or roof rock is great, otherwise collapse would take place.

Sand occurring on the sea floor in Kimmeridgian times is not the only source from which the injected material could have been derived, since under certain conditions it may have originated in layers interbedded with the shales through which the injections now pass, or in a sandy horizon below them. The conditions required are that the sand should be potentially mobile and that sufficient pressure should be exerted on it to force it up any lines of weakness which are present in the strata above. That these favourable conditions are commonly produced during an earthquake is suggested by Prof. W.J. Mead (Shrock, 1948, p. 214):

> "The successive S and P waves deform the sand, forcing it first into loose packing then into close packing. In the latter condition interstitial water is released under pressure and forced upwards into any existing fractures, carrying sand and silt with it. If the source bed is then changed to a loosely packed condition or sheared, the water just ejected may be drawn back into the sand, but the material injected into the fracture will remain there, for under these conditions it cannot flow downward".

Injection into the Kimmeridgian strata of sand and water under pressure obviates the necessity of producing and maintaining tensional cracks and low-angled fissures, since the sand could support /

support the roof rocks after injection, downward presure being insufficient to force it back into lower strata.

The strongest evidence that the sand has intruded into the strata from beneath is the occurrence of the sandstone sills, particularly the transgressive sill already described (p. 26). In this case it would appear that the incoming sand has travelled up the bedding planes of the shale, transgressing into higher strata until the base of the second limestone was reached. Since the injected material could not breach this strong, impervious bed, it was confined to a level between the base of the limestone and the shale, except where small cracks in the limestone permitted vein-like injections to penetrate it. A similar mechanism may have caused another sill-like injection to be confined under the intermediate limestone, and may have also produced the many small veins of sandstone which penetrate it and the first limestone.

The compositions and textures of the sandstone in the dyke-like and sill-like injections are identical. It would therefore seem most likely that the material present in both types of injection has come from the same source and that the mechanism of injection has been the same in each case.

The nature of the calcite cement when examined in thin section /

section shows that it is a secondary growth in the sand and was not present as a crystal mush during injection. The grains have probably acted as centres of growth for the cement, the calcite having subsequently recrystallised. This growth would take place in the loose sand after injection and might separate the grains by pushing them apart, thus producing the texture already described, in which each sand grain appears as an isolated fragment in the calcite cement. The sandstone injections would act as pervious channels through the impervious shale for the circulation of water, which may have been responsible for the introduction of the very large amount of calcite into the sandstone.

Conclusion

1. Lines of weakness were developed in the lower Kimmeridgian strata by earth-movements during later Kimmeridgian times.

2. Sand was injected along these lines of weakness, probably under pressure from below.

3. The loose sand was consolidated after injection by the growth of the calcite cement.

PALAEONTOLOGY

Introduction

Previous research has shown that a knowledge of the nature and extent of the Jurassic faunal provinces will be of great value in elucidating the palaeogeography and climatic zones of Jurassic times. That an accurate record of the faunal assemblage in the Scottish Jurassic rocks should be obtained is of great importance, since they lie between those of Southern England, with a marked affinity to the Mediterranean faunal province, and the rocks of Boreal aspect in Spitzbergen and Greenland. Our knowledge of the taxonomy and distribution of the ammonites of the Mediterranean and Boreal faunal provinces is more complete than that of other Jurassic fossils. In the Kimmeridgian of Eathie the contrast between the Mediterranean and Boreal types is very well seen among the ammonites and the writer is of the opinion that further research will reveal the same contrast among the other groups.

The microfauna embraces at least ten genera of foraminifera and two genera of cyrtoid radiolaria. An exhaustive study of the microfauna of the area is beyond the scope of this thesis; the results obtained, however, suggest that such a study offers a profitable field for further research.

Three /

Three new lamellibranch species are described, Nucula finlayi, Melagrinella leeana, and Astarte eathiensis. Other species have been added to the faunal list of the locality. Weir's suggestion that Lima concentrica might be an 'Aucella' (Buchia) has been confirmed by a study of the structure of the cardinal area of this form. Although the lamellibranchs have not proved valuable in zoning the strata, they have been used in elucidating the order of succession and in determining the conditions of sedimentation of the beds.

Because of their zonal significance, the ammonites have been studied by several previous workers. The names of the ammonites already recorded from the locality have been revised, and six additional species have been found. Among the latter is Amoeboceras subkitchini, previously recorded in Greenland, and two species of Prorasenia.

The three belemnite species found at Eathie have already been described by other workers. The variation in Cylindroteuthis obeliscus, noted by Phillips in his description of the species, has been studied in detail. Two of the species have been re-described from specimens showing characters not seen in the holotypes.

List /

List of species obtained at Eathie:-

Cyrtocalpis sp.
Eucyrtidium sp.

? Psammosphaera sp.
Ammodiscus sp.
Glomospira sp.
Quinqueloculina sp.
Robulus sp.
Lenticulina sp.
Dentalina sp.
Nodosaria sp.
Lagena sp.
Elphidium sp.

Nucula finlayi, sp. nov.
Grammatadon sp.
Buchia concentrica (J. de C. Sow.)
Meleagrinella leeana, sp. nov.
Inoceramus sp.
Camptonectes sp.
Ostrea cf. bononiae (Sow.)
Ostrea cf. roemeri (Quenst.)
Astarte eathiensis, sp. nov.

Amberleya sp.
Cerithium sp.

Amoeboceras (A) kitchini (Salfeld)
Amoeboceras (A) subkitchini, Spath
Amoeboceras (A) sp. nov.
Amoeboceras (A) aff. rasense, Spath
Amoeboceras (A) beaugrandi (Sauvage)
Rasenia aff. orbignyi (Tornquist)
Rasenia sp. nov.
Pararasenia cf. mutabilis (J. de C. Sow.)
Prorasenia bowerbanki, Spath
Prorasenia aff. triplicata (J. Sow.)

Cylindroteuthis obeliscus (Phillips)
Cylindroteuthis spicularis (Phillips)
Pachyteuthis abreviatus (Miller)

Fish remains (jaws, scales, plates, bones and teeth)

THE MICROFAUNA

No study of the microfauna of the Jurassic rocks of North-east Scotland appears to have been made hitherto. A microscopic examination of selected specimens from the Kimmeridgian shales and limestones of the Eathie shore, however, shows that a profitable field of research lies in this direction.

Five specimens of shale from different levels in the succession were selected for preparation, their stratigraphical positions being as follows:-

B. 145.	Shale above Second Limestone	Mutabilis Zone.
B. 87.	Shale between First & Second Limestone	Cymodoce Zone
B. 175.	Shale below First Limestone	Cymodoce Zone
B. 198.	Shale at base of the 'Astarte' band	Cymodoce Zone
B. 70.	Shale below 'Astarte' band at the base of the Eathie exposure.	Cymodoce Zone

Micro-sections were also made of the First and Second Limestones.

Method of extraction of the microfauna from the bituminous shale.

Boiling.

The shale was first broken into small chips. To two or three grams of these chips an equal weight of sodium sulphate crystals was added and the mixture heated. When the shale had been soaked in the solution formed by the extraction of the water of crystallisation from the crystals, the whole was allowed to cool and formed a solid mass of salt mixed with rock fragments. The /

The growth of the sodium sulphate crystals in the pores of the rock caused the disruption of the shale and, on the addition of water, the rock disintegrated to form a fine muddy sediment. Any larger fragments remaining were easily crushed between the fingers. The sodium sulphate was then carefully removed by decantation and the sediment was washed and boiled in water for about half an hour to ensure that none of the matrix remained adhering to the tests.

Screening.

Screening was carried out using sieves of 30, 100 and 200 mesh. A jet of water was directed over the sample while the sieves were gently shaken. Most of the protozoa were obtained on the 200 mesh.

THE PROTOZOA

Description of Species

Incertae Sedis

Test free, unilocular, globular. The wall is composed of sand grains firmly cemented by calcite. No aperture is seen, but the test often has a slight neck. Diameter up to 0.50 mm.

The grain size of the agglutinated material varies, in different individuals, from coarse to exceedingly fine. The organism /

organism has shown selectivity by the incorporation of only one mineral into the test. This mineral is light brown to colourless, transparent, with a refractive index well below that of calcite; it appears isotropic between crossed nicols. It is not attacked by dilute hydrochloric acid.

Considerable variation in the proportion of cement to foreign material is shown in different individuals, those in which the foreign material is of a fine grain having more cement than those in which this material is coarse.

In most cases the tests are filled with calcite, otherwise they have been flattened.

This form, abundant in that part of the R. mutabilis zone exposed at Eathie, appears to bear affinity to Psammosphaera, though the 'chitinous' inner wall of the test associated with this genus could not be seen in any of the specimens examined. The presence of a neck in some forms would suggest that this organism is a Saccammina, but since there is no definite aperture and no 'chitinous' inner layer it cannot be given this name.

Foraminifera

Family Ammodiscidae

Ammodiscus sp. Reuss, 1861. (Plate IX Fig. A.)

Test free, composed of a globular proloculum, and a long /

long tubular undivided second chamber, coiled in a plane spiral. The whorls are fairly closely appressed; spiral sutures depressed, conspicuous especially in transmitted light. The wall is finely arenaceous with a large amount of yellowish to reddish-brown cement. Aperture simple, being the open end of the tube, slightly lunate.

Microspheric form - Proloculum small, tubular second chamber narrow, whorls numerous (over 9), fairly closely appressed. Diameter 0.17 mm.

Megalospheric form - Proloculum large, second chamber thicker than in the microspheric form, whorls less numerous (over 5), fairly loosely coiled.

Glomospira sp. Rzehak, 1888. (Plate IX Fig. B)

Test free, consisting of a fairly large proloculum and a long monothalamous second chamber winding about the proloculum and earlier coils in various planes. Wall finely arenaceous with yellow to reddish-brown cement. Aperture simple, terminal, round. Diameter 0.12 mm.

Glomospira sp.

The tubular second chamber is narrower than that of the species described above and winds many times about the proloculum. Moreover the development of the

test /

test has been emphasised in one direction to give an elliptical outline. Length of Long Axis 0.12 mm.; length of Short Axis 0.08 mm.

Family Miliolidae

(?) Quinqueloculina sp. d'Orbigny, 1826 (Plate IX Fig. C)

Test free, septate, chambers coiled about a longitudinal axis with two chambers in each coil. Test calcareous, imperforate and porcellanous. Length 0.12 mm.; breadth 0.06 mm.

Family Lagenidae

Robulus sp. Montford, 1808 (Plate IX Fig. D)

Test involute, planispiral, bilaterally symmetrical, laterally compressed, keeled. Eight chambers are visible, chambers triangular in side view, embracing to the umbilicus, suture flush with surface of the wall. Wall hyaline, smooth. Aperture situated near the peripheral margin, shape not seen due to breakage. Diameter 0.20 mm.

Lenticulina sp. Lamarck, 1804 (Plate IX Fig. E)

Test free, bilaterally symmetrical, compressed throughout. Chambers numerous (over 8), planispirally coiled, involute in the early portion, evolute in the later portion; chambers oblique /

oblique, the later ones nearly reach back to the involute portion. Sutures distinct, slightly depressed. Wall hyaline, surface smooth. Aperture terminal at outer margin of the last chamber but broken. Length 0.25 mm.

Dentalina sp. d'Orbigny, 1826 (Plate IX Fig. F)

Test free, elongate, strongly curved, oval in cross section, chambers numerous - 6 present - inflated, fairly closely appressed, uniserial, chambers gradually enlarging throughout the test. Sutures distinct, moderately deep, very oblique, directed towards the concave margin. Wall hyaline, smooth. Aperture terminal, round, radiate, submarginal on the concave side of the test.

Dentalina sp. (Plate IX Fig. G)

Test free, elongate, slightly curved, round in cross section, chambers numerous - over 4 chambers present in broken specimen - slightly inflated, closely appressed vertically, uniserial, chambers gradually enlarging throughout the test. Sutures distinct, oblique, directed towards the concave margin, shallow. Wall hyaline, smooth. Aperture terminal, round, sub-marginal on the concave side of the test.

This /

This species differs from that previously described in the following respects:

1. The test is not so strongly curved.
2. The cross section is round, not oval.
3. The inflation of the chambers is much less marked.
4. The chambers are more appressed vertically.
5. The sutures are less oblique and shallower.
6. The enlargement of the chambers throughout the test is not so rapid.

<u>Nodosaria</u> sp. Lamarck, 1812 (Plate IX Fig. H)

Test free, uniserial, rectilinear, round in cross section. Only the two latest chambers have been preserved. The sutures are distinct and deep and are at right angles to the axis of the test. Wall calcareous, hyaline. There are two types of longitudinal costae, those extending from suture to suture, intercalated with shorter ribs which extend over only the wider part of the chamber. There are also a few connecting transverse costae. The aperture is terminal, central, round. Diameter of ultimate chamber = 0.12 mm.

<u>Lagena</u> sp. Walker and Jacob, 1798 (Plate IX Fig. I)

Test free, unilocular, ovoid and flask shaped, round in /

in cross section. Wall hyaline. Surface ornamented with numerous hairs or tubercles. Aperture round, terminal, central, having an elongate external neck, and a phialine lip. The external neck is smooth. Length 0.25 mm. Maximum diameter 0.12 mm.

Elphidium sp. Montford, 1808 (Plate IX Fig. J)

Test free, planispiral, bilaterally symmetrical, chambers numerous and distinct, involute, closely appressed, embracing to the umbilical region which is filled with secondary tissue. The last two chambers are larger than the others. Wall calcareous, sutures raised, with a regular series of ridges and depressions connecting them. A single row of pores is present on each chamber, the pores being situated in the posterior portion of the depression. The aperture was not seen owing to breakage. Maximum diameter 0.41 mm.

Radiolaria

Family Cyrtoidea

Cyrtocalpis sp. Haeckel, 1862.

Complete lattice test, unilocular, helmet-shaped, having a closed capitulum and simple open basal pole. There are no radial /

radial apophyses and no appendages about the basal pole. The longitudinal axis is straight and longer than the transverse axes. The greatest diameter lies about two-thirds of the length from the apical pole. A short, simple and well developed spine is preserved in many specimens, which is set at an angle to the longitudinal axis of the test. Length 0.21 mm.

