SOME STRATIGRAPHICAL AND SEDIMENTOLOGICAL STUDIES ON THE DEVONIAN OF THE TRONDHEIMSLED, NORWAY

David Philip Spencer Peacock

A Thesis Submitted for the Degree of PhD
at the
University of St Andrews

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SOME STRATIGRAPHICAL AND SEDIMENTOLOGICAL STUDIES ON THE DEVONIAN OF THE TRONDHEIMSLED, NORWAY.

by

D.P.S. Peacock, B.Sc.

A thesis submitted to the University of St. Andrews, in application for the degree of Doctor of Philosophy.

1965.

COMMENTS on Thesis entitled "Some stratigraphical and sedimentological studies on the Devonian of the Trondheimsled, Norway." by D.P.S. Peacock.

The presentation is very good though I object to 'meter' for 'metre' and 'pointing' direction for 'sense of movement'. The figures are good though well over half do not show anything exceptional or even useful. The straight-line boundaries on Map 2 look very unnatural. They suggest that the candidate has taken no account of the topography.

p. 29 If the boundary between the Balsnes Cong. and the underlying beds is oblique to the bedding then may this not be due to faulting?

p. 58 ff An ideal cycle is erected without any indication of the number of occurrences of either the cycles themselves or the beds within the cycle. This treatment is in marked contrast to the careful statistical analysis of current directions and grain-size.

p. 78-79 (figs. 58-59) Illustrations suggest shearing of cohesive sediments as suggested by Sanders (1960. Geol. Mag.)

Fig. 61 This structure should not be called convolute lamination.

p. 87 Breccia-bed, not well described and figure indistinct.

p. 86 ff. Pseudo nodules - an inordinately long description to very little point. Idea of sinking due to standing waves new and interesting but would vertical (sinking) forces be important at high velocities? Why not sinking due to dune-formation? Original linear structures are not essential because the shock waves may effect the sinking in elongate zones.

p. 95 To quote a vector mean to an accuracy of minutes (299°28') is ludicrous. Fig. 81 shows a possible bi-modal distribution - was this considered?

p. 106 Again was a polymodal distribution (this is indicated by the results) considered? Such a distribution would obviously cut down the significance of the mean.

p. 109 The point about log scale producing straighter curves is surely laboured. Author seems to miss the points (a) that many distributions are log normal and (b) this was one of the reasons for Krumbein introducing the ø scale in the first place.

p. 115-117 At best the expression here is poor, at worst the discussion shows muddled thinking. There are two distinct questions to be considered (a) origin of log-normal distribution and (b) origin of sorting. The author asks the first but his answer appears only to relate to the second.

p. 119 ff. Correlations between grain-size parameters should have been investigated by calculation of regression lines.

The sections on petrography and provenance are satisfactory but over-long.

The main conclusion with regard to the estuarine environment would have been strengthened if sedimentary structures in other regions, e.g. flood-plains had been considered. Similarly in discussion of the grain-size distribution the author is content to point to similarities with tidal flat deposits. But how do they compare with fluviatile, open marine sands, deltaic sands? Are the differences and similarities sufficiently marked to warrant the conclusion that the environment was estuarine? On p. 68 we find "However, the Hitra deposits are unlikely to have formed in a deltaic environment since the sandy siltstones are interbedded with coarse to medium-grained sandstones and conglomerates, which are not common in present day deltas". Are they any more common in present-day estuaries?

VOLUME I : TEXT.

PREFACE.

Academic Career

I first matriculated at St. Andrews University in October 1957 and in 1961 obtained a Second Class Honours degree in Geology. The same year I enrolled as a research student to study Old Red Sandstone stratigraphy and sedimentation under the supervision of Dr. A.R. MacGregor. The results of my research are embodied in this thesis.

Certificate of Originality.

I certify that this thesis is my own composition and is based on research carried out by me in the Department of Geology, St. Andrews University between 1961 and 1965. It has not been previously submitted to another University.

....

Supervisor's Certificate.

I certify that David Philip Spencer Peacock has pursued a course of research under my supervision and has fulfilled the requirements of Ordinance 16 (University of St. Andrews). He is qualified to submit this thesis in application for the degree of Doctor of Philosophy.

....

ABSTRACT

Introduction

The Devonian rocks considered here, outcrop over a distance of 100 kms. along the northern side of a strip of water, known as the Trondheimsled, near Trondheim, Norway. Since time did not permit complete examination, two areas were selected for detailed study:

1) the western end of the outcrop on the large island of Hitra, where fossils suggesting an Upper Silurian or Downtonian age had been found; and

2) the outcrops on the island complex south of the neighbouring island of Smøla. The precise age of these beds was unknown.

An attempt was made to establish the stratigraphy of both areas, and to deduce the environment of deposition, the nature of the source area, and the direction of derivation of the sediments.

Hitra

The succession (1055 m. thick) has been divided into a number of stratigraphical units on the basis of lithology. Much of it is made up of thick sandstones, often pebbly or conglomeratic, and alternating sandstone/siltstone sequences. Study of the sedimentary structures and size distributions of these sequences suggests that the cycles have

been produced in an inshore estuarine environment, as a result of the lateral migration of channels.

The petrography of the sandstones and conglomerates shows that the sediments were derived from a source area composed mainly of plutonic rocks, while current direction analysis shows derivation from the northwest.

Smøla

The Smøla Series, composed of 3745 m. of conglomerate, has been divided petrographically into four units. The oldest conglomerate lies unconformably on the beds below and is made up of large boulders of locally derived material. The younger conglomerates are composed of abundant pebbles of green sandstone (possibly the Ordovician Hovin Sandstone), and various igneous and metamorphic pebbles which are difficult to match with rocks now exposed in Norway.

The sediments were derived from the north and were probably deposited in a piedmont environment.

Relative age of the Hitra and Smøla Series

Consideration of the stratigraphical, petrographical, and sedimentological evidence shows that the Hitra sediments are older than those of Smøla. A reconsideration of the palaeontological evidence suggests that the Hitra beds could be of Upper Wenlockian or early Ludlovian age, while the Smøla beds are probably Lower or Middle Devonian.

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CHAPTER I.

INTRODUCTION

I. INTRODUCTION

1. Scope of the Study.

This thesis is an account of some studies on the stratigraphy and sedimentation of the Devonian rocks, which outcrop along the northwestern side of a strip of water known as the Trondheimsled, near Trondheim, Norway.

Previous workers have suggested that deposition commenced in Downtonian or Upper Ludlovian times, in contrast to the other areas of Norwegian Devonian, which are probably much younger. The age of the beds and their unconformable lower boundary suggests analogies with strata at Stonehaven, Scotland, and Spitsbergen rather than with other areas in Norway (Holtedahl 1920, 1952, Bailey and Holtedahl 1938). However, in spite of this, little was known of the stratigraphy and practically nothing of the sedimentation, and so it was thought that further studies would be profitable.

The distribution of outcrops is shown on the location map (1). Beds of conglomerate and sandstone occur as far west as Indgripene, off Kristiansund N., but there are more extensive exposures, with steep dips on the island complex south of Smøla. The outcrop on the southern side of the large island of Hitra is about 1.5 - 2kms. wide, and beds of conglomerate, sandstone, and sandy siltstone are folded into a tight syncline.

Beds of conglomerate and sandstone outcrop further to the east on Storfosen and on the Ørland peninsula, but the synclinal structure is much shallower.

A few isolated exposures of sandstone occur north of the Ørland peninsula on Asen, and Tristenen, and on some skerries just off Tarva.

Time did not permit examination of the whole of the sediment strip and so two areas were selected for detailed study :

1) the western end of the Hitra outcrop, where fossils suggesting a Downtonian or Upper Ludlovian age have been found; and

2) the exposures on the island complex south of Smøla. The precise age of these beds was unknown.

Both areas are well exposed : inland, there are plenty of opportunities for study in stream sections, road cuttings, along the shores of lakes, and on the many glaciated knolls and hillocks, while the coastal exposures are practically continuous. The areas were mapped on aerial photographs at a scale of approximately 1 : 13,000 (Hitra) and 1 : 40,000 (Smøla). An attempt was made to establish the stratigraphical succession, and to deduce the environment of deposition, the nature of the source area, and the direction of derivation of the sediments.

2. Geological setting of the Trondheimsled Devonian.

The rocks surrounding the sediments will not be discussed in detail but the pre-Devonian geology of the area may be summarised very briefly as follows:

a) Smøla is composed mainly of diorite with some Ordovician volcanics and a limestone.

b) Hitra is made up of a large pluton of diorite (including some tonalite) and granodiorite.

c) Frøya, and the mainland south of Hitra and Smøla, are both composed of gneisses, which may be metamorphosed Cambro-Silurian rocks.

d) The Ørland peninsula comprises gneisses and Cambro-Silurian sediments.

3. Terminology and Abbreviations

Before commencing the description of the areas studied it is necessary to define some of the terms used.

a. Textural terms

The distinction between clastic sediments of different grainsizes is based on the Wentworth scale given in table 1.

Table 1.

Sediment		Size limits in mms.
Boulder conglomerate		> 256
Cobble conglomerate		256 - 64
Pebble conglomerate	Coarse	64 - 16
	Fine	16 - 2
Sandstone	Coarse	2 - .5
	Medium	.5 - .25
	Fine	.25 - .0625
Siltstone		.0625 - .004 (Less than 30% clay)

The word 'pebble' is also used as a general term to cover all rounded clastic fragments greater than 2 mms. in diameter, since it is not always convenient to make distinctions. However, the sense in which the term is used will be clear from the context.

b. Igneous rock terminology.

The names given to igneous rocks are those of Johannsen (1939) except where an alternative name has become established by usage.

The term 'diorite' is frequently used in a wide sense to cover rocks ranging in composition from diorite *sensu-stricto* to tonalite.

c. Some common Norwegian words.

The following Norwegian words appear frequently in full or abbreviated form in the text and on the map.

Dal ... Valley

Elv ... River

Fyr ... Lighthouse

Holme . (Hl, plural hlne) Holm, Islet

Kirke . Church

Nes ... Point, Headland

Skjaer (Skj)., Skerry

Vann ., Vatn (Vn) Lake

Vik ... Bay

Ø, Øy,. Island

d. References to literature.

The names of periodicals refered to are abbreviated in accordance with the system used in the World List of Scientific Periodicals.

CHAPTER II.

HISTORY OF RESEARCH ON THE DEVONIAN OF THE TRONDHEIMSLED.

II. HISTORY OF RESEARCH ON THE DEVONIAN OF THE TRONDHEIMSLED.

The first scientist to mention the geology of the Trondheimsled in his publications was Johann Christian Fabricius, Professor of Natural History at the University of Kiel. In his book about his travels in Norway (Fabricius 1779, p. 291) he mentioned that while travelling through the Trondheimsled towards Kristiansund he came to a spot called 'Solschen', where in several places the rocks consisted entirely of 'large and small stones set together'. It is probable that 'Solschen' is Solskjaer, on the island of Stabben, and that the rock refered to is the conglomerate of Edøy, which is very close to that spot.

Though Fabricius was the first scientist to visit the area, the rocks had not escaped the attention of the local inhabitants. A legend relates that the Edøy conglomerate is a heap of hailstones sent by a witch as St. Olaf and his fleet sailed up the sound between Smøla and the mainland.

After Fabricius' visit the area received no attention from scientists for over 30 years, but in 1811 Vargas Bedemar visited it in the course of a journey through Norway, Sweden, and Lappland (Vargas Bedemar, 1819).

In 1835 Münzmeister Langberg studied the geology of the district, and 1836, 1841 and 1846, the Norwegian naturalist B.M. Keilhau did geological fieldwork. Langberg did not publish his results, but his manuscript was available to Keilhau who drew on it freely when he published his observations in the third part of his monograph on the rocks of Norway, 'Gaea Norvegica' (Keilhau 1850). A whole section of this volume is devoted to a description of the rocks of the Trondheimsled and it is remarkable for its detail and accuracy.

Accompanying 'Gaea Norvegica' is a first attempt at a Geognostical map of Norway and on it is shown the distribution of the Trondheimsled conglomerate - sandstone series.

In 1868, Hauan mapped the area for Norges Geologiske Undersøkelse but did not publish a description. However, his observations were incorporated in Kjerulf's (1871) account of the geology of the Trondheim region, in which it was stated that the Hitra 'syenite' was younger than the sedimentary rocks of the Trondheimsled. In a later paper synthesising the geology of southern Norway, Kjerulf (1879) again mentioned the conglomerate-sandstone series, but only to record briefly a few of the pebbles types present.

However, in 1896 the islands of Hitra and Smøla were examined in more detail by Per Schei. After returning from the second 'Fram' expedition, he continued his researches and in the summers of 1902 and 1904 travelled over practically the whole of the two islands. Unfortunately, his untimely death the following year prevented him from publishing his results. However, his records were available to

J. Schetelig who published an account of the geology of the islands in 1913. Schetelig was convinced that the diorite of Hitra and Smøla was younger than the sediments and produced field evidence to support this. He considered the sediments to be of Middle Silurian age.

Meanwhile H.H. Reusch had visited the district and thought that the diorite was older than the conglomerate-sandstone series. However, on reading Schetelig's paper he returned to the area to review his conclusions and the following year (Reusch, 1914) published an important paper recording a wealth of detail. He discussed the localities which had been used to demonstrate the age relationship between the conglomerate-sandstone series and the diorite, and showed that Schetelig had misinterpreted them; the sediments were younger as he had originally thought. He collected fossils from the siltstones at Balsnesaunet and though they were poorly preserved, Kiaer was able to identify Dictyocaris, thus showing the beds to be of Upper Silurian or Downtonian age.

Later the eastern end of the Trondheimsled conglomerate-sandstone series was investigated by Th. Vogt (1924 a & b, 1928) who found Devonian plant fossils at a number of localities, thus establishing the Devonian age of this part of the outcrop. Some of the fossils were later examined by Høeg (1945) who refered the Ørland material to Psilophyton rectissimum and Hostimella sp., suggesting a Lower or even lower Middle Devonian age. On the other hand the flora from Tristenen off Vallersund contained Hyenia sp. indicating a Middle Devonian age.

In 1935 Størmer re-examined the fossil material from Hitra and tentatively identified Dictyocaris slimoni, Hughmilleria (?), and Stylonurus (?). On the basis of this he suggested that the beds were of Upper Ludlovian or Downtonian age.

Holtedahl (1944), published a note on the boundary between the conglomerate-sandstone series and the underlying igneous rock. On a skerry just north of the island of Kuli (south of Smøla) irregular masses of conglomerate apparently lie in the igneous rock suggesting that they are xenoliths. However, Holtedahl explained this as conglomerate deposited in pockets and irregularities of the old land surface.

In 1947 Richter published an account of the Devonian of the eastern end of the outcrop and in 1958 again mentioned the conglomerates in a more general account of the geology of the Ørland peninsula. He discussed the general distribution of the outcrops and gave qualitative sedimentological data on the distribution of the conglomerate and the sandstone facies, and the composition of the conglomerates and sandstones. He mentioned the imbrication of the pebbles and stated that on Fosenhei (Storfosen) it showed derivation from the south. He concluded that facially and lithologically the Trondheimsled Devonian was a typical Molasse comparing well with that of the Allgäu and Eastern Switzerland, while in tectonics and distribution it compared with the inner basins of the Variscan mountain chain, e.g. the Upper Carboniferous of the Saar -Thüringen area.

An important aspect of his work was his re-assessment of certain beds of green sandstone with pebbles of quartz, quartzite, and granite which outcrop principally at Bejan, Hovde, and Østråt, on Ørland. These had previously been considered Devonian (Keilhau, 1850; Reusch, 1914), but Richter correlated them with the Hovin group (Ordovician) on lithological grounds.

CHAPTER III

STRATIGRAPHY AND STRUCTURE.

III STRATIGRAPHY AND STRUCTURE

Introduction

In this chapter details of the stratigraphy of the Hitra and Smøla beds are recorded for the first time. In both cases the succession is divided on the basis of lithological and petrographical characteristics as palaeontological zoning was impossible. The few fossils recovered are discussed on pp. 29-34 and 46

The structural history of the area was not studied in detail, but the general style of folding and faulting was revealed during mapping. The main characteristics of the structure are summarised in section 4 (A & B).

A. HITRA

1. Succession.

Table 2 gives the rock succession established for the Balsnes district of Hitra (map 2). It has been divided into three main groups, the names of which were coined from farms on or near the best exposures.

The Aune Group is made up of three units, a basal conglomerate, a coarse grey or reddish sandstone, and a dusky red sandy siltstone. These three different lithologies are grouped together because they represent unusual conditions at the beginning of sedimentation. They are followed conformably by the Vollan Group, which is by far the thickest of the three groups.

It consists of alternating dark sandy siltstones and grey or dark greenish grey sandstones which may be pebbly or conglomeratic. It was found convenient to divide it into nine lithological units.

Table 2

Formation	Main features	Thickness (maximum)
	Top eroded away	
m	? The Balsnes Conglomerate ?	63 m.
	THE VOLLAN GROUP	
l	Sequence of alternating sandy siltstones and sandstones.	200 m.
k	Grey sandstone, pebbly or conglomeratic (Vollan Conglomerate).	157 m.
j	Dark sandy siltstones with carbonate concretions and a few thin grey sandstone lenticles	7 m.
i	Grey sandstone with pebbly and conglomeratic patches (Vollan Conglomerate).	78 m.
h	Sequence of alternating sandy siltstones and sandstones.	25 m.
g	Grey sandstone	10 m.
f	Grey sandstone with some 1 cm. pebbles.	3.5 m.
e	Sequence of alternating sandy siltstones and sandstones.	122 m.
d	Grey sandstone with pebbles.	230 m.
	THE AUNE GROUP	
c	Dusky red sandy siltstones with some grey sandstone beds.	77 m.
b	Coarse grey or reddish sandstone, with a few siltstone intercalations.	18 m.
a	Basal dioritic conglomerate with large boulders (Aune Conglomerate).	65 m.
	Diorite	
	Total :	1055 m.

Lying on top of this, possibly unconformably, is the massive Balsnes Conglomerate, which may be seen best in the cliffs of the hill above Balsnes.

Reusch (1914) estimated the Hitra succession to be about 500 m. thick (excluding the Balsnes Conglomerate), but in fact it is nearer twice that thickness.

2. Detailed stratigraphy.

a. The boundary between the diorite and the sediments.

The relationship between the sediments and the underlying diorite was carefully examined since this has been a subject of discussion and controversy in the past.

A critical locality, mentioned by both Schetelig (1913) and Reusch (1914) lies at the mouth of the Aune river (Map ref. MR/893393), where the basal Aune Conglomerate is well exposed in the wave washed rocks along the shore. Schetelig thought that the conglomerate was intruded by the diorite at this point, but Reusch corrected this and showed that it lay unconformably on a very irregular diorite surface. He stated that there was a transition from the diorite to the angular blocks at the base of the conglomerate, while better rounded boulders appeared some distance above the unconformity.

The writer re-examined this locality but found the junction between the two rock types poorly exposed. There was no sign of the angular blocks refered to by Reusch and all the large boulders at the base of the conglomerate showed signs of rounding. However, the surface of deposition was certainly irregular and at one point there were small rounded diorite pebbles in what must have been a crack in the diorite surface. The evidence suggests that an irregular cracked diorite surface was covered and filled with more or less rounded boulders.

The northern boundary of the sediments was carefully mapped in order to obtain information about the surface of deposition. The diorite/sediment junction could be accurately followed as exposures are plentiful, but the precise line of contact is rarely exposed. However, the exception is the small peninsula on the eastern side of Balsnes Hus Vann (Map ref. MR/925403), where the basal Vollan sandstone (d) lies directly on the diorite. The contact is shown in fig. 1. Pockets of pebbles at the base of the sandstone mark the approximate line of unconformity while in the foreground of the photograph there is a sandstone 'dyke' filling a crack in the old diorite surface.

Just west of this point there are numerous bodies of sandstone and pebbly sandstone which apparently lie in the diorite in a manner which suggests that they are xenoliths engulfed by the pluton (fig. 2). However, in one or two places dips and strikes could be taken and these showed that the bodies had not been rotated as one would expect if this were the case. Furthermore thin section examination failed to reveal contact metamorphism and the sandstones were similar to those further away from the contact. There can be no doubt that the 'xenoliths' are sediment filled cavities in the diorite surface, similar to those discovered by Holtedahl (1944) north of Kuliø.

The southern boundary between the sediments and the diorite is faulted and is well exposed on Kalvhaugtenna (Map ref. MR/933390), Langnes (Map ref. MR/956399), and certain offshore skerries. On Kalvhaugtenna (fig. 3) a very fine-grained greenish micro-breccia with white calcite veins, separates sandstone from the diorite, which here is veined by a light reddish-grey granitic rock. The micro-breccia occurs elsewhere along the fault plane but is absent at Langnes.

h. The Aune Group.

The type locality for the Aune Conglomerate is situated in the shore exposures just east of the mouth of the Aune river, where it reaches its maximum development of at least 65 m. (not 20 - 30 m. as stated by Reusch). The boulders, which are always rounded and often elongate, do not weather out and may be examined in glaciated and wave-washed sections (fig. 4). Over 95% of them are of locally derived diorite, but there are occasional granitic pebbles and some dark fine-grained dioritic ones which are identical to xenoliths found in the Hitra diorite (p. 143). The matrix of the conglomerate, which is scarce due to tight packing consists of highly epidotised, coarse lithic sandstones and grits. Most of the boulders are about .5 m. across in their longest dimension, but there are all sizes up to about

1.5 m. The average pebble size decreases slightly upwards, but not markedly.

The junction between the conglomerate and the overlying coarse sandstone is rapidly gradational. The pebbles at the top of the conglomerate are about 15 cms. across and there is a transition within about half a meter into sandstone with very rare pebbles.

This sandstone (b) which is coarse grained and greyish or slightly reddish, is about 18 m. thick at this point. It is highly jointed and bedding is not well developed, but some trough-bedded units can be seen. At the top of the bed (on the small headland at the mouth of the Aune river) there are a few lenticles of reddish (and occasionally greenish) sandy siltstone about 10 cms. thick. At low tide it is possible to follow the succession further, and within a few meters beds of sandy siltstone are more abundant than the sandstone. The point where the sandy siltstones make up more than 50% of the rock is taken as the arbitrary dividing line between the b and c formations of the Aune Group.

The Aune Conglomerate is again exposed in a road section, between the trackway to the hamlet of Aune and the Aune river bridge, and there is a continuation in the steep wooded country to the north-west. Here the conglomerate is only about 40 m. thick. It is succeeded by the grey - reddish sandstone (b) and this is in turn followed by the uppermost beds of the Aune Group, the reddish sandy siltstones (c).

Though the contact between formations b and c is obscured, there are fine exposures of the c formation in a road cutting just east of the trackway to Aune. The commonest rock type is a hard dusky red sandy siltstone, with streaks of fine sand and lenses and flaser structure (p. 64). Scattered throughout are horizons with irregular calcite concretions, usually 1 - 5 cms. long and elongated in the direction of the bedding. They are made up of radially arranged needles of calcite and often weather to leave holes in the rock surface. There are also minor horizons, 10 - 20 cms. thick, of greenish grey sandy siltstones and occasional beds (less than .5 m. thick) of grey sandstone.

The succession can be followed upwards from this roadside exposure, and in the crags immediately above it there are a few meters of greenish grey sandy siltstone followed by reddish siltstones before the overlying Vollan sandstone (d) is reached.

The c formation is normally 77 m. thick, but around the hamlet of Aune there is about 140 m. This is clearly due to repetition by faulting, but exposure did not permit location of the fault or faults.

North of Fløos Vann the structure is again complicated, but unfortunately the exposure is also poor. However, outcrops occur along the small stream running southwards into the lake. The c formation is apparently 130 m. thick, but this is undoubtedly due to faulting, perhaps in the style illustrated on the map.

Another stream connects Grund Vann with Floos Vann, and just west of Grund Vann there are low cliffs on either side in which rocks are exposed. On the north side there are reddish sandy siltstones, while on the south there is about 3 m. of fine grey siltstone succeeded by 1 m. of medium to fine-grained grey sandstone, sharply and conformably overlain by the basal Vollan sandstone (d). The fine grey siltstone is almost without bedding due to disturbance by burrowing. (p. 33).

Outcrops to the north of this stream are rare, but the basal conglomerate, which must be very thin here, can be seen in several places.

To the west of Grund Vann, a fault displaces the whole of the Aune Group to the south. To the east of this the Aune Group thins out rapidly against the diorite, due to the irregular diorite surface.

Two-thirds of the way along Grund Vann a groove in the topography marks the line of an important fault, at which the junction between the d and c formations is displaced 140 m. to the southeast. The line of disturbance can be traced in a southeasterly direction, past the end of the southern limb of Balsnes Hus Vann where the sandstones are highly jointed and sheared, and it re-appears in the stream joining Balsnes Hus Vann to the sea, where there is further jointing and shearing.

To the east of this fault the junction between the c and d formations lies to the south of Grund Vann. The dioritic Aune Conglomerate re-appears to the north of the lake and the b formation is probably present but un-exposed. The beds of reddish sandy siltstone on either side of the Grund Vann fault have different thicknesses, probably because it has brought different irregularities of the surface of deposition into juxtaposition.

The junction between the sandy siltstones and the basal Vollan sandstone (d) can be followed eastwards without disruption and there are good exposures south of the moraine covered ground separating Balsnes Hus Vann and Grund Vann. To the north the reddish sandstone (b) is exposed, and there is at least 60 m. of it overlying the Aune Conglomerate. There is no evidence to suggest faulting and so the unusual thickness must be due to the sediment filling an irregularity in the old land surface.

Along the northern shore of Balsnes Hus Vann, the sandy siltstones (c) lie on the diorite and the a and b formations are absent. The c formation is much coarser here and contains a great number of gritty beds. Further to the east to Aune Group is absent entirely and the Vollan Group lies directly on the diorite. Details of the transgression are reconstructed in fig. 5.

Along the shore of Balsnes Hus Vann the strike of the sandy siltstones frequently follows the irregularity of the diorite but this is probably a secondary phenomenon due to compaction.

The Aune Group is not restricted to the localities described above, and very similar rocks occur 12 kms. to the east at Sandstad. Here the following succession was observed in a section along the Melandsjø road, beginning approximately 1 km. inland from the coast.

Table 3.

Top	
Jointed dark sandy siltstone	40 m.
Gap	70 m.
Reddish and greyish siltstones	35 m.
Gap	50 m.
Jointed greyish siltstones	1 m.
Gap	113 m.
Dioritic Conglomerate	1 m.
Diorite	
Total	400 m.

The dioritic conglomerate probably corresponds to the Aune conglomerate while the reddish colour of some of the siltstones suggests that they may be equivalent to the c formation.

c. The Vollan Group.

The Vollan Group commences with a greenish - grey, coarse to medium-grained sandstone (d) which reaches a maximum thickness of 230 m. It is a massive well cemented rock and does not tend to split or weather along the bedding, though there are numerous joint planes along which it may be parted. It is occasionally flat-bedded but more frequently trough-bedded, the sets reaching a maximum thickness of 15 cms. The bottom sets of these trough-bedded units are usually a little finer grained and are greenish due to chloritic minerals, which give the rock a streaky appearance. Pebbles, usually 5 - 10 cms. long, are scattered fairly infrequently throughout, but sometimes form pockets of conglomerate which usually die out within a meter or so. They are mainly of granitic rock types.

The westernmost outcrop of the basal Vollan sandstone is faulted against the Aune Conglomerate, 250 m. northeast of the mouth of the Aune river. It occurs on Asvikholme and forms the low rounded cliffs from Aune to Fløos Vann, and exposures are plentiful inland.

The top of the sandstone runs along a line corresponding approximately with the southern edge of Fløos Vann. To the south of this it is succeeded sharply and conformably by a sequence of alternating dark sandy siltstones and grey sandstones, which are well exposed along the coast. The units are of variable thickness but are usually of the order of 3 - 4 m. The dark sandy siltstones contain lens and flaser structure and are very similar to the reddish sandy siltstones described above. They are usually poorly fissile and contain occasional horizons with concretions of microcrystalline carbonate.

The alternating sequence is succeeded by formations f and g, both of grey sandstone. They are similar to the grey sandstones of the e and h formations and are part of this sequence, but have been given stratigraphical status on account of f having pebbles and g being exceptionally thick (10 m.).

They are followed by a further 25 m. of alternating sandy siltstones and sandstones (h), similar to the e formation.

These are succeeded by formation i, which consists of 78 m. of coarse to medium-grained sandstone with granitic pebbles, usually up to 15 or 20 cms. across. The tenor of pebbles is variable and the rock has pebbly and conglomeratic phases (termed the Vollan Conglomerate). Formation i forms the small headland just north of Langholme.

This is followed by 7 m. of dark siltstones which are more fissile than the ones lower in the sequence. They contain many carbonate concretions, which may be elongated along the bedding to a maximum of 1 m. Intricate convolute structures are common (p. 80).

On top of these beds is 157 m. of sandstone, pebbly sandstone or conglomerate (k), which is devoid of dark sandy siltstone apart from two thin lenticles near the base. The conglomerates are similar in composition to those mentioned above and are again refered to as the 'Vollan Conglomerate' (fig. 6).

Lying sharply and conformably above is the l formation, a further sequence of alternating dark sandy siltstones and grey sandstones and this occupies the whole of the centre of the synclinal structure west of Balsnes. The sandy siltstones are again similar to those lower in the sequence (formations e and h) but are more flaggy and slightly coarser.

Towards the top, the sandstone beds contain patches and pockets of 1 - 2 cm. pebbles, lying in hollows eroded into the underlying sandstone. Good examples may be seen along the shore west of the farm of Balsnes (map ref. MR/920393 and MR/920392). These beds of conglomerate (refered to as the Upper Vollan Conglomerate) are seldom more than half a meter thick and die out laterally.

The top of the l formation is nowhere exposed. Beds belonging to this formation outcrop along the coast section to the east of Langholme and West of Balsnes. The exposures on the skerries and islands from

Kjeø to Smaaholme, which represent the southern limb of the syncline, undoubtedly belong to this formation also.

The small islands of Rundholme and Flatskjaer appear to be situated in the centre of the syncline and probably represent the highest horizons of the 1 formation. Rundholme is composed of jointed grey sandstone with patches of conglomerate (pebbles up to 15 cms. across). On the western side of the skerry, there are conglomerates of small pebbles, which bear a strong resemblance to the Upper Vollan Conglomerate.

The Vollan Group was mapped inland as well as on the coastal sections in order to study lateral variations. It was easy to distinguish rocks of this group as the greenish-grey sandstones and the dark sandy siltstones are not found in either the Aune Group or the Balsnes Formation, though it was more difficult to distinguish the various formations within the Vollan Group.

One of the easiest beds to trace is the basal sandstone (d). It runs inland from the coast and most of the faults described above for the Aune Group, displace it also. Good exposures of the sandstone may be seen at Balsnes Hus Vann, where it forms the tongue of land separating the two limbs of the lake. It is 200 m. thick here. To the east of the lake it lies directly on the diorite (p. 17) and is much thinner (50 - 90m. thick). About half way along Balsnes Lang Vann it dies out altogether and there are exposures of dark siltstones which are so close to the diorite that they must have lain directly upon it.

However, 200 m. to the northwest, there are further exposures of grey sandstone and there can be little doubt that they belong to the d formation. Pebbles are scattered throughout, and in places there are pockets of basal conglomerate with dioritic as well as granitic pebbles. It is interesting to note that the conglomerate occurs in what were hollows in the old land surface.

Unfortunately, it is impossible to distinguish formations e, f, g, and h away from the shore, possibly because both f and g have lost their distinctive features. However, the sandy siltstones and sandstones exposed around the southern limb of Balsnes Hus Vann undoubtedly belong to these formations, though the combined thickness cannot be more than 120 m.

Further to the northeast it is impossible to apply the stratigraphy established on the Vollan shore, but undoubtedly all the units have thinned markedly and there is interdigitation of the sandstone and sandy siltstone units.

Good exposures of the Vollan Group can also be seen along the shore to the east of Balsnes and this was mapped as far as Olsvik. The dominant rock type is grey highly jointed and sheared, sandstone with patches of granitic conglomerate, though there are occasional beds of sandy siltstone (between 15 cms and 5 m. thick). The sedimentary structures such as cross-bedding, show that the beds young to the northwest and beds dipping southeast have been overturned. The lithology indicates that the rocks belong to the Vollan Group, but it was not possible to assign them to specific formations.

d. The Balsnes Conglomerate.

The Balsnes Conglomerate forms the hill which dominates Balsnes Bay (fig. 7) and is the cause of a ridge of high ground stretching away to the northwest. The road runs along it for much of its course and so fresh exposures are available in the numerous cuttings.

The conglomerate (fig. 8) consists of tightly packed, rounded cobbles in a matrix of greenish grey sandstone. They are usually between 5 and 25 cms. across and are composed of a great number of rock types. The proportion of pebbles of different composition varies markedly in both horizontal and vertical directions. A rock type dominant at one point may be sparse or absent a few meters away.

The conglomerate is thoroughly indurated and the pebbles do not weather out. It is highly jointed but bedding planes can rarely be seen. The few dips and strikes shown on the map were obtained from occasional sandstone lenticles. These are usually between .5 and 2 m. thick and rarely have distinct bedding, but the dip and strike of the beds can often be estimated from the disposition of the lenticles within the conglomerate. They are composed of the same greenish-grey sandstone that forms the matrix of the conglomerate and are generally free of pebbles.

The edge of the outcrop follows the regional strike, but it is frequently oblique to the local strikes of both the Balsnes Conglomerate and the Vollan Group. A possible explanation is shown in fig. 9.

It is possible that the Balsnes Conglomerate is unconformable on the beds below, but unfortunately no contact could be found to prove or disprove this.

It is likely that the steep western face of the hill above Balsnes is a fault scarp face. The beds of the Vollan Group at its foot strike in a northwesterly direction, which contrasts markedly with the strike a few meters away on the shore. This is best explained by the presence of a fault, which may well be an extension of the Grund Vann fault mentioned above (p. 21). It is not possible to correlate the rocks on either side of the fault at this point.

e. The Geitheia Area.

The maps of Hauan and Schetelig show a small triangular patch of the conglomerate-sandstone series lying inland on the diorite. It is situated about 1 km. west of Neset on the road from Badstuvik to Utset and occupies Geitheia and surrounding hills. The writer carefully examined this area but could find no trace of the sediments. It may possibly be a colouring error on Hauan's map, which was later copied by Schetelig.

3. Palaeontology.

An attempt was made to recover more fossils from the Hitra succession to enable better correlation with other areas, but the results were disappointing. Numerous small fossil fragments were found in the dark sandy siltstones throughout the succession but they were rarely identifiable due to extremely poor preservation. Most of the fragments consist of a thin film of pyrite, glistening on broken surfaces, but frequently it has been oxidised to a white powder.

However, a few tentative identifications were possible and table 4 gives a complete list of the fossils recovered to date.

Table 4

Dictyocaris slimoni, Salter
Hughmilleria (?) sp.
Stylonurus (?) sp.
Pterygotid (?) fragments
Plantae
'Glauconome'
Granularia
Worm burrows

Dictyocaris slimoni Salter

Dictyocaris sp. was first identified by Kiaer from fragments collected by Reusch (1914) at Balsnesaunet. Reusch's material was later examined in more detail by Størmer (1935) who identified a few specimens of D. slimoni Salter. He also studied numerous specimens of Dictyocaris from different deposits and concluded that it was a large crustacean of the order Phyllocarida as originally suggested by Salter.

However, Ritchie (1963) was not convinced by Størmer's arguments. He considered it strange that only one specimen out of thousands should show segmentation, and that the fragments should frequently have many randomly spaced circular holes, unlike other organisms from the same horizon. He suggested that Dictyocaris was a plant and that the holes in it were caused by an organism feeding on it.

Hughmilleria (?) sp. and Stylonurus (?) sp.

Størmer (1935) described and illustrated eurypterid remains from Reusch's collection and tentatively refered them to the above genera.

Pterygotid (?) fragments

Professor Størmer kindly examined the arthropod fragments collected by the writer and reports as follows:

"The arthropod remains from Hitra evidently belong to eurypterids.

A larger fragment shows several segments of the mesostoma of a fairly large specimen (width of body about 50 mm). Since no distinct sculpture is preserved a closer determination is not possible. The size and shape of the body may suggest the family Pterygotidae.

Another fragment, a smooth, narrow ovoid plate, may possibly represent the metastoma of a pterygotid eurypterid."

The specimens were recovered from the locality shown on log 1 (Map ref. MR/908397).

Plantae

Kiaer (in Reusch 1914) mentioned forms recalling deformed plant remains. Professor Høeg kindly examined the writer's collection from Hitra and confirmed the presence of plants, though the preservation did not permit more precise determination.

'Glauconome'

One specimen of a problematical fossil was found at the locality shown on log 1, and is illustrated in fig 10. The specimen, which is well preserved in pyrite, has an overall height of 5 mm. and a width of 4 mm. It consists of a central stem (maximum width 1 mm.) with five pinnate branches on either side. Each branch has a dark line down the centre. The spacing of the limbs becomes closer towards the apex.

This fossil compares favourably with the apical five limbs of specimens from the Silurian of Scotland refered to '*Glauconoma disticha*' Goldfuss by Peach and Horne (1899, pp. 585, 712). Rolfe (1961) however, has described examples from the Hagshaw Hills and shown that they are not the bryozoan *Glauconomella disticha* (Goldfuss) but must be refered to *incertae sedis.* They are common in his ('*Glauconome*') band in the Glenbuck Group, which lies in the so called 'Downtonian' of Peach and Horne. Fig. 11 shows a specimen from this band for comparison.

Granularia (?)

Two specimens from the locality shown on log 1 are tentatively refered to the trace fossil *Granularia.* They consist of a tapering central stem (about 10 mm. wide), with two tapering 'pinnate' branches (about 5 cm. long), and are preserved on bedding planes in oxidised pyrite. The specimens compare with Häntzschel's description of *Granularia* (in Moore *et al*. 1962 p. W194), but without the sediment fill. The specimens cannot be refered to Chondrites since the width of the branches is not constant throughout the system.

Worm burrows

Worm burrows are restricted to the c formation of the Aune Group. Burrowing activity is fairly common in the reddish sandy siltstones and sometimes obliterates the original bedding (fig. 12). The grey siltstone member at the top of the c formation shows examples of lined burrows (map ref. MR/912401). The burrows, which are rather irregular, consist of tubes approximately 2-3 mm. across filled with silt or fine sand. They are lined with a patchy coating of fine black silt (generally ca. 0.1 mm. thick) now seen as fine detrital grains in a matrix of green chlorite. (figs. 13-14).

The age of the Hitra fauna

Størmer (1935, p. 286) stated that the Hitra deposits were of Downtonian or possibly Upper Ludlovian age. His conclusion was based mainly on the presence of Dictyocaris slimoni, since his studies had shown that in spite of the considerable vertical range of the genus Dictyocaris, D. ramsayi was characteristic of the non-marine Wenlock, while D. slimoni was a guide fossil for the non-marine Downtonian (pp. 285-286).

However, work on the Silurian of Lesmahagow and the Hagshaw Hills in the south of Scotland, has thrown doubt on the value of D. slimoni as a stratigraphical indicator. Here, according to Ritchie (1963), it is the commonest form of Dictyocaris.

Peach and Horne (1899) suggested that deposition continued into the Downtonian, but study of the fish fauna from their so called Downtonian has suggested that this was not the case. Heintz (1939) for example, considered the fauna to be Middle - Upper Ludlow, while Westoll (1945, 1951) thought that it was older than the Downtonian and that a late Wenlock to early or Middle Ludlow age would seem reasonable. Lamont (1947), on the other hand considered it to be not later than Wenlock. Recently Ritchie (1963) has tentatively suggested an age around Upper Wenlock - Lower Ludlow.

Thus, although D. slimoni occurs frequently in Downtonian strata, it appears that it can be common in beds as early as the Lower Ludlow or perhaps the Upper Wenlock, if we accept the ages suggested above.

The Hitra deposits therefore, could lie anywhere in the range Upper Wenlock - Downtonian. The presence of 'Glauconome', so common in certain bands of the Lesmahagow and Hagshaw successions could support the possibility of the Hitra beds belonging to the earlier part of the range.

4. Structure

a. Folding

The rocks of the Balsnes district are folded into a syncline as shown on map 2. However, the style of the fold differs on either side of a line running from approximately the southwestern tip of Balsnes Hus Vann to west Havnø. It is probable that this line represents the continuation of the Grund Vann fault as argued on p. 29.

To the west of the line, the syncline is comparatively shallow and plunges to the southwest at about 10°. The northwestern limb has dips varying between about 35° and 65° southeast but the dip is generally about 45°, while the poorly preserved southeastern limb dips at about 10 - 20° northwest.

To the east of the line the fold is tighter. Its centre is marked by the outcrop of the Balsnes Conglomerate, which may have behaved incompetently during folding. The northwestern limb has variable dips, but they are generally about 65° southeast, while in the southeastern limb the strata are approximately vertical or occasionally overturned to the southeast.

b. Faulting

Two sets of faults can be seen on the map, one distributed along the northwestern boundary of the sediments and the other along the southeastern boundary. The northwestern ones are not exposed but are necessary to explain the juxtaposition of certain strata. They are probably mainly tear faults.

The most important fault on the map is the one running southwest - northeast along the southeastern limb of the syncline. This separates the diorite from the sediments and is accompanied by micro-breccia along much of its length. The strike of the beds in the southeastern limb of the syncline is frequently approximately northnortheast - southsouthwest in contrast to the regional northeast - southwest trend. This probably resulted from tear movement along the fault.

The small faults which offset this fault are clearly later and may be tear faults also. They are not exposed but their courses are marked by grooves in the topography and they are required to explain the distribution of the component parts of the main fault.

Numerous other lesser faults can be seen everywhere, but they are not marked on the map as their displacement is too small. Fig. 15 shows one of these which has caused brecciation of the sandstone.

B. SMØLA

1. Succession

The following table summarises the stratigraphical division of the Smøla beds (map 3). The names of the units are taken from the places where they are best exposed.

Table 5.

Formation	Main Features	Thickness
	Top eroded away	
d	The Southeast Kyrhaug Conglomerate Pebbles of green sandstone with some of grey sandstone and metamorphic rocks. No reddish igneous pebbles.	310 m.
c	The Edøy Conglomerate Pebbles of green sandstone and reddish igneous rocks.	1850 m.
b	The Northwest Kyrhaug Formation. Conglomerate with decayed diorite pebbles interbedded with greyish brown sandstones.	555 m.
	FAULT	
a	The Glasø Conglomerate. Mainly boulders of diorite.	1030 m.
	Pre-Devonian rocks.	
	Total :	3745 m.

2. Detailed Stratigraphy

a. The Glasø Conglomerate.

The basal unit of the Smøla series is the Glasø Conglomerate which forms a series of islands and holms to the south of Smøla, in a line from Remingene to Henningholme. It undoubtedly continues to the southwest and forms the large island of Kuli but this lies outside the study area. Exposures are excellent everywhere, but the unit is best displayed on Glasø.

Almost the whole of this island is composed of conglomerate, with rounded boulders of diorite and a scatter of smaller pebbles of dark green porphyry and green fine-grained sediments, comparable with the local Palaeozoic rocks (fig. 16). The pebbles are of all sizes, but the dioritic ones usually have a maximum diameter in order of 1m. Pockets of pink and white 'granitic' pebbles are scattered sparsely throughout. They are rarest in the southwestern half of the island but are commoner in the northeast and are the dominant rock type in places. Pockets of this composition may be several meters thick and appear to pass laterally and vertically into the dioritic variety without erosional or sharp contacts. They probably represent cross sections of channels, the erosional contacts being obscured by the coarseness of the sediments.

The matrix of the conglomerate is a soft grey sandstone or grit, which weathers easily so that the pebbles stand out from the weathered surface, in contrast to the Hitra conglomerates. The proportion of matrix is very variable: at the southwestern end of the island there is very little and the pebbles are frequently in contact with one another, but at the northwestern end the matrix tends to be more plentiful. At one locality there are occasional diagenetic carbonate concretions which have grown in the matrix (p. 104).

Sandstone lenticles are not common, but when present they are usually less than half a meter thick and die out rapidly. Most of them are greyish in colour but occasionally they may be greyish brown. They are either unbedded or flat-bedded, and are mostly coarse or medium-grained, but there is one of fine sandstone (up to 2.5 m. thick), 15 m. above the base of the conglomerate on the northwestern side of the island.

Structures can rarely be seen in the coarse conglomerates but those with smaller pebbles usually have well developed imbrication (p. 100).

Pre-Devonian porphyries and altered fine-grained sediments outcrop along much of the northwestern shore of the island, and the unconformable contact between these and the overlying conglomerate appears to have been perfectly straight originally, though it has since been displaced by tear faults. Boulders of the underlying rocks occur at the base of the conglomerate, but dioritic types are dominant. Some of these are enormous and one had a maximum diameter of 3 m. (fig. 17). The unconformity is well exposed again on the eastern tip of the island, due to faulting, and sand can be seen filling cracks in the surface of the older reddened fine-grained sediments (fig. 18). The basal conglomerate here is a local pocket of granitic composition.

The conglomerate on Nord Remingene is similar to that on Glasø and contains many granitic pockets but few sandstone lenticles. However, the small skerries and holms from Sør Remingene to Purkholme are less variable : they consist of tightly packed conglomerate of diorite boulders, up to about 1 m. across, with a scatter of pink and white granitic pebbles and some of fine-grained green sediment, comparable to the rocks beneath the unconformity. No sandstone lenticles were seen.

The island of Orten is very similar to Glasø, being composed for the most part of an identical dioritic conglomerate. Pockets of granitic pebbles are scattered sparsely throughout, but as at the southwestern end of Glasø, they are not common. The few sandstone lenticles are mostly coarse or medium-grained, but there is 11 m. of fine sandstone, 14 m. above the base of the succession on the western end of the island.

The northernmost spur of the island is composed of sediments and porphyries of pre-Devonian age and there is a black shale, which was unsuccessfully searched for fossils. The Devonian sediments lie on top of these rocks with a sharp straight unconformity (fig. 19) which can be traced across the island and its position shows that there must be a fault between Glasø and Orten. Again large boulders of diorite (up to 5 m. across) overlie the unconformity. in places.

To the south of Orten is Løvø, and a fault runs between the two islands, so that on Løvø basal dioritic conglomerate rests unconformably on earlier diorite. The Stakholmene and Rørskjaer, which lie between the two islands, are composed of diorite with reddish granitic ramifications, while Smaaskjaer is of similar 'basement' rocks to those on Orten and Glasø. Most of the boulders in the Løvø conglomerate are of diorite and they are all sizes up to a maximum of 130 cms. As on Orten and Glasø there is a scatter of smaller green pre-Devonian boulders, but granitic ones are very rare. Sandstone lenticles are rare, except along the south-eastern shore of the island. Here, there are thick sandstone beds which have yielded indeterminable fossils, and a few thin red siltstones.

The Glasø Conglomerate outcrops again on the islands of Krongleholme, Lille Havreø, Stor Havreø, and associated holms and skerries. The diorite forms a narrow strip along the northwestern shore of Krongleholme and above it is a conglomerate with diorite boulders up to 1.5 m. across. Again there is a scatter of smaller pebbles of dark green pre-Devonian rocks, but there are also occasional ones of reddish quartz porphyry. There are a few sandstone lenticles up to 1.5 m. thick and they occasionally have cross-bedding. The succession continues to the south on Stor Havreø. The whole island is composed of conglomerate and there are very few sandstone lenticles. Here the composition is rather different as granitic and dark green pre-Devonian rocks are much more plentiful and in places are more abundant than diorite. The pebbles are of all sizes up to a maximum of 2 m. across, but the largest boulders are always of diorite. A further outcrop occurs on the small wave washed rock in the Kulisvaet between Stor Havreø and Edøy, and here diorite is the most abundant pebble type.

On the southeastern-most tip of Stor Havreø there is a bed, less than a meter thick, of a conglomerate with pebbles (1-2 cms. across) of green sandstone. This type of conglomerate was not seen elsewhere in the Glasø Conglomerate, but the pebbles are identical to those in the Edøy Conglomerate.

The rocks of Lille Havreø are very similar to those of Krongleholme. An exposure of the unconformity between the underlying diorite and the conglomerate occurs on the southwestern point (fig. 20). Immediately above it there is 15 m. of conglomerate with angular blocks of diorite (up to 1.5 m. across) and other rocks from the 'basement', set in a reddish sandy matrix. It is overlain fairly sharply by conglomerate with better rounded pebbles (20 - 30 cms. across, maximum 1 m.), composed of diorite with rare granitic types (fig. 21). A similar conglomerate occurs at the western end of Stor Havreø and on Henningholme. The unconformity is exposed on the northern side of Henningholme, but there is no basal breccia as there is on Lille Havreø.

b. The Northwest Kyrhaug Formation.

The principal rock type in this formation is conglomerate with pebbles of decayed diorite, up to 30 cms. across but usually 10 - 15 cms. Other pebbles are rare but there are occasional quartsites. The matrix is a friable coarse greyish-brown sandstone. The conglomerate is interbedded with coarse to medium-grained greyish brown sandstone, which is the dominant rock type in places. It is either flat-bedded or frequently cross-bedded.

The junction between this formation and the overlying Edøy Conglomerate is well exposed along the northwestern shore of Kyrhaug. It is fairly sharp and there is very little intermixing of the distinctive pebble types (fig. 22), though there is local interbanding, particularly at the northeastern end of the outcrop. The layers of alternating composition are about .5 - 1 m. thick and lense out laterally.

Further outcrops of the Northwest Kyrhaug Formation occur along the northwest shore of Edøy, though exposures are poor. Here a pebble of soft greyish brown sandstone was found embedded in the sandstone, showing 'intraformational' erosion.

c. The Edøy Conglomerate.

This conglomerate forms the greater part of Edøy and Kyrhaug. It is composed of green and reddish pebbles mixed in various proportions, though the green types are usually predominant. They consist mainly of green sandstones and with occasional pebbles of fine green tuff and of conglomerate (fig. 23). The reddish pebbles are mainly of various granites with some quartz porphyry. Metamorphic fragments are very rare. Pebbles of fresh grey diorite (unlike the decayed Northwest Kyrhaug diorite) occur fairly frequently in the basal hundred meters of the conglomerate but are not found elsewhere.

The pebble sizes were observed in the field to see if there was any regular variation over the outcrop, but the differences are not great. The maximum pebble diameters are incorporated in fig. 122 .

In most places the majority of the pebbles are between 5 and 10 cms. in diameter, while the maximum pebble size is 30 cms. In the basal 100 m. of the formation most of the pebbles are 15 - 20 cms. across with a maximum of 40 cms. but this is due to the larger boulders of diorite.

The matrix of the conglomerate is a greyish brown coarse to medium-grained sandstone, which is soft and friable so that the pebbles stand out from the rock surface.

On Kyrhaug the conglomerate is cut by a fault running north-south. It is evidenced by slightly different strikes on either side and by the presence of the Southeast Kyrhaug Conglomerate. Typical Edøy Conglomerate occurs on both sides of the fault but the proportion of sandstone is different. To the west, the conglomerate has lenticles of coarse to medium-grained greyish brown sandstone, which occur very frequently (say every 3 m.), but are mostly less than 50 cms. thick and die out rapidly laterally. Thicker lenticles are not common but are scattered widely over the outcrop : only 6 were found with maximum thicknesses between 50 - 100 cms. and only 8 between 1m and 4 m. One lenticle, near the top of the sequence, on the shore by Tomten, was 12 m. thick and this was the maximum to the west of the fault.

To the east of the fault the oldest rocks outcrop on the headland to the north of Kyrhaug Kai and here there are frequent lenticles of greyish brown sandstone, up to 1.5 m. thick. The thickness of the lenticles increases upwards until at Kyrhaug Kai there is one 12 m. thick. To the south of this there is an alternating sequence of soft grey or light brownish grey sandstones and Edøy Conglomerate, the units of each rock type being 10-20 m. thick. This continues for a thickness of approximately 540 m. before it is overlain by the Southeast Kyrhaug Conglomerate.

The rocks to the north of Kyrhaug Kai are comparable with the youngest rocks to the west of the fault, and the presence of the 12 m. sandstone near Tomten suggests that this horizon is just below the alternating sandstone/conglomerate sequence to the east of the fault. If this is correct, the fault must have displaced the Edøy Conglomerate by 1,150 m. dexterally and the Conglomerate must have been at least 1850 m. thick originally.

Many of the lenticles are apparently structureless but flat-bedding with primary current lineation is common. Cross-bedding, usually between 10 - 20 cms. thick is also common, but trough-bedded units are rare. One of the sandstones to the east of the fault has an intraformational conglomerate of dark purplish mudstone. The contact between the lenticles and the conglomerates is usually sharp and conformable, but sometimes the conglomerate is deposited on a surface of erosion cut into the sandstone below (p. 103). Other structures include imbrication (p. 100) and a 'deformational structure'(p.103).

d. The Southeast Kyrhaug Conglomerate.

This conglomerate is the youngest formation of the Smøla beds and only outcrops to the east of the fault described above. Like the Edøy

Conglomerate it contains pebbles of green sandstone, tuff, and conglomerate, but there are many pebbles of dark grey fine or medium-grained chloritic sandstone, and these are often more abundant than the green sediments (see p.173). Unlike the Edøy Conglomerate there are frequent pebbles of metamorphic rocks, usually coarse cataclastic schists. However, the most striking feature is the almost complete absence of the reddish igneous rocks which are common in the Edøy Conglomerate. Usually the only reddish component is rare pebbles of crystalline limestone. Vein quartz pebbles are also present in minor amounts.

There are occasional beds of gravel size fragments but the pebbles are normally between 5 and 10 cms. across and the maximum diameter recorded was 30 cms. They are usually well rounded.

Sandstone lenticles are not as common as in the Edøy Conglomerate but there are some, up to 20 cms. thick and rapidly dying out. Just north of the southeastern point of Kyrhaug there is a soft brown-weathering grey sandstone 12 m. thick with a 30 cm. band intraformational mudstone conglomerate in the middle. The sandstone shows well developed flat-bedding. To the south of this sandstone, the conglomerate contains reddish granitic pebbles but these rapidly die out and are not found elsewhere. Two 5 m. sandstones occur on the headland just east of the fault, but no other thick sandstones were seen.

The boundary between the Southeast Kyrhaug Conglomerate and the underlying Edøy Conglomerate is gradational : there is interbanding of the two types and a certain amount of mixing of the distinctive pebbles. The uppermost Edøy Conglomerate sometimes contains pebbles of dark grey sandstone and schist and the lowermost Southeast Kyrhaug Conglomerate has a few pebbles of reddish granites and porphyries.

3. Palaeontology.

A new fossil locality was found at the top of the Glasø Conglomerate in beds of fine sandstone on the south side of Løvø. Unfortunately it could not be investigated properly without explosives, but it yielded some fragments (probably of eurypterids) which were rather better preserved than the Hitra fossils.

It is hoped that this locality will eventually provide material for correlation of the Smøla beds.

4. Structure.

a. Folding.

The Smøla beds probably represent the steep northwestern limb of a syncline, the southeastern limb of which, has not been preserved. The Glasø Conglomerate is overturned and usually dips between 65° and 80° northwest. The Northwest Kyrhaug Formation and the basal Edøy Conglomerate are also overturned but the dip lessens to the southeast and the strata cease to be overturned. Along the southeastern shore of Edøy the dip can be as little as 45° southeast, presumably due to a flattening of the beds as the centre of the original syncline is approached.

b. Faulting.

A number of faults are indicated by the geographical distribution of the strata, and these are shown on map 3; they are probably mainly tear faults.

The most important one runs southwest-northeast and separates Kyrhaug and Edøy from the islands to the northwest. The strip of water between the island groups (the Kulisvaet), is probably the result of a line of weakness caused by this fault. It is evidenced by slight differences in strike in the Glasø and Edøy Conglomerates which are particularly clear on air photographs, but the displacement is unknown. It was probably one of the latest faults to be formed since the fault separating Edøy and Kyrhaug does not continue onto Stor Havreø, and the large tear fault to the east of Tomten, with a displacement of about 1,150 m. does not disrupt the strata on Løvø. These were probably earlier faults later truncated by the main fault.

CHAPTER IV.

SEDIMENTARY ORGANISATION AND STRUCTURES.

IV. SEDIMENTARY ORGANISATION AND STRUCTURES.

Introduction

This chapter is a more detailed discussion of the rock types present in the stratigraphical columns and their depositional features. The lithologies and the sedimentary structures associated with them are reviewed in sections A1 and B1, and the colour variations of the rocks are recorded in detail here. The colours were determined by comparing wetted or polished surfaces with the Geological Society of America Rock Color Chart (Goddard, et al. 1963). The colour terms are those of the closest parallel on the chart and the numbers refer to the Munsell designation of that colour. Details of the grainsize and petrography of the rocks are considered in chapters V and VI.

Sections A2, A3, A4 and B2 deal with the arrangement of the rock types in typical vertical sections i.e. the sedimentary organisation. This is followed by detailed descriptions of the individual sedimentary structures and an attempt is made to evaluate their environmental significance and genesis in the light of recent research by other workers. Finally the direction of derivation of the sediments is discussed.

A. HITRA

1. Lithology and Structures

There are five main lithological types in the Hitra succession:

sandy siltstones, medium to fine-grained sandstones, coarse to medium-grained sandstones, pebbly sandstones and conglomerates. These textural types are characterised by different suites of sedimentary structures.

a. Sandy siltstones.

The finest sediments, termed sandy siltstones, are found interbedded with the coarse to medium-grained and pebbly sandstones in the Aune and Vollan Groups.

These beds are best developed in the Vollan Group and have a dark appearance : closer examination shows that they consist of greenish black (5G2/1) layers of fine sandstone, usually between . 5 and 1 cm. thick, interbedded with coarse olive black (5Y2/1) or black (N1) siltstone of about the same thickness. Lens and flaser structure is abundant throughout but sometimes the fine sand occurs in relatively even layers which occasionally show grading. Ripple marks occur on bedding planes but ripple drift bedding is rare. Other structures which are scattered throughout the succession are, load casting, convolute lamination, pseudo-nodules, and deformation ripples, together with a sag structure and shrinkage crack, and these are described in detail below. Carbonate concretions occur at certain horizons, particularly where the siltstones are exceptionally fine-grained.

The c formation in the Aune Group is made up of sandy siltstones with some sandstone intercalations. In this formation however, the siltstones are blackish-red (5R2/2) or dusky-red (5R3/4) while the lenses and laminae of fine sandstone are slightly lighter in colour. Lens and flaser structure and interlamination of siltstones and sandstones is again common, but no sedimentary deformation structures were recorded. However, unlike the sandy siltstones of the Vollan Group, worm burrows are plentiful and in places the primary structures have been locally disturbed to produce a mottled rock.

b. Medium to fine-grained sandstones.

These sandstones make up only a minor part of the succession, and are found associated with the sandy siltstones. The boundaries between the two rock types can be sharply conformable but are frequently gradational. The sandstones are grey in colour (N3 - N4) and are usually characterised by flat bedding, though one or two thin examples show ripple bedding.

c. Coarse to medium-grained sandstones.

Beds of coarse to medium-grained sandstone alternate with beds of sandy siltstone in the Vollan Group. They are grey (N3 - N4) or dark greenish grey (5GY4/1) in colour and are usually cross-bedded. However, flat-bedding is often present instead or the two structures may co-exist in the same bed. When this is the case the flat-bedded unit usually occurs in the lower part of the bed.

Below the k formation the coarse to medium-grained sandstones usually have sharply conformable upper and lower boundaries. However, in the upper part of the Vollan Group (l formation) the lower bounding surface is often erosional and associated with an intraformational conglomerate.

Other structures are not common, but occasional ripple marked surfaces can be seen. Examples of pseudo-nodules, convolute lamination 'breccia bed' and detached masses from these beds are described below, but they are rarities.

d. Pebbly sandstones.

The pebbly sandstones are identical to the coarse to medium-grained sandstones described above except that pebbles are present. The tenor of pebbles may be up to 50% and above this the rock is called a conglomerate. The term 'pebbly' is used in a broad sense, since both pebbles (sensu stricto) and cobbles may be present. Cobbles are generally commoner than pebbles, except in the upper part of the Vollan Group.

The fragments are usually rounded and are frequently well rounded (roundness .60 - .70, determined by comparison with the charts of Dmitrieva et al.,1962). The thicker sandstones seem to be pebbly, whereas the thinner ones are generally devoid of pebbles.

e. Conglomerates.

Patches of conglomerate occur locally in the Vollan Group and the components are usually of cobble size, though in the 1 formation there are frequent pockets of pebble conglomerate. There is rapid lateral and vertical transition into pebbly sandstones.

The Aune and Balsnes Conglomerates have rounded (.40 - .60) boulders and are tightly packed with very little matrix. Analysis of the Balsnes Conglomerate matrix shows that it is identical to the coarse to medium-grained sandstones described above. The Aune matrix is a coarse lithic sandstone or grit.

The variations in composition of the conglomerates are described below. (p. 137).

2. Detailed logs of parts of the succession.

Graphical logs were drawn up for parts of the alternating sandstone/sandy siltstone sequences in the Vollan Group in order to record details of typical parts of the succession, and to facilitate possible comparison with other formations in different parts of the world.

The logs are enclosed at the end of volume 2, and the main features of three of the successions are summarised pictorially in fig. 24. They were all measured on coastal exposures and the following table gives their geographical and stratigraphical location.

Table 6

Log number	Map ref. of log base.	Formations represented	Height of log base above base of formation in which it commences.
1	MR/90853970	e	10 m.
2	MR/90903965	e	70 m.
3	MR/90953960	e. f. g. h	112 m.
4	MR/91353940	l	28 m.

Logs were not drawn for the upper parts of the 1 formation in spite of interesting erosional features, since the shallow dips and minor faulting made accurate measurement difficult.

The system of representation is essentially that of Bouma (1962) though some modifications have been made to facilitate coverage of large sections. The columns of the logs are allocated as follows :

1st column : thickness.

The thickness of the section measured is recorded in meters on a scale of 1 : 50.

2nd column : rock type.

The following rock types occur and are ornamented as indicated:

Coarse to medium sandstone

Sandy siltstone

Medium to fine sandstone

Pebbles

3rd column : bedding plane properties.

The nature of the lower bounding surface of the rock unit is recorded in the left hand part of the column as follows :

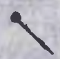
Sharp; erosional; - - - - - gradational.

The bedding plane structures recorded in the right hand part:

Primary current lineation; load casting.

4th column : current directions.

The direction of derivation of the Hitra sediments was determined by study of the orientation of ripple marks from many parts of the outcrop. Some of these fell along the sections measured and their position and approximate directions are given here.

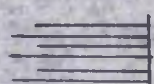
 Line of flow and pointing distinct.

 Line of flow distinct, pointing doubtful.

5th column : layer properties.

This column is divided into a number of subcolumns, each of which is allocated to a different sedimentary structure. The columns are headed with both words and symbols. The distribution of each structure is indicated by the vertical black line.

6th column : lithology.

This column is divided into three subcolumns. The texture of the sediment is indicated in the left hand part, the hatching giving field estimate of the size grades present. Thin alternations of sandstone and sandy siltstone are indicated thus:  . To the right there are subcolumns for field estimates of the percentage of carbonate and for any other supplementary data.

7th column : fossils.

Only one fossil locality of significance was found and it is indicated by an 'F' on log 1.

8th column : induration.

The hatching indicates that the cement is of variable mineralogy (described on p. 131), and the dark line shows that the induration, which is constant throughout, is of Bouma's grade 5. This is distinguished by fractures passing through the grains, and is termed 'weakly metamorphic'.

9th column : colour.

The numbers refer to the nearest parallel on the Geological Society of America Rock Color Chart (Goddard et al., 1963).

10th column : layer numbers.

Each layer is numbered for ease of reference.

11th column : remarks.

Any additional information is recorded here. The numbers prefixed 'S' refer to specimens collected, and those with 'R' to ripple mark measurements.

12th column : mineralogy.

Laboratory studies were not restricted to samples taken along measured sections but were widely distributed in order to assess lateral as well as vertical variations. However, some of the samples fell along the sections logged and the results of the modal analysis are summarised here. The percentage of the following components is indicated by the extent of the hatching:

Quartz   Felspar   Rock fragments

13th column : size frequency.

The laboratory analyses falling on the measured sections are summarised graphically. The following ornaments are used to indicate the proportion of the various size grades.

Coarse sandstone   Fine sandstone
Medium sandstone   Siltstone

3. Statistics of lithology and bed thickness

Study of the bed thickness data from the sections logged shows that the various lithological groups are present in the following proportions:

1) Coarse to medium-grained sandstones (including pebbly sandstones) 41.6 %

2) Medium to fine-grained sandstones .... 16.3 %

3) Sandy siltstones .... 42.1 %

If the measured sections are taken as representative of all the alternating sandstone/sandy siltstone sequences it is possible to estimate the lithological composition of the Vollan Group as a whole:

1) Coarse to medium-grained sandstone (including pebbly sandstones and conglomerates) 74.1 %

2) Medium to fine-grained sandstones .... 7.3 %

3) Sandy siltstones .... 18.6 %

The thickness distributions of the beds in the graphical logs were plotted on logarithmic/probability paper (fig. 25). The curve for each lithological type approximates to a straight line showing that the distributions are nearly log normal. Results similar to this have been found by a number of workers (e.g. Allen 1962; Schwarzacher, 1953).

In this case there is no simple linear correlation between bed thickness and grainsize.

4. The ideal cycle.

The alternating sequences in the Vollan Group are made up of repetitions of the rock types and characteristic structures described above in section 1. The conglomerates and pebbly sandstones are usually restricted to the thick beds separating the formations under consideration here, though some do occur in the sequences, particularly towards the top of the 1 formation.

Study of the beds in the field and on the graphical logs shows that the rock types and the sedimentary structures associated with them, tend to appear in a definite order. It is possible to establish an ideal cycle, and this is shown schematically on fig. 26. The cycle begins with a bed of coarse to medium-grained sandstone, usually about 3 or 4 m. thick, which is separated from the bed below by a surface which is either sharply conformable, or erosional and associated with intraformational conglomerate (indicated by 1 on the diagram). An example of a flat conformable contact is shown in fig. 27, while figs. 28 and 29 show examples of erosional contacts.

The second feature of the ideal cycle is a basal flat-bedded unit in the coarse to medium-grained sandstone (2). The upper part of the same sandstone shows interfering trough-bedded sets (3), and the basal troughs cut down into the flat-bedded unit as illustrated in fig. 30.

The next unit in the cycle, the sandy siltstone with lens and flaser bedding (4), shows a marked change in grainsize and lies with sharp conformity on the coarse to medium-grained sandstone.

Unit 5, the flat bedded, medium to fine-grained sandstone occurs anywhere within unit 4 and has either gradational or sharply conformable boundaries with the sandy siltstone.

It must be emphasised that this sequence is ideal and a complete cycle is the exception rather than the rule. Any unit can be missing, but the scheme shows the order in which the features of the cycle appear when they are all present. For example, if an erosional surface is present it will always be overlain by a coarse to medium-grained sandstone. If flat-bedding and cross-bedding co-exist in the same coarse to medium-grained sandstone bed, the flat-bedding will underlie the cross-bedding (only one exception to this was found).

The size frequency of the sediments will be disucussed in detail in chapter V, but the distribution of size grades throughout the cycle is relevant to this discussion. Units 2 and 3 have mean sizes between .27 and .75 mm., while units 4 and 5 have sizes less than .24 mm. Hjulström (1935), Inman (1949), and Sundborg (1956) have shown that grainsizes greater than approximately .2 mm. tend to be transported as bed load, while grainsizes smaller than .2 mm. travel as suspended load. Thus in this case, units 4 and 5 were probably transported mainly as suspended load while units 2 and 3 were bed load.

The order in which the sedimentary structures occur in the ideal cycle may be significant. Simons _et al._ (1961) and Allen (1963,a), have shown that the structures developed on the surface of a sand bed vary with increasing flow regime : small ripples ⟶ large ripples (dunes) ⟶ plane bed ⟶ sandwaves ⟶ antidunes.

The structures in the cycle vary as follows from top to bottom : ripples (represented by the lens and flaser structure) ⟶ cross-bedding (formed by the migration of dunes) ⟶ flat-bedding ⟶ erosion. Thus there is evidence to suggest decreasing flow regime from the base to the top of the cycle. However, the analogy with the work on Simons _et al._ and Allen cannot be pressed too far because of several differences.

1) As stated above the grainsizes suggest that the cycles are partly suspended and partly bed load.
2) The flat-bedded unit 5 is an enigma.

(3) The ripples of the lens and flaser bedding are a mixture of various types and are not all of the asymmetrical type produced in the flume experiments.

5. Detailed description of the sedimentary structures.

a. Cross-bedding.

Cross-bedding is abundant in the coarse to medium-grained sandstones, but unfortunately the induration of the rocks does not permit detailed examination in three dimensions. Weathering tends to obscure rather than emphasise the cross strata and so detailed observations had to be restricted to relatively recent unweathered fractures. It was not convenient to use the structure as a current direction indicator, but it is clear, even without statistical analysis, that the majority of units were formed by currents flowing from a northerly rather than a southerly direction.

Nearly all the cross-bedding is of the same type (figs. 31 and 32). The cosets are made up of interfering sets of cross-strata, generally between 5 and 10 cms. thick. The lower bounding surface of each set is probably a shallow scoop shaped surface of erosion which usually plunges at one end only. The sets which fill the hollows lie on this surface with weak discordance. The grainsize is fairly uniform throughout, but the forsets are defined by a slight concentration of chloritic material, which may once have been argillaceous matter.

The most recent attempt at a classification of cross-stratification is that of Allen (1963, b) who expanded and developed a scheme originally put forward by McKee and Weir (1953). The bedding described above seems closest to Allens 'pi' type of cross-stratification. There are at least three possible explanations of the formation of these units, but Allen favours an origin due to the migration of large scale, lunate, asymmetrical, ripple marks. However, more work is required to obtain a fuller understanding of the mode of formation and environmental significance.

Fig. 33 shows another variety of cross-bedding, rare on Hitra. This example, which is 104 cms. thick, consists of a solitary set of concave strata resting with slight discordance on a planar non-erosional lower bounding surface. It is of Allen's 'alpha' type, which probably formed in shallow water by the building of a solitary bank, and which is commonplace today in braided river deposits, estuaries, beaches, and in the shallows just off beaches.

b. Flat-bedding and primary current lineation.

Primary current lineation is a series of parallel, off-set, windrow-like ridges and hollows of a very low relief, developed on the bedding planes of sands and sandstones. It is a characteristic structure of flat-bedded sandstones.

On Hitra, flat-bedding occurs in both coarse to medium, and medium to fine-grained sandstones and a few examples of current lineation were noted in each (fig. 34). The structure is not commonly seen due to the high state of induration which normally prevents the rocks splitting along the bedding planes.

It has been described a number of times in the literature, the principal older works being those of Sorby (1859), Cloos (1938), Stokes (1947), and Crowell (1955) who termed it 'parting lineation'. However, recently it has been studied in detail by Allen (1964,a). He examined specimens from the Lower Old Red Sandstone of the Anglo-Welsh basin, and showed that it is associated with a parallel prefered dimensional orientation of the sand grains and grain imbrication. He demonstrated experimentally that it can only form as a stable bed configuration in the upper flow regime (Froude number $\geqslant .75$).

The intimate association of the flat-bedded medium to fine-grained sandstones with the sandy siltstones is surprising since the lens and flaser structure of the latter suggests a lower flow regime. Perhaps the formation of the structure depends on the size distribution of the sediment transported as well as on the flow regime, so that it is produced under different regimes in different sediments. This has not been investigated since Allen used the same grade of sand in all his flume experiments.

The structure is not indicative of any particular environment as it can form anywhere where the hydrodynamic conditions are satisifed. However, Allen states that it can arise in at least two distinct geographical environments : a) the zone of swash and backwash currents on beaches, which sometimes give rise to two directional systems and b) submerged sandbars in channels where the flow is persistantly unidirectional (freshwater rivers) or unidirectional for relatively long periods (tidal ebb-flood channels). The direction of the Hitra lineations varies but each bedding plane has a unidirectional system and no examples were found with two different lineations superimposed. In view of this, it seems likely that they originated in one of the latter environments.

c. Lens and Flaser Structure.

Figs. 35-38 show a structure which is abundant in the sandy siltstones throughout the whole of the Hitra succession, the beds being made up of innumerable layers of silt and fine sand. The sandy layers are usually in order of .5 to 1 cm. thick or less, but may rarely be thicker, up to a maximum of 5 cms., and the silt layers are generally of the same order of thickness. The two sediment types are seldom mixed and are usually separated by smooth sharp boundaries. The individual layers, particularly the sandy ones, thicken and thin laterally and often pinch out so as to form lenses. Usually these only persist horizontally for a few centimeters, but the thicker ones sometimes continue for several meters. The sand lenses bear no relationship to one another vertically but appear to lie in horizontal planes. In section, they usually show small scale cross-bedding and resemble ripple marks.

The silt layers generally bend round the lenticular sand layers and are usually bedded parallel to the contacts, though they may thicken slightly in the hollows.

Graded and flat-bedded laminae are associated with this structure and there are occasional minor surfaces of erosion but they are not common (fig. 39).

The type of bedding under consideration here strikingly resembles that found today in the 'Wattenschlick' (tidal mud) of the German North Sea coast and the Dutch Wadden Sea (fig. 40). It is particularly common in places where rapid deposition prevents burrowing organisms destroying the structure, i.e. in tidal channels and the lower parts of tidal flats. Its occurrence in the German area has been described by Häntzschel (1936), and Reineck (1958; 1960), while van Straaten (1954, a), De Ridder (1960) and Oomkens and Terwindt (1960) have described examples from the Dutch 'delta' area. The principal work is that of Reineck (1960) who has published a detailed account of the structure and defined two different bedding types which are frequently associated. He applied the term 'lens bedding' (Linsenschichten) to cases where sandy lenticles are embedded in a muddy groundmass, and the term 'flaser bedding' (Flaserschichten) to wavy lenses of mud embedded in sand (fig. 41). Both types are found in the sandy siltstones of Hitra, but lens bedding is by far the commonest.

He thought that both structures had a common origin and there are often gradations between the two types. The bedding is the work of tidal currents perhaps supplemented by wind and wave action. The sand beds are deposited as a series of incomplete ripples which migrate across the surface of the mud, when the current velocities are relatively high during ebb or flood tides. The mud is deposited at slack water between the tides and covers the ripples thus formed. Details of the formation of the two structures are given by Reineck and so will not be repeated, but the mechanism is summarised in figs. 42-43. Fig. 42 shows the bedding resulting from tidal systems where both ebb and flood currents are able to ripple the sand, and fig. 43 shows the case where the flood current is able to transport the sand, but the ebb current is too weak, or vice-versa. Both systems are common in the 'Watt', but the Hitra beds are nearly all of the second type.

Oomkens and Terwindt (1960, pp. 709 - 710) have suggested an alternative mechanism ; "During neap tides and current speeds are lower than normal and clay can be deposited; during normal and spring tides only sand can be laid down". However, this theory is not widely accepted.

At first sight the stronger currents would be expected to remove the finer material deposited during slack water, so that mud layers would rarely be preserved. However, this has been considered by van Straaten (1954, a) who listed four factors whioh prevent the removal of newly deposited mud:-

1) The Hjulström effect. The minimum current velocity required to erode loose sediments is always greater than the maximum velocity at which sedimentation can take place.

2) Compaction. Water is expelled from the mud by its own weight.

3) Drying out during tidal exposure.

4) The binding action of benthonic diatoms.

Some or all of these factors may have been active in the Hitra beds, though there is no evidence for the last two.

Present day environmental distribution.

Van Straaten (1959) illustrated this and associated structures and stated that they are most abundant and best developed in the lower parts of tidal flats, tidal channels, and in certain deltaic environments. Similar structures may develop locally in other environments, e.g. in certain lagoons or shelf sea areas but they are usually partly or completely disturbed by burrowing organisms.

The work of Shepard (1956) and Moore and Scruton (1957) has shown that this structure is best developed in the delta front platform environment of the Mississippi in water less than 6 - 8 feet deep. The writers thought that it was mainly due to short term and seasonal variations in the volume and character of the river load.

Similar structures have been found in other deltas : Allen (1964,b) recorded laminations from the Niger, and they have been observed in the delta fronts of the Fraser and Rhône rivers (van Straaten 1959).

Thus it appears that this type of bedding can form in two different environments where different processes are dominant:

1) in tidal deposits, where ebb and flow of the current cause differentiation of the finer and coarser fractions; and

2) in the shallower parts of deltas (proximal fluviomarine deposits) due to slight variations in the volume of the river load.

However, the Hitra deposits are unlikely to have formed in a deltaic environment since the sandy siltstones are interbedded with coarse to medium-grained sandstones and conglomerates, which are not common in present day deltas. The structure probably formed in an estuary due to tidal influence.

d. Ripple marks.

Ripples occasionally occur in the sandstones of the Vollan Group but are much commoner in the sandy siltstones. Examples are illustrated in connection with the lens and flaser bedding to which they give rise but the morphology will be discussed in more detail in this section.

Most of the ripples consist of approximately parallel, straight dune-like ridges which anastomose in places (figs. 44-45). The wave length varies from 4 cms. to 9 cms. with an average of 4.9, while the average amplitude is 3.6 mm. The mean ripple index is 13.6. Three types of ripples are present, the asymmetrical current variety, the symmetrical oscillation type and the intermediate 'half stationary' type.

Asymmetrical ripples have recently been studied by Allen (1963,c) and the ones under consideration here compare with his 'straight small scale' class, which form under 'form drag' conditions when the Froude number is between .30 and .60. However, the Hitra examples are only weakly asymmetrical due to their development in material less than 200 μ in diameter, which resulted in deposition from suspended rather than bed load (Allen 1963, c, p. 205). Examination in section shows that the ripple drift bedding is rare, though several interfering sets may be superimposed. The dune-like ridges of fine sand migrated horizontally across the surface of the silt by stoss side erosion and lee side deposition without addition of material from suspension during migration. Frequently there was insufficient sand to form a continuous layer and so the under-lying silt was exposed in the troughs (incomplete ripples; Shrock, 1948).

When ripple drifting did occur the bed developed is seldom more than about 5 cms. thick. It is usually of the type where the cross stratified units are bounded by surfaces of erosion. Allen (op. cit. p. 206) has explained how this type can form when a little sediment is added to the ripple during migration.

One example of a different type of ripple mark was noted (Log 1, bed 58; fig. 46), and it is closely comparable with Allen's 'linguoid small scale asymmetrical' class. In this case each ripple has a width of approximately 10 cms. and they are arranged in roughly parallel rows.

Allen states that they seem to form in comparatively shallow, swift flowing, turbulent, water in which the flow lines are sinuous.

Asymmetrical ripple marks have a very widespread distribution and are commonplace on beaches, in estuaries, lakes, and rivers, and are also known from the deep sea.

Symmetrical oscillation ripple marks with rounded crests and troughs are not common but several examples were observed. Reineck (1961) has explained how these can be formed by wave action.

However, Reineck's 'half stationary' oscillation type (halbstationäre Oscillations-Rippeln) is much commoner. They are normally roughly symmetrical or weakly asymmetrical in section and are internally cross stratified. They are intermediate between the current and oscillation varieties and result from the combined action of waves and weak currents. This variety is very common in the German Watt as a result of wavy water transgressing the Watt surface, and the internal cross strata frequently dip towards the land. Figs. 36-38 show examples of cross-sections through this kind of ripple which compare well with the structures in the Watt (cf. e.g. Reineck, 1961, fig. 8.).

e. Scoured surfaces.

Scoured surfaces are common in the upper parts of the Vollan Group, but exposure never permits examination in more than two dimensions. They occur either as cuts into sandy siltstone which are filled with sandstone and frequently associated with intraformational conglomerate, or, as cuts into sandstone filled with more sandstone or frequently the gravelly Upper Vollan Conglomerate.

Examples of the former type are illustrated in figs. 28 and 29. The sandstone discordantly fills sinuous irregularities in the surface of the underlying sandy siltstone, but closer examination reveals many minor protuberances, presumably due to hard and soft layers in the underlying bed. The maximum relief is about 50 cms.

Conglomerate filled cuts into sandstone are rather different (fig. 47). The smooth surface is more markedly sinuous and may be completely blanketed with conglomerate, but frequently rounded lobes of sandstone stand up between wider rounded conglomerate filled hollows. The maximum relief is about 30 cms. Originally, the surface probably consisted of a braided system of small scale high velocity channels with rounded lobes of sand between them.

f. Intraformational conglomerates.

The term 'intraformational' conglomerate was introduced by Walcott (1894, p. 192) to describe conglomerates made up of material derived from within the formation in which they occur. Figs. 28 and 48 show examples made up entirely of fragments of sandy siltstone, identical to the sandy siltstone in the bed below. They are fairly common in the upper part of the Vollan Group, where the fragments are usually embedded in the lower part of a coarse to medium-grained sandstone which rests on a surface of erosion cut into the underlying sandy siltstone.

The fragments are irregular tabular bodies with angular edges and are often practically unrounded. They are of all sizes but are generally not more than 30 cms. long. Good imbricate structure is usually developed.

Conglomerates of this type occur in many recent deposits but they are usually found as lag deposits in channel bottoms. They probably originate by bank caving or floor erosion during the migration of the channel (Allen, 1964, c, p. 173). However, the fragments are usually well rounded (e.g. Oomkens and Terwindt, 1960, p. 707), and thus the lack of rounding in the Hitra pebbles must indicate exceptionally rapid erosion and redeposition.

g. Graded bedding.

A few crudely graded units of fine sand occur as laminae in the sandy siltstones of the Vollan Group, but are of minor importance. One example is shown in fig. 58.

The coarse to medium-grained sandstones rarely display this structure, but four examples were found in the lower part of the 1 formation. The thickest of these (S.56, 8,5 cms, thick) was examined in detail and is shown in fig. 49. The base of the bed lies sharply but conformably on the underlying silt, unlike another example (S. 87, Log 4, bed 30) which lies on an erosional surface. The lowermost 3 cms. shows a marked decrease in grainsize in an upward direction but there is only the faintest suggestion of bedding. It passes upwards into a zone about 5.5 cms. thick which displays marked lamination together with a continued upward decrease in grainsize.

The grainsize distribution of the bed was studied in thin section by the method described in chapter V. The unit was divided arbitrarily into four zones, A, B, C and D (fig. 49) and the mean distribution of each zone was determined on a vertical thin section. The results of the analyses are shown graphically in fig. 50 and the parameters determined from these curves are tabulated below :

Table 7

Percentiles	A	B	C	D
ø5	1.35	.87	.69	-.38
ø16	1.80	1.45	1.18	.03
ø25	2.05	1.64	1.40	.25
ø50	2.58	2.13	1.90	.78
ø75	3.03	2.67	2.47	1.46
ø84	3.24	2.88	2.70	1.90
ø95	3.84	3.38	3.30	2.83
Parameters				
Mz	2.54	2.15	1.93	.90
σ_I	.74	.74	.78	.95
Sk_I	-.036	.022	.063	.280
K_G	1.04	1.00	1.00	1.09
K'_G	.51	.50	.50	.52

The characteristics of A, B and C are very similar, but D shows abrupt increases in the parameters.

The change in kurtosis (K'_G) throughout the unit is negligible but the skewness varies from positive to slightly negative. There is a marked decrease in the mean size (Mz) which is accompanied by an improvement in sorting (σ_I)

Pettijohn (1957, p. 171) compared a graded bed produced by a turbidity current with one produced by a normal waning current, and found that the turbidite showed a slight improvement in sorting from the base to the top, whilst the other (a glacial outwash sand) became more poorly sorted upwards. Further work (e.g. Bouma, 1962) has tended to confirm that turbidites have an improvement in sorting upwards, but little work has been done on the other type of grading.

The improvement in sorting in S. 56 is not as marked as is usual for turbidites, and the petrography argues against a turbidity current origin since the sediment is a subgreywacke, identical to the other sandstones on Hitra, which normally display structures such as cross-bedding.

Bouma (1962, p. 48) studied graded bedding in a typical turbidite sequence at Peïra Cava, France, and found that the ideal turbidity current deposit is made up of a number of intervals with different structures (labelled T_{a-e}). The sequence is usually incomplete, giving rise to 'base cut out', 'truncated', or 'truncated base cut out' sequences. The graded beds on Hitra are identical to the truncated sequence, type T_{a-b}. However, this particular sequence is extremely rare in the Peïra Cava area and comprises only .752% of the beds.

Thus if there were isolated turbidity currents during the deposition of the Hitra sediments it is statistically improbable that they would result in this sequence. In any case, Bouma's T_{a-b} types are between 40 and 1000 cms. thick and are due to erosion of the uppermost intervals by subsequent currents. The Hitra examples have a maximum thickness of 8.5 cms. and do not have scoured upper surfaces.

Thus although the grading in S. 56 shows an upward improvement in sorting it was probably produced by a waning current.

h. Carbonate concretions.

Carbonate concretions occur occasionally in some of the finer beds of the Hitra series. Two types are present :

1) aggregates of microcrystalline calcite, probably with some finely disseminated argillaceous matter; and
2) aggregates of fine radiating calcite fibres.

The first variety is commonest and occurs in the greenish grey sandy siltstone member of the c formation as well as in the sandy siltstones of the Vollan Group. The carbonate is usually in the form of symmetrical oval nodules, flattened parallel to the bedding, with dimensions in the order of 10 cms. X 5 cms. X 3 cms. Some of these have septarian structure, and fig. 51 shows a nodule from the e formation with a polygonal network of cracks filled with crystalline calcite.

Septarian structure is common in nodules from the c formation, but is not usually well developed. It frequently consists of three vertical cracks filled with calcite, which commence about .5 cm. from the edge of the nodule and widen towards the centre.

The fibrous radiating variety occurs in the dusky red sandy siltstone member of the c formation as irregular nodules about 5 cm. long and 1 cm. thick (fig. 52). Sectioning shows that they consist of calcite fibres radiating crudely from a central plane. Further examples of this type occur in a fine horizon of the 1 formation, and they consist of flattened discs of carbonate about 3 cms. in diameter and .5 cm. thick with fibres radiating in a horizontal plane from a central point (fig. 53). The radiating structure is probably due to recrystallisation, though it is not clear why some nodules should recrystallise and others not.

The symmetry of the nodules suggests that they formed within the deposited sediment rather than on the surface of deposition, since, if only one surface was in contact with the sediment it would differ from the free surface of accretion and produce an asymmetrical nodule. The concretions must therefore, belong to Pantin's (1958) 'diagenetic' or 'epigenetic' types, but there is no evidence to suggest whether they formed before or after lithification, so it is not clear to which of these categories they belong. However, both Pantin and Weeks (1957) have given examples of calcareous nodules formed relatively quickly and soon after deposition of the sediment and this may well be the usual time of growth.

Weeks suggested that many concretions in argillaceous deposits are due to anaerobic decomposition of nitrogenous organic matter. This releases ammonia and amines which raise the pH so as to permit the precipitation of carbonate.

The Hitra concretions are found in sediments which have structures suggesting an origin under tidal influence (p. 68). Van Straaten (1954, a) has shown that anaerobic conditions can develop in the tidal sediments of the Wadden Sea soon after deposition and so it is reasonable to suggest that these conditions could have been present in the Hitra sediments when soft. If this was the case a mechanism similar to that suggested by Weeks could account for the concretions. On the other hand there are no fossils in the nodules as in the examples cited by Weeks, and the situation is further complicated by the septarian structure which indicates that the nodules must have been in the state of a colloidal gel at one stage and later chemically desiccated.

i. Load casting.

Small scale load casting is fairly common in the sandy siltstones throughout the succession. The base of the fine sandstone component sometimes shows a series of irregular pockets, usually no more than a few millimeters across, where the fluid sand has sunk down into the soft silt before consolidation. A typical example is shown in fig. 54. The pockets of sand are usually structureless, and are continuous with the overlying sand bed which is weakly flat-bedded or structureless as well.

The upper surface of the sand shows no sign of disturbance, which indicates that it must have been extremely fluid at the time of formation. The grainsize is usually constant throughout the whole sand layer.