Sub Family Stichocyrtida

Eucyrtidium sp. Ehrenberg, 1847 (sensu mutato Haeckel 1862)

Complete lattice test, elongate, divided into seven or eight parts, one above the other, by radial strictures. The test becomes wider until the fourth loculum after which it gradually narrows towards the basal pole. The first loculum is conical and more than twice as long as the subsequent locula. It is as long as it is broad. Capitulum closed, basal pole open and simple. There are no radial or basal spines but there is a well developed simple apical spine continuous with the longitudinal axis of the test. Length 0.25 mm. This species is very similar if not identical with that described by Ehrenberg under the name Eucyrtidium acuminatum.

Stratigraphical /

Stratigraphical distribution.

The variation in the abundance of species and individuals of the macrofauna at different horizons of the succession is paralleled in the microfauna of these horizons.

The grey muds at the base of the succession, containing only a few specimens of lamellibranchs and cephalopods, have not so far yielded any fossil micro-organisms. The prolific 'Astarte muds' above however, rich in the number and variety of its molluscs, is rich also in foraminifera. Twelve specimens of Lagenidae comprising five genera and at least seven species were found in the sample of shale taken from this horizon. The genera present are *Robulus*, *Lenticulina*, *Dentalina*, *Nodosaria*, and *Lagena*, the most numerous being the '*Cristellaria*' and *Dentalina* types.

The black bituminous shales below and above the first limestone contain similar microfaunas though Radiolaria, abundant below the limestone, do not appear in the shales above it. Radiolaria were not seen in thin sections of the limestone. Three specimens of *Glomospira* and many of *Ammodiscus* were obtained from both horizons. Single specimens of (?) *Quinqueloculina* and *Elphidium* were found in the specimen taken from below the first limestone.

Radiolaria /

Radiolaria again become abundant in the second limestone and in the bituminous shales above. With the Radiolaria, in both the Second Limestone and the shale above, occur great numbers of an agglutinated foraminifer (?) <u>Psammosphaera</u>.

TABLE SHOWING THE STRATIGRAPHIC DISTRIBUTION OF GENERA OF PROTOZOA AT EATHIE

		B 70	B 198	B 175	B 87	B 145
Radiolaria	CYRTOCALPIS			⋇		⋇
	EUCYRTIDIUM			⋇		⋇
Foraminifera	(?) PSAMMOSPHAERA					⋇
	AMMODISCUS			×	×	
	GLOMOSPIRA			×	×	
	(?) QUINQUELOCULINA			×		
	ROBULUS		⋇			
	LENTICULINA		⋇			
	DENTALINA		⋇			
	NODOSARIA		×			
	LAGENA		×			
	ELPHIDIUM			×		

× = present ⋇ = abundant

It will be seen from the above Table that the calcareous forms, with the exception of Elphidium, are confined to specimen B.198 from the base of the 'Astarte' Band; the rest of the succession yielding only siliceous and arenaceous tests.

THE LAMELLIBRANCHIA

The following is a list of the lamellibranch species found at Eathie by the writer:-

Family NUCULIDAE, Gray.	
Genus Nucula, Lamarck.	Nucula finlayi, sp. nov.
Family PARALLELODONTIDAE, Dall.	
Genus Grammatodon, Meek	Grammatodon sp.
Family MYALINIDAE, Frech.	
Genus Buchia, Rouillier.	Buchia concentrica (J. de C.Sow.)
Family PTERIDAE, Meek.	
Genus Meleagrinella, Whitfield	
	Meleagrinella leeana, sp. nov.
Family PERNIDAE, Zittel	
Genus Inoceramus, J. Sowerby.	Inoceramus sp.
Family PECTINIDAE, Lamarck.	
Genus Camptonectes, Meek.	Camptonectes sp.
Family OSTREIDAE, Lamarck.	
Genus Ostrea, Linneaus.	Ostrea cf. bononiae (Sauv.)
	Ostrea cf. roemeri (Quenst.)
Family ASTARTIDAE, Gray.	
Genus Astarte, J. Sowerby.	Astarte eathiensis, sp. nov.

Specific descriptions

Genus NUCULA, Lamarck

Nucula finlayi, sp. nov.

Plate X Figs. A & B.

Diagnosis:- Shell small, ovate, moderately inflated. Umbones small, feebly salient, situated at the posterior margin. Carina from umbo to antero - ventral angle swollen. A strong dorsal shoulder runs anteriorly from the umbo. Dorsal margin sharp, prominent, higher than umbones. The ventral and anterior margins curve regularly with the dorsal margin to form a perfect oval, broken only by the slight concavity of the pseudo-lunule. Posterior margin truncated, short. Margins smooth. Surface ornamentation wanting except for fine concentric growth-lines.

Measurements:- The elongation of the shell was taken as the maximum distance between the umbo and the antero-ventral margin.

The height was measured between the dorsal and ventral margins at a point one-third of the length of the shell anterior to the umbones. (See Fig. 8)

Specimen	Elongation	Height	Inflation
B 121a	9 mm.	7 mm. (78%)	5 mm. (56%)
B 121b	9.5 mm.	7.5 mm. (79%)	5.5 mm. (58%)
B 121c	9 mm.	7.2 mm. (80%)	5 mm. (56%)

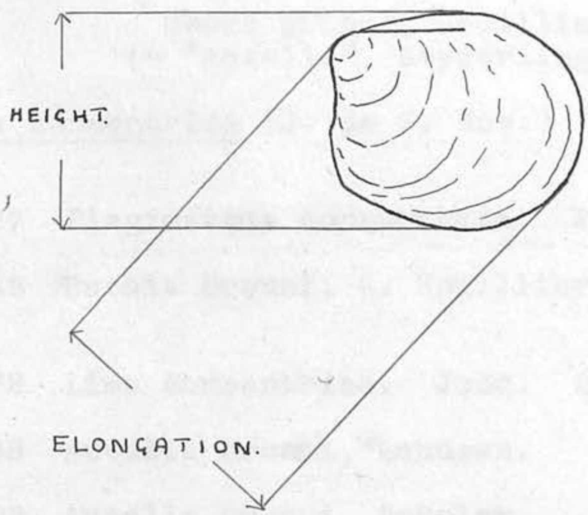


Fig. 8.

Affinities:- The dorsal margin of the Lower Kimmeridgian form from Market Rasen, Nucula obliquata, Blake (Blake 1875, p. 228 and pl. xii, fig. 5) is not sharp and elevated like that of the Eathie species, but forms a nearly straight line leading from the terminal umbos to the antero-dorsal angle. The umbones of N. obliquata are therefore 'higher' than the dorsal margin, and the outline of the shell is trigonal.

The Eathie species resembles certain Cretaceous Nuculas more closely than other Jurassic forms. The Gault specimen from Folkestone of N. albensis, d'Orb. described and figured by Woods (1899-1903 p. 24 and pl. iv, figs. 9 and 16), is very similar in shape, but is less inflated and not so perfectly oval as N. finlayi.

Genus /

Genus BUCHIA, Rouillier, 1845.
(= "Aucella", Keyserling, 1856).

Buchia concentrica (J. de C. Sow.)

Plate XIII Figs. B.

1827 Plagiostoma concentrica. J. de C. Sow. Min. Conch. VI

1848 Buchia bronni, C. Rouillier. Bull. Soc. Imp. Nat. Moscou. XXI

1872 Lima concentrica. Judd. Q.J.G.S., Vol. 29, p. 184

1888 Aucella bronni, Lahusen. Mém. Com. Geol. St. Petersburg.

1909 Aucella bronni, Sokolov. Mém. Com. Geol. St. Petersburg.

1925 Lima concentrica, Lee. Mem. Geol. Surv., East Sutherland

1930 Lima concentrica, Macgregor, Read, Manson & Pringle. P.G.A.

1932 (?) Lima concentrica, Bailey & Weir. Trans. Roy. Soc. indicated Aucella Bronni. Edin., Vol. lvii

1933 Lima concentrica, Arkell. The Jurassic Rocks of Great Britain.

1935 Buchia aff. bronni, Spath. Med. om Grønland, Bd. 99, Nr. 2, p. 53.

Non. Buchia (Aucella) concentrica (Fisch) and d'Orb.

Buchia (Aucella) concentrica (Keyserling).

Remarks:- After J. de C. Sowerby described Plagiostoma concentrica from Eathie, British workers accepted this lamellibranch as a species of the Limidae until Weir (1932, p. 464) drew attention to its marked external similarity to Aucella bronni (Rouillier). Weir remarks:-

"Comparison /

> "Comparison of a suitable range of British material of 'Lima' concentrica with figures of Aucella bronni - must convince the observer of the similarity of external morphology within the respective limits of variation. The characteristic ornament is the same in both subjects; both have thin shells, subequal, limiform valves, similar in obliquity and lateral contour, and with similar limitations in the variability of outline - a variability that is greater than usual in a Lima".

The name Lima concentrica was retained by Weir, however, since the structure of the cardinal region had not been determined.

The writer was fortunate in obtaining several well preserved specimens, and was able to excavate the cardinal regions of seven right valves and one left valve - the latter incomplete. The left valve is higher than the right, and the umbo appears to be more prominent. The cardinal area is edentulous. There is a small well developed anterior or byssal wing on the right valve which forms a sharp fold in the cardinal area. The area continues anteriorly into a deep byssal groove which separates the anterior wing from the rest of the shell. Two small and weakly developed longitudinal ridges extend posteriorly along the cardinal region from the anterior wing.

The form of the cardinal area of the left valve is imperfectly known owing to breakage. There is evidence, however, that a triangular, ligamental pit occupies a central position beneath /

beneath the umbo. The posterior wing is well developed in both valves.

The similarity of external form and the structure of the cardinal area leaves little doubt that 'Lima' concentrica and Buchia bronni are synonyms. The genus Buchia was proposed by Rouillier in 1845, eighteen years after Sowerby had described 'Plagiostoma' concentrica, and as Weir remarks (p. 465):-

> "It was inevitable therefore, that Sowerby should refer to Plagiostoma his subequivalve fossil with the limiform contour. It is strange, if Sowerby's species is really a Lima, that no forerunner can be recognised among the varied and intensively studied British Corallian Limidae".

Rouillier described the cardinal region of the shell in 1848 under the name Buchia bronni. Sowerby's specific name, however, being the older, must be retained. The form should therefore be called Buchia concentrica.

Genus MELEAGRINELLA, Whitfield.

<u>Meleagrinella leeana</u>, sp. nov.

Plate XII Figs. A,B & C.

1925 Pseudomonotis sp. nov. Lee, Mem. Geol. Surv. East Sutherlandshire.

Diagnosis:- Shell aviculoid. Left valve convex, sub-oval, slightly inequilateral. Umbo small, rising only to the margin of /

of the cardinal area. The length of the hinge line is rather more than half the length of the shell. Anterior and ventral margins regularly rounded; posterior margin obliquely truncated between the hinge extremity and the postero-ventral angle. Postero-dorsal angle obtuse. Anterior wing rudimentary. Posterior wing large, triangular, unornamented except for growth-lines, becoming slightly auriculate in large specimens. Except for the posterior wing, the shell is ornamented by fine, very numerous, sharply defined, irregular, unequal radiating ribs, interrupted at wide intervals by inconspicuous growth halts. Ribs increase in number ventrally by intercalation just below the umbo.

Except for growth-lines, the left valve of the young stage is unornamented. It is more elongate than the adult and the posterior wing is not differentiated from the rest of the shell. The umbo is salient.

Measurements:-

Specimen	Length	Height
M 3522g (3539)*	30 mm.	30 mm. (100%)
R 70 A	14.5 mm.	15 mm. (103%)
R 70 B	13 mm.	13 mm. (100%)
R 70 C	13 mm.	13 mm. (100%)
R 70 D	12 mm.	12.5 mm(104%)

Remarks:- Although the shell occurs in great numbers at certain horizons at Eathie, only the left valve has been found.

The /

*Geological Survey (Scotland) collection.

The shell is very thin, and specimens in the shale are flattened; unflattened casts, however, occur in limestone nodules. Owing to its fragility and nature of preservation, it has not yet been possible to investigate the structure of the cardinal area. The form and external characters of the shell leave little doubt as to its generic identity. The species which has the closest resemblance to the Eathie specimens is the continental, Upper Jurassic form Monotis similis, Goldfuss.

Genus ASTARTE, J. Sowerby

Astarte eathiensis, sp. nov.

Plate X Fig. C & Plate XI.

Diagnosis:- Shell ovate, slightly to moderately inflated, obliquely inequilateral. Umbones small, depressed, anteriorly directed, situated one-third to one-half of the length of the shell from the anterior margin. Escutcheon elongate. Lunule small, heart-shaped. Anterior margin rounded, more acute than the truncated posterior margin. Postero-ventral extremity sub-rectangular, varying from obtuse to acute. Ridge between umbo and postero-ventral angle moderately inflated. Ornament consists of conspicuous, irregular, and sharply defined concentric ribs. The sulci are about the same width as the ribs and are concentrically striated.

The /

The hinge is composed of two diverging cardinal teeth on both valves, the posterior cardinal tooth in the right valve being large and triangular in shape. The posterior lateral teeth appear to be fairly well developed in both valves. The adductor impressions are ovate, strongly marked and sub-equal. A strong pedal impression is present above the anterior adductor scar. The pallial line is simple, rather distant from the crenulated margin.

Measurements:-

Specimen	Length	Height	Inflation
B. 101.1	17 mm.	14 mm. (82%)	8.5 mm. (50%)
B. 101.2	23 mm.	18.5 mm. (80%)	11.5 mm. (50%)
B. 101.3	17.5 mm.	15 mm. (85%	9 mm. (51%)
B. 101.4	16 mm.	13 mm. (81%)	8 mm. (50%)
B. 101.5	10.5 mm.	9 mm. (86%)	5 mm. (48%)
B. 101.6	14 mm.	12 mm.	6.5 mm. (46%)

Remarks:- Since the cardinal area was preserved in closed shells, the structure of the hinge line was first investigated by making serial sections through the shell. The shell was ground at right angles to the cardinal area from posterior to anterior. (Diagram Front Cover Pocket.). The reconstruction of the hinge line has been confirmed by the cardinal area of a right valve which was obtained later. This specimen (B.102) although incomplete, shows the cardinal teeth and the long posterior lateral tooth.