Occasionally, long drawn out tongues of silt project upwards into the sand and these frequently show orientation (fig. 55). They are similar to 'flame structures' described by Walton (1956) from turbidites in the Southern Uplands of Scotland. They have been discussed a number of times in the literature, but the most satisfactory explanation of their origin is that of Kuenen and Menard (1952), who suggested that they result from two factors acting simultaneously :

1) the drag exerted by a turbidity current on its bed; and
2) local settling and squeezing caused by the rapid accumulation of overburden on the highly mobile foundation.

There is no reason why this theory cannot be applied to the Hitra structures, except that the drag was probably from ordinary rather than turbidity currents.

Figs. 56-58 show larger scale load casting which occurs in the 1 formation (Log 4, beds 41 and 44). A layer of sand has sunk down into the plastic sandy siltstone below and deformed it into a series of ripple like ridges and hollows. The saddles are rounded but the crests are very sharp and sometimes overturned or pulled out into 'flames'. The 'ripples' show internal convolutions due to plastic flowage, but the overlying sand must have been even more fluid because it shows more complicated structures. The regular ridge and hollow form may be due to deposition on a slope so that the load casting was influenced by a gravitational component along the bedding which caused crinkling. Alternatively, it may be due to the upward migration of ordinary ripple mark crests during loading as advocated by Kelling and Walton (1957). This is supported by the wavelength of the corrugations which is similar to that of ripple marks (5 - 10 cms.).

Most of the load casting described in the literature is from turbidites, but it can form in any environment where a soft muddy or silty bed is able to yield to the superincumbant load. Pannekoek (1960) has cited examples from the Haringvliet estuary, while van Straaten (1959) has stated that it is sometimes associated with the laminae in 'proximal fluviomarine' deltaic deposits.

j. Deformation ripples.

The sandy siltstones of the 1 formation show occasional ripple - like corrugations (fig. 59). These appear to plungein approximately the same direction as most of the true ripple marks and are frequently very difficult to distinguish from them. However, in cross section it is clear that they are sedimentary deformational structures because the gentle corrugations persist through a thickness of 5 - 10 cms. of sediment, and small cross-bedded lenses are often bent. The corrugations have a wave-length between 5 and 10 cms., and the crests and saddles of each component layer are coincident in position with those above and below. The amplitude of the waves becomes weaker upwards and downwards and they gradually die out giving way to normally bedded sandy siltstones. The structure is reminiscent of very weak convolute bedding and may represent the initial stages of the formation of this.

Kuenen (1948) has described similar structures from the Carboniferous of South Wales and the near-by Tremadocian, which he refered to as 'pseudo ripple marks'. However, this term is preoccupied as Ingerson (1940) used it for small ripple-like drag folds in metamorphic rocks. The term 'deformation ripples' is proposed for the structures under consideration here. Kuenen concluded that they were formed by lateral compression of the semi-consolidated sediment by the action of gravity either working on the mass itself or pushing neighbouring strata against it.

k. Convolute lamination.

Convolute lamination consists of a series of parallel corrugations interbedded with undisturbed strata. It is not common on Hitra, but several examples were found.

Fig. 60 shows an example from the sandy siltstone of the j formation which shows surprisingly little disruption of the strata in spite of intricate folding. Just left of centre there is a patch of authigenic pyrite, and in three dimensions this has a rod-like form, running parallel to the fold axis. Four distinct zones are visible within the specimen.

The lowest of these (a) consists of practically undisturbed muddy silt, and is followed by zone b, 3 cm. layer of sandy silt with intense and intricate folding. Zone c is a layer less than 1 cm. thick which shows some signs of disturbance particularly in the right hand part. It is overlain by undisturbed muddy silt (d).

It seems likely that the main deformation took place immediately after the deposition of the beds represented by zone b. Zone c was probably deposited while some movement was taking place, and was followed by zone d when movement had ceased. If this is correct the structure must be 'syndepositional', i.e. formed on the surface of the deposit during the deposition of sediment. The intricate folding must be due to the water content which rendered the sediment hydroplastic, but there is no evidence to suggest the cause of the folding.

Fig. 61 shows a further example of convolute lamination from the 1 formation. This is different in that the tops of the folds have been truncated by a surface of erosion on which subsequent sedimentation has taken place. The structure must have formed on or near the sediment surface soon after deposition and it may well be syndepositional like the example described above.

The literature on convolute lamination has recently been extensively reviewed by Einsele (1963) and also by Potter and Pettijohn (1963). The structure is extremely difficult to explain and as yet there is no general agreement on the mode of formation. However, recently

Nagtegaal (1963) published an account of its occurrence in an exposure near Pobla de Segur (Spain) and stated that a zonation similar to that described above is common. He suggested that convolute lamination is related to slumping and is the result of gravity induced lateral movements during or shortly after deposition.

However, Nagtegaal's deposits are turbidites, unlike the Hitra sediments. Sanders (1960) thought that convolute lamination occured only in turbidites but Dott and Howard (1962) and Einsele (1963) have corrected this, though it is probably commonest in these deposits. According to Einsele it is restricted to sediments with a certain grainsize distribution.

The evidence seems to suggest that the structure forms on the surface of a sediment during deposition. It can form in any environment when the grainsize and mineralogy permit sufficient water to be retained to render a layer capable of plastic deformation, and is a result of the sliding and folding of this layer under the influence of gravity.

1. Detached masses.

Fig. 62 is a measured section through a structure which occurs in a sandstone of the 1 formation (Log 4, bed 61). It is well exposed on the wave-washed foreshore and the arrow indicates the orientation of the exposure. Bed 'a' thins out markedly when traced along the strike in a southwesterly direction and was undoubtedly much thicker when originally deposited. The sandy silt bed (b) was deposited on top of it and some consolidation took place. The sediments must then have been injected with water which preferentially saturated the more porous sand and caused it to flow and break through the sandy silts, carrying large blocks with it. Alternatively the water may have been trapped in the sand when it was capped with the sandy silts and failure caused by the weight of the sandy silt or possibly earth tremors.

The crude orientation of the blocks must have been caused by flowage from the left to the right of the diagram possibly because of a subaqueous slope.

The structure fits Bouma's (1962) definition of 'detached masses', though the writer knows of no previous record of structures on this scale.

m. Sag structure.

This structure (fig. 63) can be seen in the cliffs at the western end of Kjeø. It consists of a large corrugation which appears to have sagged down into the bed below and hence the term 'sag structure' is proposed.

The sag is for the most part made up of sandy siltstones but the lowermost bed (c) is a medium-grained grey sandstone. This bed is of relatively uniform thickness to the right (i.e. south) of the corrugation but thins markedly at its centre. The sandstone in the left hand limb is very much thinner than that in the right and thickens less rapidly. The relationship of this bed to the sandy siltstone below

(b) is interesting. The right hand limb of the sag shows a concordant relationship and the sandy siltstone (b) is bent round with the sandstone. However, in the left hand limb the sandstone lies discordantly on the underlying siltstone.

The structure may be explained briefly as follows, refering to the sketch, fig. 64.

1) A series of horizontal beds was laid down.

2) A crack developed in bed b at an angle of about 30° to the bedding, when the deposits were only semi-consolidated.

3) The part of bed b to the left of the crack slid about 15 cms. further to the left, moving on its lower surface. Frictional drag caused the sand of bed c to be pulled out and thinned slightly.

4) The beds above sank down into the gap causing further stretching and thinning of bed c. The sand bed c came to rest discordantly on the left hand part of bed b but the overhanging right hand part was bent round conformably with the sand bed.

Stages 3 and 4 may well have taken place at the same time so in practice a gap would not develop: the space left as bed b moved would be filled instantaneously by the sag.

The beds making up the corrugation must have contained sufficient water to have been capable of plastic deformation. Bed b perhaps contained less water because it fractured, but was nevertheless capable of some deformation.

The writer knows of no similar structure described in the literature. Natland and Kuenen (1951) described beds from the Ventura Basin which show 'pull apart' structures, but the pull aparts are always filled with structureless sediment and never with a sag as here.

n. Shrinkage crack.

Fig. 65 shows a structure which was found in a loose block from the e formation. A layer of silty sand, 24 mm. thick, with small scale cross-bedding overlies a very fine argillaceous silt bed. The disturbance of the bedding was clearly caused soon after deposition, while the sand still contained water. A crack opened in the silt layer and the water saturated sand flowed down it producing a trough like area of disturbance 10 mm. high with a maximum breadth of 12 mm. The movement of the sand obliterated the bedding in this trough. The flowage did not reach the upper 8 mm. of the sand layer, but this subsided to compensate for the loss of material in the lower part. The reason for the cracking of the silt is obscure, but the upturned edges suggest that it resulted from the relief of tension in the almost solid bed. Had the bed not been almost consolidated the downward moving fluid would have eroded the sharp edges of the crack.

A further incipient crack can be seen to the left.

c. Breccia bed.

Fig. 66 shows a curious structure, one specimen of which was found in the e formation (Log 2, bed 6.). The structure occurs in a bed about 15 mm. thick which is separated from the strata above and below by thin (1 - 2 mm.) layers of fine black silt. The medium-grained sandstone below the silt is dominated by flat-bedding but shows rippling in the uppermost 7 mm. The bed in question is made up of elongate fragments of flat bedded sandstone, which have been rotated so that the bedding of each fragment lies between 45^{o} and 90^{o} to the silt layers. The fragments are usually up to about 20 mm. long and show signs of rounding at the corners. Their flat-bedding is frequently indistinct and shows signs of distortion indicating that they were only semi-consolidated when the disruption took place.

The strata immediately above and below this bed must have moved in relation to one another when semi-consolidated. The movement probably took place mainly along the silt layers, and the sand in between was broken and rolled by the movement.

D. Pseudo-nodules. (Ball and pillow structure).

These are nodule-like structures formed of sand that has sunk down into the finer material below before consolidation of the sediments. Five beds of them were found in the e formation and their positions are marked on the graphic logs at the end of volume 2.

Log 1, bed 19.

This bed can be traced for 10 - 15 m. along the strike but since the exposures are in wave polished surfaces, the structures can only be examined in two dimensions. The bed consists of a structureless siltstone approximately 10 cms. thick containing a more sandy horizon which was originally 1 - 2 cms. thick. This has been broken up to form pseudo-nodules and long rafts of sandstone up to about 45 cms. long, with upturned edges (figs. 67 and 68). The sand must have been laid down on a silt bed which was capable of thixotropic transformation due to its composition and water content. A disturbance, or gravitational forces, caused the flat sand bed to founder and sink into the fluid silt beneath. At the same time the silt flowed upwards through the breaks so as to completely envelop the sand. There can be little doubt that the enclosure of sand within the silt was due mainly to upwelling of the underlying bed, rather than the sand sinking, since the raft 45 cms. long could not have sunk without being broken into smaller units.

The pseudo-nodules are usually very small though there are examples up to 20 cms. across. When they are asymmetrical in section there appears to be no preferential orientation of the 'noses', and in some cases adjacent nodules point towards one another. The asymmetry is clearly due to the upturning of the edges of the sand bed during the upwelling of the silt and is of no palaeoslope or palaeocurrent significance.

The sand of which the nodules are composed was flat-bedded originally.

<u>Log 1, bed 59</u>.

The nodules of this horizon occur in a muddy siltstone bed 40 cms. thick, which shows very little trace of its original lamination. It thins out when traced along the strike to the west. The bed is overlain by a flat-bedded sandstone with basal partings of silt.

Along the top of the muddy siltstone there are several pseudo-nodules up to about 20 cms. across (figs. 69-70) in the form of elongate rolls. Fig. 71 shows a section through one of these. It is made up of a medium-grained sandstone which was originally flat-bedded. The internal lamination follows the contours of the outer surface of the nodule, except towards the centre, where there has been crinkling and distortion. The upper surface has apparently been planed by erosive currents and is overlain discordantly by more silts and sands which show some disturbance.

On the same horizon there is an undulating sandstone, originally flat-bedded, which shows an incipient nodules still attached to the parent bed (fig. 72). The line marked 'x' was probably a plane of weak erosion, as the crests of the sand waves were scoured soon after they began to form. However, the plane was later involved in the more intense folding which followed due to further foundering of the sand bed.

In the lower part of the muddy siltstone there are numerous sandy patches up to about 5 cms. across, which contain very few signs of structure (fig. 72). These are probably detached globules of sand which have sunk through the fluid silt and perhaps flowed internally so as to destroy most of the original structure.

The base of the siltstone shows well developed large scale flames and puckers and in between vague sandy pseudo-nodule like structures have developed. It is probable that the base of the silt bed contained rather more sand, and that flowage of the upper layers exerted a drag on the base which caused the development of these structures.

Log 1. bed 63.

This bed which is 17 cms. thick, occurs 35 cms. above bed 59, and also thins out to the west. The most spectacular nodules are those shown in fig. 73, which are elongate rolls of what was originally medium-grained flat-bedded sand. Closer examination of the one nearest the hammer shows that it is a recumbent fold of sand, and it is remarkable that there has not been more crinkling and distortion during its formation. Again the nodules must be the result of a sandy layer foundering into the more fluid substratum, but details of the formation of this complex structure are not clear : perhaps some horizontal movement was involved. The upper surface was planed during a time of erosion, before the overlying silt was deposited.

Log 1. bed 65.

This is a bed 14 cms. thick containing small pseudo-nodules.

Log 1. bed 75.

This bed (fig. 74) occurs in a 10 cm. thick medium-grained sandstone layer which is sandwiched between undisturbed sandy siltstones. The nodules, which are asymmetrical and probably globular, are developed in what was originally flat-bedded sandstone and are succeeded by a plane of erosion and more flat-bedded sandstone. It is remarkable that the underlying bed is very little disturbed and there is practically no inter-nodule matrix.

Pseudo-nodules in other formations.

The writer examined two well known pseudo-nodule bearing formations, the Psammites du Condroz, and the Lower Emsian of Luxembourg, in order to compare the structures of those of Hitra. Figs. 75-78 show pseudo-nodules in the Psammites du Condroz at Walheim, in the Eifel Hills, Germany. The localities and structures will not be described in detail since this has been done by Macar (1948), van Straaten (1954,b), and Pannekoek (1960) for the Psammites du Condroz, and by Macar and Antun (1950) for the Emsian of Luxembourg. In re-examining the localities an attempt was made to obtain more information about the three dimensional shape of the nodules and their orientation.

Since Macar and Antun wrote their paper quarrying operations have provided a new locality with fine opportunities for studying the Luxembourg structures. The quarry is situated by the side of the road from Goebelsmühle to Heiderscheidergrund, and when examined by the writer a large area of bedding plane was exposed, on which were the imprints left by the bases of large pseudo-nodules (fig. 79).

The nodules themselves were pillow shaped or oval bodies of sandstone, usually about 100 - 150 cms. across, and were aligned in rows. Their long axes were frequently, but not always, aligned parallel to the rows.

The literature on pseudo-nodules has recently been reviewed by Potter and Pettijohn (1963) under the heading of 'Ball and pillow structure', and so this will not be repeated. Study of the literature, together with the field studies on Hitra and at the above localities suggests that the following generalisations may be made, though more work is required to confirm their validity.

1) There are basically two main types of pseudo-nodule:
   a) globular drops; and
   b) elongate rolls and pillows, perhaps commoner than the globular type.
2) The first type are randomly distributed without orientation but the second type may be arranged in parallel rows.
3) The nodules have frequently had their tops planed during a period of erosion.
4) They are usually developed in sandstones that were originally flat-bedded.

There can be no doubt that the structure originates by the foundering of a sand bed into a substratum capable of thixotropic transformation. Kuenen (1958) has shown experimentally that vibration can cause a sand layer to break up into pseudo-nodule like globules as the sand sinks into the finer sediment below.

This clearly accounts for the globular nodules, but it does not fully explain the morphology of the elongate type. The evidence from Hitra (Log 1, bed 59) suggests that these probably formed by a flat sand bed first becoming corrugated and then breaking up into a series of isolated synclines of sand which curled up into rolls as they sank into the substratum.

It is interesting to note that the nodules are nearly always developed from flat-bedded sands. The experimental work of Simons et al. (1961) and Allen (1963,a) suggests that these formed in the upper flow regime (Froude number $\geqslant$ .75). When the Froude number is even higher standing waves develop as the bed configuration, and this could be a significant factor in the development of elongate pseudo-nodules. If a flat-bedded sand was deposited on top of a thixotropic silt, an increase in velocity might cause the surface configuration to change from a flat bed to a series of standing waves. This would cause unequal loading of the silt, and the sand would subside beneath the ridges so that the whole bed would become undulating. Further sinking would cause it to break up into isolated elongate nodules. The presence of high velocity currents would also account for the fact that pseudo-nodules have frequently had their tops planed.

This is a very tentative hypothesis, but it does account for most of the phenomena associated with elongate roll-like nodules.

6. Palaeocurrent Analysis.

Unfortunately the induration of the sediments prevented accurate measurement of the orientation of cross-bedding and imbrication of the pebbles, for palaeocurrent analysis. The data were therefore obtained from :

1) field measurements of the orientation of ripple marks;

and 2) laboratory studies on the fine cross-stratification within the lens structure (intimately related to the ripples).

Unfortunately bedding planes with distinct ripple marks are not abundant, since the ripples which make up the lens and flaser bedding are often irregular and tend to produce bedding planes with vague undulations, especially when the fine sand is blanketed with a layer of silt.

However, the orientation of distinct ripples was measured and the line of the current was assumed to be at right angles to the ripple crest. The 'pointing' of the current was determined by a field examination of the internal cross-stratification, as the asymmetry is frequently too weak to be used. Both asymmetrical current ripples and 'half-stationary' ripples were measured, and are grouped together since there appears to be no appreciable difference in pointing.

Orientated specimens showing lens and flaser structure were collected in order to provide more data, and each specimen was cut and polished in two directions (at right angles and parallel to the strike). Of the specimens collected, 35 show distinct structures in two directions. 18 of these are from the e and h formations and 17 from the l formation of the Vollan Group. In each case the current direction, indicated by the fine cross-stratification, was estimated visually, since this was the only practical method due to minor irregularities.

No correction was made for the plunge of the beds on either the ripple or laboratory measurements, as this is not known exactly, but believed to be less than 10°.

Statistical analysis.

The measurements of both the ripple marks and the orientated specimens were plotted on rose diagrams (figs. 80 and 81). The data was studied statistically by Curray's (1956) vectorial method for examining circular distributions, which is essentially the same as that used by Reiche (1938). This has considerable advantages over the other methods which treat the data as a linear normal distributions. The main objection to the use of a linear distribution, as Jizba (1953) and Chayes (1954) have pointed out, is the lack of a known origin for the frequency curve. Small changes in the origin give different answers for the mean and variance and so it is difficult to use these in testing for significance.

Curray's method overcomes this difficulty. The vector direction and magnitude are calculated using the following formulae:

$$\text{Tan}\ \bar{\theta} = \frac{\Sigma n\ \text{Sin}\ \theta}{\Sigma n\ \text{Cos}\ \theta}$$

$$r = \sqrt{(\Sigma n\ \text{Sin}\ \theta)^2 + (\Sigma n\ \text{Cos}\ \theta)^2}$$

$$L = \frac{r}{\Sigma n}\ 100$$

Where, θ = azimuth from 0 to 360 of each observation.

$\bar{\theta}$ = azimuth of resultant vector.

n = observation vector magnitude.

r = magnitude of resultant vector.

L = magnitude of resultant vector as percentage.

The R, Raleigh, test is used as a test for significance as in most cases it is more sensitive than the χ^2 or F tests.

Study of the Hitra ripple mark distribution showed that the currents came from a northwesterly direction with a vector mean lying at 299° 28'. The R test showed that $p < 10^{-4}$, a result which is very highly significant, as there is less than 1 chance in 10,000 that this distribution has arisen by chance.

The vector mean of the orientated samples also indicates derivation from the northwest quadrant, i.e. 281° 35', and the R test again gave a very highly significant result ($p < 10^{-5}$).

Both sets of measurements suggest that the sediments were transported from the northwest, though the distributions do not agree exactly. The ripple mark measurements are likely to be the most accurate guide to the true direction, since the orientated samples were estimated visually and were probably biased by the direction of the polished sections. There is a great tendency to select directions lying along one of the polished sides or at 45° to them.

It was stated on p. 70 that the 'half stationary' ripples in the German Watt frequently 'point' towards land. This seems unlikely to be the case here since the asymmetrical and half stationary ripples point in the same direction. The cross-bedding of the coarse to medium-grained sandstones and pebbly sandstones is unlikely to point towards land, and indicates derivation from a northerly rather than a southerly direction(p. 61), which is in agreement with the results of the ripple orientations. Thus it is reasonable to suppose that the land area from which the sediment was derived lay to the northwest.

B. SMØLA.

1. Lithology and structures

The Smøla beds are composed of several types of clastic sediment: siltstones, sandy siltstones, fine sandstones, coarse to medium-grained sandstones, and conglomerates, but the three finest varieties make up a very small proportion of the succession.

a. Siltstones and sandy siltstones.

These occur as thin layers (usually less than 20 cms. thick) in the rare finer lenticles in the Glasø Conglomerate. They are either greyish-black (N 2) or blackish-red (5R2/2) in colour and show vague sedimentary structures. There may be an indistinct streakiness or interbanding with thin ($<$ 1 cm.) layers of sandstone or grit.

b. Fine sandstones.

Fine sandstones occur in the intercalations mentioned above but there are thicker beds near the base of the Glasø Conglomerate on Glasø and Orten (pp. 38-39). The sandstone is olive grey (5Y4/1) or greyish red (5R4/2) in colour, and on Orten it has small scale trough-bedding, flat-bedding, and occasional layers showing load casting and flame structures. The fine sandstones on Glasø are flat-bedded throughout.

One example of a fine grained sandstone was found in a flat-bedded lenticle in the Southeast Kyrhaug Conglomerate (K. 14). It has an interesting bimodal size distribution (p. 121).

c. Coarse to medium-grained sandstones.

These are by far the commonest sandstones in the Smøla series and are found as lenticles throughout the whole succession. They are usually medium grey (N5) to light olive grey (5Y6/1) in the Glasø Conglomerate, and greyish-brown (5YR3/2) in the Northwest Kyrhaug Formation. In the Edøy Conglomerate they are commonly greyish-brown (5YR3/2) while the sandstone beds at the top of the Edøy Conglomerate vary from medium grey (N5) to light brownish-grey (5YR6/1).

All the sandstones are soft and friable.

Flat-bedding is the commonest structure in the lenticles, and cross-bedding occurs frequently, but sometimes no structures are discernable. Two minor intraformational conglomerate beds were found in the sandstones near the top of the succession.

d. Conglomerates.

Conglomerate is the commonest rock type in the Smøla series although there are marked variations in the petrographical composition which will be discussed later (p. 159). The size of the fragments also varies according to the formation. The Glasø Conglomerate is made up of boulders which are generally rounded (.50) but it also contains pockets of rounded granitic cobbles (p. 37), while the other formations consist of rounded (.55) fragments of large pebble or small cobble size.

Occasional beds of small pebble conglomerate occur in all formations. One near the base of the Glasø Conglomerate, is made up of angular (.20) pebbles, usually .5 - 1 cm. across, but conglomerates of similar size in the Edøy Conglomerate have roundnesses between .50 and .55.

Imbricate structure is abundant everywhere except in the Glasø Conglomerate and here it is restricted to the 'pockets' of cobbles.

The matrix of the conglomerates resembles the coarse to medium-grained sandstones described above, but generally there is very little of it due to tight packing.

2. Sedimentary organisation.

The arrangement of the strata is the same throughout most of the Smøla series, and a typical example is shown in fig. 82. Lenses of sandstone of all thicknesses are scattered randomly throughout the conglomerate.

Reusch (1914, p. 27) claimed to have found regular alternations of sandstone and conglomerate in the Edøy Conglomerate suggesting (to him) annual fluctuations in the type of material deposited. The writer re-examined the locality (near Nøsthaug), but found Reusch's explanation unsatisfactory. The sandstone beds do not persist laterally, but are a series of lenticles which happen to be regularly spaced at this point.

The proportion of sandstone increases markedly towards the top of the Edøy Conglomerate on Kyrhaug, and the general arrangement may be somewhat different here, but it was not possible to investigate this as the beds are not preserved laterally to any extent.

Most of the sandstone lenticles throughout the succession have sharp non-erosional contacts with the surrounding conglomerate, but a few examples were found where the overlying conglomerate had been deposited on a surface of erosion. These were probably due to channel cutting. However, this is undoubtably much more important than the number of erosional contacts suggests since it would be difficult to detect a conglomerate filled channel cut into conglomerate of the same composition.

The pockets of granitic cobbles in the Glasø Conglomerate probably represent the filling of channels cut into the dioritic conglomerate, the erosive contacts being obscured by the coarseness of the sediment.

3. Detailed description of the sedimentary structures.

a. Fabric of the conglomerates.

Fabric studies were conducted on the conglomerates of the Smøla beds, since the pebbles often weather out so that their orientation can be measured. Seven localities were selected and 100 of the best exposed pebbles were measured at each. Only pebbles more than 4 cms. long were considered for practical reasons. At each locality, the area over which the readings were taken was limited as far as possible to ensure a homogeneous sampling area.

Throughout this study the morphology of the pebbles is described using the terminology proposed by Kalterherberg (1956) : the longest axis of the pebble is designated A, the intermediate one B, and the shortest C.

The orientation of the planes of greatest cross section of the pebbles (AB) was measured and the poles on the lower hemisphere plotted on a Schmidt equal area net. At each locality the dip and strike of the nearest flat-bedded sandstone was measured and this was regarded as the plane of accumulation. The points on the Schmidt net were rotated to the horizontal about the strike of this plane, and the resulting distribution contoured using a 1% circular counter centred at the insections of a grid of 1 cm. squares. Kamb (1959) stated that this method, though conventional, produces a lot of detail which is of no statistical significance. Johansson (1963) proposed an alternative method, but this is not used here as it produces deformation of certain parts of the field.

The results are shown in figs. 83-89 and since the AB planes almost invariably dip upcurrent (Potter and Pettijohn 1963, p. 35), the current directions can be deduced from them (p. 105). In each case the angle of imbrication is variable but is rarely more than about 70°. The mean angle of imbrication varies between 5° and 23° and has an average of about 13° for the seven diagrams. Cailleux (1945) studied the angle of imbrication of pebbles in different environments and concluded that marine deposits vary from 2° - 12° and fluviatile from 15° - 30°. The Smøla deposits fall in between these values, but are undoubtedly of fluviatile origin (see p. 182.).

The orientation of the A axes of the pebbles was also studied. Figs. 90-96 show contour diagrams for the points of emergence of the A axes on the lower hemisphere of the Schmidt net after rotation to the horizontal. There is a suggestion that the A axes are preferentially orientated parallel or perpendicular to the line of flow determined from the AB planes, but there is a wide spread of values.

Other writers have found that the A axis orientations are variable though there is a tendency for them to lie parallel or perpendicular to the line of flow. Unrug (1957) found that the orientation of pebbles in the Dunajec Valley depends on:

1) the size; and

2) the shape of the pebbles.

Johansson (1963) has shown experimentally how different orientations can arise. He found that :

1) transverse orientation is normal for pebbles transported as a contact load without obstacles; and
2) longitudinal orientation is
   a) retained from long jumps, or
   b) a result of turning round obstacles.

Unrug's size control clearly arises because it is the size that determines whether a pebble will travel by rolling or by jumping. With regard to the shape control, Johansson found that flat pebbles tend to be deposited parallel to the flow. When settled longitudinally they are not so easily moved by tractive forces as the non-flattened pebbles. In discoidal pebbles, the A axis is not much longer than B, and so no particular A axis orientation will be favoured.

The measurements on the Smøla beds were not differentiated with regard to size and shape and so this accounts for the spread of A axis orientations.

b. Cross-bedding.

Cross-bedding occurs in the coarse to medium-grained sandstone lenticles as solitary sets, usually between 10 and 20 cms. thick. The strata rest with slight discordance on a planar lower bounding surface, which may be non-erosional, or which may show signs of erosion (fig. 97). The cross-strata are usually overlain by flat-bedded sandstone, though one set was capped by a bed of conglomerate.

These sets correspond to Allen's (1963, b) 'alpha' and 'beta' types, which are thought to have formed in shallow water by the building of solitary banks.

c. Flat-bedding and primary current lineation.

This is common in the coarse to medium-grained sandstone lenticles and is identical to that described above (p. 62).

d. Scoured surfaces.

Two scoured surfaces from the Edøy Conglomerate are shown in figs. 98-99. Fig. 98 shows an essentially planar surface cut into a flat-bedded sandstone lenticle and overlain by conglomerate.

Fig. 99 is a smooth sinuous surface of erosion, cut into sandstone, the hollows of which are filled with conglomerate. It resembles some of the scoured surfaces of the Vollan Group (cf. fig. 47).

e. Intraformational conglomerates.

These are not common in the Smøla series, but two thin beds were found in the flat-bedded sandstones of the upper Edøy and Southeast Kyrhaug Conglomerates. They are made up of angular fragments of purplish mudstone which show imbrication. There is no sign of the parent bed and they are not associated with scoured surfaces.

The purple mudstone was probably originally deposited further upstream as thin layers, which perhaps broke up due to desiccation. The fragments were later swept into their present positions.

f. Sedimentary deformation structure.

A structure which clearly formed while the sediment was only semi-consolidated is shown in fig. 100. It consists of a pocket of conglomerate in a distorted sandstone which was originally flat-bedded. It is probably a form of load casting and resulted from the conglomerate sinking into the sandstone. After deposition, the sand was probably capable of deformation due to entrapped air and/or water.

The deformation resembles certain cryoturbation structures, but it is unlikely to be related to these as there is no other evidence to suggest permafrost conditions.

g. Concretions on Glasø.

At the eastern end of Glasø there are occasional carbonate concretions in the matrix of the conglomerate lying above the unconformity. They are restricted to the first few meters of sediment and are not found elsewhere. They consist of irregular bodies of very fine-grained grey limestone, 10 - 15 cms. across, which are moulded round and partly enclose boulders in the conglomerate (fig. 101). They ramify in all directions but seem to be preferentially developed in a plane parallel to the bedding.

Under the microscope the matrix of the conglomerate can be seen to consist of various corroded sand grains set in an abundant groundmass of twinned calcite crystals, about 100μ across. In contrast, the concretions consist of extremely fine-grained (ca. 5 - 10μ) crystalline calcite, and

and the junction between this and the carbonate in the matrix is always very sharp. Frequently the concretions contain 'rafts' and inclusions of the matrix, always with sharp boundaries.

There are numerous minute detrital fragments, and dark brown biotite is by far the commonest. The grains are usually 50μ long or less, but range up to 500μ near the edges. They are nearly always orientated so that they lie parallel to the boundaries of the concretion, and sometimes occur as trains of minute flakes. Quartz also occurs very rarely as minute corroded grains usually in the order of 50μ across. The minerals are identical to those in the conglomerate matrix.

The concretions resemble some of the cornstones described by Burgess (1961) from south Ayrshire. He suggested three stages in their development, the initial one being the formation of calcareous nodules in a sandstone matrix. These appear to be similar to the concretions described here, suggesting that at some stage the conglomerates were exposed under semiarid conditions so that the initial stages of the formation of a calcareous soil could take place.

4. Palaeocurrent analysis.

An attempt was made to deduce the direction of derivation of the sediments from the orientation of the AB planes of the pebbles since these almost invariably dip upcurrent. The directions obtained from the stereograms (figs. 83-89) are plotted on the distribution map, fig. 102.

Applying Curray's (1956) method, the directions indicate derivation from the north, with a vectorial mean of $358^\circ\ 7'$. It was not possible to examine more than 7 localities due to the time consuming nature of the studies, but Durand and Greenwood (1958) have produced a modification of the R test which enables it to be used with samples as small as this. Applying it, the probability p falls between .10 and .05, and a distribution such as this would arise by chance approximately once every 15 trials. Although this falls below the accepted probability level of 1 in 20 ($p \leqslant .05$) it is likely to be significant.

CHAPTER V.

GRAINSIZE ANALYSIS.

V. GRAINSIZE ANALYSIS.

Introduction.

Grainsize analyses were conducted on the sediments for two reasons :

1) to describe more precisely the size distribution of the clastic grains in the various lithological types; and
2) to provide more evidence for assessing the environment of deposition.

34 samples of sandstones and siltstones from the Hitra beds and 11 from the Smøla beds were examined by the method described below.

a. Method.

The Hitra beds are all highly indurated and as it is impossible to disaggregate the samples, the analyses had to be conducted on thin sections. The Smøla beds are not so thoroughly indurated, but only certain specimens can be disaggregated properly, and so the analyses were also conducted on thin sections.

Bouma (1962) described a method of thin section size analysis under the microscope using an ocular micrometer, but it was found easier to measure the grains using a microprojector as suggested by Krumbein and Pettijohn (1938). The microprojector was arranged with a 45° mirror so that an image of exactly one hundred times enlargement was projected onto a horizontal plane. The apparent long axes of 250 selected grains were measured in each slide. It was found feasible to measure down to 20μ. In order to ensure unbiased sampling the grains were selected by means of a Swift point counter, and using this a sampling grid was designed for each slide so that the 250 grains were spread over at least 75% of the section. The grain at the intersection of the cross wires was taken where possible, but when this coincided with an indistinct grain or the cement, the one nearest the centre in the top left hand quadrant was measured. The cement and micas were neglected.

The distributions were examined by Doeglas' (1946, 1950) graphical method and also by calculating statistical parameters. These two methods have been used extensively for studying the results of sieve and pipette analyses, and can be applied to thin section data. The difficulties involved in comparing the results of the different techniques are discussed below (p. 112).

The measurements were grouped into half phi classes using Krumbein's phi scale (Krumbein, 1936), and cumulative curves plotted on probability paper. Doeglas used an arithmetic scale since he found that this usually gave straighter lines. However, in this case the logarithmic phi scale was prefered since it yielded straighter cumulative curves, than the arithmetic scale. Figs. 103-104 and 105 show the same results plotted on the different scales for comparison.

Folk and Ward's (1957) Inclusive Graphic Measures were used in the statistical analysis, and these were derived from readings on the curves.

b. Reproducibility.

The reliability of the experimental method was tested by duplicating the analyses on three slides of the coarse to medium-grained sandstones (type I) and comparing their means (Mz). The same experimental conditions were maintained throughout, though the grid arrangement was altered slightly in the repeats to prevent selection of exactly the same grains. The differences between the means of the different specimens are due to a number of factors the most important of which are : 1) inhomogeneity of the parent sediment, and 2) the experimental technique. However, the differences between the originals and repeats are due entirely to the experimental technique and are an indication of its reliability.

Table 8 shows the Mz values obtained.

Table 8

Specimen	A (Originals)	B (Repeats)
S.42	1.23	1.22
S.35	1.50	1.54
B.C.18	1.61	1.58

A statistical measure of the lack of reliability may be obtained from $(\frac{1}{2} S_d^2)^{\frac{1}{2}}$, where S_d^2 is the variance of the differences between pairs. Here $(\frac{1}{2} S_d^2)^{\frac{1}{2}} = .0254$.

This may be compared with $(S_A^2 + S_B^2)/2^{\frac{1}{2}} = .196$, which is the average standard deviation of the Mz values themselves (Kenney and Keeping, 1954, p. 187).

The variances can be compared by applying the F test to see if the average variance of the Mz values is significantly greater than the variance of the differences between pairs.

$$F = \frac{(S_A^2 + S_B^2)/2}{S_d^2}$$

$$\text{Here } (S_A^2 + S_B^2)/2 = .0386$$

$$\text{and } S_d^2 = .0013$$

$$\text{therefore } F = \frac{.0386}{.0013} = 29.69.$$

There are 4 and 2 degrees of freedom in this case, and the value of F at the 5% level of significance is 19.25, while at the 1% level it is 99.25. The calculated value of F exceeds the 5% level but not the 1% and so the difference in variance is significant at the 95% level of testing.

In other words the experimental technique is satisfactory since the average variance of the Mz values is significantly greater than the variance due to the experimental technique alone.

c. Thin section corrections.

The size distribution derived from a thin section is usually slightly different to the size distribution of the same sediment by sieving. Many attempts have been made to bring the two methods into coincidence and most of the effort has been directed towards finding a mathematically derived correction factor. This approach has been employed by Krumbein (1935), Greenman (1951, a and b) and Packham (1955), amongst others.

Rosenfeld, Jacobsen and Ferm (1953) investigated the difficulties involved in a theoretical approach and listed 15 factors which they considered contributed to the discrepancy between the two techniques. All the theoretical methods consider only a few of the factors involved and fail to bring the two techniques into agreement. In view of this they favoured a practical approach and tried to measure the difference between the distributions without isolating the factors involved. The correction factor thus obtained holds only for the conditions of the experiment and was found to vary for sandstones with different compositions and size distributions.

Friedman (1958) employed a similar approach to establish a correlation between sieve and thin section analyses. He designed a graph paper which permits the construction of a sieve size cumulative frequency curve from thin section data without mathematical conversions.

However, the samples from the Hitra and Smøla beds are of very different composition to any of those studied by either Friedman or Rosenfeld, Jacobsen and Ferm and so neither method can be used with any certainty. In view of this there is at present no satisfactory way of converting the thin section data used in this study to sieve distributions, and so the results are left 'uncorrected'.

However, Rosenfeld, Jacobsen and Ferm showed that :

1) uncorrected thin section data yield coarser sizes than sieving; and

2) cumulative curves determined by both techniques are generally parallel to one another.

In view of this it is reasonable to assume that it is valid to compare thin section curve characteristics with sieve curves, providing allowance is made for different mean sizes.

A. HITRA.

1. Graphical analysis.

The graphs derived from the size frequency data of the Hitra sandstones and siltstones are shown in figs. 106-109. They have been divided into four groups labelled types I - IV for convenience. Type I corresponds to the coarse to medium-grained sandstones with trough or flat-bedding (p. 51), and type II to the medium to fine-grained sandstones with flat-bedding. Types III and IV are made up of analyses of the sandy siltstones, the lenticles of fine sand (III) being analysed separately from the surrounding silt (IV). Clay was neglected from the considerations and so the type IV distributions merely show the coarser fraction of the sediment.

Fig. 110 is a zone diagram of the curves shown in figs. 106-109. It can be seen that the four types occupy distinctive areas on the diagram and only overlap in parts, which demonstrates that the lithological types described above (pp. 49-51), have distinctive grainsize distributions.

Examination of the zone diagram and the graphs from which it was derived shows that the curves approximate to straight lines (especially in the range 1 - 99%). This means that the distributions are nearly log normal, since they are plotted on a logarithmic scale. In addition the curves tend to be parallel to one another, and this is not only true for samples of the same sediment type, but also between types. The coarser sediments show slightly less sorting than the finer ones but the difference is very small. Clearly the sediments have undergone approximately the same degree of phi sorting regardless of grainsize.

There can be little doubt that the different deposits were derived from the same source. The current directions in the coarse to medium sandstones and the sandy siltstones are in agreement (p. 96) and the various lithologies are intimately interbedded. Thus detritus from a single source must have split up to give sediments with the size distributions shown in the graphs.

Doeglas (1946, 1950) considered problems of this type and evolved a theory of sedimentary differentiation. This may be summarised briefly refering to fig. 111. Consider a bottom sediment with a nearly Gaussian normal distribution 'c'. If the velocity of the current increases the finer grains will be winnowed out so that the sediment remaining will have a distribution represented by the curve 'r' (in this case grains less than about .35 mm have been winnowed out). Now let the curve 'c' represent the distribution of a sediment travelling in suspension. A decrease in velocity and hence capacity will cause the deposition of the coarsest material so that the suspension will have the distribution 't_1'. With further decreases the suspension will have the distributions t_2, t_3, t_4, etc. If particles between t_1 and t_2 settle out from a suspension, the resulting deposit will have a distribution 's'. These theoretical distributions do occur in nature and Doeglas' theory provides a convincing explanation of them.

However, it is clear that this does not explain the Hitra distributions. Doeglas did not demonstrate how his original normal distribution 'c' came about, and differentiation merely causes deviations from the straight line. To explain the Hitra sediments we require a mechanism which will <u>produce</u> straight line log normal distributions.

In 1957 Postma published a study of the grainsize distribution of sands in the Dutch Wadden Sea, based on some 2000 bottom samples. He found that the distribution curves tended to be approximately straight lines when plotted on phi/probability paper. Moreover, the curves tended to be roughly parallel to one another and this frequently held for sediments from different environments as well as for samples from, e.g., the same tidal channel or shoal (figs. 112 and 113). This compares exactly with the relationships in the Hitra sediments and suggests that a similar mechanism was responsible for the differentiation in both cases.

Postma discussed his results in the light of factors known to operate in the shallow tidal Wadden Sea area. Although it is generally assumed that sand is transported from the North Sea to the Wadden Sea interior, this is negligible compared with the to and fro transport caused by the tides. The current velocities present are theoretically quite adequate to erode and transport all grainsizes, and determination of the maximum grainsizes of suspended matter in water from different Wadden localities shows that this is the case in practice. Although coarse sand is normally transported in the channels it may not be commonly transported on the flats. However, it will certainly be moved during strong winds, and everywhere the turbulence is likely to be adequate to cause intensive transport from time to time. Thus the grainsize distributions cannot be the result of simple winnowing and redeposition of the finer grains, but are rather the result of a repeated process of selection so that the grainsizes become completely adapted to the areal turbulence differences. Consider grains of a particular diameter : they will not be deposited where the turbulence is too great and will be winnowed out more easily than the large grains. They will not reach the quiet places as easily as the smaller grains, and so will be concentrated in areas of intermediate turbulence. Different grainsizes will have maxima at different places, though the smaller grains, due to their greater transportability, will be dispersed over a larger area and show less pronounced maxima. The frequency curves will reflect the areal distribution of the individual grainsizes and the sediment will therefore be unimodal and the grainsize spectrum will be broader when the sediment is coarser.

The Hitra size distributions could have been produced by a mechanism similar to that outlined above, though it is impossible to say whether it was identical in detail. The presence of lens and flaser bedding supports a tidal origin.

2. Statistical analysis.

Statistical analysis was conducted to provide quantitative data about the sediments. This brings the results into line with the approach frequently employed in America, where it has been shown that size parameters can help in distinguishing one environment from another (see e.g., Inman and Chamberlain, 1956).

Values for the phi mean size (Mz), sorting (standard deviation) (σ_I), Skewness (Sk_I), and kurtosis (K_G), were calculated from readings of the 5th, 16th, 25th, 50th, 75th, 84th, and 95th percentiles using the formulae suggested by Folk and Ward (1957). The parameters are thus based on readings taken over 90% of the distribution. They could have been calculated by the method of moments, but the graphical approach is nearly as accurate and very much quicker. The values of the percentiles and the size parameters are tabulated in Appendix II.

Mean size (Mz).

The mean size varies from 4.86ø in the finest type IV siltstone to .40ø in the coarsest sandstone examined.

Sorting (Standard deviation). (σ_I).

The range of values of sorting is very limited (.48 to .99). Folk and Ward suggested that values between .35 and .50 should be described as well sorted, while those between .50 and 1.00 should be termed moderately sorted. Only one of the Hitra samples falls into the well sorted category (S.28F, of type IV), and the remaining samples may be described as moderately sorted.

Skewness (Sk_I).

Folk and Ward set the following verbal limits on skewness values : -1.00 to -.30 very negative skewed; -.30 to -.10 negative skewed; -.10 to +.10 nearly symmetrical; +.10 to +.30 positive skewed etc.

An inspection of Appendix II shows that the majority of the Hitra samples are nearly symmetrical. Less than a third of the 34 samples are positvely skewed, none are negatively skewed and only one may be described as very negatively skewed (S.28F).

(<u>Kurtosis K_G and K'_G</u>)

Folk and Ward set the following verbal limits on kurtosis measure : under .67, very platykurtic; .67 to .90, platykurtic; .90 to 1.11, mesokurtic; 1.11 to 1.50, leptokurtic; 1.50 to 3.00, very leptokurtic; over 3.00 extremely leptokurtic. Inspection of Appendix II shows that all of the type IV sediments are platykurtic with the exception of S.95F, which is very platykurtic. Of the remaining samples, S.95C is platykurtic but the rest are meso or lepto-kurtic. There are nearly three times as many mesokurtic as leptokurtic samples.