Astarte /

Astarte eathiensis is similar in outline and ornamentation to the Corallian species Prorokia problematica (Buvignier), but the distinctive characters of the adductor impressions of Prorokia are not present in the Eathie specimen.

Genus CAMPTONECTES, Meek

Camptonectes sp.

Plate XIII Fig. A.

This species, from the black muds at the base of the Astarte band, is a small, exceedingly thin-shelled form. The auricles are unequal, a well-developed byssal sinus is present beneath the anterior auricle of the right valve, the apical angle is approximately a right angle. The shell is orbicular in outline, the height being equal to the length. Regular concentric ribbing predominates in the ornamentation of both valves and is thus distinctive. Fine radial striae interrupted by the concentric ribs are present. Owing to the extreme fragility of the shell the specimens obtained were fragmentary.

GASTROPODA

Amberleya sp. Plate XIII Fig. C.

Description:- Shell acute and regularly conical, turreted. Suture distinct, moderately deep. Whorls convex, five to six in number, the last being much the largest - about one-half the total length of the shell. Whorls ornamented with a cancellated pattern. The axial striae are developed on the second whorl before the spiral ribs and are dominant in the early whorls becoming less conspicuous in the later ones. The axial striae are more numerous in the anterior part of the whorls than in the posterior. Spiral ribbing is also developed on the second whorl and becomes dominant in the later whorls. Tubercles are developed where the axial striae cross the spiral ribs. Aperture broken. The breadth of the last whorl is about 72% of the total length of the shell which in the largest example found - a crushed specimen - was 18 mm.

THE AMMONOIDEA

Introduction

Ammonites occur in great numbers throughout the Kimmeridgian rocks at Eathie except in the grey muds at the base of the succession where they are much less abundant. A great many flattened specimens are found in the black shales and bituminous limestones, while limestone nodules in the shale yield perfectly preserved, unflattened specimens. Most of the ammonite shells lie parallel to the bedding planes. The writer was fortunate in finding in the 'Astarte muds' near the base of the succession, a band hardened by impregnation with calcite, which readily yielded many perfectly preserved, unflattened specimens.

The ammonites belong to two families, the Cardioceratidae and the Perisphinctidae. Previous research has been devoted largely to the Cardioceratids, Eathie Haven being the type locality for the following forms:-

Genus Amoebites, Buckman, 1925.

Amoeboceras (Amoebites) kitchini (Salfeld 1915).
Amoeboceras (Amoebites) pingue (Salfeld 1915).
Amoeboceras (Amoebites) akanthophorus (Buckman 1925).
Amoeboceras (Amoebites) salfeldi, Spath 1935.

Dr. Spath (1935, p. 31) considers A. akanthophorum (Buckman) to be scarcely separable from A. kitchini (Salfeld) but retains the genus Amoebites, Buckman, as a sub-genus to include /

include the tuberculate Amoeboceratids.

List of Species

The following is a list of the ammonites found at Eathie by the writer:-

Family CARDIOCERATIDAE

Sub-Family CARDIOCERATINAE

Genus Amoeboceras, Hyatt

Sub-genus Amoebites, Buckman

A. (A) kitchini (Salfeld)

A. (A) subkitchini, Spath

A. (A) sp. nov.

A. (A) aff. rasense, Spath

A. (A) beaugrandi (Sauvage)

Family PERISPHINCTIDAE

Sub-Family PICTONINAE

Genus Rasenia, Salfeld

R. aff. orbignyi (Tornquist)

R. sp. nov.

Genus Pararasenia, Spath

P. cf. mutabilis (J. de C. Sow.)

Genus Prorasenia, Schindewolf

P. bowerbanki, Spath

P. aff. triplicata (J. Sow.)

The Ammonite Names

It has been found impossible to give precise names to many of the ammonites since so few described species are available for comparison. When a form in the writer's collection bears affinity to a holotype, the specific name of the holotype is given and the characters which distinguish it from the holotype are described.

Genus AMOEBOCERAS, Hyatt

Sub-genus Amoebites, Buckman.

Amoeboceras (Amoebites) kitchini (Salfeld) Plate XIV Figs. A.& B.

Measurements:-

Specimen	B.120	B.117
Maximum diameter	80 mm.	57 mm.
Measurements taken at	78 mm.	56 mm.
Whorl height	45%	44%
Whorl thickness	34%	32%
Width of umbilicus	28%	32%
Ribs number	34 at 80 mm. 30 at 35 mm. 27 at 15 mm.	33 at 57 mm. 26 at 30 mm. ?

Remarks: The measurements given above agree in their proportions with those given by Salfeld (1915). The specimens figured and described by him, however, were only inner whorls, and the outer whorl of the largest example which he figures (Plate XX, fig. 16) - a specimen from Cromarty - is crushed.

Spath (1935) figures another specimen from Cromarty which /

which he considered typical (Plate 1, fig. 9a & b). The specimens B.120 and B.117 in the writer's collection from this locality cannot be classified with this figured specimen. Because of their greater involution and whorl height their umbilical diameters are less than that of the specimen figured by Spath. The diameter of the umbilicus of Spath's specimen is about 39% of the total diameter (calculated from the figure) whereas those of the more involute specimens are 28% and 32% of the total diameters.

Amoeboceras (Amoebites) subkitchini, Spath

Plate XIV Figs. C.& D.

Measurements:

Specimen	B.53
Maximum diameter	36 mm.
Whorl height	39%
Whorl breadth	31%
Diameter of umbilicus	33%
Ribs number	?40 at 36 mm. 42 at 15 mm. ?

Remarks:- The specimen B.53 in the writer's collection has been recognised by Spath as belonging to his species A. subkitchini which he described from a flattened specimen from Greenland (1935, p. 30 and Pl. 1, fig. 3).

The Eathie specimen, preserved in a limestone nodule, is not flattened, and measurement of the true breadth was therefore /

therefore possible. It was found to be 31% of the maximum diameter, a value which agrees with Spath's estimate of 30 to 33% for the flattened holotype. Although the Eathie specimen is not complete to the aperture, it shows that the body chamber must have occupied at least half of the outer whorl.

The suture line is well preserved (Plate XIV Fig. C.), its trace being very similar to that of Amoeboceras kitchini figured by Spath (1935 pl. 6 fig. 2).

Amoeboceras (Amoebites) sp. nov.

Plate XV figs. C.& D.

Measurements:-

Specimen number	B.122
Maximum diameter	34 mm.
Whorl height	44%
Whorl thickness	50%
Width of umbilicus	29%
Ribs number	21 at 34 mm.
	21 at 15 mm.
	19 at 5 mm.

Remarks:- The robust and involute whorls, the coarse ribs and tubercles, and the finely beaded keel are similar to those of the fragmentary holotype of Amoeboceras salfeldi, Spath. Ventrally the lateral ribs of the writer's specimen are inclined to the posterior, as are the tubercles on the peripheral margin. In this they differ from the ribs and tubercles of the holotype. The /

The lateral ribs tend to bifurcate at the lateral tubercles. Unlike A. salfeldi, the ribbing appears on the early whorls, where it is fairly coarse.

Both the ribbing and the tubercles are coarser than those of 'Cardioceras' pingue Salfeld. The beading of the keel is also very much finer. It further differs from both A. pingue and A. salfeldi in that the ribbing is not extended directly to the keel but is produced anteriorly on the periphery towards the transverse ridges of the keel in advance of the corresponding lateral ribs.

Amoeboceras (Amoebites) aff. rasense, Spath
Plate XV Figs. A.& B.

Measurements:-

Specimen	R.126	B.103
Maximum diameter	45 mm.	56.5 mm.
Whorl height	40%	41%
Whorl breadth	31%	?
Width of umbilicus	31%	32%
Ribs number	37 at 45 mm.	43 at 56.5 mm.
	32 at 25 mm.	35 at 27 mm.
	?	?

Remarks:- The ribbing on the outer whorls of most of the specimens in the writer's collection differs from that of the holotype of A. rasense, the ribs being almost straight and not reaching the elongate outer tubercles but extending over only three-fifths of the side of the whorl.

The /

The ventral ornamentation of the Eathie specimens (C.D.W. Col.) closely resembles the ornamentation of A. rasense, the outer whorls being "greatly produced in the periphery in the form of fine striae, leading up to the transverse ridges of the keel, far in advance of the corresponding ribs". They further resemble this species in the relatively coarse nature of the ribbing. One specimen (B.103) shows clearly the degeneration of the ribbing near the aperture to irregular costae and striae - noticed by Spath in A. rasense.

Genus RASENIA, Salfeld

Rasenia sp. nov.

Plate XVI Figs. A.& B.

Measurements:-

Specimen	R.78
Maximum diameter	37 mm.
Whorl height	35%
Whorl breadth	43%
Diameter of umbilicus	41%
Ribs number	17 at 37 mm. 25 at 25 mm. Ribbing is developed on the second whorl the first whorl being smooth.

Remarks:- The form whose measurements are given above resembles Rasenia evoluta (Salfeld M.S.) but differs from it in two /

two particulars. The whorl-breadth is much less than that of typical examples of similar diameter belonging to the R. involuta-evoluta group (e.g. specimens 25551 and 25550 in the Geological Survey, Collection). The Eathie form may also be distinguished from the Survey specimens by its finer ribbing, although the pattern is the same.

Genus PRORASENIA, Schindewolf

Prorasenia aff. triplicata (J. Sow.)

Plate XVII Figs. A. to D.

Measurements:-

Specimen	B.119
Maximum diameter	42 mm.
Whorl height	34%
Whorl breadth	39%
Diameter of umbilicus	45%
Ribs number	20 at 42 mm.
	16 at 25 mm.
	15 at 12 mm.

The first whorl is smooth.

Remarks:- The species Prorasenia triplicata (J. Sow.) requires redefinition since the holotype, a small disintegrating nucleus from the Lower Kimmeridgian of Portland Roads (B.M. No. 43955), is too small to show the adult characters of the species. Other labelled specimens of this species in the British Museum and Geological Survey collections are also nuclei, distinguished by the /

the triplicate branching of the ribs. No larger labelled specimens could be traced.

The Eathie specimen is complete to the apertural border, which is partly preserved. The body chamber occupies nearly three-quarters of the last whorl. The whorls are moderately depressed and evolute. The whorl section is rounded with an evenly arched venter and rounded lateral area. The first whorl is smooth. The three succeeding whorls are ornamented with fairly coarse triplicating ribs. The triplicate branching of the ribs is present over more than half the body chamber. The last two primary ribs bifurcate and alternate with a single secondary rib. The primary ribs of the inner whorls are raised to form strong primary ridges which die out before reaching the last whorl. The form may therefore be transitional between Rasenia and Prorasenia.

BELEMNOIDEA

The belemnoidea are an important part of the Jurassic fauna of the Eathie shore, members of the order being abundant throughout the whole succession in the area.

Historical

The belemnites of this locality have long been known to the naturalist. They are first spoken of as 'aeriolites', and in his youth Hugh Miller was familiar with the belemnites under this name. He formed a large collection of belemnites, most of which is now preserved in the Royal Scottish Museum. In his book 'The Old Red Sandstone' he gave a generalised description of a belemnite from Eathie, and mentions that eight or ten varieties of this order are found there. He made a more detailed study of these belemnites in another of his geological works 'Sketch Book of Popular Geology' in which he remarks:-

> "I have found considerable difficulty in classing according to their species the Belemnites of the Lias. I soon exhausted the species enumerated as peculiar to the formation by (J.S.) Miller, and found a great many others".

Hugh Miller divided his collection into two groups, the "large, massy species" Belemnites abbreviatus and B. elongatus, and the "exceedingly slim" forms Belemnites longissimus and B. penicillatus.

In /

In "A Monograph of British Belemnites, Jurassic" published by the Palaeontographical Society in 1870 Phillips describes two new species from the collection of Lieut. Patterson from Eathie and Shandwick: Belemnites obeliscus, and B. spicularis.

In a footnote to his paper 'The Secondary Rocks of Scotland' Judd (1872-3) records that:-

> "Professor Phillips in his notebook states that the inspection of Lieut. Patterson's collection in 1866 convinced him that the beds of Eathie and Shandwick belonged to two different horizons, and that peculiar long belemnites were found only at the former place. Unfortunately some specimens with a wrong locality affixed to them afterwards came into the Professor's possession, and led to the less precise statements in his account of the Belemnites in the memoir".

In the same work Judd records the two species described by Phillips, and to these he adds a third, Belemnites abbreviatus Miller.

About 1921 or 1922 B.N. Peach named and catalogued the Hugh Miller collection in the Royal Scottish Museum, and the names which appear in this catalogue - which is not yet published - are as follows:-

Belemnites (Megateuthis) sp.
Belemnites (Pachyteuthis) aff. acutus. Mill.
Belemnites (Belemnopsis) hastatus. Blainville.
" " aff. paxillosus
" " aff. caniculatus.

In the collection made by the Geological Survey for the Memoir /

Memoir of 1925, Dr. Lee recognised only the two species described by Phillips. Subsequent authors seem to have quoted this Memoir

Preservation and Occurrence

The best preserved specimens are found in the black bituminous shales of the Kimmeridgian. Guards found in this matrix clearly show growth lamellae, both in transverse and longitudinal section, except when masked by subsequent pyritisation. Those from the sandy limestones of the Kimmeridgian and from the Corallian sandstone of Learny Skerry do not show the growth lamellae, the aragonite of the guard being of a uniform, horny appearance. Exfoliation of the lamellae occurs only when the guard has been exposed to weathering.

The pro-ostracum has never been found from the shales at Eathie, but the phragmacone is often beautifully preserved in calcite, the primary spherule, walls, and septa being seen clearly in section. The anterior part of the alveolar region is so frequently broken and flattened that the measured length of the guard rarely corresponds with that of the specimen in life.

Normally straight, the belemnites are occasionally curved or 'faulted' due to the nearby growth of concretions, or to movement of the shale.

The /

The long pencil-like guards are found in the shale, limestone and sandstone at every angle to the bedding, even piercing the bedding planes at right angles.

Belemnites are most readily obtained and most abundant in the shale. Within the shale there appear to be some horizons which are more prolific than others, and their abundance seems to vary laterally along these horizons.

Morphology and Terminology

The hard parts are named and the morphology described by Phillips in his monograph. The terminology used in this monograph with some additional criteria was adopted by Professor H.H. Swinnerton in his study of the Cretaceous Belemnites (1935-6 The terms used in these two works are adopted in this thesis.

Method and Technique

1. Sectioning.

The ontogeny of a specimen must be known to the same as that of a described species before it can be given the specific name of that species, because homeomorphic adults might result from quite distinct young forms. The shapes of the larval and early growth-forms of a belemnite guard, however, are masked by later growth-laminae. It is therefore desirable that the guard should be sectioned whenever possible in order that the ontogeny /

ontogeny of the individual may be recognised.

Belemnites found suitable for sectioning were large, well preserved, uncrushed specimens which had not been pyritised. The broken fragments of a specimen separated from the matrix were re-assembled using santolite plastic. The specimen was then measured and the lateral and ventral aspects photographed. In order to make dorsi-ventral longitudinal sections - most useful as they show the profile of the apical line - it was necessary to support the guard while grinding. This was readily done by mounting the specimen in plaster of paris. The guard was placed in a paper container with the centre of the alveolus and the apex in a horizontal line, the dorsi-ventral plane being parallel with the side chosen as the grinding surface. The specimen was held in this position by pins while the plaster was poured over it, the pins being removed when the plaster had set. Grinding was carried out in three stages; begun with 400 grade carborundum, followed by 600, the centre being reached using Tripoli powder, and the ground surface being finally polished with Jeweller's Rouge. Water was used as a grinding lubricant, the santolite used in assembling the parts of the specimens being insoluble in water.

Serial cross sections of the guard show the radial relation of the apical line, and the shape of the transverse section of the young growth-laminae. Cross sections were made by grinding /

grinding the guard at right angles to the axis.

2. Determination of the Point of Maximum Inflation

The degree of inflation of some of the Eathie belemnites is much less than that of the majority of Cretaceous Acroteuthids described by Professor Swinnerton, and the determination of the point of maximum inflation, especially in the younger forms, was consequently more difficult. In such cases it was found that theerror due to parallax introduced in Swinnerton's method proved so great that no reliance could be placed on the result.

In order to overcome this error it was found most convenient to project the silhouette of the profile and dorsi-ventral views of the guard on a piece of graph-paper and trace the outline. Swinnerton's method was then employed, using the trace of the dorsi-ventral view, the parallel lines being drawn on a piece of transparent paper and placed over the trace. In addition to this determination the length and the transverse and dorsi-ventral diameters of the guard at various points along its length could be read directly from the graph-paper.

Fig. 9.

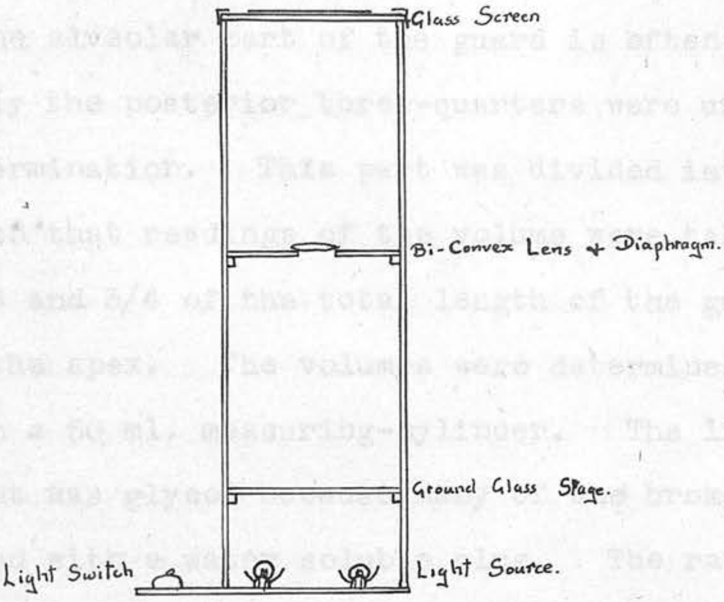


Diagram of the apparatus used for the projection of belemnite silhouettes.

3. Determination of Volume.

In the study of the variation within the species Belemnites obeliscus Phillips, it was found necessary to obtain criteria additional to those used by previous workers, the established methods of measurement not proving sufficiently accurate to define the varieties. A suitable measurement was the determination of the volume of the guard at selected points along its length. When these measurements were plotted graphically the resulting curve was a sufficiently accurate expression of /

of the shape of the guard to be used in comparative work.

As the alveolar part of the guard is often crushed and broken, only the posterior three-quarters were used for volumetric determination. This part was divided into four equal lengths so that readings of the volume were taken at 0, 3/16, 3/8, 9/16 and 3/4 of the total length of the guard measured from the apex. The volumes were determined by liquid displacement in a 50 ml. measuring-cylinder. The liquid used for displacement was glycol because many of the broken specimens were reassembled with a water soluble glue. The ratio of the volume to the length of the guard is a continuous expression, so that the five points on the graph given by these measurements may be joined to give a curve which is the graphical representation of the shape of the guard.

Description of Species

Family BELEMNITIDAE. de Blainville

Sub-Family Cylindroteuthinae. Naef.

Genus. Cylindroteuthis. Bayle, 1878.

Cylindroteuthis obeliscus (Phillips)

Within this species two distinct forms of belemnite, having unequal proportions, were recorded by Phillips. In one the adult guard is relatively longer than in the other. The long form is called here α and the short form β.

Form /

Form α Plate XVIII Figs. A & B.

Guard. Outline elongate, slender; the maximum diameter lies near the alveolar rim. Length 20 to 25 times the maximum diameter. Inflation slight, the form of the guard approximating to that of the ideal cone. Margins straight and uniformly convergent in the alveolar and stem regions, becoming slightly curved in the apical region where convergence is more rapid. The apical angle is very acute (4° to 6°).

In profile the maximum diameter is near the alveolar rim. The margins are straight and uniformly convergent throughout the alveolar and stem regions; in the apical region the ventral margin becomes slightly curved causing convergence to be more rapid.

The guard is compressed laterally so that a cross section in the alveolar and stem regions is sub-oval; posteriorly the ventral half is wider than the dorsal half. The cross section in the apical region is quadrate owing to the presence of a narrow and sometimes very shallow ventral groove, which extends along 1/3 to 1/4 of the length of the guard from the apex. Strong median ridges extend along the whole length of the guard, from a mid-lateral position in the alveolar region to the ventral surface of the apex. The apex is slightly epicentric, bearing terminal striations. The surface of the remainder /

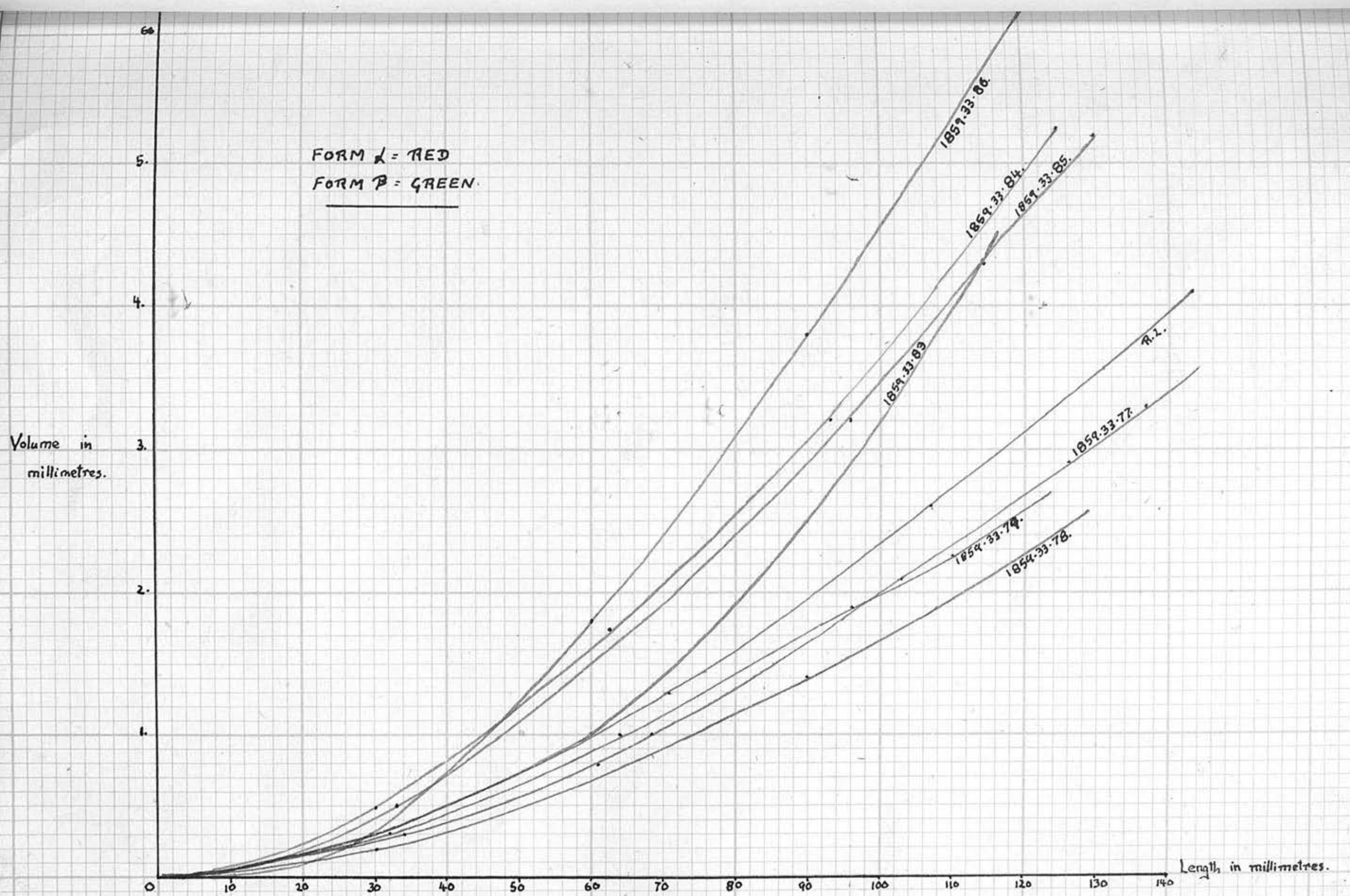
remainder of the guard is smooth. The substance of the guard varies in colour from brown to honey-yellow.

Phragmacone. The alveolus occupies between 8% and 9% of the length of the guard. The cross section is less elliptical than the sectional outline of the guard, the guard fibres being longer on the dorsal and ventral margins than laterally. The walls of the phragmacone are thin and appear to be made up of three layers, whereas the septa are composed of a single layer; the septa are very numerous. The walls possess a nacreous layer which is seen as a pearly lustre. The walls of the phragmacone diverge from the small primary spherule at an angle of between 25° and 30°. The shape of the phragmacone is conical. The apex is eccentric with a radial relation of 1:1.25.

Measurements Specimen P41

Length of guard (actual)	132.5 mm.
Length of guard (estimated)	151.0 mm.
Length of alveolar region	13.0 mm.
Length of stem region	97.5 mm.
Length of apical region	40.5 mm.
Length of axis (stem and apex)	138.0 mm.
Transverse diameter of alveolar region	6.5 mm.
Transverse diameter of apical region	4.5 mm.
Apical angle of guard	4° - 6°.
Apical angle of alveolus	26°
Radial relation of apical line at Alveolus ..	1 : 1.27
Radial relation of apical line at apical region	1 : 1.25
Length of alveolus as percentage of guard length	8.7%

The specimen of greatest length of this form is in the Hugh Miller collection and is 235 mm. in length (H.M. Col., 1859 33.82)



GRAPH TO ILLUSTRATE THE VARIATION IN
CYLINDROTEUTHIS OBELISCUS (PHILLIPS)

Length to Volume relations

Specimen		Fraction of total guard length from apex			
		3/16	3/8	9/16	3/4
a.	Vol. Length	0.3 ml. 34.3 mm.	1.0 ml. 68.6 mm.	2.1 ml. 102.9 mm.	3.3 ml. 137.2 mm.
b.	Vol. Length	0.2 ml. 30.2 mm.	0.8 ml. 60.4 mm.	1.4 ml. 90.6 mm.	2.3 ml. 120.8 mm.
c.	Vol. Length	0.3 ml. 31.9 mm.	1.0 ml. 63.8 mm.	1.9 ml. 95.7 mm.	2.9 ml. 127.6 mm.
R.2	Vol. Length	0.4 ml. 35.6 mm.	1.3 ml. 71.2 mm.	2.6 ml. 106.8 mm.	4.1 ml. 142 .4 mm.

<u>Length to breadth relations</u>

Specimen*	P.41	a	b	c	d	e	R.2
x = width of alveolar rim	7.0 mm.	9.0 mm.	8.0 mm.	9.0 mm.	9.0 mm.	9.5 mm.	9.5 mm.
y = length of guard	151.0 mm.	183 mm.	161 mm.	170 mm.	195 mm.	195 mm.	190 mm.
x/y	21.4	20.3	20.1	18.9	21.5	20.5	20.0
Specimen	R.S.M. 1859.33.82. Cephalopod Hall						
x = width at alveolar rim	11.0 mm.						
y = length of guard	235 mm.						
x/y	21.4						

*The following numbered forms (specimens a - e) are in the Hugh Miller collection of the Royal Scottish Museum:-

a = 1859.33.77
b = 1859.33.78
c = 1859.33.79
d = 1859.33.80
e = 1859.33.81

Form β Plate XVIII Figs. C & D.

Guard. The outline is elongate and conoidal, the maximum diameter lying at the alveolar rim. Length 12 to 15 times the maximum diameter. Inflation moderate, greater than in form α. Convergence of the sides is more rapid in the anterior part of the alveolar region than in the stem region where the sides are straight and convergence is regular. In the apical region they become very slightly curved as convergence becomes more rapid.

Except for the less elongate proportions just described, the remaining characters in profile and cross section are the same as for form α.

Alveolus. The alveolus occupies 15% of the length of the guard, the cross section being similar in shape to that of the guard in the alveolar region. The apical angle of the alveolus is about 20°. A nacreous layer is present on the walls, and the septa are numerous. The apex of the alveolus has a radial relation of 1 : 1.27, that is the same as for form α.