The distribution of K_G in sediments is strongly non normal and therefore the values were normalised during the transformation:

$$K'_G = K_G/(K_G + 1)$$

The K'_G values are used in all further considerations.

<u>Inter-relations of the size parameters</u>.

The inter-relations of the size parameters were studied graphically by means of scatter diagrams.

<u>1. Mean size versus sorting</u>

This is shown on fig. 114, and the broken line encloses the main concentration of points. It can be seen that there is a general decrease in the degree of sorting with increasing size, although inspection of the σ_I scale shows that this decrease is slight.

Folk and Ward found much more marked changes in their study of the

Brazos River Bar. They suggested that if the range of grainsizes is large enough the trend of mean size versus sorting should be a broadened 'M' shape. If only a limited range is available a 'V' or inverted 'V' shape results. In this case, if the broken line is neglected, it can be seen that the points are distributed so as to suggest a very rough 'V'. However, this may be fortuitous and the trend could equally well be linear.

The limited change in σ_I shows that the factors which normally produce changes in sorting with mean size were only weakly active during the deposition of the Hitra beds. This is reflected in the parallelism of the distribution curves discussed above.

2. Mean size versus Skewness.

The relationship between mean size and skewness is shown in fig. 115. The change in skewness is very slight, but there seems to be a general tendency for a predominance of slight negative skewness to give way to slight positive skewness with increasing size. However, the changes are very small and the majority of the skewness values fall in the 'nearly symmetrical' range.

Folk and Ward found a clear sinusoidal trend in the Brazos River bar and the variation in skewness was very large compared with that under consideration here. This suggests that the factors which normally produce changes in skewness were not active during the deposition of the Hitra beds. It is interesting that the Wadden Sea sediments studied by

Postma (1957) also had approximately symmetrical distributions throughout, although no attempt has been made to explain this.

3. Mean size versus kurtosis.

This relationship is shown in fig. 116. The type IV sediments have somewhat lower K'_G values than the rest of the samples, but otherwise there is roughly horizontal trend showing that there is no regular change in kurtosis with increasing size.

B. SMØLA.

1. Graphical analysis.

Analyses were conducted on the lenticles of sandstone in the conglomerates, and the curves are shown in figs. 117 and 118. The locations of the specimens studied are given in Appendix I. The 'K' type sediments, shown in fig. 118 and zoned in fig. 117, are a closely related group of sandstones collected at regular intervals across the Edøy and Southeast Kyrhaug Conglomerates on Kyrhaug. The bimodal sample K.14 is one of this series of specimens but it differs, and does not fall into the well defined zone. Under the microscope it can be seen to consist of fine sand with larger grains lying along certain horizons. However, it is an isolated example and no other lenticles were found with similar distributions.

Gl.3 is a sample of a typical sandstone lenticle from the Glasø Conglomerate, and Gl.1 and O.1 are specimens of fine sandstone from near the base of this conglomerate.

The curves indicate that the distributions tend to be roughly log normal, and that the 'K' type sediments are better sorted than the typical Glasø sandstone (Gl.3). The parallelism between Gl.1, O.1, and the 'K' zone is of no significance, since they may be from different sources.

2. Statistical analysis.

The values of the percentiles read from the graphs are tabulated in Appendix II together with parameters calculated from them.

The mean size (Ms) varies from 3.99ø in the finest sediment examinated to .79ø in the coarsest, and all of the samples are moderately sorted, except K.14 which is poorly sorted. Most of the distributions are nearly symmetrical or positively skewed, but K.14 is very negatively skewed. The kurtosis shows very little variation and all the values are mesokurtic.

Inter-relations of the size parameters.

The relationship of the mean size to the sorting, skewness, and kurtosis are shown in figs. 119-121 respectively. No distinct trends can be discerned.

3. Conglomerates.

Size analyses were not conducted on the conglomerates because of the practical difficulties. However, the average and maximum pebble sizes were recorded in the field, and details of the latter were mentioned in the description of the stratigraphy (chapter II). Fig. 122 shows the variation in maximum pebble size throughout the succession. The largest boulders occur at the base of the Glasø Conglomerate and above this there is a marked drop. The maximum size then gradually decreases throughout the rest of the succession from about 1 m. to 30 cms. The low value between 1000 and 2000 m. represents the conglomerate in the Northwest Kyrhaug Formation.

CHAPTER VI.

PETROGRAPHY.

VI. PETROGRAPHY.

Introduction.

Details of the petrography of the sediments are recorded in this chapter. The composition of the sandstones and siltstones was studied qualitatively and quantitatively under the microscope, and the results are given in sections A 1 - 3 and B 1 and 2.

Field estimates of the compositions of the conglomerates are given in sections A 4 and B 3, while the petrography of the pebbles (based on a detailed examination of more than 130 thin sections), is considered in sections A 5 and B 4. There are many pebble varieties even within the petrographical groups and examples of the main types are described. The percentage of critical minerals in the pebbles was estimated roughly by point counting (500 points) when this was necessary to classify the rock, and in some cases the thin section work was supplemented by staining the potash felspar in polished sections to facilitate determination of the potash felspar/plagioclase ratio. The technique used was that of Chayes (1952) and Broch (1961).

Some of the pebbles are compared with local pre-Devonian rocks but this is not done in every case since it demands a more intimate knowledge of the geology of the Trondheim region than is possessed by the writer.

A. HITRA.

1. Mineralogy of the coarse to medium-grained sandstone.

Examination under the microscope shows that the coarse sandstone of the b formation in the Aune Group, is composed of detritus which was probably derived from the local diorite. However, the other Hitra sandstones have a different composition and examination in thin section shows that the main constituents are, grains of quartz and felspar and fragments of plutonic and volcanic or hypabyssal rocks. They are tightly packed and set in a matrix of predominantly chemical origin. Fig. 123 shows a typical example.

Comparison with visual charts (Dmitrieva et al., 1962) shows that the roundness of the grains rarely exceeds .25 and they may be described as angular or subangular. Fragments of volcanic and hypabyssal rocks are generally slightly better rounded than the other grains.

The rock is frequently cut by thin ($<$ .2 mm.) veins of quartz, quartz and carbonate, or carbonate. The secondary quartz sometimes grows in optical continuity with detrital quartz grains. Often, the rock is cut by shear planes (usually less than .5 mm. thick), which contain brecciated grains set in a fused groundmass.

Quartz.

The quartz grains are always strained and have undulose extinction and numerous trains of bubbles (Böhm lamellae). Other inclusions present are minute needles and irregular opaque specks.

Strained quartz is sometimes considered indicative of a metamorphic source, but this is unacceptable here, since the same phenomenon is present in the quartz of igneous pebbles. Hansen and Borg (1962) have shown that strain lamellae can develop in unmetamorphosed sediments as a result of comparatively weak tectonic forces. In this case the strain was probably imposed during the tectonic history of the Hitra beds.

Felspar.

The dominant felspar is usually plagioclase which may be untwinned or twinned on any of the usual laws (e.g. albite, carlsbad, combined carlsbad and albite, or pericline). It is usually andesine with a composition about $Ab_{64}An_{36}$. The predominant potash felspar is microperthite, and orthoclase and microcline are much less common.

The felspars sometimes contain inclusions, principally of quartz and epidote. They are always clouded and sometimes contain flecks of sericitic mica. The effects of post-depositional straining are widespread and it results in, cracking and disruption of the grains, bending of the twin lamellae, and somewhat undulose extinction.

Plutonic rock fragments.

Coarsely crystalline fragments composed of quartz and felspar occur in all the sections examined. The fragments sometimes contain a little mica or amphibole in addition, but this is not common. Epidote occurs more frequently. The mineralogy and texture compares well with that of the plutonic pebbles examined and there can be no doubt that the grains are fragments of plutonic rocks.

The texture of the coarser polycrystalline quartz grains compares favourably with the quartz in plutonic rocks, and so these are included under this heading. No evidence was found to suggest that they are fragments of metamorphic rocks.

The quartz and felspar in the fragments is identical to that of the discreet grains and so the description will not be repeated.

Volcanic and hypabyssal rock fragments.

Both acid and intermediate fragments are represented but the acid ones are always predominant. These usually consist of micro- or cryptocrystalline quartz and felspar, sometimes with finely divided green chlorite and iron ore. Fine grained epidote is sometimes present and is probably a secondary mineral. Euhedral or subhedral phenocrysts of felspar occasionally occur in the fragments, and exceptionally anhedral quartz phenocrysts can be seen. Petrographically the fragments compare well with the pebbles of quartz porphyry (p. 147) and the grains without phenocrysts are clearly pieces of the groundmass of this rock.

Frequently the 'groundmass' fragments are partially or completely replaced by a fine interlocking quartz mosaic of grainsize less than .05 mm., and there is often no trace of the original texture. When the replacement is complete, the grains could be mistaken for 'chert', but comparison with pebbles shows that they are likely to be pieces of the groundmass of silicified quartz porphyry (p. 148). The fragments show all degrees of replacement.

The intermediate grains consist of small laths of andesine felspar with a composition of approximately $Ab_{66}\ An_{34}$, together with chlorite and iron ore. Epidote may also be present. The grainsize of the component minerals is usually less than .1 mm.

Metamorphic rock fragments.

There are very few grains which can be identified as metamorphic rocks. However, there are occasional schistose fragments made up of an interlocking mosaic of fine-grained ($<$ .02 mm.) quartz and felspar, with abundant chlorite or muscovite mica preferentially orientated so as to impart a foliation. A few crystals of epidote are present in some of the fragments.

The sandstones contain occasional rounded grains made up entirely of epidote and quartz. These may be the metamorphic rock 'epidosite' but are more likely to be fragments of plutonic rocks replaced by epidote.

Sedimentary rock fragments.

Sedimentary rock fragments are not common. Some pieces of very fine-grained black silt are present and there are a few fragments of sandstone, with grains of quartz, highly clouded and sericitised felspar and interstitial chlorite.

Micrographic intergrowths.

Grains made up of a micrographic intergrowth of quartz and felspar are scattered throughout the sandstones.

Mica.

The detrital micas include muscovite, biotite, and chlorite. They occur as flakes up to about .5 - 1 mm. long, which are randomly orientated and scattered throughout the sandstones. They are often bent and have undulose extinction due to compaction and tectonic straining.

Biotite is not common, but differs from the usual deep brown variety : it appears to be 'bleached' and is a much paler brown. It frequently alters to a green or almost colourless chloritic mineral.

In some cases the micas have a little epidote along some of the cleavage planes and they may have inclusions of apatite and iron ore.

Similar types may be seen in many of the pebbles examined in thin section.

Other detrital minerals.

The following minerals occur in accessory amounts, as grains generally about . 1 - .2 mm. in diameter.

Sphene is present in nearly all sections as irregular or sometimes approximately euhedral crystals.

Detrital epidote occasionally occurs as rounded polycrystalline grains, while rounded grains of apatite and garnet are extremely rare and only present in a few sections.

Ragged, detrital grains of amphibole, pleochroic from blue-green or green to pale brown, are present in some of the slides examined.

Magnetite is the commonest opaque mineral and it occurs as angular grains occasionally rimmed with sphene. Sometimes ilmenite, altering to leucoxene, is present.

Pyrite is present in most sections and is frequently accompanied by a translucent red-brown alteration product. The grains are usually irregular and although some are clearly authigenic (fig. 124), others could well be detrital.

Hematite is not common, but occurs as finely divided translucent material in the Aune Group.

Matrix.

The matrix between the sand grains is very indistinct and is of variable composition. It is generally fine-grained and is made up of small crystals of secondary quartz, epidote, and chlorite. The proportion of the minerals varies widely from sample to sample, but all three are usually present. The quartz occurs as an interlocking mosaic of small grains which sometimes grow in optical continuity with the detrital quartz grains. Green chlorite occurs as small interstitial grains, and epidote, which is frequently the commonest mineral may either be finely divided or present as anhedral crystals up to about .3 mm. across. The textures indicate that the minerals are not detrital.

Epidote and chlorite have been found in the matrix of other Norwegian Devonian sandstones. Bryhni (1964, p. 16), following Helland

and Kolderup, suggests that they formed at the expense of clastic amphibole and mica.

Carbonate is present in many sections. It forms small patches which 'corrode' the surrounding quartz and felspar grains. In some sections the entire matrix is of carbonate but this is unusual. In one example (OL.1) it has formed at the expense of other minerals, particularly felspar and rock fragments, and the remaining grains are corroded and veined.

2. Mineralogy of the finer sediments.

The same minerals are present in the finer sediments as in the coarse to medium-grained sandstones, although the proportions differ. With decreasing grainsize there is an increase in the tenor of quartz and a marked decrease in rock fragments. On the whole there appears to be more clastic mica in the finer sediments.

The nature of the matrix also differs. In the medium to fine-grained sandstones, quartz, chlorite, epidote and carbonate are present as in the coarser sediments, but generally there is rather less chlorite and epidote. However, in the finer sandstones and siltstones the difference is even more marked and epidote is very sparsely distributed. Patchy carbonate is present in some cases but the matrix usually consists of finely divided silica and chlorite. A little sericitic mica can be seen in the finest sediments.

Typical examples are shown in figs. 125-127.

3. Modal analysis.

The quantitative composition of the sandstones was studied in order to obtain information about the nature of their source and to see if there were any lateral or vertical variations within the area mapped. The samples selected for modal analysis were widely distributed, but were restricted to coarse to medium-grained sandstones to facilitate intercomparison and also to keep operator variance to a minimum, since smaller fragments are often difficult to identify.

Thin sections were analysed on a Swift point counter, and in each case 1800 points were counted over an area of 300 $mm.^2$. Two traverses were made per millimeter and the interval between points in each traverse was .3 mm. The number of components was restricted to eleven : quartz, plagioclase, untwinned felspar, microperthite (including microcline when present), detrital mica, plutonic rock fragments (including polycrystalline quartz), volcanic and hypabyssal rock fragments, sedimentary and metamorphic rock fragments, micrographic intergrowths, accessory minerals, and matrix. Indistinct grains were included with the matrix. The results are given in Appendix III and the localities of the specimens refered to are listed in Appendix I.

Soloman (1963), following Hasofer (1963), has shown that the counting and sampling errors in modal analysis may combine to give a variance equal to or less than :

$$\frac{44\ p\ a^3}{R\ A}\left[1 + 5.8\left(\frac{R}{a}\right)^3\right]$$

where A = measurement area, a = grid spacing, R = grain radius, and p = the percentage of the particular mineral in the rock. It can be seen from Appendix III that the percentage of a mineral is usually less than 20%; thus assuming p = 20%, R = .25 mm., A = 300 mm.^{2}, and a = .4 mm., the variance,

$$\sigma^2 \leq 1.81$$

If there is as much as 25% of the mineral in the sample,

$$\sigma^2 \leq 2.26$$

Ternary diagrams.

Selected components were plotted on ternary diagrams (figs. 128 and 129). Fig. 128 demonstrates that all except one of the samples fall in the 'subgreywacke' field as defined by Pettijohn (1957, p. 291), since less than 15% of the rock matrix is of detrital origin and the rocks cannot be termed greywackes. The matrix values in Appendix III are higher than this, but they include the unidentifiable indistinct grains and non-detrital carbonate cement. The epidote, chlorite and quartz could have been formed by the break-down of detrital minerals, but it is difficult to estimate the percentage of detritus present originally. However, it was certainly less than the critical 15%.

Pettijohn separated the arkoses and subgreywackes by means of a provenance factor, assuming that plutonic rocks contribute mainly grains of quartz and felspar whereas the finer-grained supracrustal contributions are rock fragments. Thus arkoses have more felspar than rock fragments due to derivation from a plutonic terrain. However, although rock fragments are more abundant than felspar in the Hitra sandstones most of these fragments are from plutonic rocks (fig. 129). Thus, the sediments were derived from a dominantly plutonic area and so they could be termed arkoses rather than subgreywackes, on this basis.

Indices.

Table 9 gives the values of a number of indices calculated from the modal analyses.

Table 9

Sample	Indices.			
	R	I	F	M
S.6	.53	3.15	.51	.46
S.35	.47	3.40	1.31	.50
S.42	.71	2.35	.67	.35
S.51	1.07	1.31	.76	.32
A.8.1	1.58	1.01	1.07	.31
A.6.1	1.01	1.41	1.23	.42
Kj.1	.76	2.67	1.41	.37
R.1	1.04	2.91	1.72	.27
C.6	1.35	2.02	1.17	.26
B.1	1.39	1.54	.91	.29
B.2	.83	1.25	1.60	.32
Ol.1	1.19	.58	1.97	.76
Fl.1	.83	2.67	1.36	.38
V.4.2	.94	1.94	1.37	.30
F.C.35	1.32	1.83	1.89	.29
B.C.18	1.01	3.34	1.49	.36
F.5.1	.81	3.04	1.82	.38
G.C.33	1.88	.87	.81	.24

The total rock fragment index (R) (Allen, 1962, p. 669), was calculated from :

$$R = \frac{\text{Percentage rock fragments}}{\text{Percentage quartz + Percentage felspar}}$$

The values indicate that the proportion of rock fragments present is high and is frequently in excess of the discreet grains of quartz and felspar.

The proportion of plutonic to volcanic and hypabyssal rock fragments is expressed in terms of an igneous rock index (I), where

$$I = \frac{\text{Percentage plutonic rock fragments}}{\text{Percentage volcanic and hypabyssal fragments}}$$

The values indicate a high proportion of plutonic fragments, and hence derivation from a dominantly plutonic terrain.

A felspar index (F) was calculated from:

$$F = \frac{\text{Percentage plagioclase (twinned)}}{\text{Percentage untwinned felspar + Percentage microperthite.}}$$

A value greater than unity indicates a predominance of plagioclase, but a value less than unity does not necessarily indicate a predominance of potash felspar, since the untwinned felspar can be either plagioclase or potash. However, 13 out of the 18 values are greater than unity indicating that the sandstones have a predominance of plagioclase felspar and were probably derived from a terrain where this was plentiful.

The maturity index (M) is based on the ratio of quartz to other grains (Walton, 1955, p. 348), thus,

$$M = \frac{\text{Percentage quartz}}{\text{Percentage other grains}}$$

All the values are very low indicating that the sediments are very immature.

Lateral and vertical variations in composition.

The results of the modal analysis and the indices calculated from them indicate limited variation in composition and hence provenance. However, the results show some variability, but this could not be related to the geographical or stratigraphical position from which the sample was taken.

4. The composition of the Conglomerates.

The proportion of different pebbles present in the conglomerates was estimated visually in the field and the results are summarised in table 10. The following abbreviations are used: NK = not known; VR = very rare; R = rare; C = common; A = abundant. It was impractical to make more precise quantitative determinations, since the local variation within a conglomerate is often so large that many 'counts' would have to be made before an estimate of the overall composition could be obtained. Moreover the range in pebble sizes is so great that it would be difficult to get an accurate estimate of even the local composition by the conventional method of pebble counting.

Inspection of the table shows that the Vollan and Balsnes conglomerates have very similar compositions and contain many different rock types. Pebbles of plutonic rocks are not common in the Upper Vollan Conglomerate, and it also differs from the other conglomerates in having a lot of intraformational siltstone fragments. The basal Aune Conglomerate is made up almost entirely of dioritic material.

Table 10.

Pebble type	Conglomerate			
	Aune	Vollan	Upper Vollan	Balanes
Granite	R	C	R	C
Granodiorite	NK	C	NK	C
Diorite (and tonalite)	A	C	R	C
Xenoliths from diorite	C	R	NK	R
Meladiorite	NK	C	NK	C
Trondhjemite	NK	R	NK	R
Quartz porphyry	NK	C	C	R
Dolerite	NK	NK	R	NK
Intermediate volcanic and hypabyssal rocks	NK	C	C	C
Gneiss	NK	R	NK	R
Jasper	NK	NK	NK	R
Limestone	NK	NK	NK	R
Sandstone	NK	NK	NK	VR
Siltstone	NK	NK	C	VR

5. Petrography of the pebbles.

The main variations in the petrography of the pebbles are discussed below.

a. Granite.

According to Johannsen (1939) granites are acid plutonic rocks in which 50 to 95% of the felspar is potash felspar. Pebbles of this composition occur frequently in the Hitra conglomerates and four of them were examined in thin section, (A.C.8, F.C.3, F.C.24, and F.C.31).

A.C.8, F.C.3, and F.C.24, are coarse-grained grey or reddish-grey leucocratic rocks composed principally of quartz and felspar with hypidiomorphic texture. F.C.24 is shown in fig. 130.

The quartz is present as anhedral grains, between .5 and 2mm. across, which usually have undulose extinction due to straining. Inclusions are present as trains of minute bubbles and as small needles and irregular specks.

The subhedral grains of felspar are always clouded and sericitised to some extent. The principal felspar is microperthite but othoclase and microcline are usually also present. The plagioclase is andesine and it is twinned on any of the common laws. It is sometimes zoned.

The principal dark mineral is mica, which never comprises more than 10% of the rock. Bent crystals of green chlorite altering after pale brown biotite, are present in all the slides examined and F.C.3 also contains muscovite. The chlorite is often 'dirty' and associated with small irregular grains of magnetite. Accessory epidote is present together with secondary carbonate.

F.C.31 is porphyritic granite with large pink phenocrysts of microperthite (1 - 2 cms. long) set in a hypidiomorphic groundmass of of quarts and felspar (grainsize ca. .25 mm.). The phenocrysts contain inclusions of zoned sodic andesine, and this mineral is abundant in the groundmass although it is usually unzoned. A little microperthite is also present in the groundmass. A few subhedral hornblende crystals occur and they are sometimes associated with a little green chlorite. The most abundant accessory mineral is sphene, which occurs as fairly large subhedral grains and there is a scatter of small rounded apatite crystals, and rare cubes of pyrite. Sometimes the sphene and chlorite are rimmed by coronas of an unidentified pleochroic red-brown mineral with a high refractive index.

b. Granodiorite.

Granodiorites are plutonic rocks with quartz, felspar, and biotite, pyroxene or amphibole. Between 5 and 50% of the felspar is potash felspar and thus the monzonites are included within this group (Johannsen, 1939).

Pebbles of this composition are common in the Hitra conglomerates and typical examples were examined in thin section (F.C.19, F.C.26, F.C.28, F.C.32, B.C.15). They are mostly greyish or greyish-green in the hand specimen and sometimes have pinkish potash felspar, but F.C.32 is pink coloured throughout.

The rocks consist principally of a hypidiomorphic combination of quartz and felspar, with a grainsize of 1 - 2 mms. B.C. 15 has pink 1 cm. phenocrysts of microperthite in addition. The texture of F.C.26 is unusual, as the felspars are often rimmed with potash felspar (fig. 131).

Most of the slides examined show small patches of micrographic intergrowth.

The quartz occurs as anhedral grains which invariably show signs of straining. Irregular specks, minute needles, and trains of bubbles are present as inclusions.

The dominant felspar is subhedral or anhedral plagioclase, which is twinned on any of the common laws. It is clouded and sericitised to some extent, and the alteration increases towards the centre of the crystals, suggesting zoning. The composition varies from oligoclase to sodic andesine. The tenor of potash felspar varies widely between the limits of this group. It is usually microperthite but a little orthoclase or microcline are often present.

Dark minerals are not common and make up less than 5% of F.C.32, which may therefore be termed a 'leucogranodiorite'. However, there is never more than 10% in any of the other sections examined. The commonest dark mineral is 'dirty' green chlorite, which occurs as ragged crystals often associated with irregular magnetite grains, but F.C.26 has a little green hornblende also.

Muscovite mica is present in some of the slides examined.

F.C. 19 has a little aegirene, but the commonest accessory minerals are apatite, zircon, magnetite, and epidote which is often interleaved with the muscovite. Veins and patches of secondary carbonate occur in most sections.

c. Diorite (including tonalite)

Pebbles of dioritic composition are widespread in the Hitra conglomerates, and four samples were examined in thin section (A.C.2., A.C.2, B.C.17, and B.C.19). A.C.2 is shown in fig. 132.

They are coarse-grained (ca. 2 mm.) rocks which contain approximately equal proportions of light and dark constituents. The texture is hypidiomorphic but there are occasional small spots of micrographic intergrowth.

The main constituent is subhedral or anhedral plagioclase felspar which is invariably sodic andesine, twinned on any of the usual laws. There is always some clouding and sericitisation and this is frequently more intense towards the centre of the crystals suggesting zoning. Sometimes the alteration is extreme and determination is very difficult (B.C.17, B.C.19).

The quartz is always strained and occurs as interstitial anhedral grains. There is between 7 and 20% of it in the sections examined and so these specimens are 'tonalite' by Johannsen's definition. However, some of the other pebbles contain less quartz and are probably quartz diorites. The rocks are grouped together under the general heading of 'diorite' since there are all gradations between the types and they are very similar in appearance.

All the slides examined have between 5 and 15% chlorite, produced by the alteration of biotite. Epidote and sometimes muscovite are occasionally interleaved with the dark mica.

Green hornblende is present in some of the specimens as short ragged crystals but it is usually rather decayed and 'dirty'. Some of the crystals of hornblende in A.C.2 enclose relicts of augite.

Grains of magnetite are scattered throughout and may form 1 - 2% of the rock. They are frequently associated with the chlorite and hornblende.

Accessory minerals include, epidote, sphene, apatite, and hematite dust.

There can be no doubt that the pebbles are locally derived. Much of Hitra is composed of 'diorite' and the writer examined thin sections of specimens from the Aune district and also from Hestvika (eastern Hitra). They proved to be tonalites with between 10 and 20% quartz, and they are comparable with the examples described above. One specimen from the centre of the diorite mass (along the road from Sandstad to Melandsjø) is a quartz diorite (less than 5% quartz), but is otherwise similar.

d. 'Xenoliths' from the diorite

The conglomerates contain occasional small pebbles resembling xenoliths enclosed in the underlying diorite. In the hand specimen they are fine grained melanocratic rocks, the finer ones superficially resembling dolerites.

Six specimens were examined in thin section (A.C.6, A.C.9, F.C.5, F.C.9, B.C.16, 2 B.C.5). Mineralogically they are similar to the diorites described above and so this description will not be repeated. However, they are much finer grained, the average grainsize being about .5 mm., and are more basic in composition as between 40 and 50% of the rock is composed of dark minerals, principally hornblende.

In some cases the plagioclase tends to be calcic rather than the sodic andesine typical of the diorites. It is always clouded and sericitised and in some cases the felspars are almost completely pseudomorphed by fine sericitic flecks. They are rather poorer in quartz than the diorites described above and 2B, C.5 and B.C.16 contain none at all.

Examples of xenoliths in the diorite are shown in fig. 133 and a specimen from Hestvika (eastern Hitra) was examined in thin section (H.1.2). It compares precisely in texture and mineralogy with the pebbles. Figs. 134 and 135 show photomicrographs of specimens A.C.6 and H.1.2 for comparison. Some of the pebbles (e.g. F.C.9) still have pieces of the diorite attached.

e. Meladiorite.

Pebbles of a coarse-grained (1 - 10 mms.) melanocratic rock composed principally of amphibole and interstitial 'felspar' are common in the Vollan and Balsnes Conglomerates.

Eight specimens were examined in thin section. The texture is hypidiomorphic and the amphibole usually occurs as subhedral crystals. In most cases it is green hornblende but in one specimen (B.C.12) it is a pale green amphibole. Pyroxene is rare, but in one case (F.C.25) there are relicts within the amphibole.

The principal leucocratic mineral was originally felspar, but it has been so extensively altered that the crystals have been practically pseudomorphed by fine sericitic mica. Minute polysynthetically twinned relicts of felspar can be seen in F.C.23 and the maximum extinction angle shows that the felspar was originally andesine ($Ab_{52}An_{48}$).

Quartz is present as small interstitial grains in four of the eight specimens examined but it usually comprises less than 5% of the rock.

Chlorite, altering after biotite, is present in some of the slides and a little pyrite and magnetite are occasionally present.

F.C.25 contains a little of an unidentified translucent yellow brown mineral as an alteration of the amphibole. It is associated with magnetite.

Apatite, sphene, and hematite occur as accessory minerals.

The rock is difficult to name as the felspar is usually unidentifiable. However the pebbles may well be from amphibole rich phases of the diorite and so they are designated 'meladiorite' (Johannsen, 1939).

f. Trondhjemite.

Trondhjemite has been defined by Johannsen (1939), following Goldschmidt, as a leucocratic acid plutonic rock consisting essentially of soda rich plagioclase and quartz. It has a small quantity of mafic constituents and is wanting in potash felspar.

Two pebbles were found with this composition, F.C.10, from the Vollan Conglomerate and B.C.14 from the Balsnes Conglomerate. The lack of potash felspar was confirmed by staining.

F.C.10 is a greyish-white moderately coarse-grained rock with streaks of orange-red staining and an orange-red weathered surface. The texture is hypidiomorphic, but there is a distinct foliation caused by the concentration of the quartz along certain planes.

About 25% of the rock is quartz which occurs as strained anhedral grains.

Subhedral crystals of sodic andesine, twinned on any of the usual laws, make up over 70% of the rock.

A little green chlorite is also present and a few grains of apatite, magnetite and zircon occur as accessories.

BC.14 is a white medium-grained rock consisting principally of quartz and felspar. The texture is hypidiomorphic, but there are occasional small patches of micrographic intergrowth. The felspar is andesine and is always clouded and sericitised. Dark minerals are scarce, but there is a little 'dirty' green chlorite. Accessories include apatite, epidote, magnetite, and microcline, but there are only a few grains of each.

g. Quartz porphyry.

Pebbles of quartz porphyry are particularly common in the Vollan and Upper Vollan Conglomerates, and there are occasional pebbles in the Balsnes Conglomerate. They are all greyish or dark greenish-grey in colour, and there are no examples of the distinctive reddish quartz porphyry, typical of the Edøy Conglomerate. The pebbles vary in composition, and some representative examples are described below.

Specimen F.C.12 (fig. 136) is a very fine-grained dark grey rock with numerous large (3 mm.) phenocrysts of quartz and felspar.

The quartz occurs as rounded anhedral crystals which frequently have reaction rims. It is always strained and has undulose extinction and trains of minute bubbles. Minute irregular specks are also present.

The felspar phenocrysts are subhedral and most of them are of sodic plagioclase which is twinned on any of the usual laws, but a little orthoclase is also present. All the crystals are clouded and sericitised to some extent.

The microcrystalline groundmass contains twinned and untwinned felspar and a lot of silica, much of which must be secondary. Sericitic mica is scattered throughout the groundmass together with a little epidote, green chlorite and magnetite. Occasionally micrographic intergrowths are present and they sometimes form small spherulites.

F.C.33 (fig. 137) is similar to this specimen but the phenocrysts of quartz and felspar are frequently polycrystalline. Most of the felspar is andesine.

The groundmass consists of fine-grained ($<$ .05 mm.) silica with a little untwinned felspar and a scatter of small crystals of green chlorite, sericite, opaque minerals and secondary carbonate. There are occasional patches of rather coarser anhedral granular quartz in the groundmass.

Much of the silica in the groundmass of F.C.12 and F.C.33 must be secondary, but frequently the replacement is more extensive and the rock may be termed 'silicified' quartz porphyry. F.C.6 (fig. 138) is a typical example, and the whole of the groundmass has been replaced by anhedral grains of quartz (grainsize .05 - .025 mm), with a little twinned felspar. The rock has flow banding defined by planes with specks of hematite and chlorite.

The quartz phenocrysts have been completely recrystallised and consist of polycrystalline aggregates, which often have an elongate 'augen'-like form, 1 - 2 mm. long. The felspar phenocrysts are subhedral and are probably oligoclase.

Accessory minerals include pyrite cubes, epidote, and an unidentified colourless crystal with a high refractive index.

The specimens described above are typical of the quartz porphyry pebbles but there are gradations between these types. Often phenocrysts are not as common as in the examples cited.

h. Dolerite.

One small pebble of dolerite was seen in a slide (V.3.1) of the Upper Vollan Conglomerate, but no other examples were found.

The rock has well developed ophitic texture with laths of sodic andesine felspar about .4 mm. long. A little clinopyroxene is present, but pale blue-green amphibole is much commoner and is probably a secondary alteration product.

Similar alteration occurs in the Ordovician volcanics of Smøla described by Carstens (1924), and this suite may be the source of the pebble, although no dolerite has been found *in situ*.

i. Intermediate volcanic and hypabyssal rocks.

Pebbles of this type are common in the Hitra conglomerates. Many different varieties are present and some typical examples are described below.

Specimen F.C.13 (fig. 139) is a very dark green fine-grained rock with paler greenish 1 - 5 mm. phenocrysts of euhedral felspar. In thin section they can be seen to be zoned plagioclase, twinned on any of the usual laws, although the clouding and sericitsation are so intense that determination is impossible. The groundmass, which has an average grainsize of .1 - .2 mm., is composed of simple or twinned andesine laths, pale green amphibole, biotite, magnetite and a little green chlorite.

Specimen F.C.15 is a fine grained black rock with numerous ragged patches of epidote, up to about 1 cm. across. In thin section, it is clear that the polycrystalline epidote pseudomorphs felspar phenocrysts. Sometimes only the centres of the felspars are replaced, forming what may be termed "gefüllte felspäte". The original felspar was probably andesine. The groundmass consists essentially of small felspar laths about .1 mm. long, which are either twinned or untwinned. Green chlorite and some finely divided epidote are also present. Accessory minerals include apatite, sericite, sphene, and secondary carbonate.

F.C.29 (fig. 140) is similar. It is a fine grained dark green rock packed with numerous 2 mm. sperules and creamy-white euhedral felspar phenocrysts, 2 - 10 mms. long. The felspar phenocrysts are of andesine, twinned on the usual laws and they are often partially replaced by epidote, especially towards the centres, possibly because the felspar was zoned. The spherules are often completely replaced by epidote, but they frequently have a corona of radial chlorite. Some of the spherules are composed of calcite with epidote inclusions. The rock was clearly vesicular before replacement.

B.C.7 from the Balsnes Conglomerate, is a fine grained dark grey rock with very elongate, pale greenish felspar phenocrysts up to 1 cm. long, which appear to be preferentially orientated. They have been intensely sericitised and are indeterminable in thin section. The groundmass consists of small orientated felspar laths together with epidote and a little secondary silica.

B.C.9 is a dense dark grey rock composed of closely packed phenocrysts of bluish-green amphibole and of felspar. The latter was probably zoned plagioclase, but it has been almost completely sericitised. The amphibole is not fresh and occurs as discreet subhedral phenocrysts or as fibrous clusters pseudomorphing another mineral. The groundmass is of fine-grained ($<$ .1 mm.) quartz and felspar, but the quartz is probably secondary.

The pebbles considered in this section could have been derived from beds contemperaneous with the Ordovician volcanics of Smøla. Carstens (1924), does not describe any exact parallels, but porphyritic texture is common and the types of minerals and alterations are similar.

i. Gneiss.

Pebbles of metamorphic rocks are scattered throughout the Vollan and Balsnes conglomerates and several were examined in thin section.

Most of them are coarse-grained (.5 - 1 mm.) greyish or pinkish quartzo-felpathic gneisses, with weak foliation caused by the orientation of the dark minerals.

The dominant mineral is quartz which often shows typically metamorphic 'sutured' outlines and has undulose extinction, in thin section.

Felspar is always abundant, but the ratio of plagioclase to potash felspar varies markedly from specimen to specimen. They are all clouded and are usually sericitised to some extent. The plagioclase is usually oligoclase, twinned on the usual laws and the potash felspar is frequently microperthite, but orthoclase is dominant in some of the thin sections examined. Microcline is much rarer.

The dark minerals are usually scarce but there is always a little chlorite, altering after pale brown biotite, and a scatter of magnetite grains.

Muscovite is often present as well.

Accessory minerals include hematite dust, pyrite, sphene, apatite, zoisite, zircon, and epidote.

B.C.1 (fig. 141) has a greater proportion of dark minerals than usual and is distinctly banded. A lot of fresh (often greenish) biotite is present together with some hornblende.

k. Jasper.

Small pebbles of Jasper are scattered throughout the Balsnes Conglomerate. They are a bright red-brown colour and are cut by numerous thin white irregular carbonate veins. The facture is usually hackly. The pebbles were not examined in thin section.

Jasper occurs in the Trondheim district where it is connected with sulphide deposits (Holtedahl, 1960, p. 205), and this may be the source of the pebbles.

l. Limestone.

Small pebbles of limestone are scattered sparsely throughout the

Balsnes Conglomerate. They are composed of grey or very light grey microcrystalline carbonate.

Kjerulf (1879) recorded pebbles of limestone with encrinites and strofomena in the "conglomerate-sandstone series", but there were no fossils in any of the pebbles examined by the writer.

m. Sandstone.

One pebble of sandstone was found in the Balsnes Conglomerate. It is grey, weathering brown, and consists principally of fine-grained quartz.

n. Siltstone.

Pebbles of dark sandy siltstones are common in the Upper Vollan Conglomerate, and one example was found in the Balsnes Conglomerate. The fragments compare well with the Hitra sandy siltstones and this is clearly the source.

B. SMØLA.

1. Mineralogy of the sandstones.

The mineralogy of the Smøla sandstones is very similar to that of the Hitra sandstones, but on Smøla the cement is mainly carbonate. The grains are usually angular or subangular (roundness less than .25), and are often tightly packed. A typical sandstone is shown in fig. 142.

Quartz.

The quartz is similar to that in the Hitra sandstones, and is always strained.

Felspar.

The plagioclase felspar, which is twinned on any of the common laws or untwinned, is andesine with a composition about $Ab_{64}An_{36}$. The dominant potash felspar is microperthite and a little microcline is present in some of the thin sections examined.

All the grains are clouded and most of them contain small flecks of sericitic mica. They sometimes contain secondary carbonate. Occasionally alteration almost obliterates the original felspar.

Plutonic rock fragments.

The plutonic rock fragments are identical to those in the Hitra sandstones and so the description will not be repeated.

Volcanic and hypabyssal rock fragments.

These consist entirely of fragments of quartz porphyries and no intermediate fragments were observed. However, there are two distinct types, one of which is colourless in plane polarised light and the other a pale red-brown.

The colourless grains are commonest and compare well with those in the Hitra sandstones, described above. Silicified quartz porphyries are also represented, but they are not as common as on Hitra.

The red-brown grains are identical to the groundmass of the reddish quartz porphyry pebbles (p. 164).

Metamorphic rock fragments.

These are not plentiful, but there are occasional quartzo-felspathic metamorphic fragments which have a foliation imparted by chlorite or muscovite mica. The component grains are usually about .1 mm. across and the quartz is frequently elongated parallel to the foliation. One fragment shows distinctly undulose foliation.

Sedimentary rock fragments.

Sedimentary rock fragments are commoner than in the Hitra sandstones and most of them consist of fragments of siltstone and sandstone

The siltstone is very fine-grained and contains a lot of argillaceous matter. It frequently contains a lot of finely divided epidote. The fragments of sandstone contain grains of quartz, felspar, plutonic fragments, and abundant volcanic and hypabyssal fragments : they are similar to the pebbles of green sandstone which occur in the conglomerates.

Micrographic intergrowths.

A few grains with micrographic intergrowth of quartz and felspar are present.

Detrital mica.

Flakes of biotite, muscovite, and chlorite are present and they are frequently undulose in cross section, probably due to compaction.

In contrast to the Hitra sandstones, biotite is common. It is usually dark brown and sometimes almost opaque.

Other detrital minerals.

The following accessory minerals occur as grains .1 - .2 mm. across.

Detrital epidote is present as rounded polycrystalline grains.

Sphene is common as irregular or subhedral grains, but rounded grains of garnet are present in only a few of the thin sections examined.

Small ragged crystals of amphibole can be seen in some of the sections, and pale green amphibole can be present in the same thin section green hornblende.

Irregular grains of magnetite are scattered throughout, and hematite occurs as a red-brown dust within or on the surface of some of the sand grains.

Matrix.

The cement is mostly carbonate which is usually twinned. It may 'corrode' the quartz and felspar but not as extensively as in the Hitra sandstones.

A little silica cement is present in places.

The source of the grains.

Many of the grains in the Smøla sandstones compare well with those in the pebbles of green sandstone (p. 171) which occur in the Edøy and Southeast Kyrhaug Conglomerates. Most of the volcanic and hypabyssal fragments, except the red-brown grains, are likely to be from this source. Some of the quartz, felspar, and plutonic fragments, may also be second cycle grains, although there were undoubtedly contributions from other sources.

2. Modal Analysis.

Modal analyses were conducted on coarse to medium-grained sandstones from lenticles and beds within the Smøla conglomerates. The samples were analysed in exactly the same way as the Hitra sandstones, and the results are given in Appendix III.

Ternary diagrams.

Fig. 143 demonstrates that the sandstones fall in Pettijohn's (1957) subgreywacke field. The trend of the area occupied by the points indicates that the tenor of felspar is remarkably constant, in spite of variations in the ratio of quartz to rock fragments.

Fig. 144 shows the relationships of the various rock fragments. Plutonic fragments are only slightly in excess of the volcanic and hypabyssal. Sedimentary fragments are commoner than in the Hitra sandstones, which is to be expected in view of the abundant pebbles of sandstone in the Edøy and Southeast Kyrhaug conglomerates.

Indices.

Table 11 shows the indices calculated from the analyses.

Table 11.

Sample	Indices			
	R	I	F	M
O.5	2.19	.83	.50	.21
Gl.3	1.66	.99	.78	.33
K.NW.1	.60	1.32	.68	.98
E.1	.94	1.64	.91	.73
E.2	.57	1.08	.68	1.08
K.2	2.37	1.17	.16	.26
K.5	.70	2.17	.35	.97
K.9	.76	1.36	.65	.80
K.12	.86	1.46	.41	.64
K.16	1.58	.78	.39	.46

The total rock fragment index (R) varies from .57 to 2.37, and is probably related to grainsize.

The igneous rock index (I) indicates a slight predominance of plutonic fragments in seven samples, while the remaining three have values less than unity indicating slightly more volcanic and hypabyssal fragments.

The Felspar index (F) is always less than unity and is therefore not significant.

The maturity index (M) is very low indicating that the sandstones are very immature.

Lateral and vertical variations in composition.

The lateral variations in composition were not investigated, but the samples were chosen in order to study the vertical changes. Samples O.5 and Gl.3 are from the Glasø Conglomerate, K. NW.1 is from the Northwest Kyrhaug Formation, and the remainder are from the Edøy Conglomerate, with the exception of K.16 which is from the Southeast Kyrhaug Conglomerate.

The samples from the Glasø Conglomerate and the Southeast Kyrhaug Conglomerate have slightly higher total rock fragment indices than most of the others and the 'I' indices are less than unity indicating a slight predominance of volcanic and hypabyssal fragments. However the changes are not related to changes in the petrography of the conglomerates (see section 3), and the differences are slight : the ternary diagram show that the Smøla sandstones fall into a well defined group. This suggests that the sands throughout the succession came from a similar source and this was independent of the source of the pebbles in the conglomerates .

3. Composition of the conglomerates.

The composition of the conglomerates was discussed in chapter III, but the variations in the overall composition are summarised in table 12. The abbreviations are the same as those in table 10.

Table 12.

Pebble type	Conglomerate			
	Glasø	Northwest Kyrhaug	Edøy	Southeast Kyrhaug
Granite	R	NK	C	VR
Potash rich granite	R	NK	C	NK
Granodiorite	R	NK	NK	NK
Diorite (including tonalite)	A	A	R	NK
Trondhjemite	R	NK	NK	NK
Reddish quartz porphyry	R	NK	C	NK
Dolerite	VR	NK	NK	NK
Intermediate volcanic and hypabyssal rocks	C	NK	NK	NK
Metamorphic rocks	VR	NK	VR	C
Jasper	VR	NK	NK	NK
Carbonate rocks	R	NK	R	R
Sandstone	R	VR	A	A
Siltstone	C	NK	C	C

The 'granitic' pockets in the Glasø Conglomerate contain concentrations of a great variety of pebbles, principally, granite, potash rich granite, trondhjemite, and quartz porphyry.

4. Petrography of the pebbles.

The main petrographic variations are discussed below.

a. Granite.

Most of the pebbles of granite from the Smøla conglomerates are reddish coloured in the hand specimen. They consist of coarse-grained (1 - 3 mm.) quarts and felspar with a hypidiomorphic texture. There are a few small patches of micrographic intergrowth.