Measurements Specimen B.194

Length of guard (actual)	159 mm.	
Length of guard (estimated)	159 mm.	
Length of alveolar region	24 mm.	
Length of stem region	106 mm.	
Length of apical region	29 mm.	
Length of axis	135 mm.	(1500)
Transverse diameter of alveolar region	9 mm.	(100)
Transverse diameter of apical region	6.5 mm.	
Apical angle of alveolus	21°	
Radial relation of apical line at alveolus	1 : 1.27	
Radial relation of apical line at apical region	1 : 2.1	
Length of alveolus as percentage of guard length	15.1%	

The /

Length to breadth relations

Specimen*	B.194	f	g	h	i
x = width at alveolar rim	11.0 mm.	12.0 mm.	11.0 mm.	12.0 mm.	11.0 mm.
y = length of guard	159.0 mm.	153.0 mm.	166.0 mm.	174.0 mm.	160.0 mm.
y/x	14.5	12.75	15.1	14.6	14.6

*The following numbered forms (specimens f - i) are in the Hugh Miller collection of the Royal Scottish Museum:-

f = 1859.33.83 h = 1859.33.85
g = 1859.33.84 i = 1859.33.86

Length to volume relations

Specimen		Fraction of total guard length from apex			
		3/16	3/8	9/16	3/4
f.	Vol. Length	0.3 ml. 29.7 mm.	1.0 ml. 59.4 mm.	2.5 ml. 89.1 mm.	4.3 ml. 114.8 mm.
g.	Vol. Length	0.5 ml. 31.1 mm.	1.75 ml. 62.2 mm.	3.2 ml. 93.3 mm.	5.25 ml. 124.4 mm.
h.	Vol. Length	0.5 ml. 32.6 mm.	1.75 ml. 65.2 mm.	3.2 ml. 97.8 mm.	5.2 ml. 130.4 mm.
i.	Vol. Length	0.3 ml. 30.0 mm.	1.8 ml. 60.0 mm.	3.8 ml. 90.0 mm.	6.2 ml. 120.0 mm.

The length of the largest complete specimen seen (H.M. Col.) 1859.33.85 is 174 mm. A broken specimen in the same collection 1859.33.87 having only the apical and stem regions preserved, has a maximum width of 17 mm. If the y/x value for the specimen was that of the average, i.e. 14.31, the length of this specimen would have been 243.27 mm.

Development

The larval stages of both forms are clavate and elongate, and are hardly distinguishable from one another. The young belemnites are very much more elongate than the adult forms, but the differences in the morphological ratios become apparent when the guard is between 30 and 50 mm. in length. At this stage of growth the shape of the young form approximates to that of the adult.

Observations

The graph of the relation of volume to length shows that the shapes of the two forms α and β are distinct. Anterior to the point of maximum inflation, which is about 1/4 of the length of the guard from the apex, the margins of the form continue to diverge throughout the stem and alveolar regions much more rapidly than those of the form α. The ratios of the /

the length to the breadth at the alveolar margin are also distinct for the two forms, that for α being in the order of 20 whereas that for β is about 14.

Unfortunately there has not been enough adult material available to subject these results to analytical methods, but the results for the two characters given show that at least for the specimens examined the characters measured are distinctive. The differences between the forms are certainly not specific, although a varietal distinction might be given. Phillips in his discussion of the variation within the species suggested that the differences might be sexual. This hypothesis is perhaps supported by the fact that the forms do not appear to grade into one another, and that the differences in form become more pronounced as ontogeny proceeds. That the whole group may only bear a sexual distinction from Cylindroteuthis spicularis, as is suggested by Phillips, seems unlikely.

Until our knowledge of the group is increased by the measurement of many other adult forms, these observations can only be hypothetical, hence the word 'form' is used here in a purely morphological sense.

Cylindroteuthis λ

Cylindroteuthis spicularis (Phillips) Plate XIX.

Description of Adult

Guard. The outline is elongate. Maximum diameter at the alveolar rim remains practically the same throughout the stem region. Length of the guard 14 times the maximum diameter. Inflation moderate, sides of the alveolar and stem regions almost straight, converging with moderate rapidity posteriorly. In the apical region the sides curve slightly and converge more rapidly. The apical region is nearly four times as long as it is broad. Apical angle acute = 15'

In profile the maximum diameter is at the alveolar rim. The form of the alveolar and stem regions is sub-cylindrical, but the ventral margin is slightly more inflated than the dorsal and therefore the profile is assymetrical. In the apical region the rate of convergence of the margins is about the same as in the outline, but the ventral margin converges more rapidly than does the dorsal, causing the apex to be slightly epicentric.

The guard is very slightly compressed to form a sub-oval cross section. The dorsal surface is semi-circular, becoming slightly elevated near the apex. The ventral surface has the same width as the dorsal in the alveolar and stem regions but is slightly greater in the apical region. Anteriorly the ventral surface is sub-semi-circular, but towards the posterior /

posterior the crest of the arch becomes depressed, forming the ventral furrow which extends about a quarter of the length of the guard from the apex. Feeble lateral furrows are present but disappear towards the apex. There may be some longitudinal striae about the apex, but the rest of the guard surface is smooth. The guard substance varies in colour from brown to honey-yellow.

Phragmacone. The alveolus occupies 21.3% of the length of the guard and in cross-section is more elliptical than the guard. The primary spherule of the phragmacone is clearly seen in longitudinal section. In the largest specimen (C.D.W. Col.) there appear to be two spherical chambers at the base of the phragmacone, the posterior chamber being much smaller than the anterior one and separated from it by a fairly thick calcareous wall. The anterior chamber is somewhat flask shaped and is succeeded anteriorly by the normal septate phragmacone. The apical angle is 19°. The radial relation of the apex of the phragmacone is 1: 1.2 (Plate XX).

Measurements Specimen P.35.

Length of guard (actual)	239.5 mm.	
Length of guard (estimated)	246.0 mm.	
Length of alveolar region	52.5 mm.	
Length of stem region	140.5 mm.	
Length of apical region	53.0 mm.	
Length of axis	193.5 mm.	(1173)
Transverse diameter of alveolar region	16.5 mm.	(100)
Transverse diameter of apical region	14.0 mm.	
Apical angle of guard	15'	
Apical angle of alveolus	19°	
Radial /		

Measurements (Contd.)   Specimen P.35 (Contd.)

Radial relation of apical line at alveolus	1 : 1.2
Radial relation of apical line in apical region ..	1 : 1.1
Length of alveolus as percentage of guard length .	21.3%

Development

The embryonic guard is less elongate than that of the adult form. It is ten to twelve times as long as it is broad. The maximum diameter lies immediately behind the middle of the guard, which has a clavate form. A cylindrical shape is gradually assumed as growth proceeds, the change being completed when the guard is approximately 40 mm. long. Before the fully cylindrical form is assumed in profile, a sub-clavate form is developed, the dorsal margin having a slight concavity in the anterior portion while the ventral margin exhibits a uniformly convex curve. The general profile therefore appears to have an upward tilt posteriorly.

Observations

Two specimens (C.D.W. Col.) show variation from the normal type of this species in that the axial length is proportionately shorter. Comparative measurements are as follows:-

	Normal form	Short form
Length of guard (actual)	239.5 mm.	142.5 mm.
Length of guard (estimated)	246.0 mm.	180.0 mm.
Length of alveolar region	52.5 mm.	44.5 mm.
Length of stem region	140.5 mm.	98.0 mm.
Length of apical region	53.0 mm.	37.5 mm.
Length of axis (stem and apex)	193.5 mm.	135.5 mm.
	(1173)	(788)

Transverse /

	Normal form	Short form
Transverse diameter of alveolar region	16.5 mm. (100)	17.2 mm. (100)
Apical angle of guard	15'	
Apical angle of alveolus	19'	21'
Radial relation of apical line		
a. at alveolus	1 : 1.2	1 : 1.28
b. at apical region	1 : 1.1	1 : 1.22
Length of alveolus as percentage of guard length	21.3%	26.8%

Phillips observes of C. spicularis that "it is difficult to fix upon any definite characters by which to distinguish this belemnite from B. owenii, except the greater proportionate length of the axis and the faintness of the apici-ventral groove". In their relative proportions these two specimens approximate closely to C. owenii (Pratt) var puzosianus; the writer hesitates to assign them to this species however, as apart from the shorter guard they appear to be identical with C. spicularis, and as no other variety of C. owenii was found they have been retained within the species C. spicularis.

Specimens which are now included in this species were called B. elongatus by Hugh Miller. B. elongatus was a widely embracing species described by J.S. Miller, the specific character being - "Guard slender, tapering to a conical point". Phillips greatly restricted the compass of B. elongatus and described the new species B. spicularis to accommodate the Eathie specimens.

Genus /

Genus Pachyteuthis Bayle, 1878

Pachyteuthis abbreviatus (Miller). var. oxyrhynchus.

This species was recorded from Eathie by Hugh Miller (1859) and J.W. Judd (1872-73), but has not appeared in the relevant literature since that time. One specimen (C.D.W. Col.) appeared to belong to this species, exhibiting the primary spherule and curved eccentric apical line in longitudinal section. The apical line shows the posterior terminations of the growth laminae running across it as described by Phillips, but no actual canal is present. The specimen is probably a young form, as it also shows a distinct ventral furrow which becomes lost in older specimens. It has not assumed the ogee curvature towards the apex shown by older specimens. Miller's specimens from Eathie of this species and variety are preserved in the Royal Scottish Museum. One specimen (1859.33.88) shows the much accentuated curvature of the type remarked upon and figured by Phillips (1870, pl. 25 and fig. 86 pl. xxxv).

Conclusions

The three species of belemnites recorded from this locality are all members of the family Cylindroteuthinae. Naef. The hastate specimens assigned by Peach to the genus Belemnopsis appear to be the young forms of these three species.

The genera have a wide range in geological time, from

the /

the middle Jurassic to Lower Cretaceous, and therefore are not significant for zoning, although C. obeliscus and C. spicularis are still unique to the Lower Kimmeridge of East Ross-shire.

PALAEOECOLOGY

Although this research is not primarily a study of palaeoecology, it should nevertheless be pointed out that faunal and sedimentary changes in the succession suggest that environmental conditions were not uniform throughout the time of deposition of the strata.

The medium-grey 'Astarte muds' at the base of the Rasenia uralensis zone are poorer in sulphides than other parts of the succession. The abundance of fossils contained in the 'Astarte muds' shows that the conditions under which the mud accumulated were more favourable for marine life than the fetid conditions which obtained during the deposition of other parts of the succession. That the mollusc shells, found in the 'Astarte muds', are preserved in their environment of growth is indicated by the occurrence of shells in all stages of development, and of the closed or slightly gaping position of the valves of many of the lamellibranchs. The dwarfed nature of the benthonic forms suggests that the environmental conditions were not ideal.

The remainder of the succession is largely composed of black carbonaceous and bituminous shales. The occurrence of marcasite nodules in the shale and the replacement of the original shelly substance of many of the invertebrate remains by /

by iron pyrites, indicates that the sediments may have been deposited under fetid conditions from poorly circulating water. The nekton survived the oncoming of black mud conditions, but many of the benthonic species, abundant in the 'Astarte muds', were killed.

The left valves of Meleagrinella leeana, which make up the shelly bands found interbedded with black shale above and below the First Limestone, were probably washed into the area by marine currents. Although young forms are found in these bands, it is improbable that Meleagrinella grew at Eathie since the valves are often broken and right valves have not been found. The curved left valves may be transported by water currents more easily than the flat right valves which would account for the extremely restricted occurrence of right valves in an area of deposition such as Eathie.

Deposition throughout the Kimmeridgian appears to have taken place on a tranquil sea bottom of moderate depth which, as is suggested by the abundance of land plant remains, cannot have been far from land. Muddy conditions predominated, but the occurrence of arenaceous limestones interbedded with the black shales shows that clearer water conditions existed while these horizons were being deposited.

STRATIGRAPHICAL AND PALAEONTOLOGICAL CONCLUSIONS

The Age of the Strata

Ammonites, abundant throughout the strata at Eathie, serve to fix the age of the deposits. The Rasenia cymodoce zone of Salfeld (1913, p. 428) includes the strata from the base of the exposure to the black shales immediately below the Second Limestone. The occurrence of the fine-ribbed Pararasenia cf. mutabilis in the Second Limestone and in the black shales above it indicates that the lower part of the overlying P. mutabilis zone is represented.

Using Spath's Ammonite Zoning of the Eo-Kimmeridgian (1935, p. 74) it is found that three zones are present at Eathie. The whole of the Rasenia uralensis and Amoebites kitchini zone appears to be represented and comprises most of the succession. The presence of Prorasenia spp. near the base of the 'Astarte muds', however, suggests that the grey muds occurring at the base of the succession, the black shales with Camptonectes, and possibly the lower part of the 'Astarte muds' are of pre-uralensis age, and would therefore be included in the zone of Pictonia baylei and Rasenia cymodoce. As with Salfeld's classification, the Second Limestone and the black shales above it fall within the Pararasenia mutabilis zone.

The /

The occurrence in the lower part of the 'Astarte mudstones' of Prorasenia bowerbanki and Prorasenia aff. triplicata with forms bearing affinity with the Rasenia uralensis group is peculiar. This assemblage has been recorded previously only in the Abbotsbury Iron Ore of Dorset (Arkell, 1937). Prorasenia is characteristic of the Lower Kimmeridge Clay of the Wootton Bassett horizon, which is older than the horizon exposed at Market Rasen in which Rasenia spp. of the uralensis group are common, but in which Prorasenia has not been found. It was suggested by Spath (1935, p. 72) that "In a slowly accumulating deposit like the Abbotsbury Iron Ore, the separation of these elements may be very difficult". It is improbable, however, that the 'Astarte mudstones' at Eathie were of slow accumulation, the green-grey shaley muds being of fairly coarse texture. It appears, therefore, that the Prorasenia and Rasenia uralensis elements are not strictly successive. There is probably an intermediate horizon where both are present.

Stratigraphical Comparisons

Corals, echinoderms and brachiopods, which are well developed in the three basal zones of the Eo-Kimmeridge in Sutherland, have not been found at Eathie. Lee (1925, p. 115), in noting the absence of these groups in the Eathie beds, remarks that /

that "whether the difference is to be attributed to physical conditions or to the incompleteness of the section cannot be ascertained". In the light of later research by Bailey and Weir (1932, pp. 443 and 457), however, it seems probable that the difference is due to physical conditions. Bailey and Weir did not find brachiopods, sea-urchins or corals in the black shales. They were present, however, in the sandy matrix of the 'boulder-beds'. This observation with additional seismic evidence, led them to conclude that in Kimmeridgian times the submarine fault-scarp of the Loth-Helmsdale fault "separated a comparatively shallow water facies, characterised by rounded pebbles, sand, Rhynchonella, Terebratula, Ostrea, sea-urchins, corals &c. from a comparatively deep-water facies, characterised by mud, debris of land-plants, ammonites &c.". They further supposed that contemporaneous movement of the fault caused landslips in which unconsolidated Mesozoic rocks from the Upthrow side, along with Old Red Sandstone boulders from the fault-scarp, spread over the deeper water muds below in the form of graded boulder-beds. The absence of boulder-beds at Eathie shows that similar 'fault-scarp' conditions did not exist in the Cromarty area. The similarity of the black-shale facies that existed on the downthrow side of the Loth-Helmsdale fault at Kintradwell with the black shale facies at Eathie, suggests that both have accumulated under similar ecological conditions.

Deposits /

Deposits of Kimmeridgian age have been described from the islands of Skye (M. Macgregor, 1934) and Mull (J. Pringle and W. Manson, 1933). The fossil assemblages from these localities in which Cardioceratid and Perisphinctid ammonites predominate, are very similar to these obtained from the black shales of the east coast of Scotland.

The Eathie fossils, apart from those newly described by the writer, have been compared or identified with characteristic Mediterranean forms found in southern England, or with Boreal forms abundant in the Kimmeridgian beds of Spitzbergen and Greenland. The contrast between Mediterranean and Boreal types is well seen in the ammonites. Rasenia, Prorasenia, and Pararasenia, which form part of the unbroken Perisphinctid succession in the Mediterranean province and predominate in southern England, are well developed at Eathie. Amoeboceras, a genus widely distributed in the Arctic and a characteristic member of the Boreal province is also abundant at Eathie.

Cylindroteuthis obeliscus and C. spicularis are the most numerous belemnites at Eathie, Pachyteuthis abbreviatus is rare. Northern characteristics therefore predominate in the belemnite assemblage, since the genus Cylindroteuthis is of Boreal affinity.

Of the lamellibranchs, many of which are new species, the most interesting is Buchia concentrica. Buchia is a widely distributed northern form of Boreal aspect.

The /

The mixed Boreal-Mediterranean assemblage at Eathie, occurring as it does in an intermediate geographical position between the faunas of true Boreal and Mediterranean aspect, has been used as evidence in support of the hypothesis - favoured by Perrin Smith (1904), Spath (1932 &c.) and others - that the formation of biological provinces is influenced by ocean currents and climate, and that the faunal gradation between the Mediterranean and Boreal provinces may be due to the existence of climatic zones in Jurassic times. Spath (1935, p. 76) remarks, however, that "We know from the distribution of the cephalopods and other mollusca, which could not have lived in an ice-covered sea, as much as from the northward extension of the range of corals, that in the Upper Jurassic the climate must have been warmer than at the present day". It is the writer's opinion that further study of the lesser known groups would reveal a similar faunal gradation. For this purpose a widespread study of the foraminifera of the Jurassic would be particularly valuable since - as Glaessner remarks (1945, p. 190) - "It has become clear to students of foraminiferal ecology that the most important factor controlling the distribution of living foraminifera is not depth but temperature.

THE BOW BUOY SKERRY

Bow Buoy Skerry is one mile south-west of Eathie Haven, and can be reached only at low spring tides. It is a minute exposure of Jurassic strata which have been downfaulted against the metamorphic rocks of Rosemarkie. The fault runs between the skerry and the beach where, fifty feet to the west, the metamorphic rocks outcrop. The Jurassic rocks are visible for only some two hundred feet along their strike. They are made up of hard arenaceous limestones and carbonaceous sandstone, and have a very steep east-north-easterly dip. The rocks are severely slickensided owing to their proximity to the fault.

Examination of the arenaceous limestone in microsection shows it to be oolitic. Angular quartz fragments are accompanied by less abundant felspar.

The carbonaceous sandstone is very similar in appearance to that which outcrops at Ardassie Point, Brora.

The following fossils were collected from the skerry:-

Cucullaea contracta, Phillips.
Placunopsis radiata (Phillips).
Chlamys (Aequipecten) cf. fibrosus (J. Sow).
Pinna sp.
Pholadomya aff. aequalis, J. Sow.
Cardioceras (Cardioceras) cf. costicardia, S. Buckman
Cardioceras sp. (Fragment of large body whorl, smooth bearing only faint striae.)
Belemnites sp.

The most common fossils at Bow Buoy Skerry are small

specimens /

specimens of two varieties of Cucullaea contracta. An oblique form, having a postero-dorsal angle of 130° was found. It is similar in outline to the specimen from the Trigonia perlata beds of Highworth drawn by Arkell (1929, p. 44, fig. 3) and is of the type of Phillips' original species C. elongata (1829, pl. iii, fig. 33). The most common type at this locality, however, is the less elongate form figured by Phillips as C. contracta (1829, pl. iii, fig. 30). It closely resembles C. ardassiensis, Arkell, in its small size and lack of surface ornamentation, but it cannot be included within this species since it lacks a median valley.

Unlike the giant specimens found at Ardassie Point the Placunopsis radiata from Bow Buoy Skerry is of normal size.

Unfortunately the ammonites which were found were in a poor state of preservation, being fragmentary and crushed. In addition to Cardioceras cf. costicardia the Geological Survey have obtained C. costellatum and C. aff. cardia from this locality (Phemister, J., 1936, p. 82). This suggests that the Bow Buoy Skerry beds are of the same age as the Studley-Horton clays of Oxfordshire which belong to the Costicardia sub-zone of the Cordatus zone of the Upper Oxford Clay (Arkell, 1947).

THE QUATERNARY

The sandy boulder-clay, which forms a steep bracken-covered slope rising from the landward margin of the twenty-five foot raised beach to a height of some 300 feet, testifies to the glaciation of the area in Quaternary times. Erosion has resulted in the disection of the boulder-clay to form steep-sided gullies, beyond which small alluvial cones extend over the twenty-five foot raised beach. The fisherman's cottage at Eathie Haven is built on the margin of one of these cones.

Deposits of the hundred-foot raised beach, common in the Moray Firth region, are not seen at Eathie. A rocky terrace occurs at the level of the hundred-foot contour on the headland which separates the Boat Hard Bay from the bay to the south. The terrace, which is bracken covered, appears to have been cut in the Moine Gneiss, possibly in pre-glacial times.

The twenty-five foot raised beach is well developed, and extends along the coast throughout the area, attaining its greatest width at Bow Buoy Skerry and on the northern shores of Boat Hard Bay. At Learny Point, south of the Bow Buoy Skerry, sea-stacks of Moine Gneiss penetrate the raised beach and a sea-cave at the twenty-five foot level is a further relic of this ancient shore-line.

SUMMARY OF RESULTS

1. The Jurassic rocks at Eathie Haven have been downfaulted against the pre-Mesozoic rocks with which they are in contact to the west.

2. With the exception of the rocks at Bow Buoy Skerry, which are of Upper Oxford Clay age, the Jurassic rocks exposed at Eathie are Lower Kimmeridgian. Three successive ammonite zones have been identified in the Kimmeridgian deposits: the zones of Rasenia cymodoce and Amoeboceras kitchini, Rasenia uralensis, and Rasenia pseudomutabilis.

3. The presence of 'marker beds' in the Kimmeridge shales enables them to be mapped and their stratigraphical succession determined.

4. Lines of weakness were developed in the Kimmeridgian strata by earth-movements during late Kimmeridgian times. Sand was injected along these lines of weakness, probably under pressure from below. The loose sand was consolidated after injection by the growth of calcite cement to form 'sandstone dykes' and 'sandstone sills'.

5. A rich microfauna is present in the Kimmeridgian rocks, ten genera of foraminifera and two of Radiolaria having been found.

6. /

6. Eight lamellibranch species were identified in the Kimmeridgian rocks, three new species being described. J. Weir's suggestion that Lima concentrica (J. de C. Sow) might be a synonym for Buchia concentrica (Rouillier) is confirmed.

7. One horizon of the Kimmeridgian yielded three species of gastropoda.

8. Ten ammonite species were obtained from the Kimmeridgian rocks, five Cardioceratids and five Perisphinctids. Prorasenia spp. were found in association with species of the Rasenia uralensis group.

9. The Kimmeridgian yielded three Belemnite species including Pachyteuthis abbreviatus.

10. The Kimmeridgian rocks appear to have been deposited in a tranquil sea of moderate depth which cannot have been far from land.

11. The presence of a mixed Boreal and Mediterranean faunal assemblage at Eathie in north-east Scotland suggests that a sea connection existed between the Boreal and Mediterranean provinces, the gradual change of aspect of the ammonite assemblage between southern England and Greenland being due to the influence of climatic zones.

ACKNOWLEDGMENTS

The research which is described in this thesis was carried out under the supervision of Professor Holmes and Dr. A.M. Cockburn, to both of whom I am indebted for advice, encouragement and constructive criticism. I also wish to express my thanks to Mr G.Y. Craig, who accompanied me on my last visit to the north, for many helpful suggestions.

The research was carried out during the tenure of a Van's Dunlop Scholarship awarded by the University of Edinburgh. I am indebted to the University of Edinburgh for a further grant to aid research.

I am under obligation to Dr. L.F. Spath and Dr. L.R. Cox of the British Museum (Natural History) and to Dr. A.C. Stephen and Mr Turnbull of the Royal Scottish Museum for their assistance in giving me access to museum collections.

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Protozoa

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PLATES

PLATE I.

View of Eathie Haven and the Boat Hard from the north.

PLATE II.

'Sandstone Dyke'. Cross-cutting injection penetrating black-shale, westward view between points 7 and 5.

PLATE III.

'Sandstone Dyke'. Cross cutting injection penetrating the First Limestone at point 7.

PLATE IV.

Strike injection. Largest sandstone injection at Eathie exposed near high water mark. Outcrop at point 3.

PLATE V.

Strike injection. Largest sandstone injection at Eathie exposed near high water mark. Outcrop between points 5 and 12.

PLATE VI.

'Sandstone Sill'. Transgressive sandstone sill penetrating black-shale. View towards the north-west from Second Limestone at point G.

PLATE VII

'Sandstone Sill'. Sandstone sill beneath the Second Limestone at point G.

PLATE VIII.

Fig. A. Photomicrograph of sandstone injection. Sandstone 'Sill' beneath Second Limestone. Crossed nicols, X 15.

Fig. B. Photomicrograph of sandstone injection. Sandstone 'Sill' beneath Second Limestone showing fragmentary quartz grains. Crossed nicols, X 15.

Fig. C. Photomicrograph of the junction of sandstone 'Sill' and intermediate limestone, showing calcite vein intruding the limestone above. Crossed nicols, X 15.

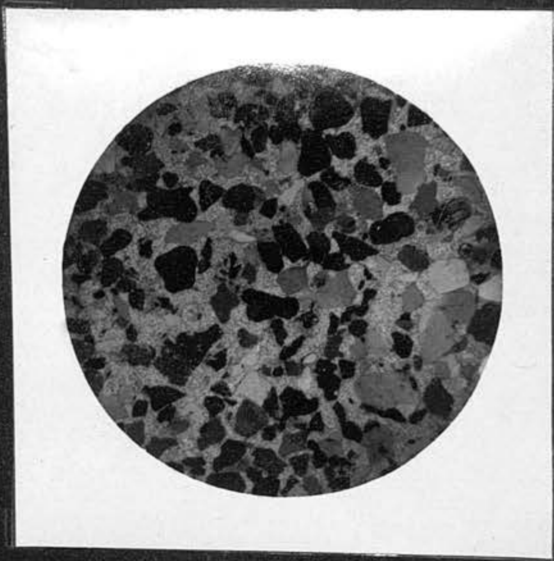
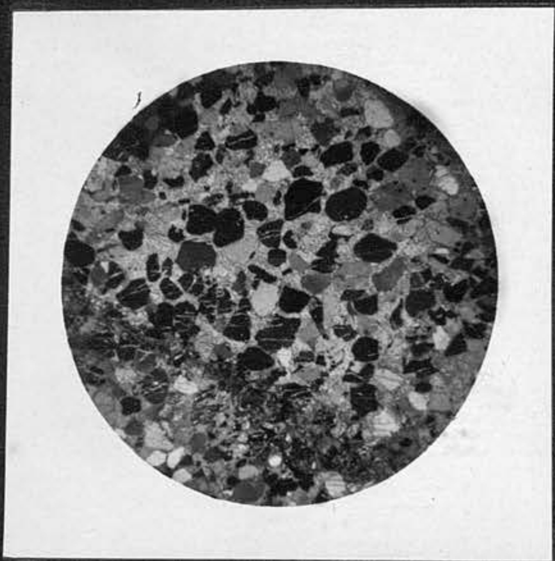


Fig. A.



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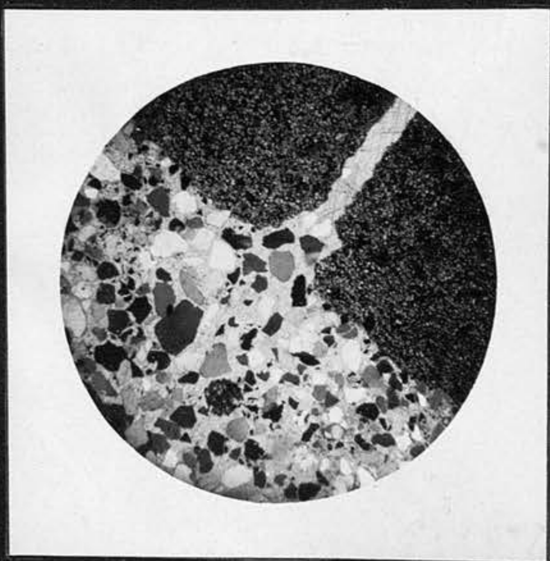


Fig. C.