The quartz occurs as anhedral grains with undulose extinction. Trains of bubbles and minute irregular specks are present.

The felspars are all clouded and a little sericitised. Potash felspar is dominant either as orthoclase or microperthite. The plagioclase is twinned on the common laws and increased alteration towards the centre of the crystals suggests zoning. The composition varies from calcic oligoclase to sodic andesine.

The percentage of dark minerals never exceeds 10%, and in several of the specimens examined (e.g. O.C.7, K.6.11) it is less than 5%. According to Johannsen (1939) granites with less than 5% mafite can be termed 'leucogranites'. The principal dark mineral is green chlorite and it is often associated with magnetite.

Muscovite is also present in a few of the thin sections examined (e.g. K.2.5) and is sometimes interleaved with the chlorite (e.g. K.2.3).

Accessory minerals include apatite and secondary epidote and carbonate.

b. Potash-rich granite.

Pebbles of granite rich in potash felspar occur in the granitic pockets of the Glasø Conglomerate but are commoner in the Edøy Conglomerate. In the hand specimen the rock is coarse-grained (1 - 2 mm.) and varies in colour from bright reddish-brown to pale purplish-grey.

Five specimens were examined in thin section, and mineralogically they are simple, being composed essentially of potash felspar and quartz. The texture varies from hypidiomorphic to micrographic and in the latter the quartz/felspar intergrowths often radiate crudely around a central euhedral potash felspar, (fig. 145), The 'spherules' thus formed are usually about 2 mm. in diameter.

The quartz occurs as anhedral crystals or as part of the micrographic intergrowth, and always shows undulose extinction. Trains of bubbles and minute irregular inclusions are present. It usually comprises about 15 - 30% of the rock and most of the remainder is potash felspar.

The dominant felspar is always microperthite, but microcline and orthoclase are also present. The crystals, which are often euhedral or subhedral are all clouded and frequently slightly sericitised and carbonated.

Dark minerals are very scarce and never make up more than 5% of the rock. However, crystals of green chlorite are scattered throughout and they are often associated with irregular or rounded grains of magnetite. Hematite is present as a dust along cracks and crystal interfaces and imparts the colour to the rock.

Plagioclase is present as an accessory mineral and is usually less altered than the potash felspar. It usually shows well developed polysythetic twinning. The plagioclase in one thin section (O.C.1) was examined on the universal stage and the composition proved to be $Ab_{68}An_{32}$. Other accessory minerals include riebeckite (in specimen Gl.C.12), sphene, apatite, zircon, and interstitial grains of twinned calcite.

Pebbles of this composition were noted by Reusch (1914) who refered to them as 'syenite'. However, the present study shows that this is incorrect : the rocks are leucogranites rich in potash felspar.

c. Granodiorite.

Pebbles of granodiorite occur in the pockets in the ~~Glass~~ Glas Conglomerate, but no examples were found in any of the other conglomerates.

They are coarse-grained (1 - 2 mm.) reddish-brown rocks which consist principally of quartz and felspar with a hypidiomorphic texture.

The quartz occurs as anhedral grains which are strained.

The felspar is subhedral in form and is always clouded and sometimes sericitised. Most of it is andesine. The potash felspar is usually microperthite but orthoclase and microcline are sometimes also present.

The only dark mineral is a little green chlorite, and it is accompanied by a little muscovite in one of the sections examined (O.C.9).

Specimen Kr. C.1 has no dark minerals or muscovite.

Accessory minerals include, epidote, which is often interleaved with the mica, sphene, and hematite dust.

d. Diorite (including tonalite).

Pebbles of diorite are abundant in the Glasø Conglomerate and the Northwest Kyrhaug Formation, and are also present at the base of the Edøy Conglomerate.

Several pebbles were examined in thin section and mineralogically they are similar to pebbles from the Hitra beds so the description will not be repeated.

However, one specimen (Gl.C.7) contains accessory microperthite, and another (O.C.11) has relicts of pale green amphibole enclosed in the hornblende crystals.

Rocks with composition varying from diorite to tonalite outcrop extensively on Smøla, and the small holms and skerries to the north of the Smøla beds, and there can be no doubt that this is the source of the majority of the pebbles.

e. Trondhjemite.

Two pebbles of trondhjemite were identified in a collection of granitic pebbles from pockets in the Glasø Conglomerate (Gl.C.2, Gl.C.6).

They are coarse-grained (1 - 2 mm.) white leucocratic rocks composed of quartz and felspar with a hypidiomorphic texture.

The quartz occurs as anhedral grains which show undulose extinction, and have trains of bubbles and minute irregular specks as inclusions.

The felspar, which occurs as subhedral grains, is oligoclase twinned on the common laws and zoned. It is always clouded and sericitised. No potash felspar could be detected in thin section or by staining.

A little green chlorite, altering after biotite, occurs and is often associated with a little magnetite.

f. Quartz porphyry.

Pebbles of quartz porphyry are common in the Ed~~d~~y Conglomerate but a few examples were found in the Glas~~s~~ Conglomerate. The rock is usually purplish or reddish brown, in contrast to the Hitra quartz porphyry pebbles which are dark grey or dark greenish grey in colour. They consist of phenocrysts of clear quartz and creamy white felspar, set in a finer groundmass.

In thin section most of the phenocrysts can be seen to consist of euhedral crystals of felspar (2 - 5 mm. long) which are always clouded and often a little sericitised. Some of the specimens show weak epidotisation (Kr. C.3) and carbonatisation (K.2.4). Most of the felspar is plagioclase, twinned on the common laws and often zoned. The maximum extinction angle shows that the composition is oligoclase, and this was confirmed by a determination on the universal stage which gave a composition of $Ab_{85}An_{15}$.

Potash felspar is always present and in one example (Kr.C.4) it constitutes half of the felspar phenocrysts. In this specimen it is mainly microperthite, but generally it is untwinned orthoclase.

Phenocrysts of quartz are present in all except one of the thin sections examined (K.2.4) but they are not as common as the felspar and are generally smaller ($<$ .75 mm.). The crystals are always strained and have minute irregular specks and bubbles as inclusions. They are sometimes euhedral, or subhedral with some faces well developed, but they are more often corroded and rounded and some of the groundmass is frequently enclosed within the crystals. In two of the thin sections (K.2.12 and K.6.7) the quartz and some of the orthoclase is rimmed by reaction haloes.

The commonest dark mineral is green chlorite which sometimes appears to pseudomorph amphibole. It is occasionally associated with 'bleached' biotite and is often accompanied by magnetite and epidote.

The quartzo-felspathic groundmass is generally fine-grained ($<$ .1 mm.) and contains finely divided hematite, and a scatter of small irregular chlorite and magnetite grains. The texture is generally hypidiomorphic with micrographic intergrowths in places.

Much of the silica in the groundmass is probably secondary and this is clearly the case in Kr. C.4 which has an excess of silica.

Epidote occurs in many of the thin sections, usually as small grains in the groundmass or as an alteration of the felspar. In one thin section (Kr. C.4) it may be primary as one of the zoned felspars has an internal ring of epidote.

Reddish quartz porphyries such as those under consideration here are difficult to match with Caledonian rocks now exposed in Norway. However, similar pebbles can be seen in the Scottish Old Red Sandstone. The writer (Peacock, 1961) found many comparable pebbles in the Upper Lower Old Red Sandstone conglomerates exposed along the river North Esk, in Northern Angus. One of the specimens (E.G.4) is identical in every respect to one from the Ed~~o~~y Conglomerate (K.6.7) Thin sections of these two pebbles are shown in figs. 146 and 147 for comparison. Similar igneous rocks must have been exposed in the source areas of both conglomerates.

It is impossible to be certain of provenance of the Norwegian pebbles as red quartz porphyry is not an unusual rock type. However, it is interesting to note that East Greenland was a centre of igneous activity in Devonian times (Noe Nygaard, 1937; Bütler, 1954; Graeter, 1957). If this was nearer Norway during the Devonian, it is possible that the pebbles could have come from rocks connected with this activity.

g. Dolerite.

Two small pebbles of dolerite were found in the Glas~~o~~ Conglomerate (LH.C.1, Gl.C.11).

LH.C.1 (fig. 148) from Lille Havreø, is a dense finely crystalline melanocratic rock and in thin section it shows ophitic texture. The felspar laths, which are .5 - 1 mm. long, are labradorite, and they are either untwinned or twinned. Pale brownish augite is present and it is usually surrounded by decomposed bluish-green amphibole and a scatter of magnetite grains.

Gl.C.11 from north Glasø is less well preserved, but has clear ophitic texture. The felspar laths, which are approximately .7 mm. long, are probably andesine, but clouding and sericitisation makes identification difficult. They are either untwinned or twinned, and show zoning. No pyroxene is present but there is abundant green amphibole and irregular magnetite grains. Sphene is present as an accessory mineral.

The texture suggests that the rock was originally a dolerite, but in view of the mineralogy it would be more accurate to term it an 'epidiorite' after dolerite.

The pebbles may have been derived from rocks connected with the Ordovician volcanics of Smøla (Carstens, 1924).

h. Intermediate volcanic and hypabyssal rocks.

Pebbles of this type are scattered throughout the Glasø Conglomerate, where they are mixed with the more abundant diorite pebbles. Many varieties are present, but they are usually fine-grained dark green rocks which are often porphyritic.

Gl.C.8 (fig. 149) is a typical example. It is porphyritic, with 1 - 2 mm. phenocrysts, but examination under the microscope shows that the phenocrysts, which were probably felspar originally, have been replaced by muscovite and epidote. Rounded vesicles are also present and these have been filled in a similar manner.

The groundmass is fine-grained ($<$ 1. mm.) and composed of altered felspar with a lot of epidote, chlorite, sericite, small magnetite grains and some quartz. A little green amphibole is also present and sphene occurs as an accessory mineral.

Specimen O.C.12 from Orten is another example of the same rock type. The phenocrysts are anhedral and consist of polycrystalline plagioclase. Sometimes the centres are filled with epidote. The groundmass consists of small altered felspar laths together with a little magnetite, epidote and secondary carbonate.

There can be little doubt that these rocks were derived from the Ordovician Volcanic suite on Smøla.

i. Metamorphic rocks.

The Southeast Kyrhaug Conglomerate is the only conglomerate in which pebbles of metamorphic rocks are common. They are mostly of cataclastic schists which are not found elsewhere. In the hand specimen they are usually greenish grey rocks with angular fragments of quartz up to about .5 mm. long. They are highly cleaved and have micaceous cleavage planes.

K.14.2 (fig. 150) is a typical example. It consists of elongate angular fragments of simple or polycrystalline quartz set in a groundmass of elongate quartz grains, muscovite, chlorite, and a little plagioclase and carbonate. The average grainsize in the groundmass is about .2 mm. but there are patches where it is of the order of .05 mm. or less. All the quartz grains are anhedral and have undulose extinction.

The micas are usually bent round the quartz fragments and the resulting foliation is wavy.

A little accessory magnetite and epidote is present.

K.14.4 (fig. 151) is another pebble from the same conglomerate. It consists of a fine-grained (.05-.1 mm.) mesh of anhedral quartz and epidote grains. Twinned carbonate is plentiful and occurs as small lenticles and patches. Magnetite is abundant as rounded and irregular grains and as trails of dust. Large flakes of green chlorite are present and muscovite occurs as small crystals. The rock has a rough foliation imparted by the parallelism of the micas, the magnetite trails and the elongate patches of the more coarsely crystalline quartz.

j. Jasper.

One pebble of jasper was found in the Glasø Conglomerate on Lille Havrø. It is a deep purplish colour with a few bright red-brown streaks. The fracture is conchoidal.

k. Carbonate rocks.

Pebbles rich in carbonate occur in the Balsnes, Glasø and Southeast Kyrhaug Conglomerates. Two types are present :

1) sedimentary carbonate rocks and recrystallised limestone; and

2) carbonate rich rocks formed by replacement.

A few pebbles of grey microcrystalline limestone are scattered throughout the conglomerates, but most of the carbonate pebbles in the Southeast Kyrhaug Conglomerate are of pink crystalline limestone. No minerals other than carbonate are present.

Specimen O.C.4 from Orten is a pebble formed of a rock that has been almost completely replaced by carbonate. In the hand specimen it is a bright red-brown colour with irregular dark greenish mottles.

Thin sectioning reveals that it is composed of carbonate and quartz filled pseudomorphs set in a matrix of thoroughly sericitised felspar, carbonate and pale green chlorite. The pseudomorphs which are up to about 4 mm. across are generally rounded or subhexagonal in form. They are highly cracked, the cracks and crystal outlines being defined by a thick deposit of hematite, which gives the rock its colour.

Although the rock is now carbonate rich, it was probably mainly olivine and felspar originally.

Pebble O.C.13 from the same locality, is a pale green banded rock (bands about 1 mm. thick) with dark greenish mottling superimposed.

In thin section it consists of cryptocrystalline carbonate and occasionally the outlines of hexagonal or subrectangular pseudomorphs can be seen. Patches of fine grained ($<$ .025 mm.) silica and some chlorite are present. The rock was probably originally an acid porphyry before being replaced by the carbonate.

1. Sandstone and other clastic sediment.

Pebbles of clastic sediment occur in the Glasø Conglomerate, but they are abundant in the Edøy and Southeast Kyrhaug Conglomerates.

The pebbles scattered throughout the Glasø Conglomerate are mostly of very dark greenish altered siltstone or fine-grained sandstone.

A typical example of a fine sandstone (O.C.8) contains small angular grains of quartz, altered felspar, magnetite, epidote, and green amphibole set in an indistinct matrix which contains a lot of micro- and cryptocrystalline silica. The amphibole and epidote are probably secondary.

The siltstones are very similar but much finer grained.

The pebbles of sandstone and siltstone compare well with the rocks beneath the unconformity on Glasø and this formation is probably the source of most of them.

A few pebbles of conglomerate (e.g. fig. 23) and of fine-grained green tuff are present in the Edøy Conglomerate, but the commonest pebbles are of green or yellow-green sandstone which varies from fine to coarse - grained, although the coarse to medium-grained varieities are predominant.

A typical example (K.6.1) is shown in fig. 152.

The grains which are usually angular or subangular (roundness less than .30), are of many different types. Quartz is present in all the thin sections examined and always shows undulose extinction. Felspar is also present, and most of it is andesine, although a little micro-perthite occurs in some sections.

Composite grains consisting of quartz and felspar and polycrystalline quartz are scattered throughout the sections and they were undoubtedly derived from plutonic rocks.

Volcanic and hypabyssal rocks are represented by fragments of quartz porphyry and occasionally intermediate grains. Some of the quartz porphyry grains have been completely silicified.

Both the felspars and the volcanic and hypabyssal rocks have been altered by clouding and sericitisation which is frequently intense making identification of the grains difficult.

Mica is scarce, but when present it is pale green chlorite.

The matrix of the rock is either well twinned calcite or it is indistinct and consists of a mixture of finely divided epidote, sericite, and silica.

Modal analyses were conducted on four of the samples and the results are given in Appendix III.

Table 13 shows the indices calculated from the modal analyses.

Table 13

Sample	Indices			
	R	I	F	M
K.2.13	1.32	.63	2.24	.33
K.2.15	1.33	1.25	1.77	.27
K.6.1	1.56	.83	.96	.25
K.6.15	1.10	.23	.60	.47

Selected components were plotted on ternary diagrams (figs. 153-154), for comparison with the Hitra and Smøla sandstones (figs. 128-129 and 143-144).

The pebbles resemble the Hitra sandstones in the hand specimen and examination under the microscope shows that the same component grains are present. However, the proportion of the different grains is not the same. The low igneous (I) index indicates that fragments of volcanic and hypabyssal rocks are much commoner in the pebbles. In view of this it is difficult to be certain that the pebbles were derived from the Hitra beds although the strong possibility exists.

Richter (1947) suggested that the pebbles were derived from the Hovin Sandstone, but the writer has not had the opportunity of studying the petrology of the sandstones on the Ørland peninsula which are ascribed to this formation, and Richter's descriptions are not detailed enough to enable comparisons to be made.

Some of the pebbles in the Edøy Conglomerate are of dark grey sandstone and this type is common in the Southeast Kyrhaug Conglomerate.

The texture is variable but most of the pebbles are of medium to fine-grained sandstone.

They contain a similar suite of minerals to the green sandstone pebbles described above, but quartz and polycrystalline quartz grains are more plentiful. There is a lot of chlorite, epidote, and carbonate in the matrix together with silica, small flecks of sericitic mica and iron ore. A typical example (K.14.1) is shown in fig. 155.

CHAPTER VII

DISCUSSION AND CONCLUSIONS.

VII. DISCUSSION AND CONCLUSIONS

Introduction

The details recorded above are synthesised in this chapter, and an attempt is made to assess the environment of deposition, the direction of derivation, and the nature of the source area, of both the Hitra and Smøla sediments.

In sections A 1 and B 1, the sediments are compared with similar recent deposits, and their mode of deposition is discussed in the light of present day sedimentation.

The results of the palaeocurrent analysis are summarised briefly in sections A 2 and B 2.

The details recorded in chapter VI are synthesised in sections A 3 and B 3 and an attempt is made to deduce the nature of the source area of the sediments.

A final section deals with the stratigraphical relationship of the Hitra and Smøla beds.

A. HITRA.

1. The environment and mode of deposition.

Most of the evidence for assessing the environment of deposition of the Hitra sediments is to be found in the alternating sandy siltstone/sandstone sequences.

It was argued on pp. 64-68 that the abundance of lens and flaser structure in the sandy siltstones is a good indication of tidal conditions, since the bedding compares well with that in the tidal sediments of the German and Dutch North Sea coast. The results of the grainsize analyses also suggest a tidal origin, since they compare remarkably with the results of Postma's (1957) research on the sands of the Dutch Wadden Sea, (pp. 115-117). In both cases the distributions are approximately log normal and the degree of sorting is nearly constant regardless of the type of sediment.

On the other hand, many of the Hitra sandstones are coarse-grained and they often contain pebbles, which suggests the presence of strong fluviatile currents. The sediments must therefore have been deposited in an environment where both fluviatile and tidal currents were active, i.e. in the estuary of a river. A number of different sub-environments are present in estuaries since they extend seawards to the point where the proportion of fresh water is neglibible and landwards to the point where the river ceases to be tidal. The coarseness of the Hitra sediments suggests that they were deposited well inshore.

Little is known of recent inshore estuarine sediments, but a few years ago an enormous excavation in the Haringvliet estuary of the Netherlands provided an unprecedented opportunity for study (Oomkens and Terwindt, 1960; Noorthoorn van der Kruijff and Lagaaij, 1960). Here, lateral migration of the Haringvliet channel has resulted in the deposition of cross-bedded sands on a surface of erosion, followed by finer beds with lens and flaser bedding (refered to as 'horizontal bedding' by Oomkens and Terwindt). The mechanism of deposition proposed by these writers is summarised in fig. 156. As the channel migrates laterally it erodes the underlying beds and the coarser cross-bedded sands (with associated intraformational conglomerate) are deposited in the high velocity part of the channel. The finer sediment is carried off and deposited in quieter water to form the so-called 'horizontally bedded' deposits.

The vertical arrangement of the beds in the Haringvliet is very similar to the sedimentary organisation of the Hitra sediments which suggests that they were formed in a similar manner. The coarse to medium-grained sandstones on Hitra, with cross or flat bedding, correspond to the high velocity channel deposits while the sandy siltstones are equivalent to the 'horizontally bedded' sediments deposited in quieter parts of the channel. It was argued on p.60 that the coarse to medium-grained sandstones were probably transported as bed load, while the finer sediments travelled in suspension and this is in agreement with the proposed mechanism of deposition. The order in which the structures occur in the ideal Hitra cycle suggests an upward decrease in flow regime (pp. 60-61) as in the Haringvliet.

On the other hand there is no evidence to suggest that the Hitra deposits were laid down on a channel slope. However, it must be remembered that the maximum slope of the Haringvliet channel is 3°, and it would be practically impossible to detect a palaeoslope of this order of magnitude.

The Hitra cycles, unlike those in the Haringvliet do not always have an erosional lower bounding surface. However, study of some of the sedimentary deformation structures (pp. 82-83) shows that the sandy siltstones must have been extremely 'tough' immediately after deposition and a very high current velocity would have been necessary to erode them.

The evidence discussed above suggests that the sandstone/sandy siltstone sequences were deposited in an inshore estuarine environment as a result of the lateral migration of channels. Since a large proportion of the succession is made up of sediments of this type, the area of deposition must have been sinking rapidly in contrast to the Dutch estuary.

The reddish sandy siltstones in the Aune Group were probably deposited under similar conditions to the sandy siltstones in the Vollan Group, but the significance of the red colour is not clear. The rate of sedimentation was probably slower since they contain worm burrows.

The thicker sandstone beds in the Vollan Group may indicate increased velocities so that the finer sediments were carried away and deposited in quieter water elsewhere. This is confirmed by the fact that the thicker sandstones tend to be pebbly whereas the thinner ones are usually without pebbles.

The size of some of the boulders in the Aune Conglomerate and the lack of distinct bedding or sandstone lenticles, suggests that it may have been deposited as a veneer of talus on the old land surface.

However, the rounded pebbles in the Balsnes Conglomerate probably indicate increased fluviatile velocities.

2. Direction of derivation.

The results of the palaeocurrent analysis were discussed on pp. 93-96. It was concluded that the sediments were laid down by currents flowing from the northwest and that there was a landmass in that direction.

3. Nature of the source area.

The compositions of the coarse to medium-grained sandstones and the conglomerates were studied in order to obtain information to assess the nature of the source area of the sediments.

The Aune Group is clearly composed of locally derived material. The basal Aune Conglomerate contains abundant pebbles of diorite which compare well with rocks outcropping over much of Hitra, and the coarse b formation sandstone, is composed mainly of dioritic detritus. The c formation may be derived from the same source.

However, the beds lying on top of the Aune Group were derived from a different source, although study of the mineralogy of the sandstones in the Vollan Group and the sandy matrix of the Balsnes Conglomerate shows that its nature did not vary greatly throughout the time of deposition.

Quantitative analysis of the sandstones shows that the area was probably composed mainly of acid and intermediate plutonic rocks, but acid volcanic and hypabyssal types were common. On the other hand, very little of the detritus came from sedimentary and metamorphic rocks. Grains of plagioclase are usually commoner than grains of potash felspar, and since most of the felspar undoubtedly came from plutonic rocks it is clear that many of these must have been plagioclase rich. In other words rocks such as diorite and granodiorite must have been more abundant than potash rich rocks such as granite.

The Vollan and Balsnes Conglomerates, which have similar compositions, were derived from a source composed principally of acid and intermediate plutonic and volcanic or hypabyssal rocks. Comparison of the petrography of the pebbles with the grains in the sandstones suggests that both the conglomerates and the sandstones were derived mainly from the same source.

The Upper Vollan Conglomerate differs in having fewer plutonic pebbles, but it is of limited stratigraphical extent and does not represent a major change of source. The sandstones associated with it have the same composition as the rest of the Vollan and Balsnes sandstones.

B. SMØLA.

1. The environment and mode of deposition

Comparison with recent sediments shows that a thick accumulation of coarse detritus such as the Smøla beds is likely to have been deposited by fluvial processes. It may have formed as a piedmont deposit or in a valley flat environment.

Piedmont deposits accumulate around the bases of highlands and are frequently associated with fault-produced relief and a semi-arid climate. Detritus from mountain canyons builds up a series of alluvial fans along the mountain front, which may coalesce laterally to produce a continuous apron of sediments known as a 'bajada'.

Valley flat deposits, on the other hand, are made up of channel and flood plain sediments laid down by a river meandering along its valley. In practice there is no sharp division between the two environments and they may pass gradually into one another.

Twenhofel (1932, p. 800 ff.) has discussed the sedimentary criteria by which the deposits may be distinguished, and more recently Blissenbach (1954) has given an account of the geology of alluvial fans. Comparison with these works shows that the Smøla sediments probably accumulated in a piedmont rather than a valley flat environment. The scarcity of fine-grained flood plain deposits suggests that a valley flat environment is unlikely, and the deposits have a number of features in common with recent piedmont sediments.

1. The Smøla beds are at least 3745 m. thick, and although great thicknesses can accumulate in the valley flat environment, they are commoner in piedmont deposits.

2. The general stratification of the Smøla sediments is poor and dips can only be measured where there are sandstone lenticles. This is a feature of piedmont sediments.
3. The lenticular nature of the stratification and the 'dovetailing' of sandstones and conglomerates is again indicative of this environment.
4. The conglomerates, like those of the piedmont, tend to be made up of a few predominant rock types. Valley flat gravels tend to be much more heterogeneous due to derivation from a wider area.

On the other hand, none of the Smøla sediments can be described as 'mudflow' deposits, and Blissenbach stated that these are a common feature of modern alluvial fans. However, they are not present on all alluvial fans and their frequency is dependant on climatic variations. Thus climate could account for their absence in the Smøla beds.

As stated on p.98, the roundness of the pebbles in the Conglomerates ranges up to about .55 (rounded), although many writers have assumed that alluvial fan deposits are invariably angular. Blissenbach (1954, p. 184) showed this to be untrue and found that pebbles (of unstated size) reached a roundness of .7 on a fan of 4 miles radius. Even higher roundnesses would be possible on larger fans, and so the roundness of the pebbles in the Smøla conglomerates does not preclude a piedmont origin.

The evidence discussed above points strongly towards a piedmont, rather than a valley flat environment for the deposition of most of the Smøla sediments. However, the fossiliferous horizon at the top of the Glasø Conglomerate (p. 46) may indicate that the area was under the aegis of a different environment for a short time.

Study of the stratigraphical succession illustrates the geomorphological development of the region. There is a general fining of the sediments upwards throughout the succession and throughout the individual conglomerate formations. This is illustrated by the decrease in the maximum size of pebbles shown graphically in fig. 122. The Glasø Conglomerate contains large locally derived boulders, up to 3 m. across, at its base, and this probably represents an accumulation of talus at the foot of a steep slope. The rounding of the boulders is probably a function of weathering rather than transportation.

Much of the Glasø Conglomerate consists of boulders up to about 1 m. across which show no sign of orientation, and there is very little sandy matrix in between them. They probably reached their present position by rolling, sliding, and slumping rather than by water transportation.

However, from the upper part of the Glasø Conglomerate onwards, sandstone lenticles and imbricate structure are commoner, and water transportation probably played a more important rôle. The lenticular nature of the beds may have been caused by deposition from braided stream systems.

As stated on pp. 41-42, the Northwest Kyrhaug Formation consists mainly of decayed diorite pebbles. It is possible that these were derived from the surface of the Glasø Conglomerate after it had been subjected to weathering caused by a period of non-deposition. This hypothesis is supported by the discovery of a pebble of grey-brown sandstone within the formation indicating erosion of Devonian sediments. The surface of the Glasø Conglomerate could have been exposed to weathering, by the entrenchment of the stream supplying the detritus into its own deposit, possibly because of a reduction in base level.

The upward development of the Glasø Conglomerate is strongly reminiscent of the development of a typical alluvial fan, and there can be little doubt that it was deposited as such.

The Edøy Conglomerate contains smaller pebbles than the Glasø Conglomerate, but it was probably also a fanglomerate though it was deposited further from the apex of the fan. It seems likely that faulting produced relief in another area, and exposed sandstones, granites, and quartz porphyries. These were then eroded to form a fan which blanketed much of the topography and fans of the Glasø period. Further faulting probably caused the change in source of the Southeast Kyrhaug Conglomerate.

The change to a more distant source area is reminiscent of the migrating basins postulated by Bryhni (1964) for other areas of Norwegian Devonian. However the remnants of the Smøla sediments are too small to permit investigation of this.

2. Direction of derivation.

Analysis of the imbrication of the pebbles suggests that the sediments may have been derived from the north (pp. 105-106).

3. Nature of the source area.

Study of the petrography of the Smøla Conglomerates indicates that the coarse material was derived from different sources during different stages in the accumulation of the sediments.

Most of the pebbles in the Glasø Conglomerate are of locally derived diorite, but pebbles of green fine-grained altered sedimentary rocks and intermediate volcanic or hypabyssal rocks are common, and these also compare closely with local pre-Devonian rocks. The Glasø Conglomerate contains 'granitic' pockets with a great variety of pebble types (including, granite, potash rich granite, granodiorite, trondhjemite, quartz porphyry). The pebbles are smaller and better rounded than the other pebbles in the Glasø Conglomerate, and have clearly come from a more distant source.

The Northwest Kyrhaug Formation contains decayed pebbles of diorite and as argued above. (p. 185), these may have been derived from the weathered surface of the Glasø Conglomerate.

However, the pebbles in the Edøy Conglomerate were derived from a very different source area. Pebbles of green sandstone are abundant, but pink or reddish granites and reddish quartz porphyry are common.

The sandstone may have been derived from rocks contemporaneous with the Ordovician Hovin Sandstone, which outcrops on the Ørland peninsula, or possibly with the Hitra beds. Some of the granites and the quartz porphyry pebbles are difficult to match with rocks now exposed in Norway. Greenland (unlike Norway) was a centre of igneous activity in the Middle Devonian and it is possible that some of the pebbles could have come from rocks associated with this igneous activity, if the Smøla beds are Middle Devonian or later, and if Greenland was nearer Norway in the Devonian, (as would seem probable on the theory of Continental Drift). However, this conclusion is very tentative and more detailed work is needed to substantiate it.

The composition of the Southeast Kyrhaug Conglomerate indicates yet another change in source area, because the pebbles of reddish igneous rocks typical of the Edøy Conglomerate, are completely lacking and their place is taken by pebbles of cataclastic schist and fine-grained grey sandstone, the source of which is unknown. However, pebbles of green sandstone are abundant, as in the Edøy Conglomerate.

Study of the mineralogy of the sandstones which occur in the lenticles throughout the succession shows that the changes in composition are slight and are not related to the changes in composition displayed by the conglomerates. This suggests that the sand was derived from roughly the same source throughout the time of the accumulation of the sediments, regardless of the changes in source of the coarser material. As stated above (p. 156) much of the detritus was probably derived by the break-down of green sandstone similar to that occuring as pebbles in the Edøy and Southeast Kyrhaug Conglomerates. However, some of the grains were undoubtedly derived from reddish quartz porphyries and plutonic rocks. The area of derivation perhaps resembled the source of the coarser material in the Edøy Conglomerate.

Relative age of the Hitra and Smøla beds.

Study of the Hitra and Smøla sediments leaves little doubt that the two rock successions belong to different parts of the Stratigraphical Column. The sandstones of the Smøla beds are relatively soft and friable and have a clean carbonate cement, but those of the Hitra beds are highly indurated and have a cement composed of epidote, silica and chlorite. The induration of the Hitra beds possibly suggests that they are older than the Smøla beds. The present research shows that they were deposited in very different environments which are unlikely to have coexisted and this confirms that they are not contemporary.

However, it is more difficult to ascertain the absolute age of the beds. As stated on pp. 33-34 age of the Hitra beds could lie anywhere in the range Upper Wenlock to Downtonian, although the presence of '<u>Glauconome</u>' which is common in the Southern Uplands of Scotland, suggests that the earlier part of this range is perhaps more likely.

It is possible that the Hitra beds can be correlated with Richter's (1958) so called 'Hovin series' on the Ørland peninsula as these have been assigned to this formation on petrographical, not palaeontological, grounds. Richter's brief petrographic descriptions suggest analogies with the sandstones on Hitra and earlier writers have regarded the Ørland beds as Devonian. However, this problem needs further investigation but is beyond the scope of this thesis.

The Smøla beds are undoubtedly Devonian, but it is not clear to which part of the Devonian they belong. The Devonian at the eastern end of the sediment strip has yielded fossils which suggest a Lower or lower Middle Devonian age but part of it is certainly of Middle Devonian age. The Smøla beds may be contemporary and thus are likely to be either Lower or Middle Devonian.

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APPENDIX I

SPECIMEN LOCALITIES.

APPENDIX I : LOCALITIES OF SPECIMENS REFERED TO

A. SANDSTONE SAMPLES.

Specimen	Group	Location
Prefixed 'S'	Vollan	Specimens taken along logged sections.
A.8.1	Vollan	MR/89453940
A.6.1	Vollan	MR/89953980
Ki.1	Vollan	Kjeø MR/91803880
R.1	Vollan	MR/91953910
C.6	Vollan	MR/92454030
B.1	Vollan	MR/93604065
B.2	Vollan	MR/92703910
Ol.1	Vollan	MR/96004070
Fl.1	Vollan	Flatskjaer MR/90703885
V.4.2	Vollan	MR/91903910
F.C.35.	Vollan Congl. matrix.	MR/90953950
B.C.18	Balsnes Congl. matrix.	MR/93203980
F.6.1	Vollan	MR/90903970
G.C.33	Vollan	Nordbottens garage site. Grindvik (eastern Hitra.)

N.B. Thin sections of sandy siltstone frequently contain both fine sand and silt. These are differentiated in Appendix II, by the suffixes C (fine sand) and F (silt).

B. PEBBLES FROM THE CONGLOMERATES.

Specimen prefix	Conglomerate	Location
A.C.	Aune	MR/89303930
F.C.	Vollan	MR/90953950
V.3	Upper Vollan	MR/91953925
B.C.	Balsnes	MR/93203980
2 B.C.	Balsnes	MR/94104015

SMØLA

A. SANDSTONE SAMPLES.

Specimen	Formation	Location
Gl.1	Glasø	Northern Glasø
Gl.3	Glasø	Eastern Glasø
O.1	Glasø	Western Orten
O.5	Glasø	Northern Orten
K.NW.1	Northwest Kyrhaug	MR/590209
E.1	Edøy	MR/581187
E.2	Edøy	MR/585189
K.2	Edøy	MR/604221
K.4	Edøy	MR/606220
K.5	Edøy	MR/607221
K.6	Edøy	MR/608220
K.8	Edøy	MR/608216
K.9	Edøy	MR/608215
K.10	Edøy	MR/608214
K.12	Edøy	MR/610215
K.14	Southeast Kyrhaug	MR/611212
K.16	Southeast Kyrhaug	MR/610207

B. PEBBLES FROM THE CONGLOMERATES.

Specimen prefix.	Conglomerate	Location
Gl.C.	Glasø	Northern Glasø
O.C.	Glasø	Western Orten
Kr.C.	Glasø	Krongleholme
LH.C.	Glasø	Lille Havrеø
K.2	Edøy	MR/604221
K.6	Edøy	MR/608220
K.14	Southeast Kyrhaug	MR/611212

APPENDIX II.

TABLE OF SIZE PARAMETERS.

TABLE SIZE PARAMETERS

(In order of decreasing grainsize).

Sample	$\phi 5$	$\phi 16$	$\phi 25$	$\phi 50$	$\phi 75$	$\phi 84$	$\phi 95$	M_z	σ_I	Sk_I	K_G	K_G'
Type I												
S.18	.45	1.00	1.27	1.90	2.50	2.80	3.30	1.90	.88	+.01	.95	.49
S.107	.37	.94	1.22	1.58	2.25	2.50	2.95	1.67	.78	+.11	1.03	.51
B.C.18	.34	.79	1.01	1.59	2.20	2.44	3.03	1.61	.82	+.05	.93	.48
S.35	.50	.89	1.10	1.45	1.84	2.15	2.90	1.50	.69	+.16	1.33	.57
S.42	.10	.51	.71	1.17	1.74	2.00	2.65	1.23	.76	+.14	1.01	.50
S.6	-.30	.28	.46	1.00	1.57	1.90	2.55	1.06	.84	+.06	1.05	.51
F.3.1	-.18	.27	.45	.95	1.57	1.85	2.30	1.02	.77	+.11	.91	.48
A.6.1	-.40	.05	.28	.75	1.28	1.72	2.27	.84	.82	+.15	1.09	.52
F.C.35	-.45	.10	.30	.80	1.25	1.50	2.17	.80	.73	+.02	1.13	.53
S.51	-.50	-.03	.20	.70	1.51	1.70	2.65	.79	.91	+.20	1.15	.53
F.1.1	-.20	.12	.30	.75	1.15	1.33	2.20	.73	.67	+.08	1.16	.54
A.8.1	-.72	-.36	-.12	.40	.87	1.17	1.80	.40	.76	+.06	1.04	.51
Type II												
S.33	2.02	2.52	2.70	3.10	3.56	3.78	4.23	3.13	.65	+.05	1.05	.51
S.45	1.74	2.13	2.34	2.80	3.15	3.37	3.94	2.77	.64	+.02	1.11	.53
S.11	1.60	2.03	2.25	2.70	3.03	3.22	3.84	2.65	.64	-.05	1.18	.54
S.50	1.63	1.98	2.15	2.59	3.01	3.19	3.70	2.59	.62	+.03	.99	.50
S.7	1.48	1.80	1.97	2.45	2.85	3.05	3.66	2.43	.64	+.04	1.23	.55
S.90	1.27	1.70	1.93	2.43	2.89	3.07	3.50	2.40	.68	-.05	.95	.49
S.38	.80	1.40	1.65	2.24	2.82	3.25	4.30	2.30	.99	+.14	1.13	.53
S.68	1.23	1.61	1.79	2.16	2.69	2.90	3.38	2.22	.65	+.14	.98	.49
S.43	.90	1.39	1.64	2.10	2.57	2.82	3.30	2.10	.72	0	1.06	.57
Type III												
S.44(C)	2.80	3.13	3.30	3.76	4.24	4.53	5.04	3.80	.69	+.12	.98	.49
S.31(C)	2.71	3.13	3.33	3.79	4.14	4.33	4.84	3.75	.62	-.06	1.08	.52
S.88(C)	2.54	2.88	3.10	3.55	3.97	4.14	4.57	3.52	.62	-.03	.96	.49
S.28(C)	2.54	2.90	3.07	3.52	3.95	4.12	4.53	3.51	.61	0	.93	.48
S.46(C)	2.10	2.73	2.95	3.47	3.96	4.16	4.70	3.45	.75	-.04	1.06	.51
S.25(C)	2.44	2.86	3.03	3.45	3.84	4.02	4.41	3.44	.56	-.02	1.00	.50
S.95(C)	2.37	2.75	2.85	3.22	3.73	3.87	4.25	3.28	.57	+.13	.88	.47

Sample	ø5	ø16	ø25	ø50	ø75	ø84	ø95	M_z	σ_I	Sk_I	K_G	K'_G
Type IV												
S.28(F)	4.00	4.28	4.52	4.98	[illegible]	5.33	5.44	4.86	.48	-.35	.75	.43
S.46(F)	3.50	3.94	4.15	4.67	[illegible]	5.27	5.38	4.63	.62	-.06	.79	.44
S.95(F)	3.20	3.63	3.83	4.40	[illegible]	5.45	5.63	4.49	.82	+.08	.55	.35
S.31(F)	3.40	3.76	3.92	4.30	[illegible]	5.07	5.32	4.38	.62	+.12	.86	.46
S.9	2.89	3.24	3.56	4.10	[illegible]	5.12	5.54	4.14	.88	+.05	.84	.46
S.25(F)	-	3.45	-	4.03	-	4.85	-	4.11	.70	+.17	-	-
Szóla												
O.1	3.06	3.40	3.56	3.92	[illegible]	4.64	5.05	3.99	.61	.15	.93	.48
K.14	-.40	2.30	2.84	3.33	[illegible]	4.08	4.50	3.24	1.19	-.34	1.86	.65
GL.1	2.20	2.54	2.72	3.10	[illegible]	3.74	4.13	3.13	.59	+.07	.99	.50
K.12	.09	1.25	1.46	1.91	[illegible]	2.66	3.20	1.94	.82	-.02	1.36	.58
K.8	.80	1.36	1.54	1.90	[illegible]	2.51	2.98	1.92	.62	+.03	1.21	.55
K.10	-	1.16	-	1.75	-	2.40	-	1.77	.62	+.05	-	-
K.6	.47	.88	1.07	1.48	[illegible]	2.19	2.85	1.52	.69	+.12	1.13	.53
K.16	-.16	.40	.68	1.30	[illegible]	2.27	2.90	1.32	.95	+.04	1.04	.51
K.4	-.35	.26	.44	.90	[illegible]	1.70	2.28	.95	.75	+.08	1.06	.51
K.2	-.33	.20	.45	.96	[illegible]	1.54	1.96	.90	.68	+.13	1.03	.51
GL.3	-.61	-.08	.20	.78	[illegible]	1.66	2.15	.79	.85	0	.93	.48

APPENDIX III

MODAL ANALYSES.

MO[illegible] [illegible]ALYSES

HIT[illegible] [illegible]STONES.

Sample	Quartz	Plagioclase	Untwinned felspar	Microperthite	[illegible]tal	Plutonic fragments	Vol. & hyp. fragments	Sed. & met. fragments	Micrographic intergrowth	Accessory minerals	Matrix
S.6	25.5	8.9	13.8	3.6	1.5	20.7	6.6	.1	.1	.2	19.0
S.35	25.1	13.9	9.1	1.5	1.7	18.2	5.3	.1	-	.1	25.1
S.42	20.4	10.1	12.6	2.6	[illegible]	22.5	9.7	.2	.2	.2	21.0
S.51	20.1	8.6	7.2	4.1	[illegible]	23.6	18.2	.8	.2	.2	16.5
A.8.1	17.8	5.7	3.9	1.4	[illegible]	22.7	22.4	.3	-	.6	24.9
A.6.1	19.8	7.2	5.0	.9	[illegible]	19.4	13.7	.1	-	.3	32.8
Kj.1	20.8	13.2	7.9	1.4	[illegible]	23.8	8.9	-	.1	.1	23.6
R.1	16.8	13.3	5.9	1.8	[illegible]	29.1	10.0	.4	-	.6	21.3
C.6	16.3	9.2	4.0	3.8	[illegible]	30.1	14.9	.1	-	.6	20.5
B.1	17.2	6.7	2.8	4.6	[illegible]	26.3	17.1	.3	.1	1.0	23.1
B.2	18.1	14.1	6.1	2.7	[illegible]	18.7	14.9	.4	-	.4	24.8
01.1	26.5	.8	.4	-	[illegible]	12.0	20.7	-	-	.8	38.6
Fl.1	20.6	11.2	6.1	2.1	[illegible]	23.5	9.0	.2	.6	.7	24.8
V.4.2	17.9	12.5	5.9	3.2	[illegible]	22.9	12.5	.3	1.5	.6	22.0
F.C.35	17.3	10.3	2.4	3.0	[illegible]	27.8	15.3	.4	.2	.2	22.8
B.C.18	15.5	7.8	4.0	1.2	[illegible]	21.9	6.6	.2	-	.7	41.8
F.5.1	21.1	13.2	5.2	2.1	[illegible]	24.8	8.2	.8	.1	.6	22.7
G.C.33	10.6	3.4	2.2	2.0	[illegible]	15.9	18.4	.1	-	1.0	45.0

Perc[illegible]ges.

MODAL ANALYSES

S[illegible]STONES

Sample	Quartz	Plagioclase	Untwinned felspar	Microperthite	Detrital mica	Plutonic fragments	Vol. & hyp. fragments	Sed. & met. fragments	Micrographic intergrowth	Accessory minerals	Matrix
0.5	9.6	2.1	2.4	1.7	2.5	15.4	18.8	-	.2	2.0	45.4
G1.3	18.1	3.4	3.1	1.3	3.5	15.2	15.4	12.2	.1	.8	26.9
K.NW.1	35.5	2.8	3.0	1.1	1.6	14.2	10.8	.4	.1	2.1	28.5
E.1	32.7	3.4	3.1	.7	.3	21.1	12.9	3.2	.1	.2	22.3
E.2	37.3	2.3	3.5	1.2	1.3	12.7	11.8	.8	-	1.0	28.1
K.2	17.9	1.0	3.0	3.0	.6	28.6	24.7	5.4	.4	1.0	14.4
K.5	38.2	1.6	3.7	.9	.8	21.2	9.8	.3	-	1.1	22.4
K.9	34.0	3.5	3.9	1.5	.6	18.1	13.4	1.3	.1	.2	23.4
K.12	26.2	2.3	3.4	2.22	3.1	17.3	11.9	-	.1	.3	33.1
K.16	23.8	1.3	2.7	.7	.7	19.4	24.9	.8	.1	.9	24.6
SANDSTONE PEBBLES FROM THE EDDY CONGLOMERATE											
K.2.13	18.5	9.3	3.3	.9	.4	16.2	25.8	-	.2	.3	25.1
K.2.15	17.2	10.8	4.2	1.9	.7	24.9	20.1	.3	.1	.6	19.3
K.6.1	16.5	7.5	5.2	2.6	.1	21.8	26.2	1.1	.1	.2	18.8
K.6.15	25.7	4.7	6.9	.8	.1	7.9	34.0	.1	-	.7	19.2

Percentages.