PLATE IX.

The figures comprising plate IX are Camara Lucida drawings or drawn from photographs.

Fig. A. Ammodiscus sp. (Microspheric form) X 110.

Fig. B. Glomospira sp. X 100.

Fig. C. (?) Quinqueloculina sp. X 160.

Fig. D. Robulus sp. X 70.

Fig. E. Lenticulina sp. X 85.

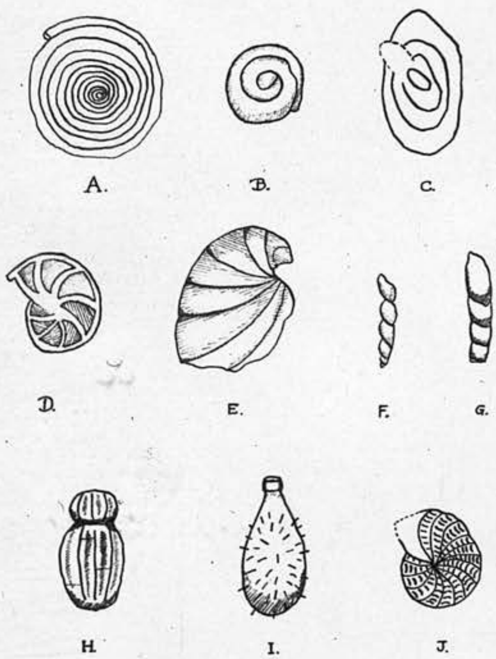
Fig. F. Dentalina sp. X 30.

Fig. G. Dentalina sp. X 30.

Fig. H. Nodosaria sp. X 70.

Fig. I. Lagena sp. X 70.

Fig. J. Elphidium sp. X 35.



FORAMINIFERA

PLATE X.

Fig. A. Nucula finlayi, sp. nov., lateral view. X 2.
Specimen B.121.C. C.D.W. Col.

Fig. B. Nucula finlayi, sp. nov., posterior view X 2.
Specimen B.121.C. C.D.W. Col.

Fig. C. Astarte bathiensis, sp. nov., lateral view,
natural size. Specimen A.4. C.D.W.
Col.

Fig. A.

Fig. B.

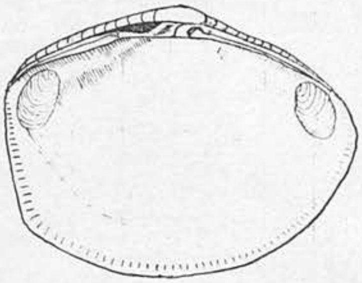
Fig. C.

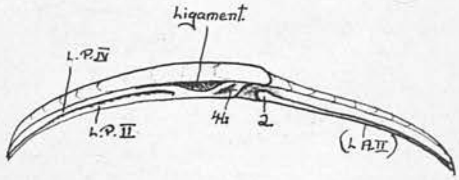
PLATE XI.

Reconstruction of the interiors of the left and right valves of Astarte eathiensis with dentition formula.

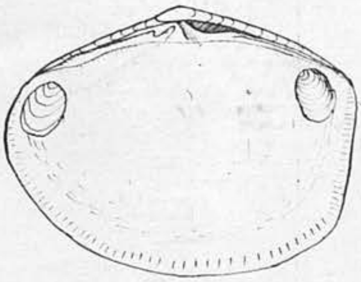
Reconstruction of Specimen B.101.D.

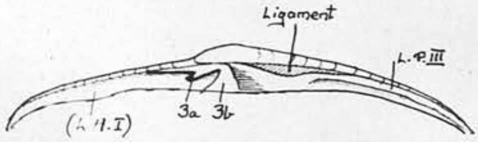
ASTARTE EATHIENSIS.





LEFT VALVE.





RIGHT VALVE.

Formula for Hinge

Right Valve. (L.A.I)?	3a : 3b :	L	L.P. III
Left Valve. (L.A.II)?	2 : 4b	L	L.P. II.

PLATE XII.

Fig. A. Meleagrinella leeana, sp. nov. Left valve of large specimen showing auriculate nature of the wing. Natural size. Specimen M 3522S (3539), Scot. Geol. Surv. Col.

Fig. B. Meleagrinella leeana, sp. nov. Left valve of adult. X 2. R.78, C.D.W. Col.

Fig. C. Meleagrinella leeana, sp. nov. Left valve of young-stage. X 3. R.70 D., C.D.W. Col.

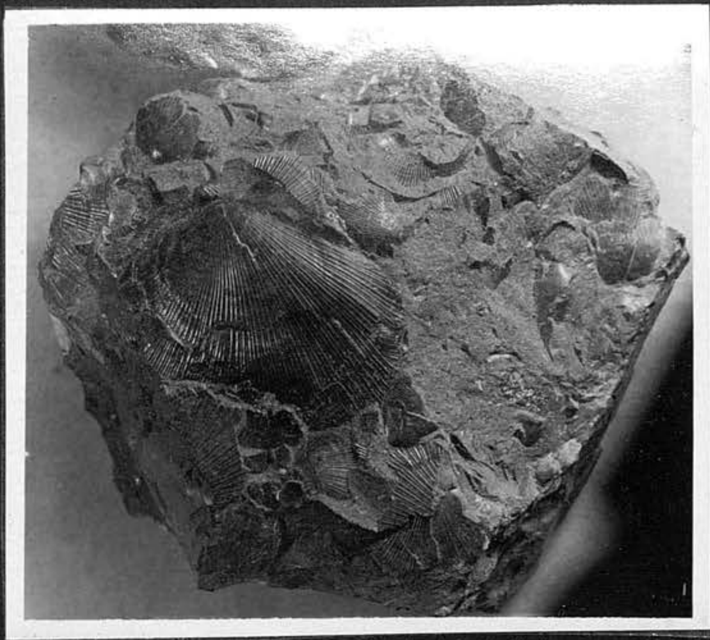


Fig. A.

Fig. B.

Fig. C.

PLATE XIII.

Fig. A. <u>Camptonectes</u> sp. X 2. Specimen B 199 A, C.D.W. Col.

Fig. B. <u>Buchia concentrica</u> (J. de C. Sow). Internal view of right valve showing hinge structures. X 4. Specimen R.26, C.D.W. Col.

Fig. C. <u>Amberleya sp</u>. X 2. Specimen B. 128 A., C.D.W. Col.

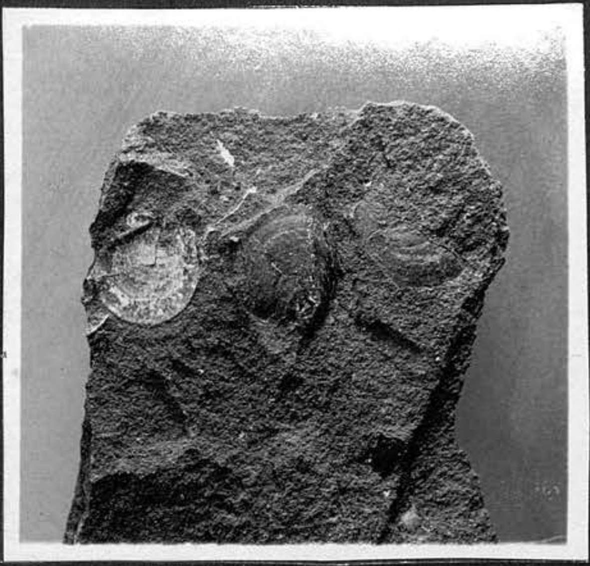


Fig. A.

Fig. B.

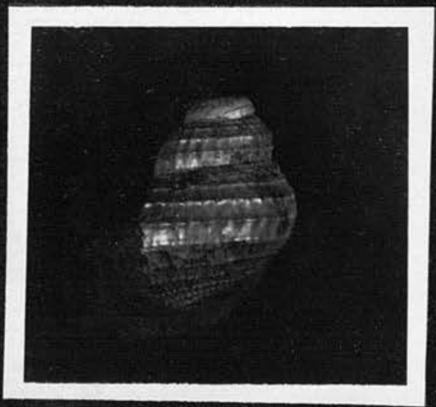


Fig. C.

PLATE XIV.

Fig. A. Amoeboceras (Amoebites) kitchini (Salfeld). Lateral view, natural size. Specimen B.120, C.D.W. Col.

Fig. B. Amoeboceras (Amoebites) kitchini (Salfeld). Ventral view, natural size. Specimen B.120, C.D.W. Col.

Fig. C. Amoeboceras (Amoebites) subkitchini, Spath. Diagram of suture line X 8. Specimen B. 53, C.D.W. Col.

Fig. D. Amoeboceras (Amoebites) subkitchini, Spath. Lateral view, natural size. Specimen B.53, C.D.W. Col.

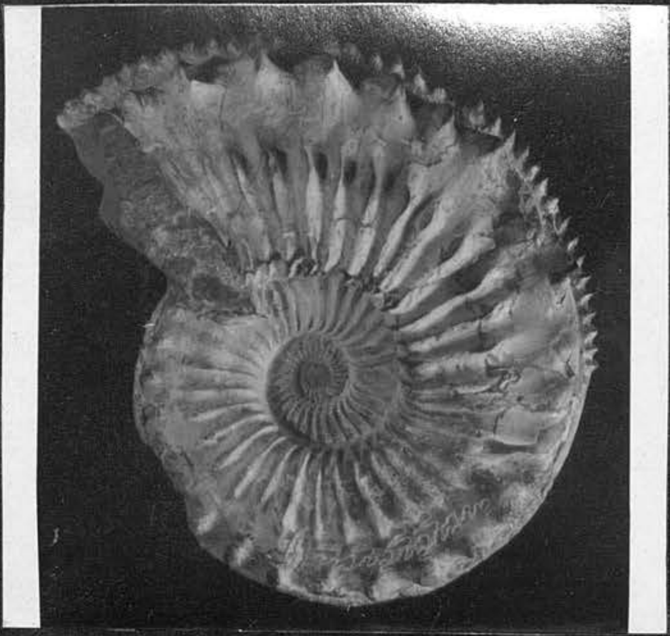


Fig. A.

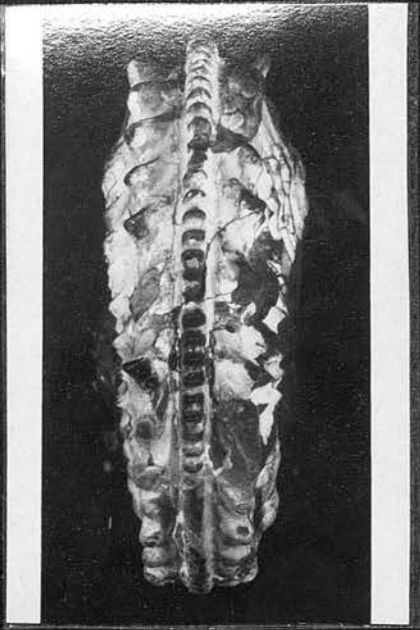


Fig. B.

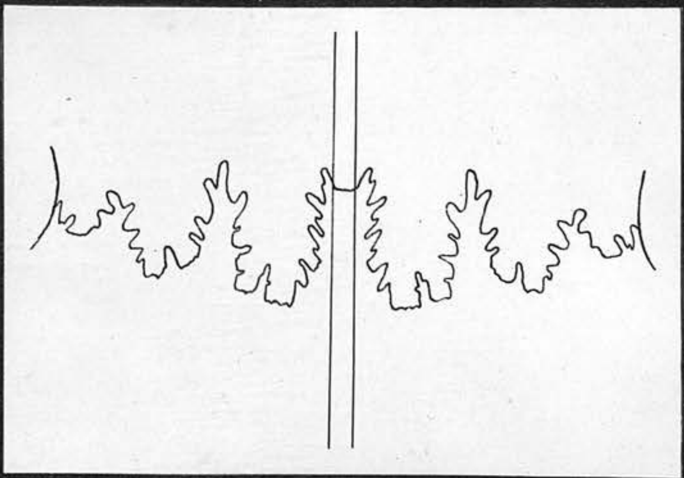


Fig. C.

Fig. D.

PLATE XV.

Fig. A. Amoeboceras (Amoebites) aff. rasense, Spath. Lateral view. Specimen R.126, C.D.W. Col.

Fig. B. Amoeboceras (Amoebites) aff. rasense, Spath. Ventral view. Specimen R.126, C.D.W. Col.

Fig. C. Amoeboceras (Amoebites) sp. nov. Lateral view. Specimen B.122, C.D.W. Col.

Fig. D. Amoeboceras (Amoebites) sp. nov. Ventral view. Specimen B.122, C.D.W. Col.

All photographs natural size.

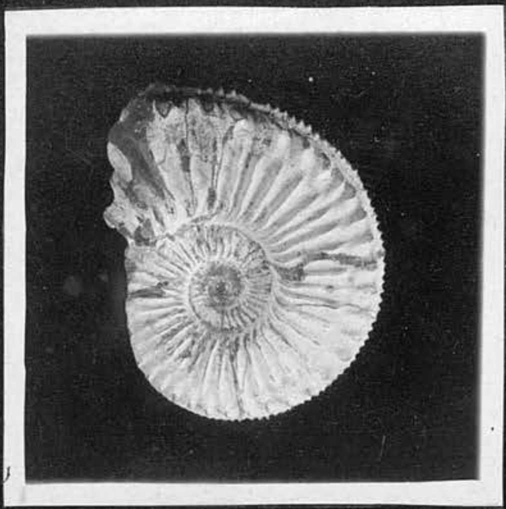


Fig. A.

Fig. B.

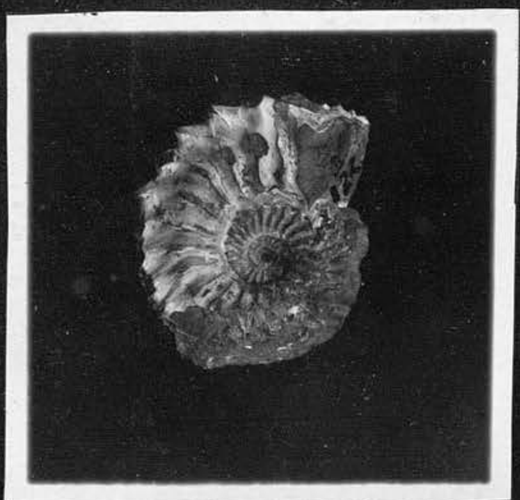


Fig. C.