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SOME STRATIGRAPHICAL AND SEDIMENTOLOGICAL STUDIES ON THE DEVONIAN OF THE TRONDHEIMSLED, NORWAY.

by

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VOLUME II : ILLUSTRATIONS.

Fig. 1 Sandstone resting on diorite. The line of unconformity is marked by the presence of pebbles. Note the sandstone filled crack in the foreground. Eastern side of Balsnes Hus Vann.

Fig. 2 A body of sandstone partially enclosed by the diorite. Eastern side of Balsnes Hus Vann.

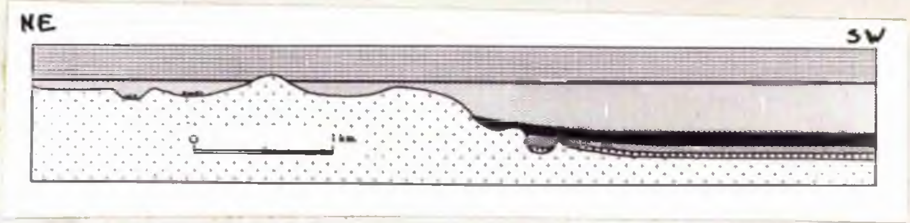
Fig. 3 Kalvhaugtenna from the west. A fault, marked by microbreccia (dark), separates the diorite (to the right of the picture) from the sandstone.

Fig. 4 The Aune Conglomerate, showing large boulders of diorite. East of the mouth of the Aune river.

Fig. 5 Northeast-southwest section showing the Vollan Group overlapping the Aune Group. The horizontal scale is indicated on the diagram and vertical scale is exaggerated approximately X 1.5.

e formation and above	)	Vollan Group
d sandstone	)	
c sandy siltstones	)	Aune Group
b sandstone	)	
a Aune Conglomerate	)	
diorite		

Fig. 6 A 'pocket' of Vollan Conglomerate in the k formation.


NE
SW
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1 km.

Fig. 7 Balsnes bay from Rundholme. The white building in the centre of the picture is the farm of Balsnes, and the hill to the left of it is formed of the Balsnes Conglomerate.

Fig. 8 Exposure of typical Balsnes Conglomerate in a road cutting. South of western end of Balsnes Lang Vann.

Fig. 9 A diagram to illustrate a possible relationship between the Balsnes Conglomerate and the Vollan Group.

Fig. 10 '<u>Glauconome</u>' from the e formation.

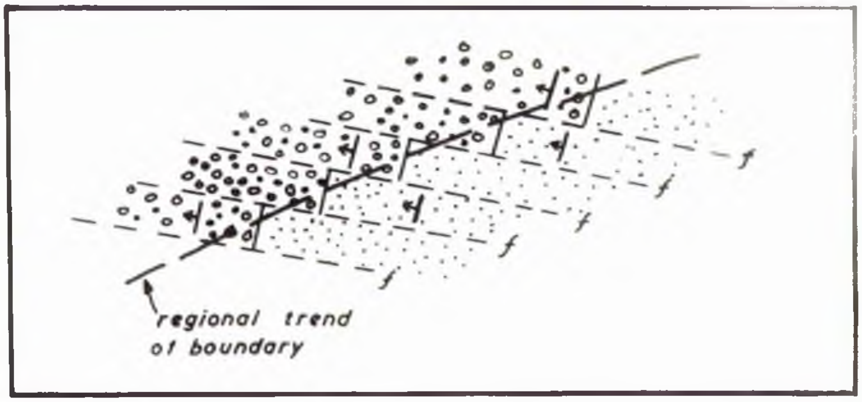
regional trend
of boundary

Fig. 11 '<u>Glauconome</u>' from the '<u>Glauconome</u>' band of the Hagshaw Hills, Scotland. Approximately X 4.

Fig. 12 Sandy siltstone from the c formation showing disturbance by burrowing.
Trackway to Aune.


0 1 2 3 4
CMS

Fig. 13 Transverse section through lined burrows from the c formation. West of Grund Vann.

Fig. 14 Approximately vertical section through lined burrows from the c formation. West of Grund Vann.


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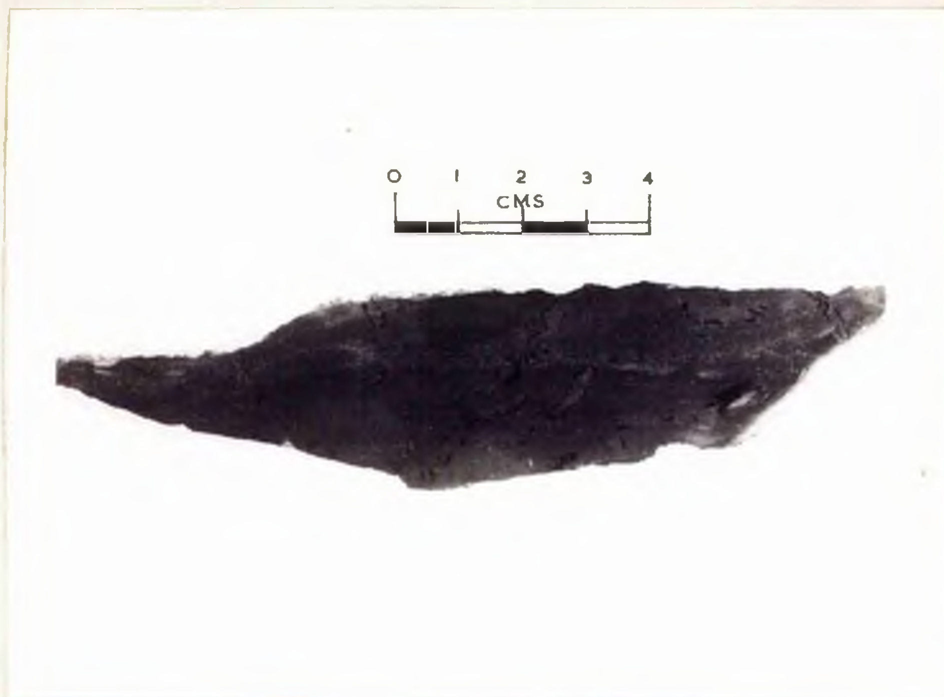
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Fig. 15 Small fault in the k formation sandstone.

Fig. 16 The Glasø Conglomerate. Western end of Glasø. Note the scale given by the hammer in the lower centre of the picture.

Fig. 17 Large boulders of diorite at the base of the Glasø Conglomerate. The unconformity, which is overturned, can be seen in the bottom left of the picture. Northwestern shore of Glasø.

Fig. 18 Unconformity at the base of the Glasø Conglomerate. Eastern end of Glasø. Scale, 5 cms. across.

Fig. 19 Unconformity (overturned) at the base of the Glasø Conglomerate on Orten.

Fig. 20 Unconformity (overturned) at the base of the Glasø Conglomerate on Lille Havrеø. Note the angular blocks in the conglomerate.

Fig. 21 Conglomerate of angular blocks of diorite overlain by better rounded pebbles. Lille Havrø.

Fig. 22 Junction between the Northwest Kyrhaug Formation (to the left of the hammer) and the Eddøy Conglomerate (to the right of the hammer). Northwestern shore of Kyrhaug.

Fig. 23 Cobble of conglomerate in the Ed~~o~~y Conglomerate. Southwestern shore of Kyrhaug. Scale, 5 cm. across.

Fig. 24 Pictorial diagram showing the main features of logs 1-3.

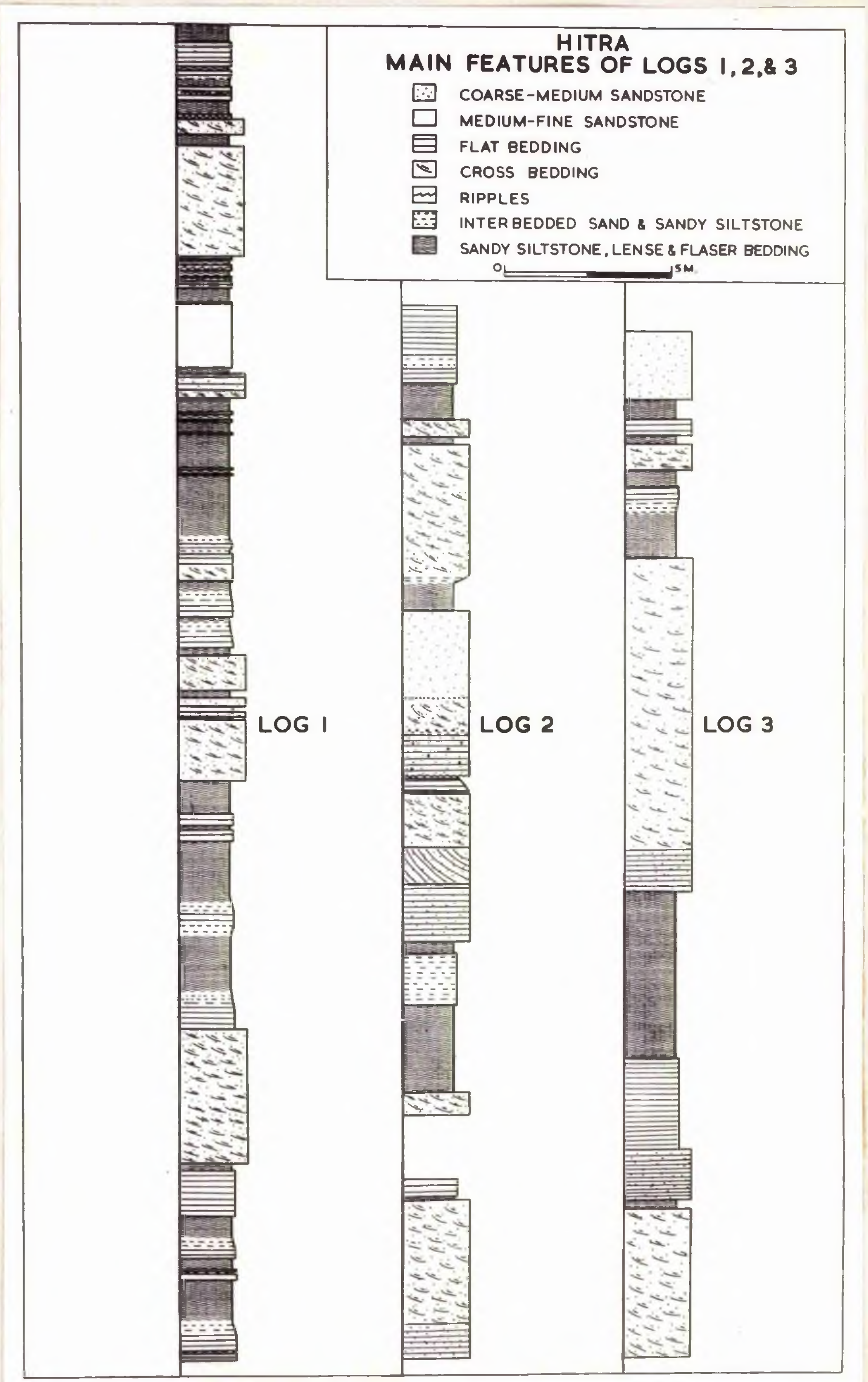

HITRA
MAIN FEATURES OF LOGS 1, 2, & 3
COARSE-MEDIUM SANDSTONE
MEDIUM-FINE SANDSTONE
FLAT BEDDING
CROSS BEDDING
RIPPLES
INTERBEDDED SAND & SANDY SILTSTONE
SANDY SILTSTONE, LENSE & FLASER BEDDING
0
5M
LOG 1
LOG 2
LOG 3

Fig. 25 Bed thickness distributions plotted on logarithmic probability paper. Top curve : medium to fine-grained sandstones; middle curve : sandy siltstones; bottom curve : coarse to medium-grained sandstones.

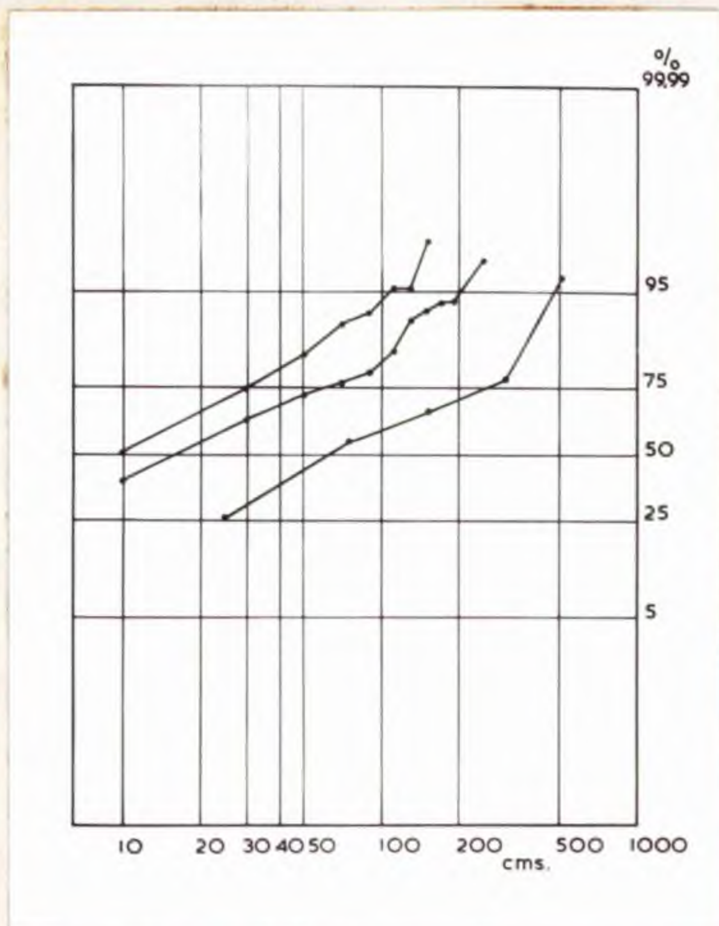
Fig. 26 The ideal cycle. The structures are indicated pictorially, and by the following symbols :

Flat-bedding,

cross-bedding,

lens and flaser bedding.

intraformational conglomerate.



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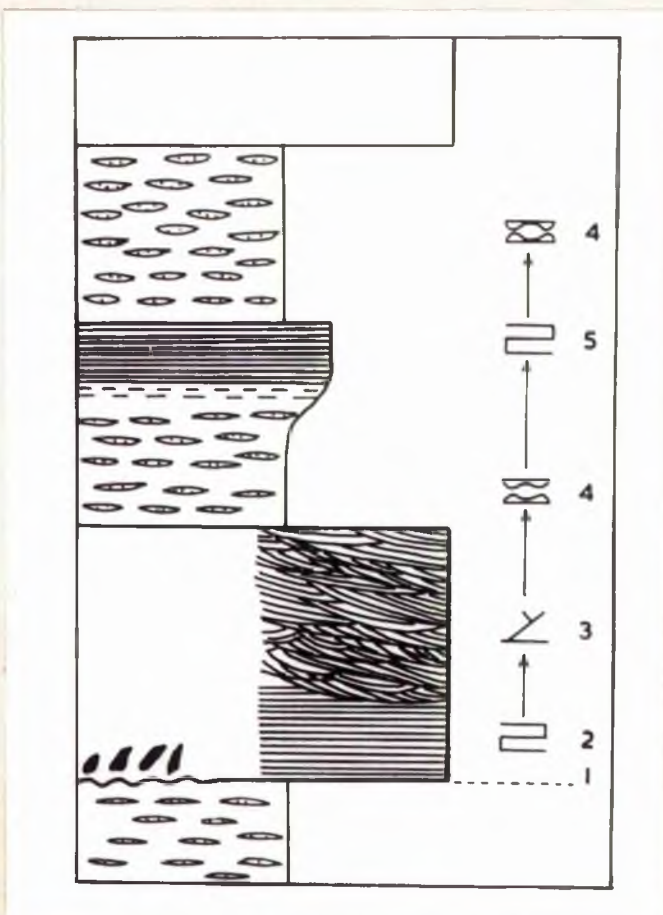

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Fig. 27 Alternating sandy siltstones and coarse to medium-grained sandstone beds with flat conformable contacts. e formation; coast south of Fløos Vann.

Fig. 28 Sandstone lying on an erosional surface cut into sandy siltstone. 1 formation; coast west of Balsnes.

Fig. 29 Sandstone lying on an erosional surface cut into sandy siltstone. Western end of Kjeø.

Fig. 30 Trough bedding overlying flat-bedding in a coarse to medium-grained sandstone. e formation; coast south of Fløos Vann.

Fig. 31 Cross-bedding in the e formation. Road cutting south of Fl~~o~~os Vann.

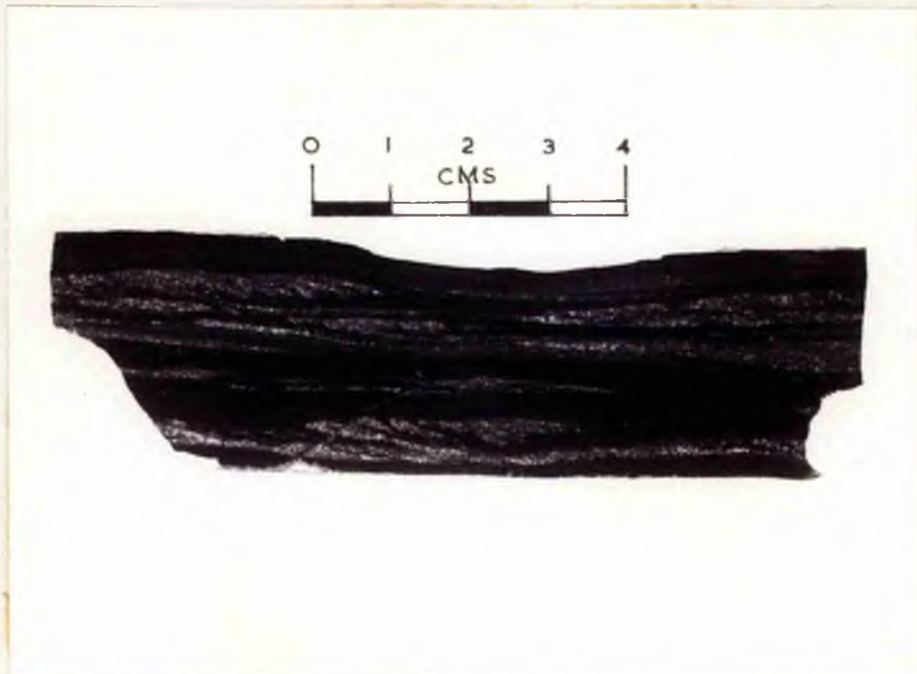
Fig. 32 Cross-bedding in a loose block, probably from the e formation. Scale, 5 cms. across.

Fig. 33 Cross-bedding. Log 2, bed 13.

Fig. 34 Primary current lineation on a bedding plane of a coarse to medium-grained sandstone. e formation; coast south of Fløos Vann. Scale, 5 cms. across.

Fig. 35 Sandy siltstone in the 1 formation, showing lens and flaser bedding. Coast south of Vollan.

Fig. 36 Polished section of sandy siltstone with lens and flaser structure.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CMS

Figs. 37-38 Polished sections of sandy siltstones showing typical structures.


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CMS

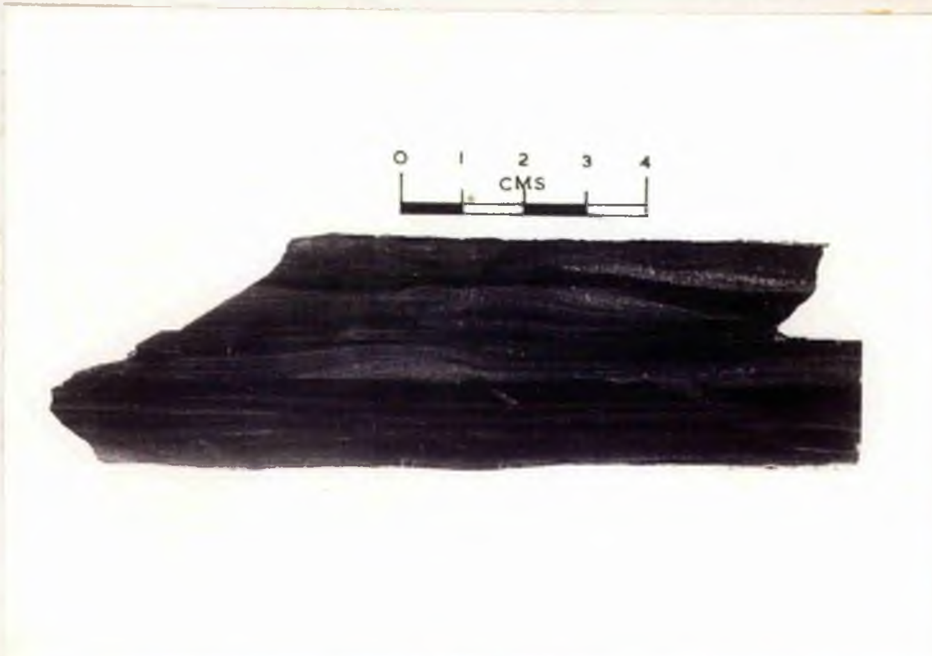
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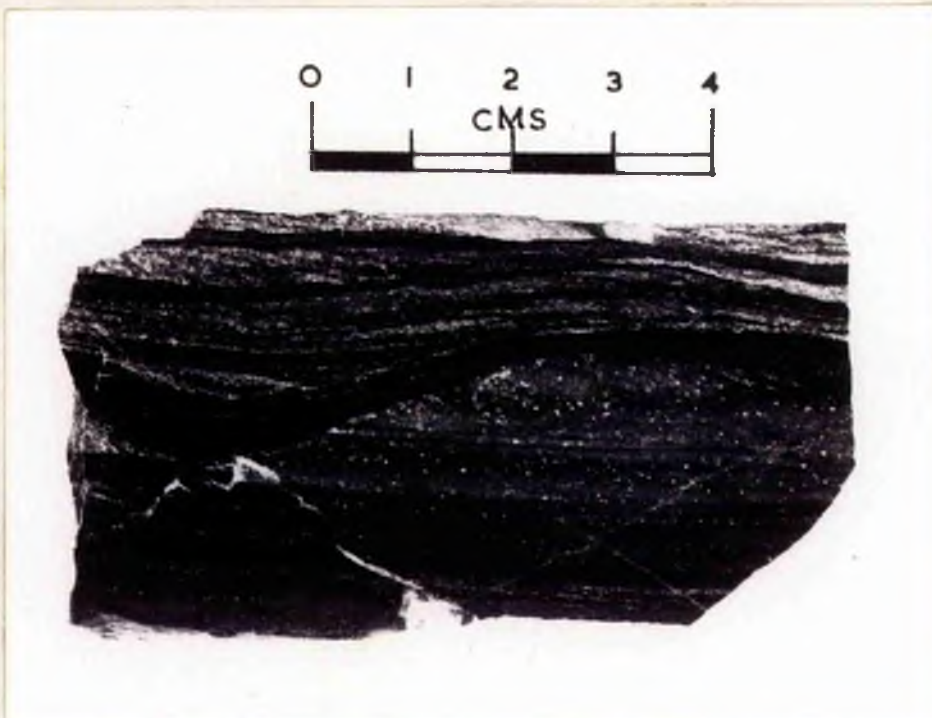
Fig. 39 Polished section through a sandy siltstone showing a minor surface of erosion.

Fig. 40 Sample from the German Wattenschlick, showing the alternation of mud and sand laminae. From Häntzschel (1936).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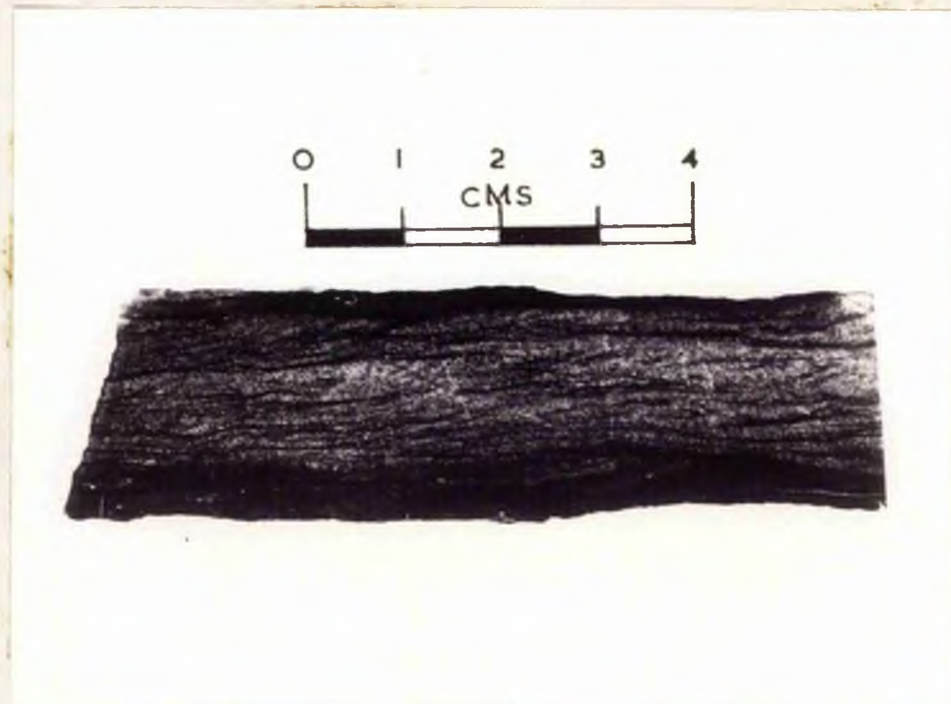
CMS

Fig. 41 Polished section through a sandy siltstone from Hitra, showing well developed flaser structure.

Fig. 42 The formation of lens and flaser bedding in tidal systems where both ebb and flood current are able to transport the sand. From Reineck, (1960).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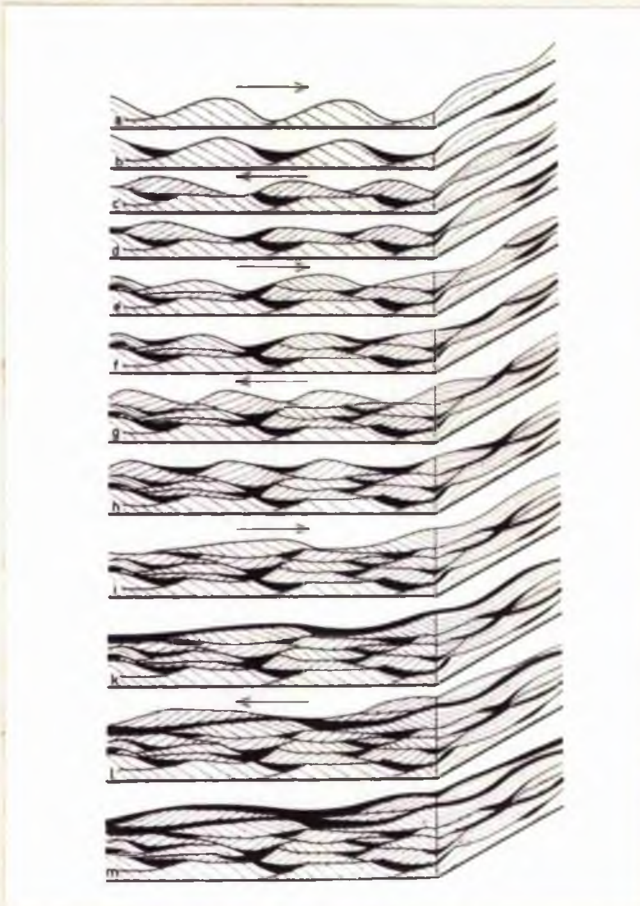
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m

Fig. 43 The formation of lens and flaser bedding in tidal systems where either the flood or the ebb current is too weak to transport the sand. From Reineck (1960).

Fig. 44 Ripple marks. e formation; coast south of Fl~~o~~os Vann. Scale, 5 cms. across.

Fig. 45 Ripple marks on a bedding plane in sandy siltstone.
1 formation; Kjeø.

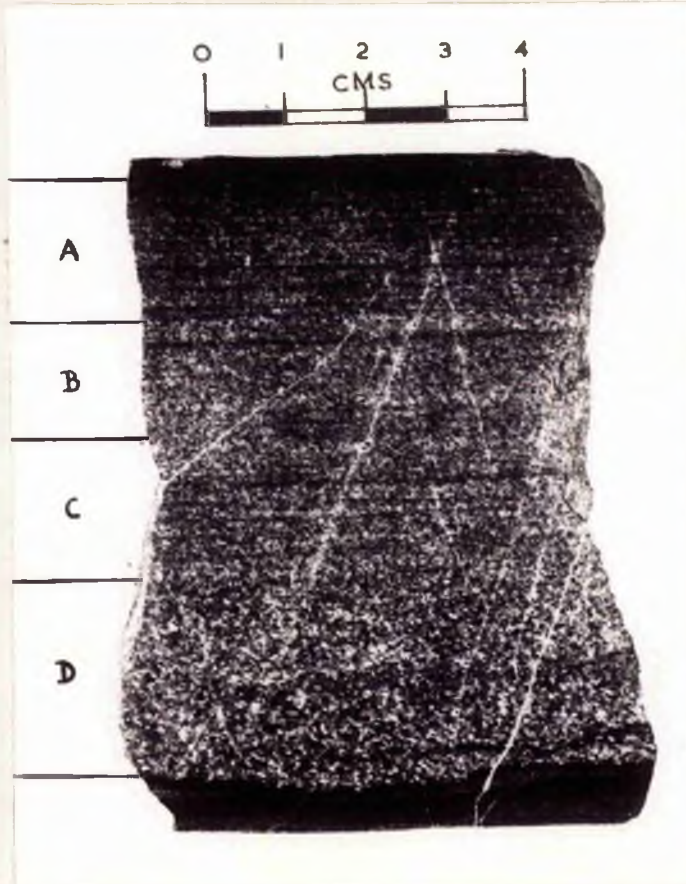
Fig. 46 Ripple marks on the bedding plane of a sandstone
(Log 1, bed 58).

Fig. 47 A conglomerate filled cut into sandstone. 1 formation; coast west of Balsnes.

Fig. 48 Intraformational conglomerate. 1 formation; coast south of Vollan.

Fig. 49   Graded bed from the l formation. Coast south of Vollan.

Fig. 50   Size distribution of the zones in fig. 49.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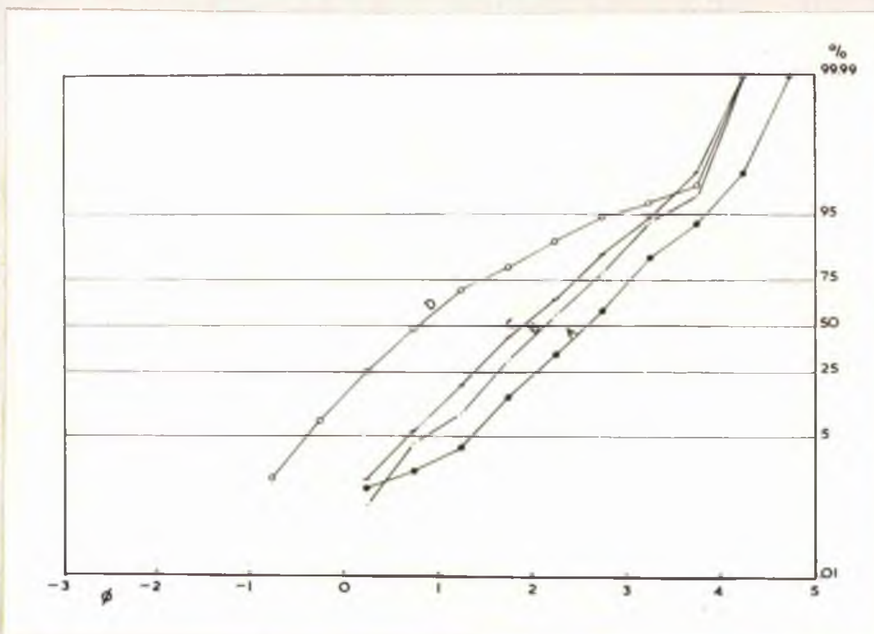
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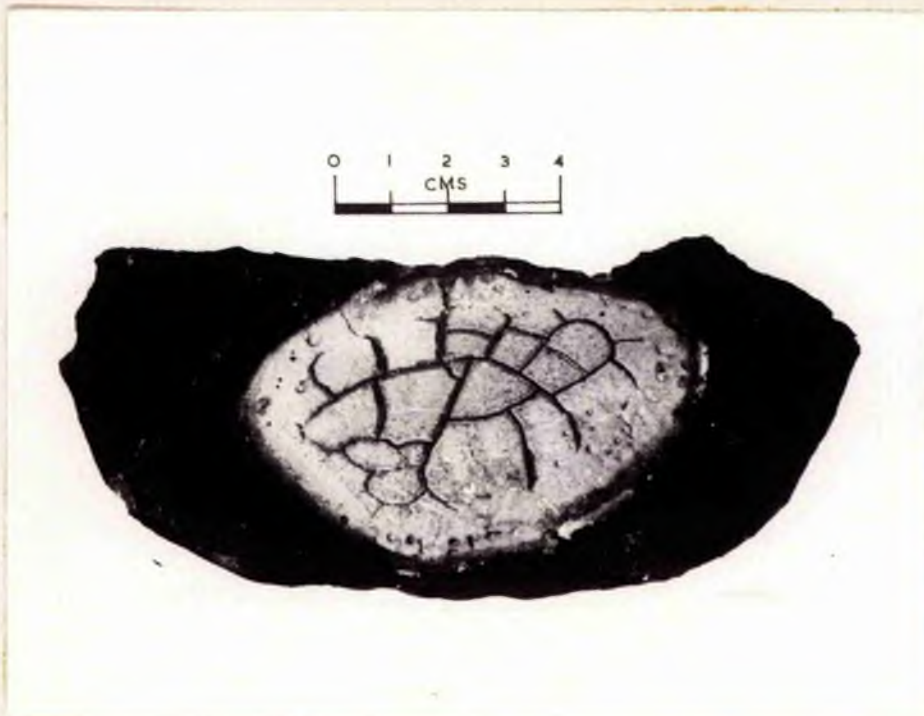
Fig. 51 Septarian nodule, from the e formation.

Loose block.

Fig. 52 Polished section through sandy siltstone from the c formation, showing an irregular carbonate nodule.

Trackway to Aune.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CMS


0 1 2 3 4
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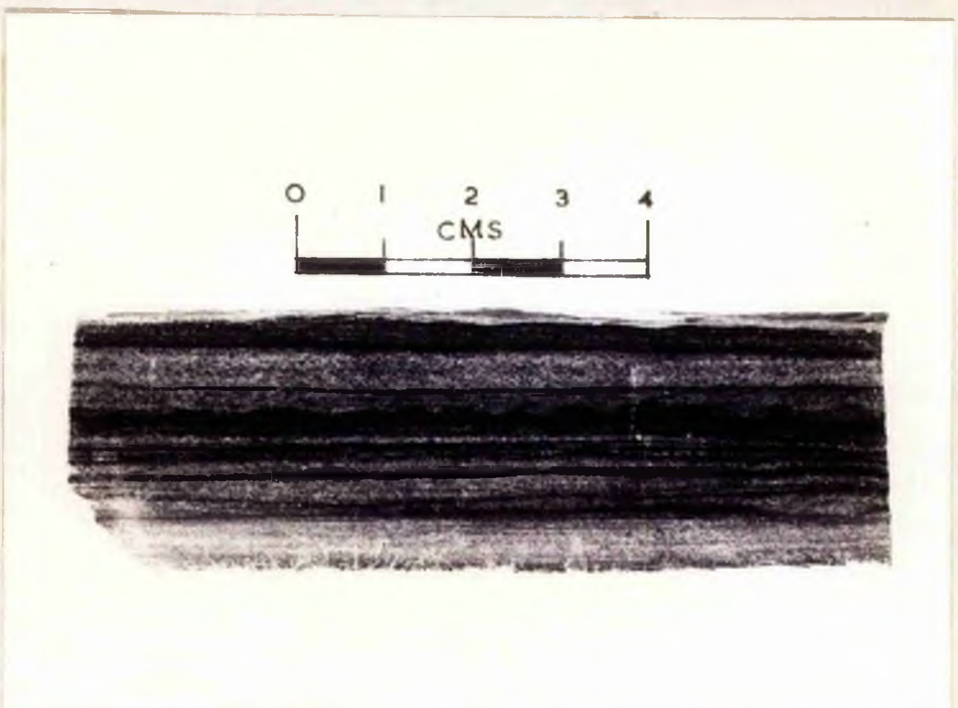
Fig. 53 Carbonate concretions in the l formation.

Un-named holm west of Balsnes. Scale, 5 cms. across.

Fig. 54 Small scale load casting in sandy siltstones of the e formation. Coast south of Fløos Vann.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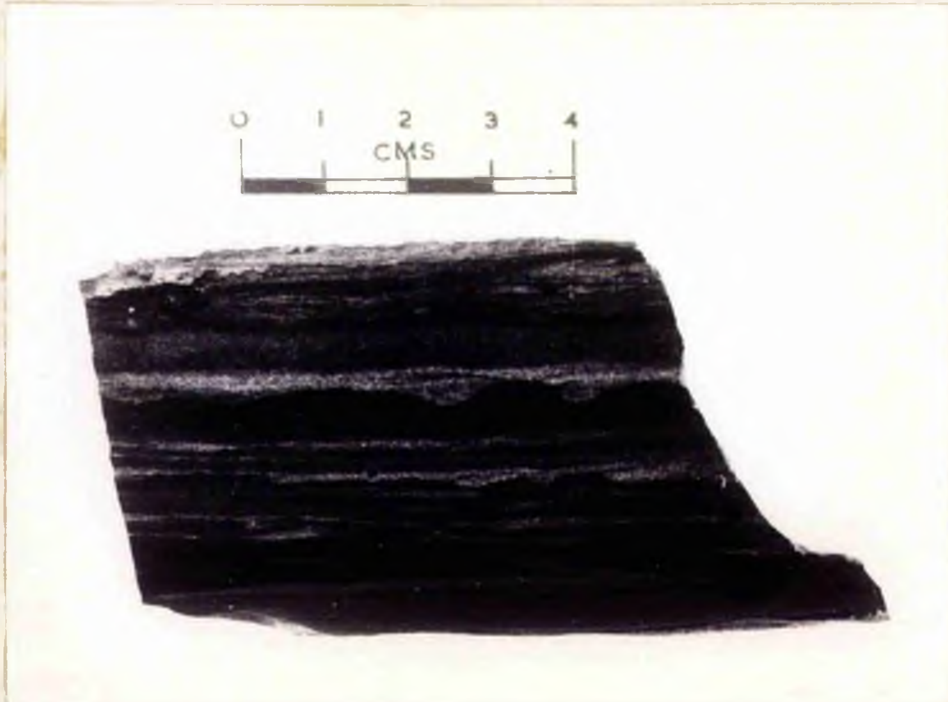
CMS

Fig. 55 Small scale load casting in sandy siltstones of the e formation showing flame-like tongues of silt projecting into the overlying sand. Coast south of Fløos Vann.

Fig. 56 Bedding plane in sandy siltstone of the 1 formation with ripple-like corrugations due to load casting (Log 4, bed 44). Scale, 5 cms. across.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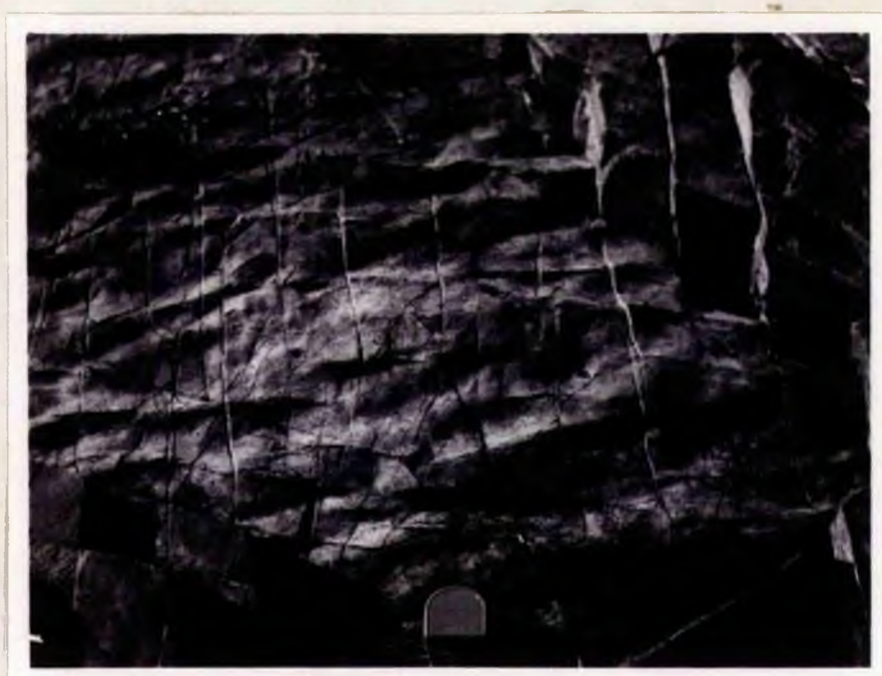


Fig. 57 Polished section through the bedding shown in fig. 56.

Fig. 58 Polished section showing load casting in sandy siltstone from the 1 formation (Log 4, bed 41). Note the layer of graded sand separating the layer with load casting, from an underlying layer with convolute lamination.


0 1 2 3 4
CMS

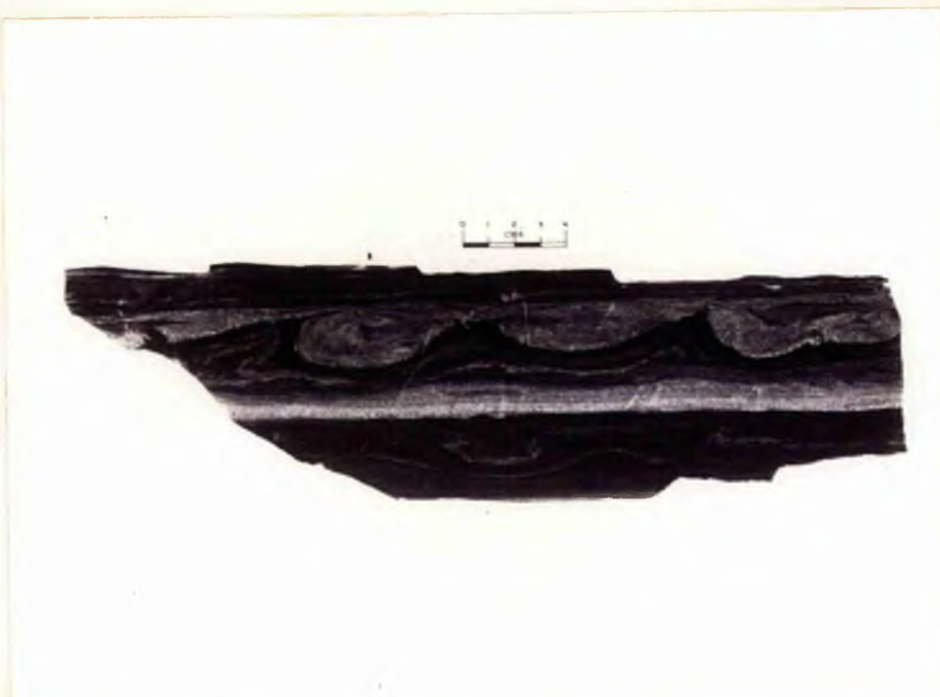
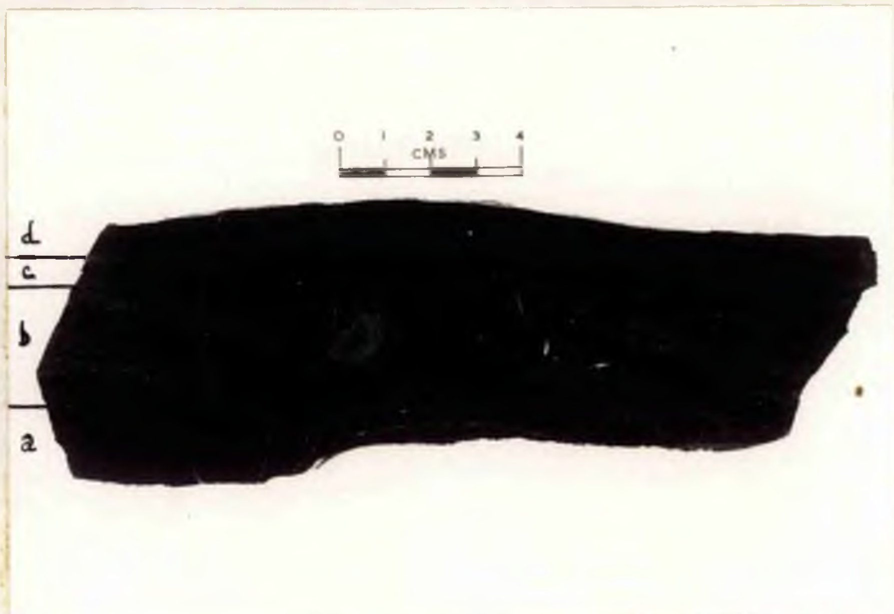


Fig. 59 Deformation ripples in a sandy siltstone of the l formation. Coast south of Vollan. Scale, (right of centre), 5 cms. across.

Fig. 60 Polished section showing convolute lamination in sandy siltstone from the j formation. Coast south of Fl~~ø~~os Vann.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c
b
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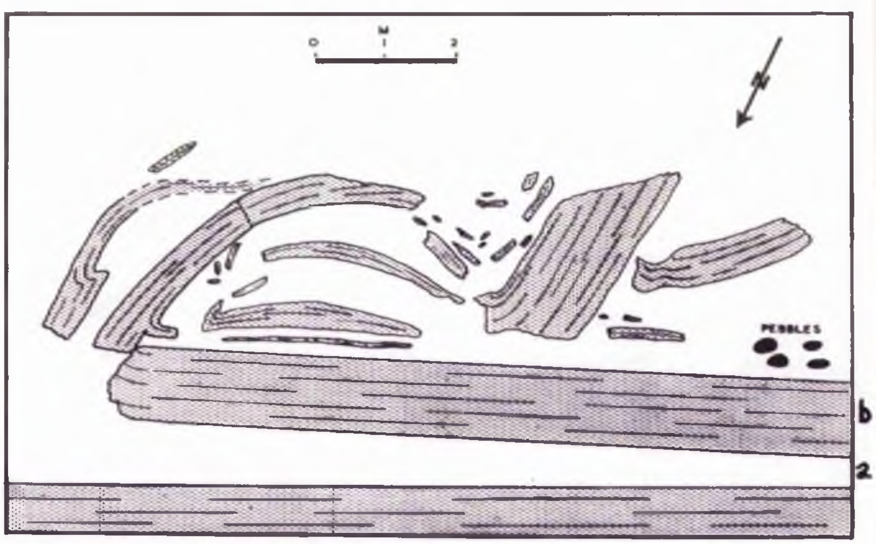
Fig. 61 Convolute lamination in sandy siltstone of the 1 formation. Coast west of Balsnes.

Fig. 62 Detached masses of sandy siltstone (stippled) embedded in sandstone (without ornament). 1 formation, Log 4, bed 61.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PEBBLES
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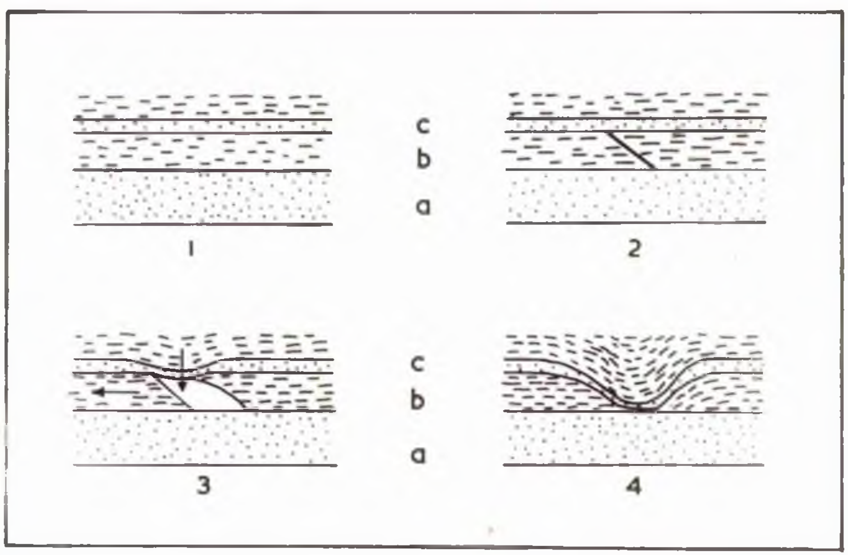
Fig. 63 Sag structure. Western end of Kjeø (1 formation).

Fig. 64 Sketch to illustrate the formation of the sag structure shown in fig. 63.


c
b
a


c
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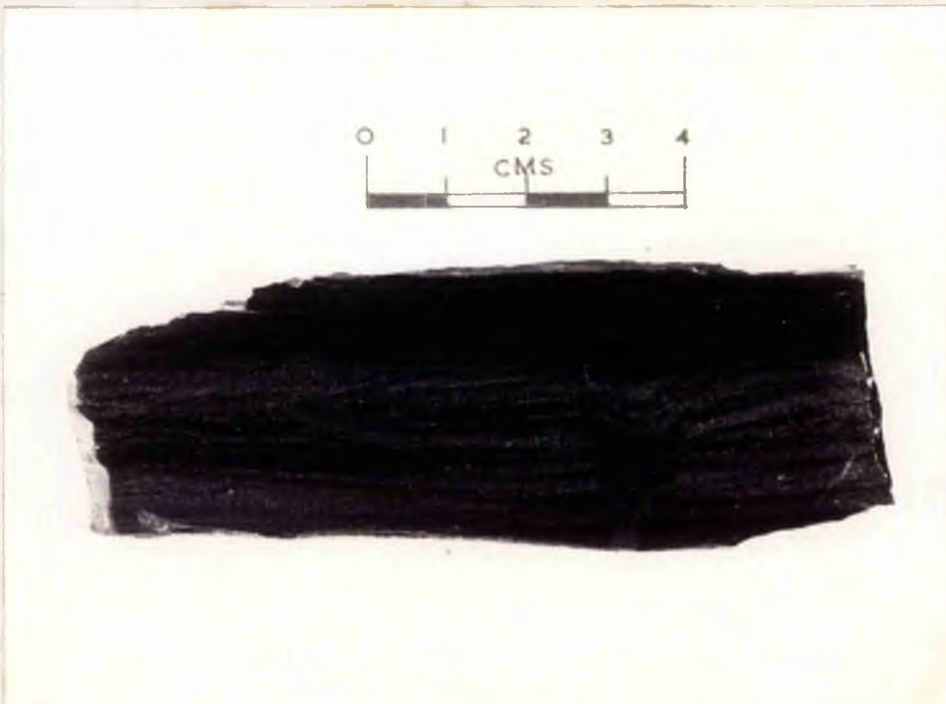
4

Fig. 65 Shrinkage crack in sandy siltstone of the e formation.
Loose block.

Fig. 66 Breccia bed in sandstone of the e formation.
Coast south of Fløos Vann.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CMS

Fig. 67 Pseudonodules in the e formation. (Log 1, bed 19). Scale, 5 cms. across.

Fig. 68 'Raft' of fine sand in siltstone. The same horizon as fig. 67. Scale, 5 cms. across.

Fig. 69 Pseudo-nodules in the e formation (Log 1, bed 59).

Fig. 70 A close-up of part of the bed shown in fig. 69.

Fig. 71 Polished section through one of the pseudo-nodules shown in fig. 69.

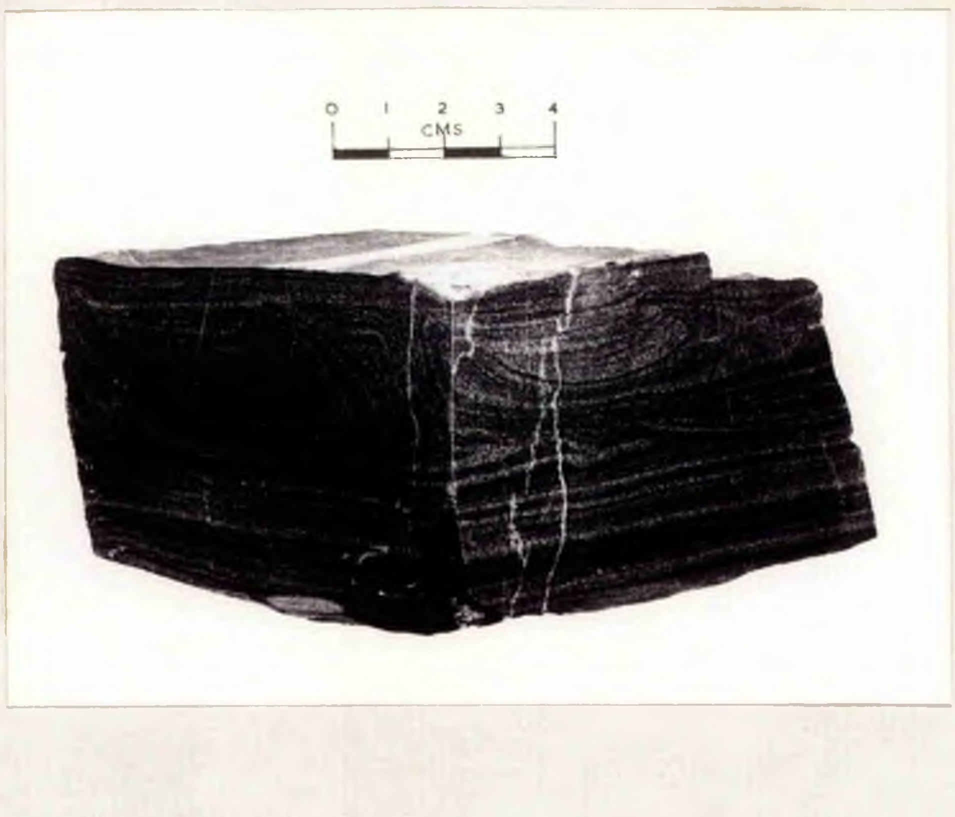
Fig. 72 Undulating sandstone bed with an incipient pseudo-nodule attached to the parent bed. Note the vague sandy patches in the lower part of the bed underlying the sandstone.


0 1 2 3 4
CMS


x

Fig. 73 Pseudo-nodules in the e formation (Log 1, bed 63).

Fig. 74 Polished section through a pseudo-nodule bed from the e formation (Log 1, bed 75).


0 1 2 3 4
CMS

Figs. 75-76 Pseudo-nodules in the Condroz Sandstone at Walheim, Germany.

Figs. 77-78 Pseudo-nodules in the Condroz Sandstone, at Walheim, Germany.

Fig. 79 Quarry between Goebelsmühle and Heiderscheidergrund, Luxembourg. There is a large detached pseudo-nodule by the figure (Ph. courtesy M.J.B. Lowe).

Fig. 80 Rose diagram of the ripple mark orientation data. The arrow indicates the grand vectorial mean. 31 measurements.

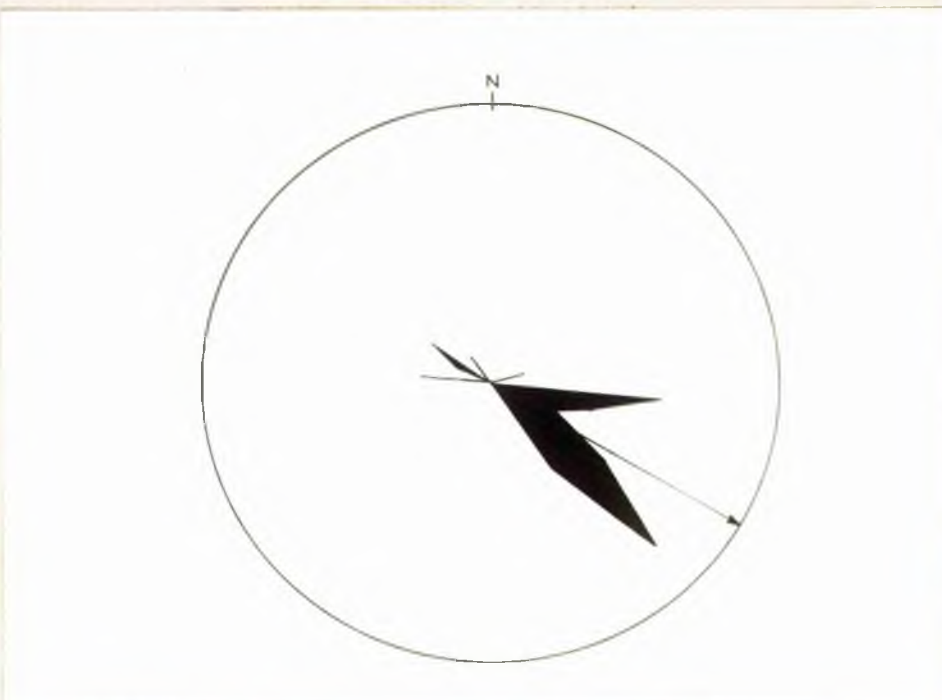

N

Fig. 81 Rose diagram of data from orientated specimens. The arrow indicates the grand vectorial mean.
35 measurements.

Fig. 82 Bedding near the base of the Eddy Conglomerate, showing the random distribution of sandstone lenticles.

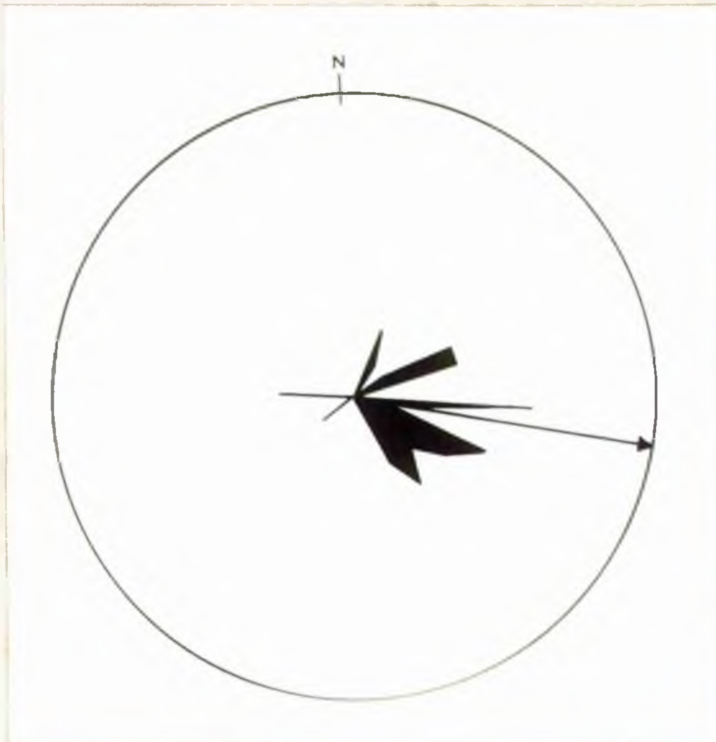
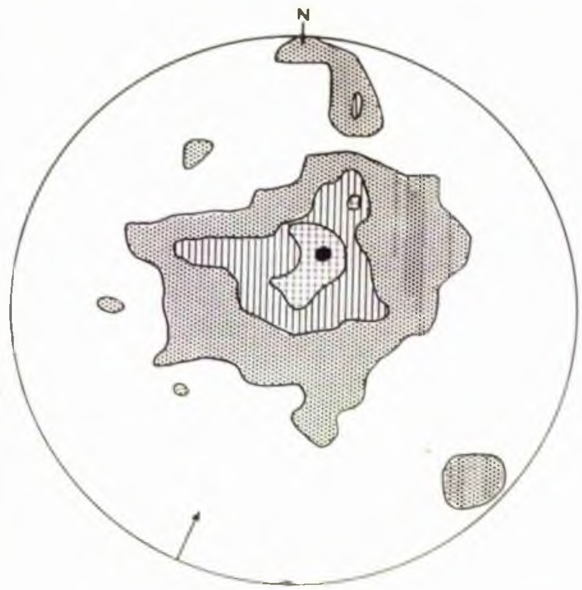

N

Fig. 83 Contour diagram of the poles of the AB planes of pebbles. Locality : northern Glas~~ø~~.

Contours at 1%, 5%, 9%, and 13%.

Fig. 84 Contour diagram of the poles of the AB planes of pebbles. Locality : western Orten.

Contours at 1%, 5%, 10%, and 15%.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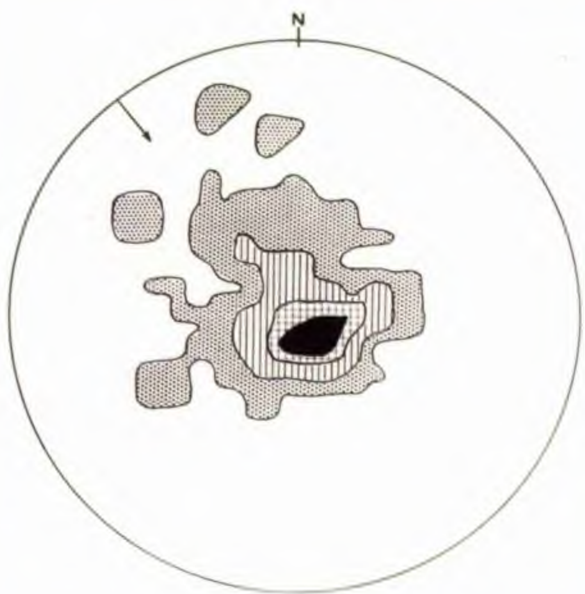
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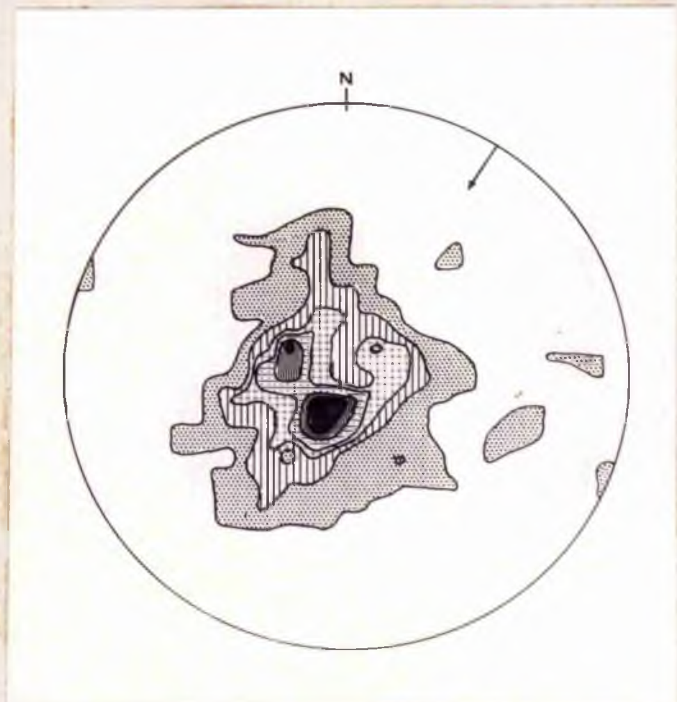
Fig. 85 Contour diagram of the poles of the AB planes of pebbles Locality : Kyrhaug Kai, map ref. MR/609219.

Contours at 1%, 3%, 5%, 7%, 9%, 11%, and 13%

Fig. 86 Contour diagram of the poles of the AB planes of pebbles. Locality : Kyrhaug, map ref. MR/592203.

Contours at 1%, .3%, 5%, 7%, 9%, and 11%.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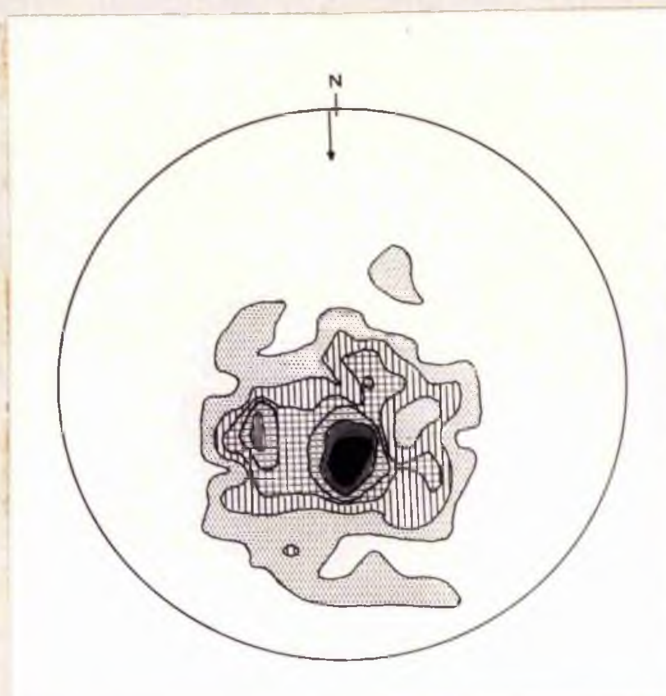
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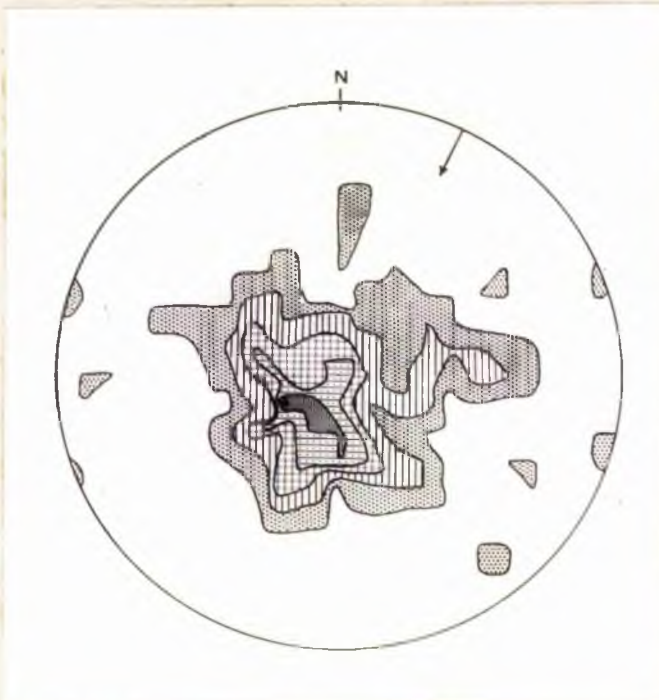
Fig. 87 Contour diagram of poles of the AB planes of pebbles. Locality : Ed~~o~~y, map ref. MR/585190. Contours at 1%, 3%, 5%, 7%, 9%, and 11%.

Fig. 88 Contour diagram of poles of the AB planes of pebbles. Locality : Ed~~o~~y, map ref. MR/582188. Contours at 1%, 3%, 5%, 7%, 9%, and 11%.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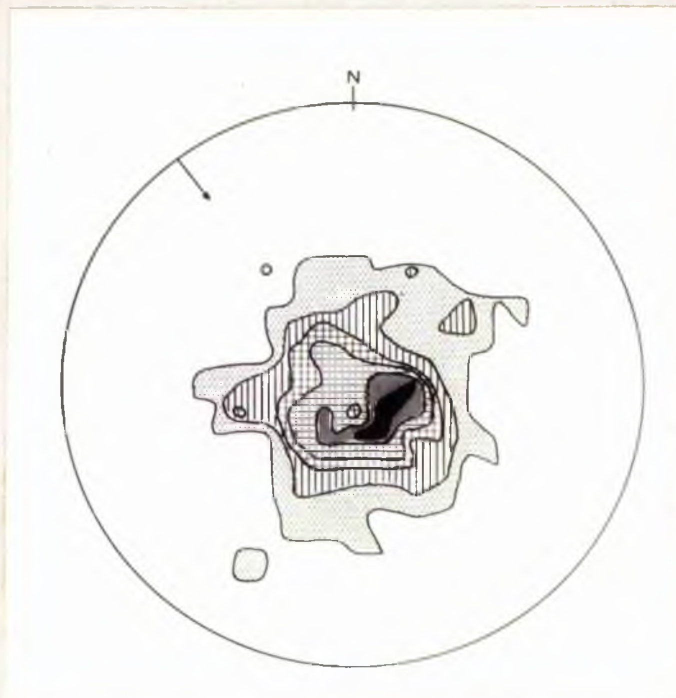
N

Fig 89 Contour diagram of poles of the AB planes of pebbles.

Locality ~~Eddy~~ : map ref. MR/569180.

Contours at 1%, 5%, 9%, 13%, 17%.

Fig. 90. Contour diagram of the A axes of pebbles.

Locality, northern ~~Glass~~ (cf. fig. 83).

Contours at 1%, 3%, 5%, and 7%

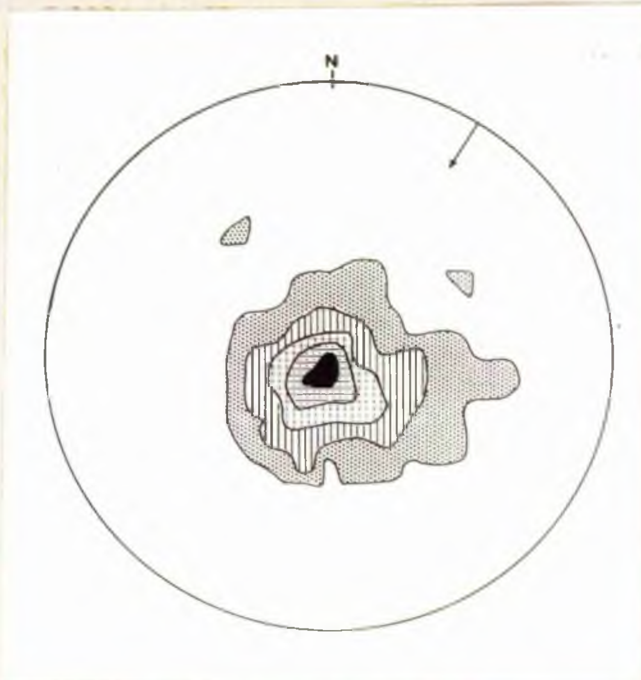
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Fig. 91 Contour diagram of the A axes of pebbles.

Locality : western Orten (cf. fig. 84).

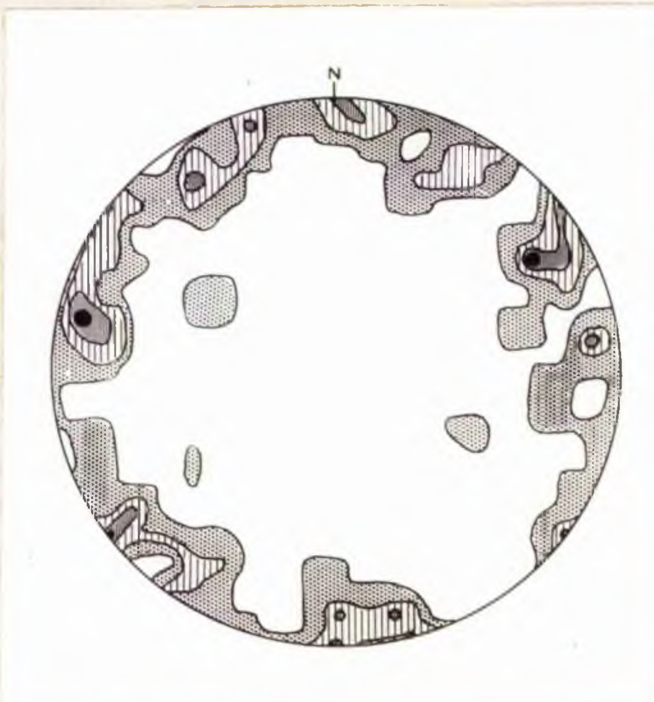
Contours at 1%, 3%, 5%, and 7%.

Fig. 92 Contour diagram of the A axes of pebbles.

Locality : Kyrhaug Kai, map ref. MR/609219.

(cf. fig. 85).

Contours at 1%, 3%, 5%, and 7%.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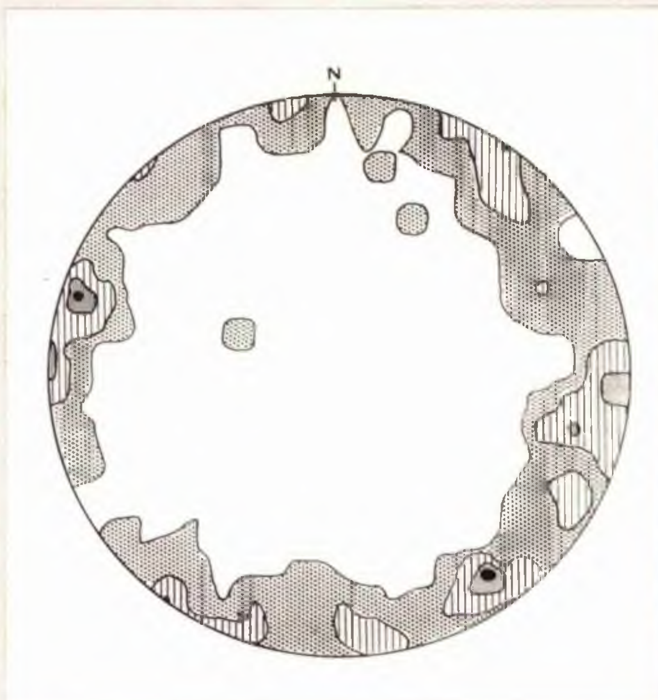
N

Fig. 93 Contour diagram of the A axes of pebbles.
Locality : Kyrhaug, map ref. MR/592203 (cf. fig. 86).

Contours at 1%, 3%, and 5%.

Fig. 94 Contour diagram of the A axes of pebbles.
Locality : Edøy, map ref. MR/585190 (cf. fig. 87).

Contours at 1%, 3%, 5%, and 7%.

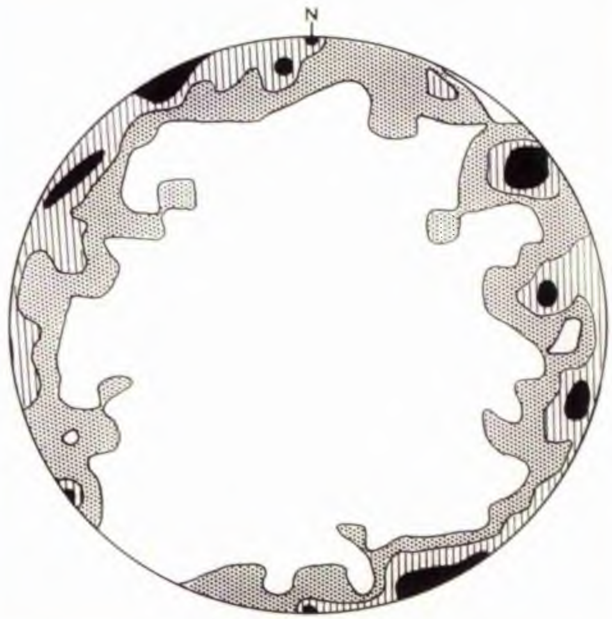
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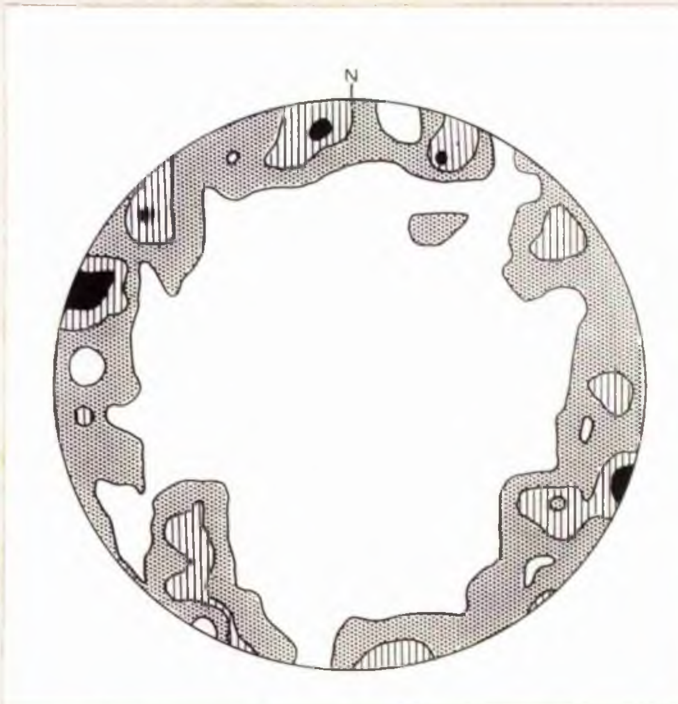
Fig. 95 Contour diagram of the A axes of pebbles.
Locality : Ed~~ø~~y, map ref. MR/582188 (cf. fig. 88).
Contours at 1%, 3%, 5%.

Fig. 96. Contour diagram of the A axes of pebbles.
Locality : Ed~~ø~~y, map ref. MR/569180 (cf. fig. 89).
Contours at 1%, 3%, 5%, and 7%.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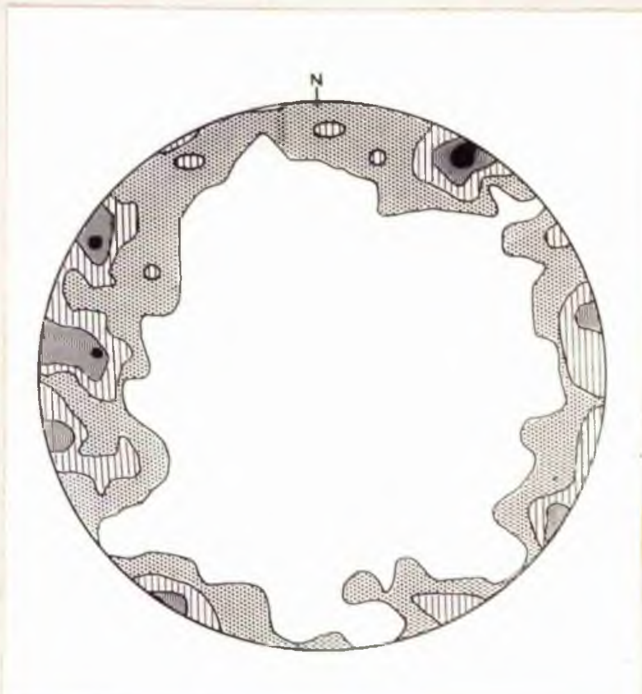

N

Fig. 97 Cross-bedding in a sandstone lenticle. Southeastern coast of Edøy. Scale, 5 cms. across.

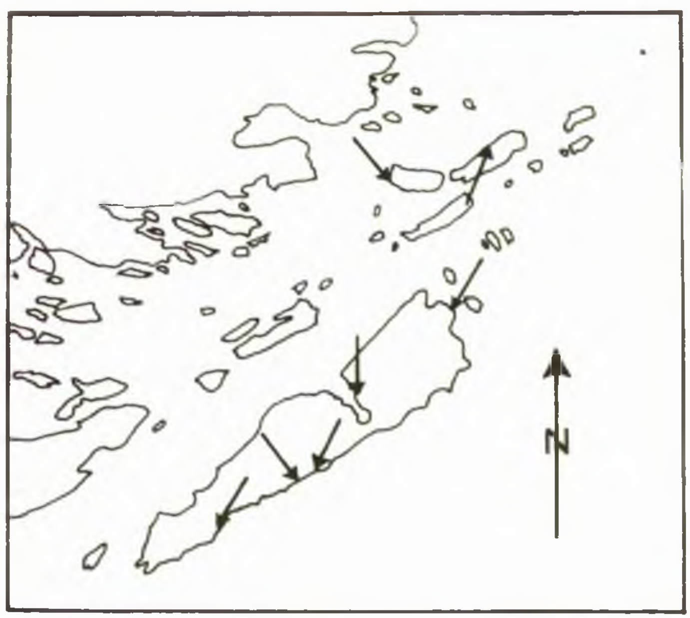
Fig. 98 Scoured surface. South of Edøy Kirke.

Fig. 99 Scoured surface. Southeastern shore of Edøy.

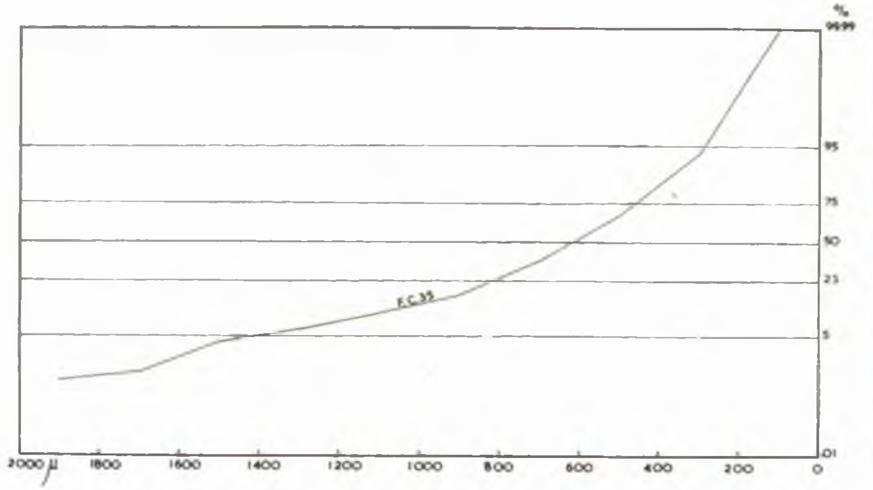
Fig. 100 Contorted sandstone and conglomerate. Southeastern shore of Kyrhaug. Scale, 5 cms. across.

Fig. 101 Carbonate concretion. Eastern end of Glas~~s~~.
Scale(partly hidden by pebble, lower centre),
5 cms. across.

Fig. 102 Distribution map showing current directions
derived from figs. 83-89.


N

Figs. 103-104 Cumulative size distributions of typical Hitra sediments on probability paper against an arithmetic scale.



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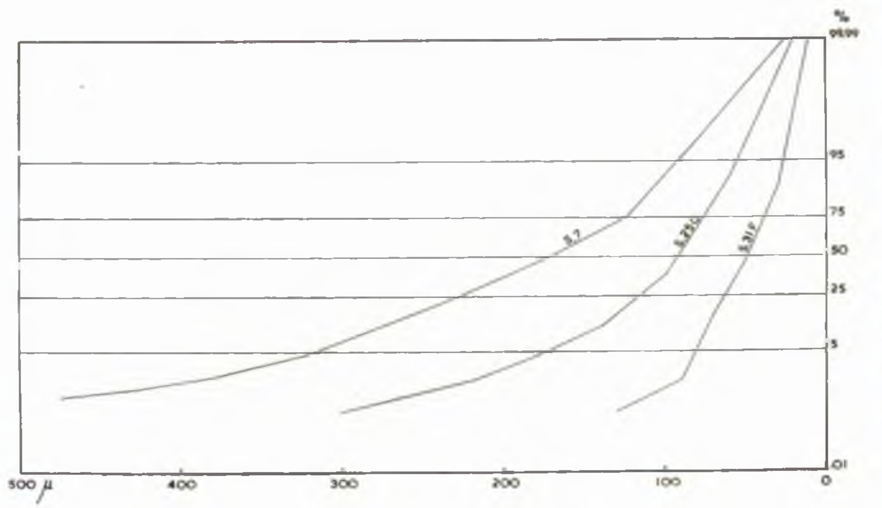
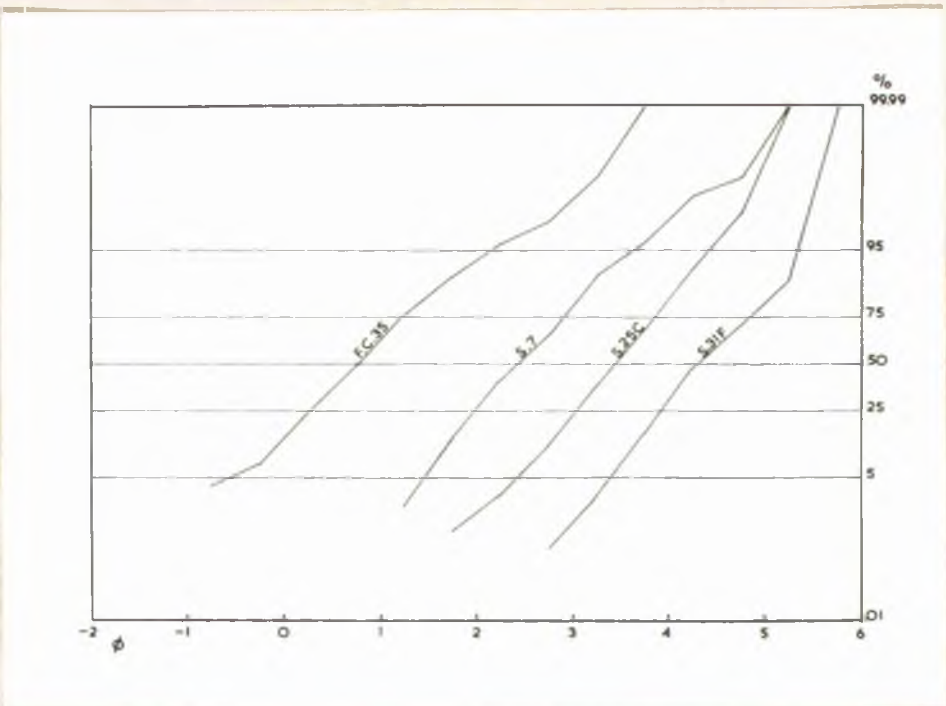
1800
1600
1400
1200
1000
800
600
400
200
0



%
99.99
95
75
50
25
5
.01
S.7
S.25C
S.31F
500 μ
400
300
200
100
0

Fig. 105 The curves shown in figs. 103-104 plotted against phi diameter.

Fig. 106 Cumulative curves of Hitra type I sediments.