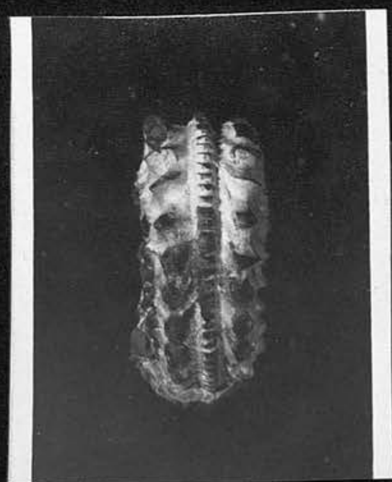


Fig. D.

PLATE XVI

Fig. A. Rasenia sp. nov. Lateral view. Specimen R.78, C.D.W. Col.

Fig. B. Rasenia sp. nov. Ventral view. Specimen R. 78, C.D.W. Col.

Fig. C. Prorasenia bowerbanki, Spath. Lateral view showing apertural lappets. Specimen B.118, C.D.W. Col.

All photographs natural size.

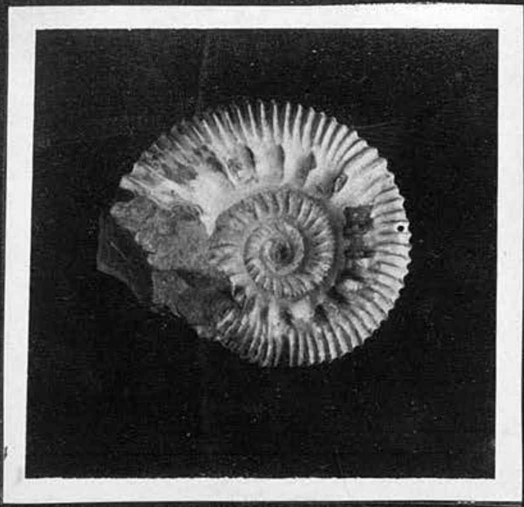


Fig. A.

Fig. B.

Fig. C.

PLATE XVII.

Fig. A. Prorasenia aff. triplicata (J. Sow.)
Lateral view. Specimen R.60. C.D.W. Col.

Fig. B. Prorasenia aff. triplicata (J. Sow.)
Ventral view. Specimen R.60. C.D.W. Col.

Fig. C. Prorasenia aff. triplicata (J. Sow.)
Lateral view. Specimen B.119. C.D.W. Col.

Fig. D. Prorasenia aff. triplicata (J. Sow.)
Ventral view. Specimen B.119. C.D.W. Col.

All photographs natural size.

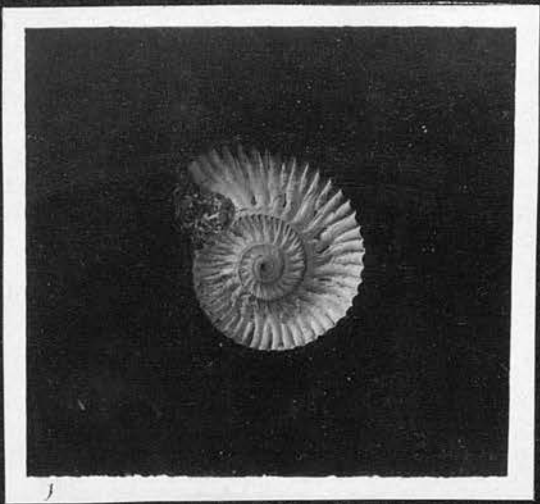


Fig. A.

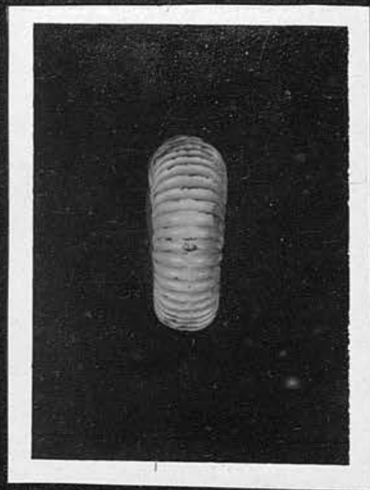


Fig. B.

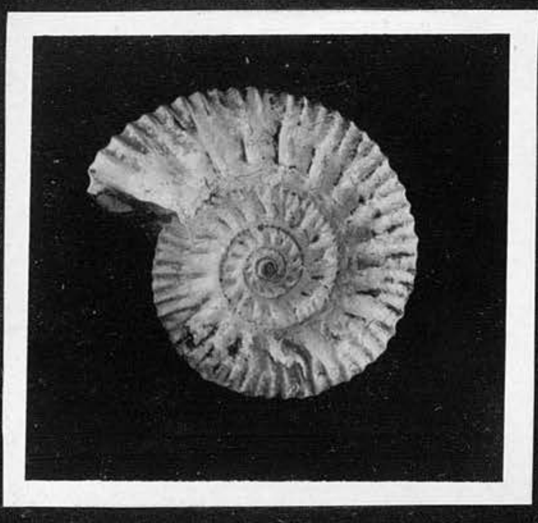


Fig. C.

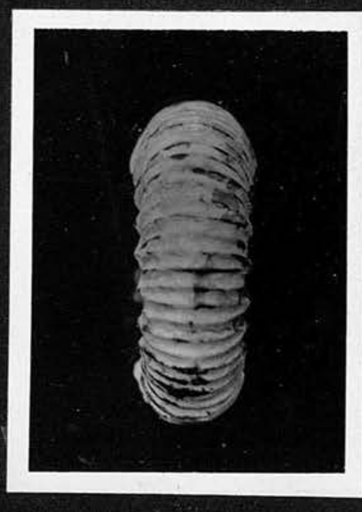


Fig. D.

PLATE XVIII

Fig. A. Cylindroteuthis obeliscus (Phillips). Form α
Ventral view, Specimen R.2. C.D.W. Col.

Fig. B. Cylindroteuthis obeliscus (Phillips). Form α
Lateral view, Specimen R.2. C.D.W. Col.

Fig. C. Cylindroteuthis obeliscus (Phillips). Form β
Ventral view, Specimen P.64. C.D.W. Col.

Fig. D. Cylindroteuthis obeliscus (Phillips). Form β
Lateral view, Specimen P.64. C.D.W. Col.

Photographs natural size.

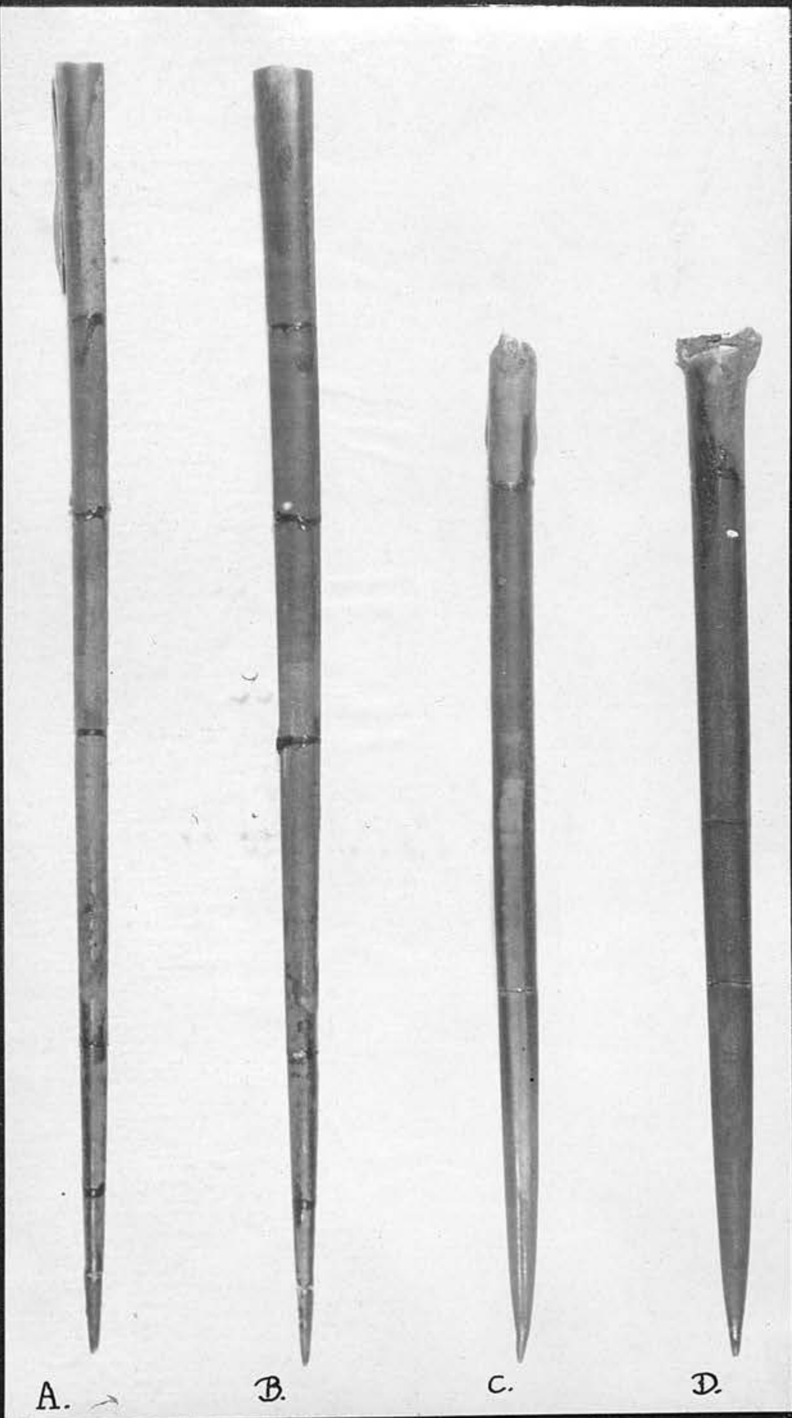

A.
B.
C.
D.

PLATE XIX

Fig. A. <u>Cylindroteuthis spicularis</u> (Phillips). Ventral view, Specimen P.35. C.D.W. Col.

Fig. B. <u>Cylindroteuthis spicularis</u> (Phillips). Lateral view, Specimen P. 35. C.D.W. Col.

Photographs X $^3/_4$.

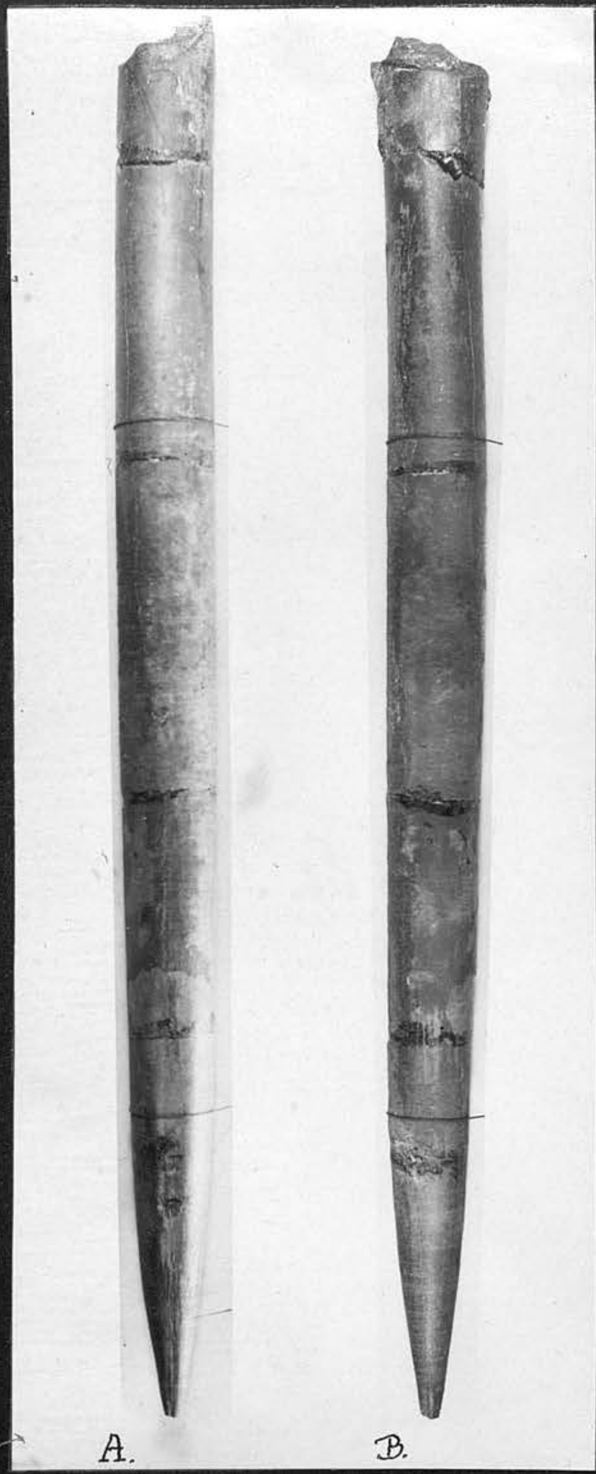

A.
B.

PLATE XX.

Longitudinal section of the phragmacone of _Cylindroteuthis spicularis_ (Phillips), Specimen P.35 C.D.W. Col., showing the structure of the primary spherule.

PLATE XXI

View of Bow Buoy Skerry from the south-west showing the position of the fault between the Moine Gneiss (left) and the Upper Oxfordian rocks (right).

PLATE XXII

View of Bow Buoy Skerry from the west.


CROMARTY, EATHIE HAVEN.
PORTION OF JURASSIC OUTCROP
SOUTH OF THE BOAT HARD.
AREA MASKED BY COURSE BEACH DRIFT.
POSSIBLY A FAULTED ZONE.
N
MAGNETIC VARIATION 12° 30' 1949
o Old Shaft
Scale. ~ 1 inch = 50 feet.
0
50
100
LIMESTONES.
MELEAGRINELLA. Shelly bands in shale.
SANDSTONE INJECTIONS.
Copy.

CROMARTY, EATHIE HAVEN.

PORTION OF THE JURASSIC OUTCROP.

NORTH OF THE BOAT HARD.