%
99.99
95
75
50
25
5
.01
F.C.35
S.7
S.25C
S.31F
−2
ø
−1
0
1
2
3
4
5
6

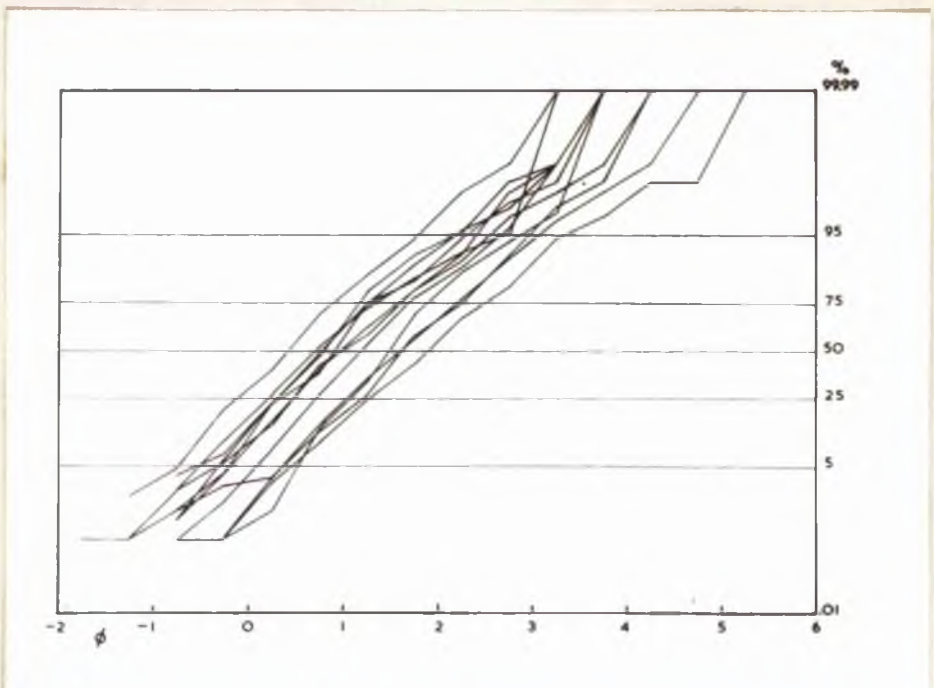
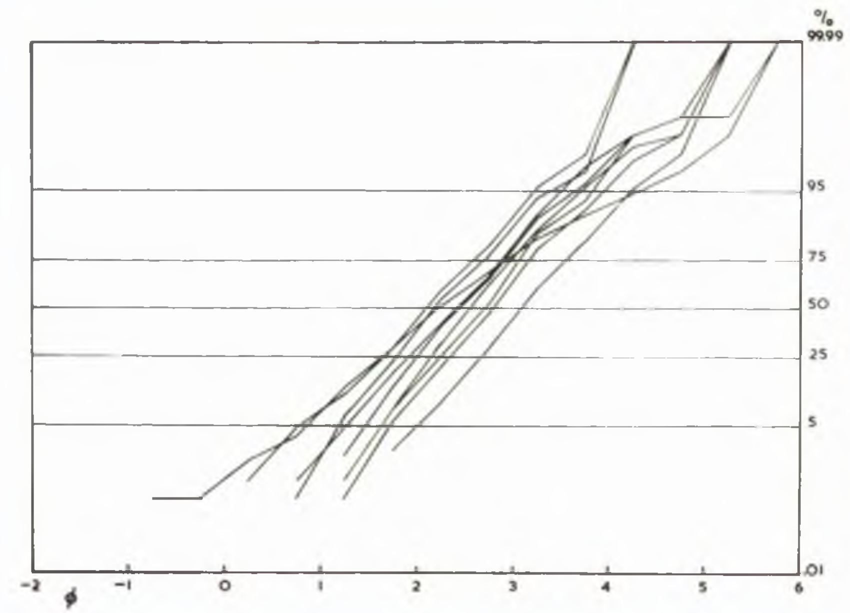

%
99.99
95
75
50
25
5
.01
−2
ø
−1
0
1
2
3
4
5
6

Fig. 107 Cumulative curves of Hitra type II sediments.

Fig 108 Cumulative curves of Hitra type III sediments.


%
99.99
95
75
50
25
5
.01
-2
-1
0
1
2
3
4
5
6
ϕ

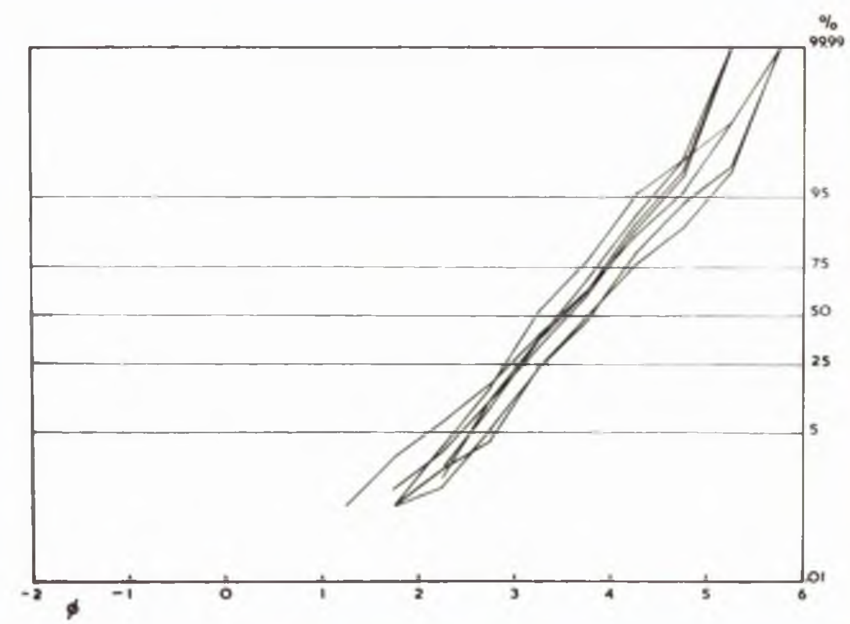
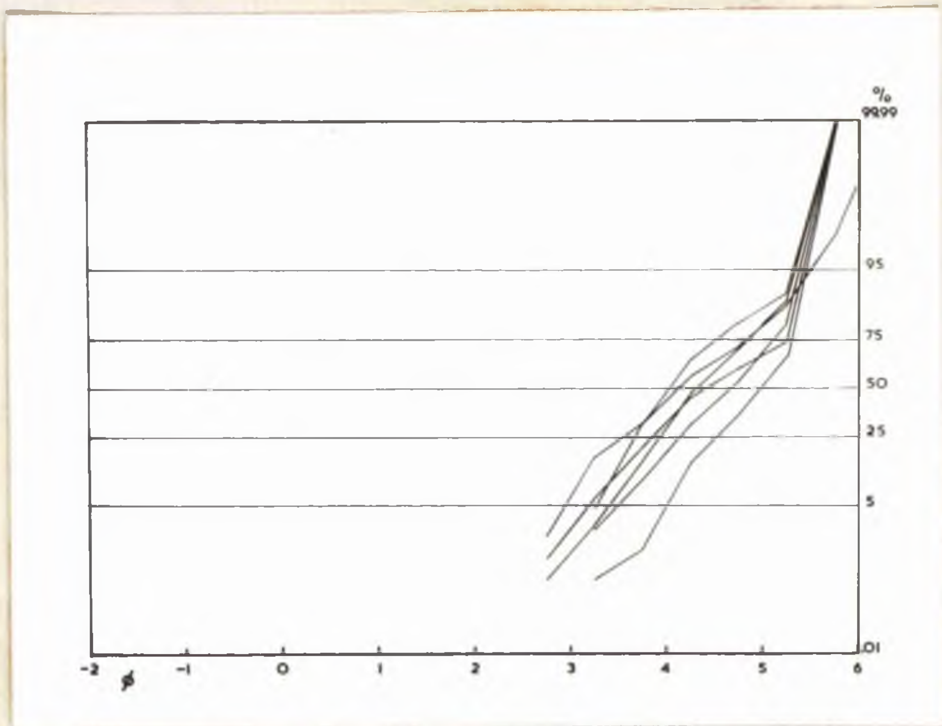

%
99.99
95
75
50
25
5
.01
-2
-1
0
1
2
3
4
5
6
ϕ

Fig 109 Cumulative curves of Hitra type IV sediments.

Fig. 110 Zone diagram of the curves shown in figs. 106-109.


%
99.99
95
75
50
25
5
.01
-2
φ
-1
0
1
2
3
4
5
6

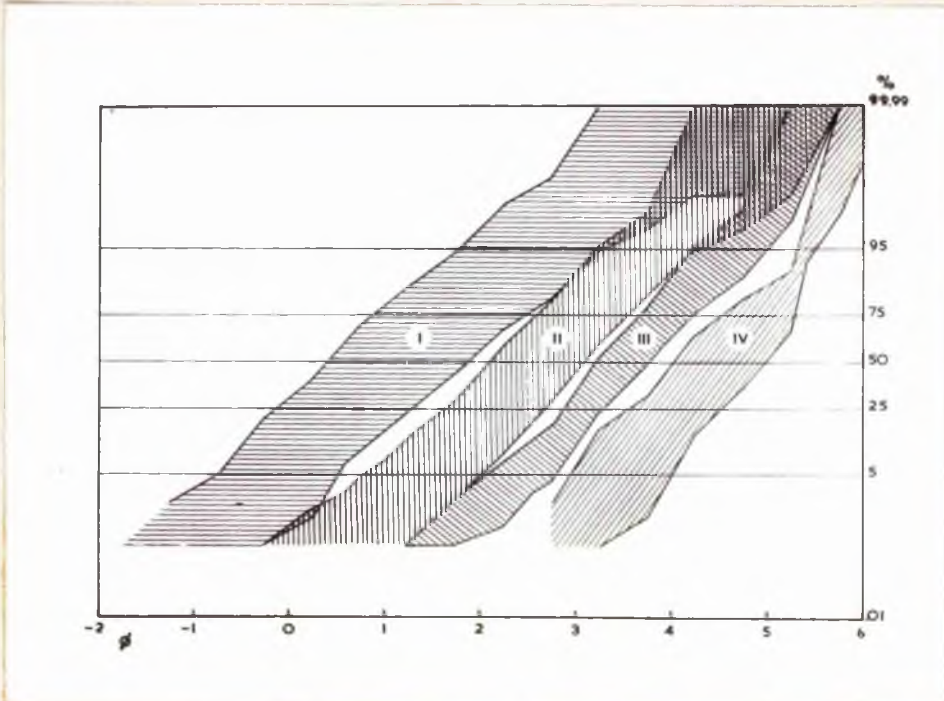
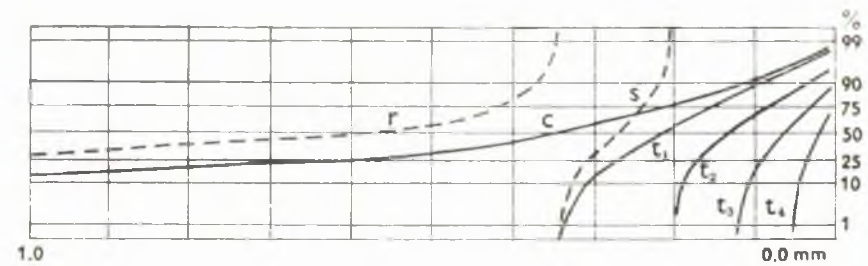

%
99.99
95
75
50
25
5
.01
I
II
III
IV
-2
φ
-1
0
1
2
3
4
5
6

Fig. 111. Diagram to illustrate Doeglas' theory of sedimentary differentiation (after Doeglas, 1946).

Fig 112 Typical cumulative curves for sediments of the Dutch Wadden Sea (from Postma, 1957).



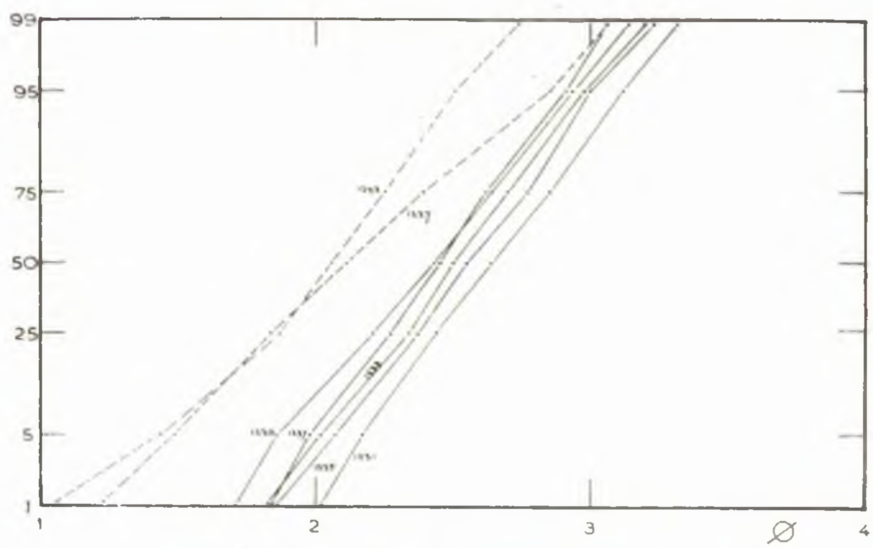


Fig. 22. Cumulative frequency diagrams of samples from tidal flat nr. 1 of fig. 1. Nrs. 1227 and 1243 represent samples from the Marsdiep (small numbers in fig. 2).

Fig 113 Typical cumulative curves for sediments of the Dutch Wadden Sea (from Postma, 1957).

Fig. 114 Scatter diagram of mean size versus sorting in the Hitra sediments.

- o Type I sediments.
- ● Type II "
- o Type III "
- ● Type IV "

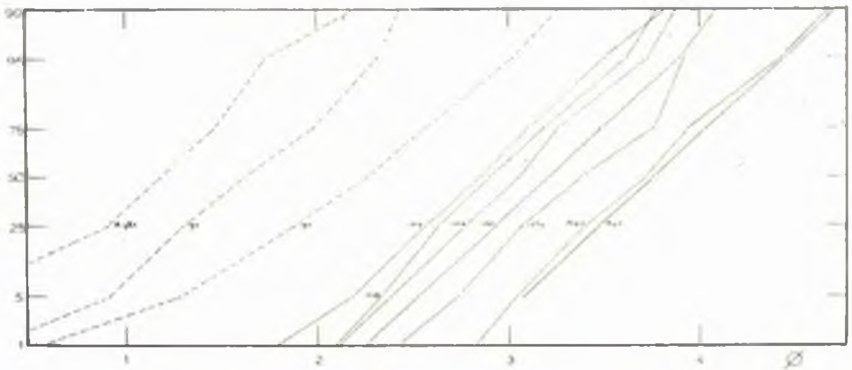


Fig. 23. Cumulative frequency diagrams of samples from tidal flat nr. 6 of fig. 1; compare fig. 7. The dashed lines represent samples from the adjoining Omdraai channel.

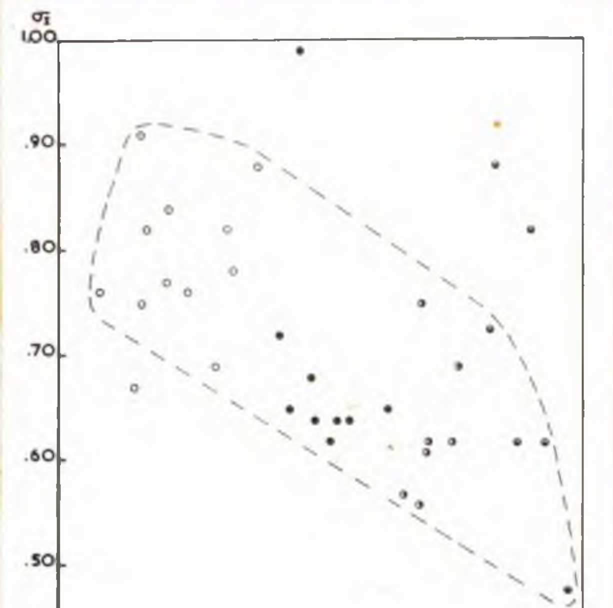
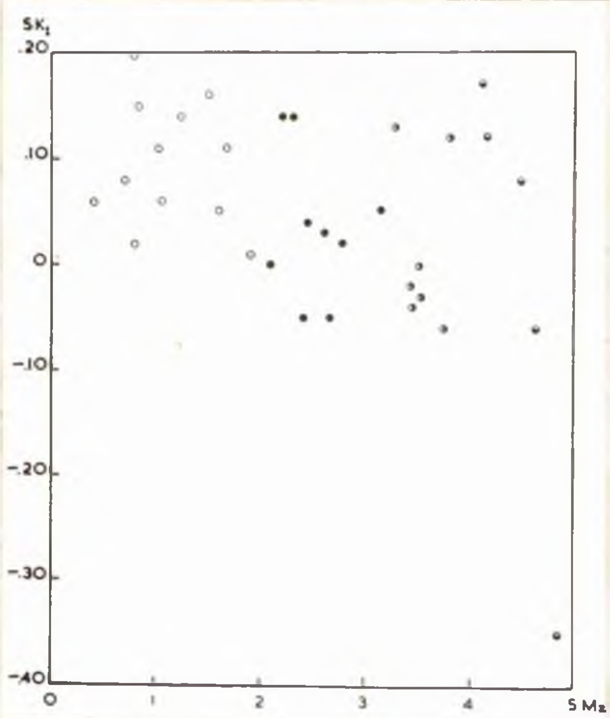


Fig. 115 Scatter diagram of mean size versus skewness in the Hitra sediments.

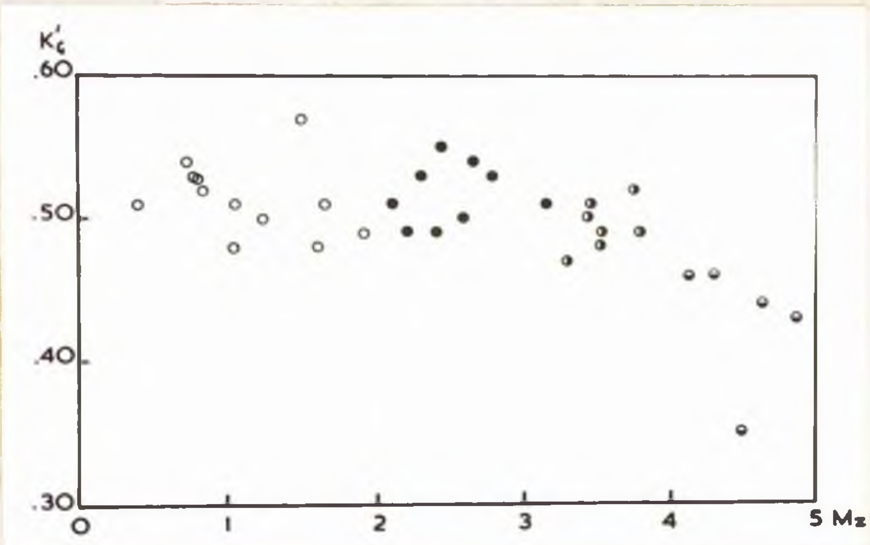
o	Type	I	sediments.
●	Type	II	"
◐	Type	III	"
◒	Type	IV	"

Fig. 116 Scatter diagram of mean size versus kurtosis in the Hitra sediments.

o	Type	I	sediments.
●	Type	II	"
◐	Type	III	"
◒	Type	IV	"



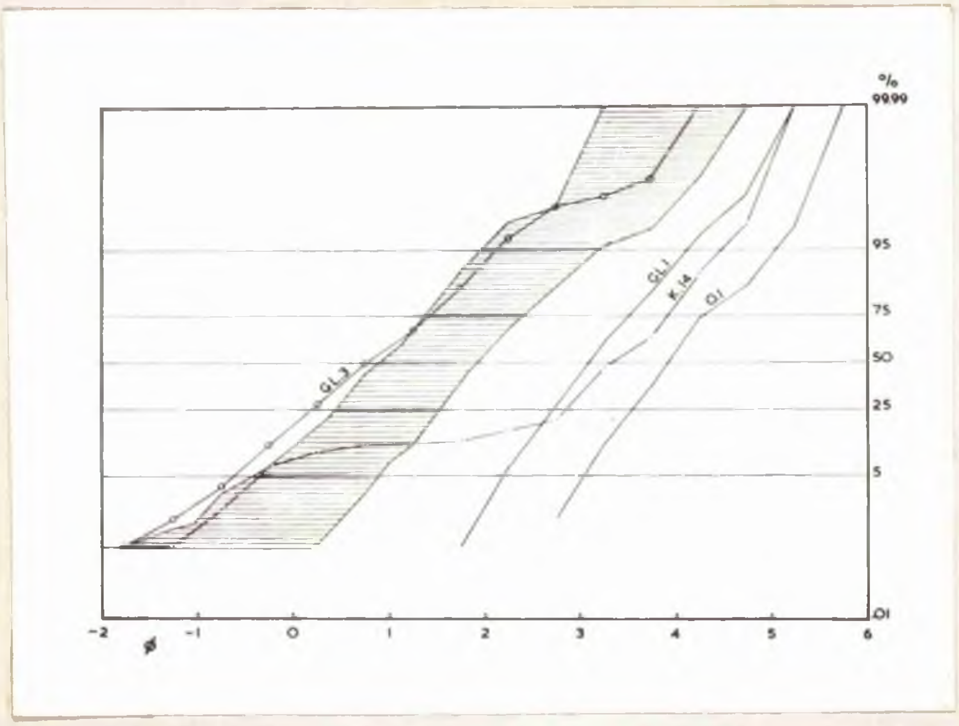
SK_2
.20
.10
0
-.10
-.20
-.30
-.40
0
1
2
3
4
5 Mz



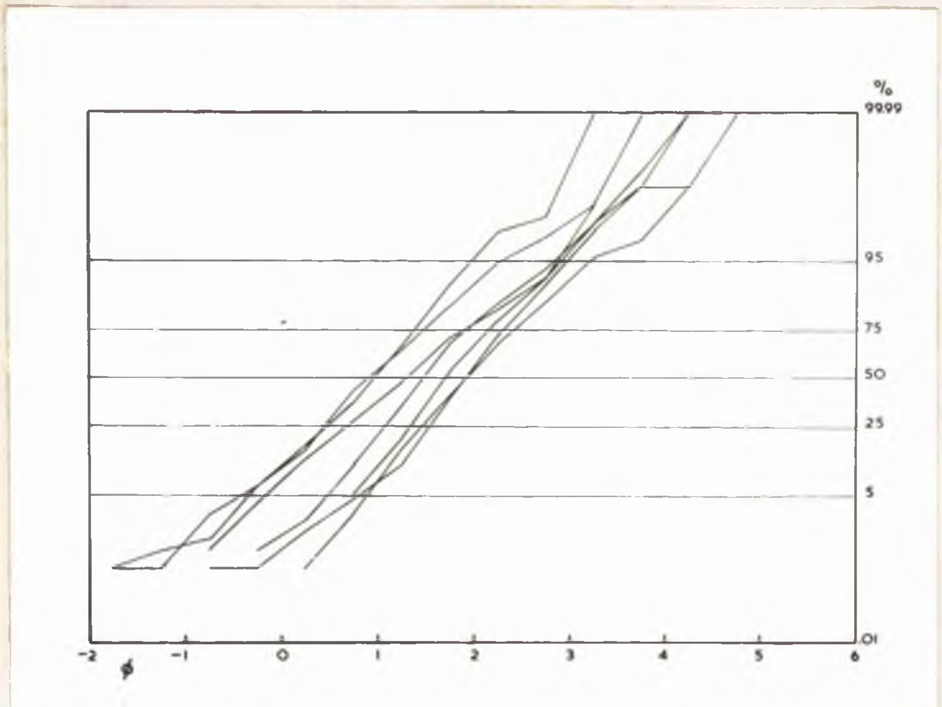
K'_4
.60
.50
.40
.30
0
1
2
3
4
5 Mz

Fig. 117 Cumulative curves of Smøla sandstones.
The 'K' sediments (except K.14) are zoned.

Fig. 118 Cumulative curves of the 'K' sediments zoned
in fig. 117.



%
99.99
95
75
50
25
5
.01
-2
-1
0
1
2
3
4
5
6
ø
GL 7
GL 1
K 14
O1



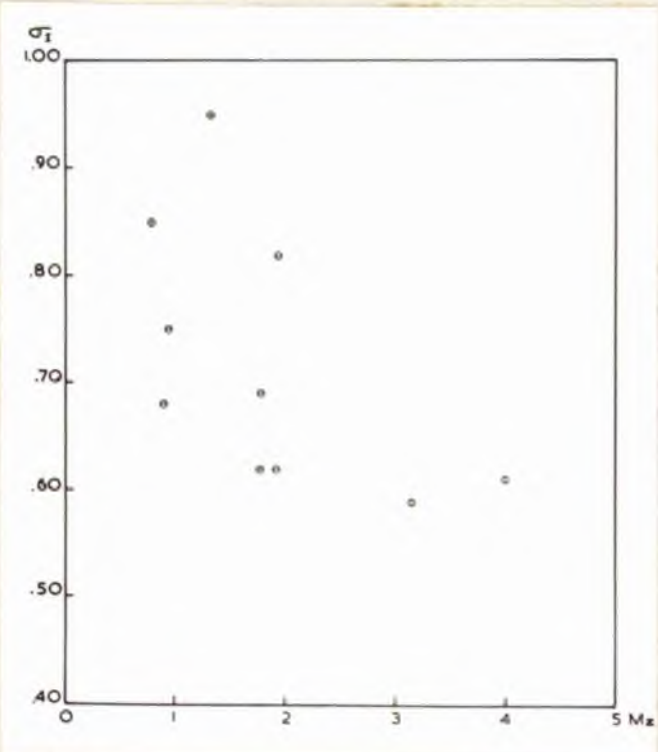
%
99.99
95
75
50
25
5
.01
-2
-1
0
1
2
3
4
5
6
ø

Fig. 119 Scatter diagram of mean size versus sorting in the Smøla sandstones.

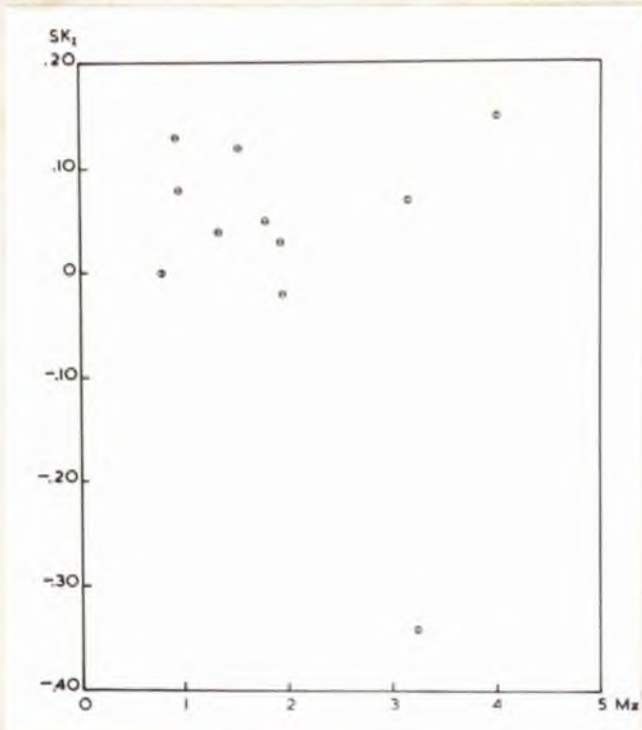
e 'K' sediments
o others

Fig. 120 Scatter diagram of mean size versus skewness in the Smøla sandstones.

e 'K' sediments
o others.



σ_I
1.00
.90
.80
.70
.60
.50
.40
0
1
2
3
4
5 Mz

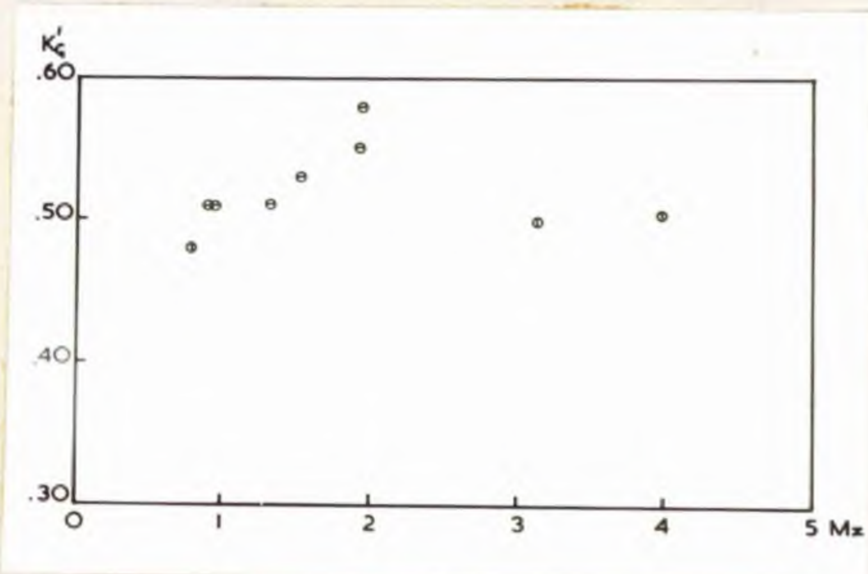


SK_I
.20
.10
0
-.10
-.20
-.30
-.40
0
1
2
3
4
5 Mz

Fig. 121 Scatter diagram of mean size versus kurtosis in the Smøla sandstones.

● 'K' sediments
● others

Fig. 122 Maximum pebble size against height above base of the succession.


K_c'
.60
.50
.40
.30
0
1
2
3
4
5 Mz

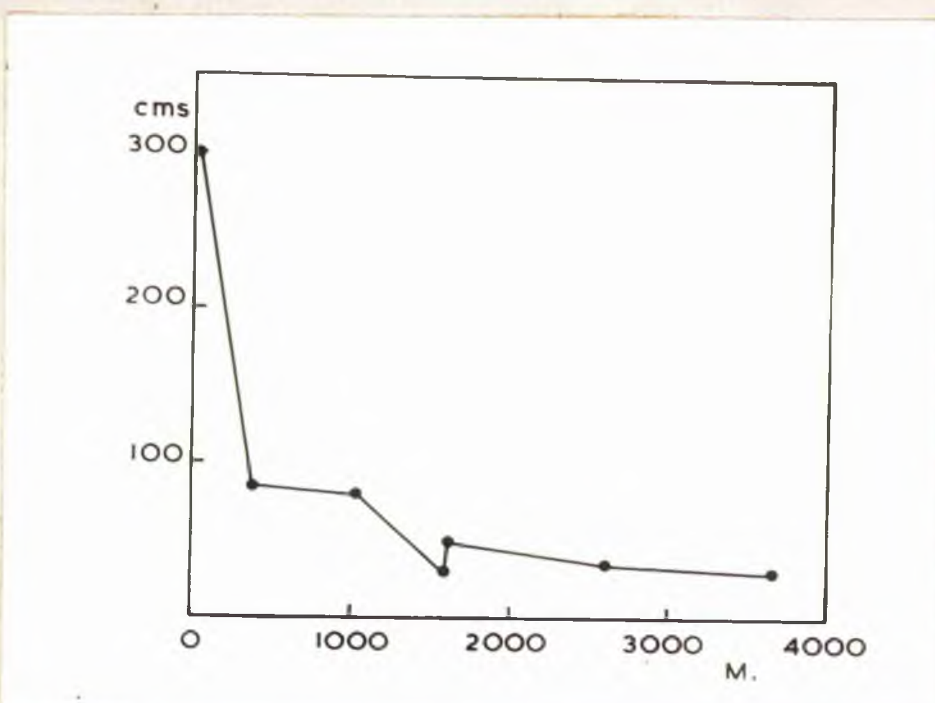
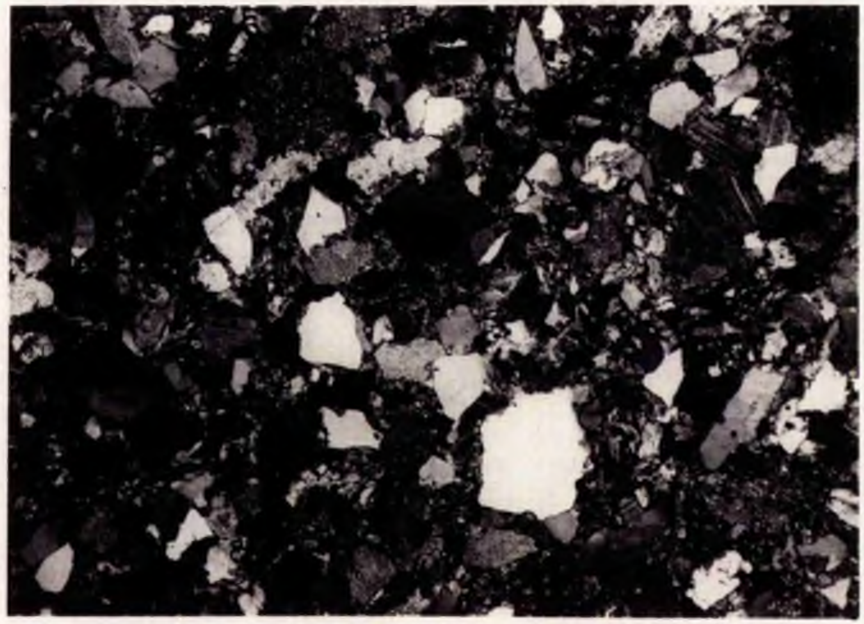

cms
300
200
100
0
1000
2000
3000
4000
M.

Fig. 123 A typical coarse to medium-grained sandstone from Hitra (specimen Kj.1). Crossed nicols. X 15.

Fig. 124 Authigenic pyrite enclosing sand grains in a coarse to medium-grained sandstone from Hitra (specimen C.6). Plane polarised light. X 15.



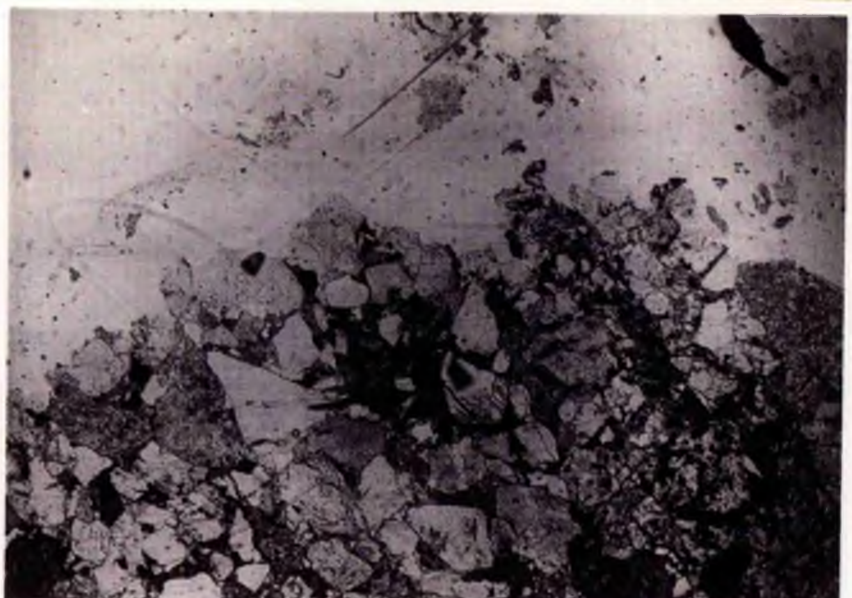


Fig. 125 A typical medium to fine-grained sandstone from Hitra (specimen S.7). Crossed nicols. X 15.

Fig. 126 Fine sand of a lens in the Hitra sandy siltstones. (specimen S.28C). Crossed nicols. X 15.

Fig. 127 Silt in the Hitra sandy siltstones (specimen S.9). Crossed nicols. X 15.

Fig. 128 Ternary diagram showing the mineralogical composition of the Hitra coarse to medium-grained sandstones.

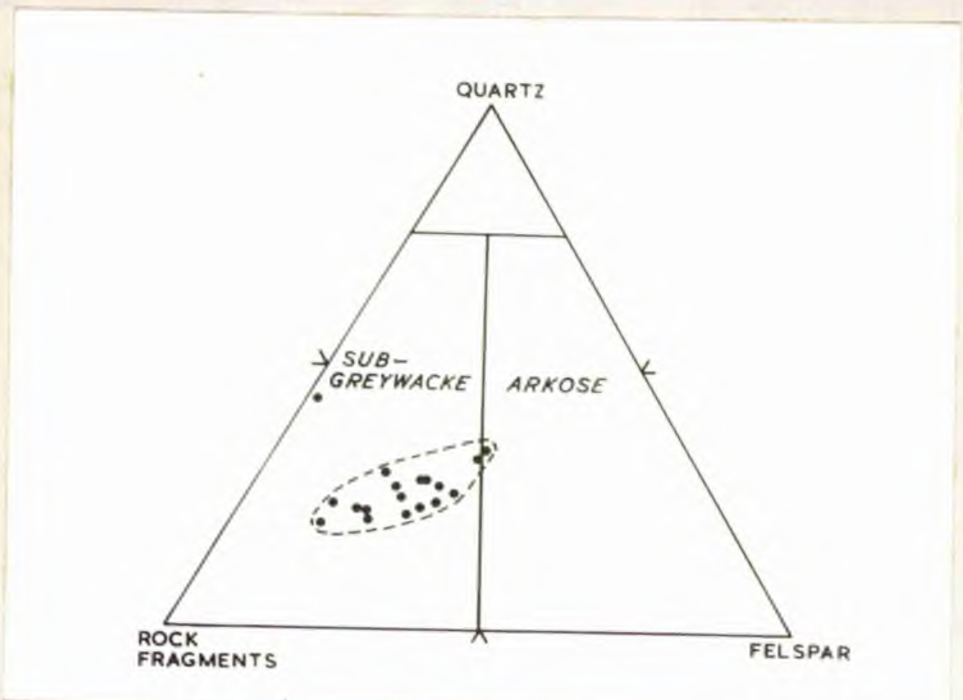

QUARTZ
SUB-
GREYWACKE
ARKOSE
ROCK
FRAGMENTS
FELSPAR

Fig. 129 Ternary diagram showing the proportion of different rock fragments in the Hitra coarse to medium grained sandstones.

Fig. 130 Pebble of granite (specimen F.C.24) from the Vollan Conglomerate. Crossed nicols. X 15.

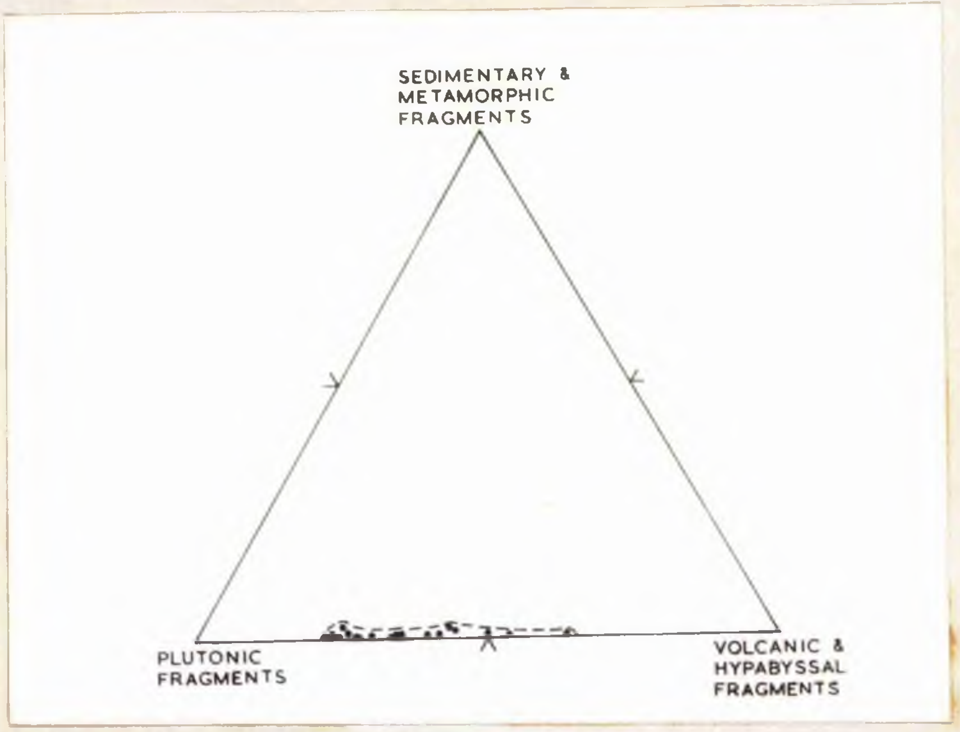

SEDIMENTARY &
METAMORPHIC
FRAGMENTS
PLUTONIC
FRAGMENTS
VOLCANIC &
HYPABYSSAL
FRAGMENTS

Fig. 131 Pebble of granodiorite (specimen F.C.26) from the Vollan Conglomerate Crossed nicols. X 15. The large euhedral zoned felspar in the centre of the picture and the small one to the left of it are rimmed with microperthite.

Fig. 132 Pebble of diorite specimen (A.C.2) from the Aune Conglomerate. Crossed nicols. X 15.

Fig. 133 Xenoliths in the Hitra diorite. Road cutting near Laksåvik.

Fig. 134 Pebble in the Aune Conglomerate (specimen A.C.6), derived from a xenolith in the Hitra diorite. Crossed nicols. X 15.

Fig. 135 Xenolith from the Hitra diorite (specimen H.I.2), Hestvika. Crossed nicols. X 15.

Fig. 136 Pebble of quartz porphyry (specimen F.C.12) from the Vollan Conglomerate. Crossed nicols. X 15.

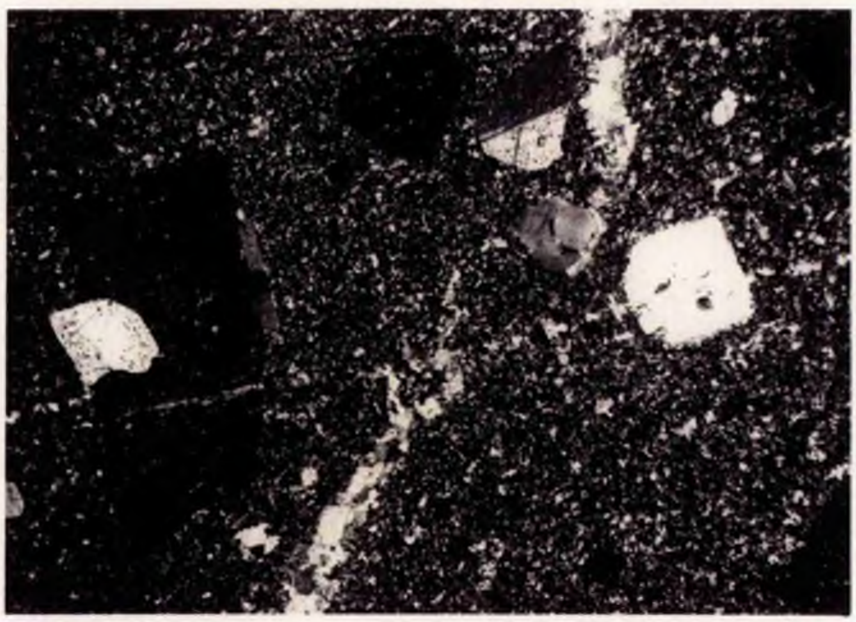
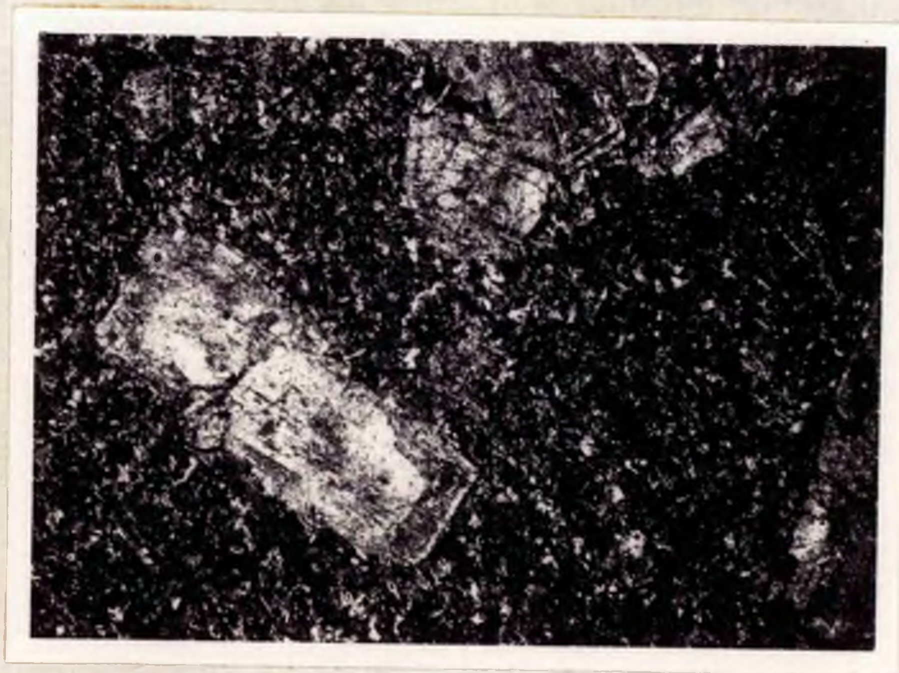


Fig. 137 Pebble of quartz porphyry (specimen F.C.33) from the Vollan Conglomerate. Crossed nicols X 15.

Fig. 138 Pebble of silicified quartz porphyry (specimen F.C.6) from the Vollan Conglomerate. Crossed nicols. X 15.

Fig. 139 Pebble of an intermediate rock (specimen F.C.13) from the Vollan Conglomerate. Crossed nicols X 15.

Fig. 140 Pebble of an intermediate rock (specimen F.C.29) from the Vollan Conglomerate. Crossed nicols. X 15.



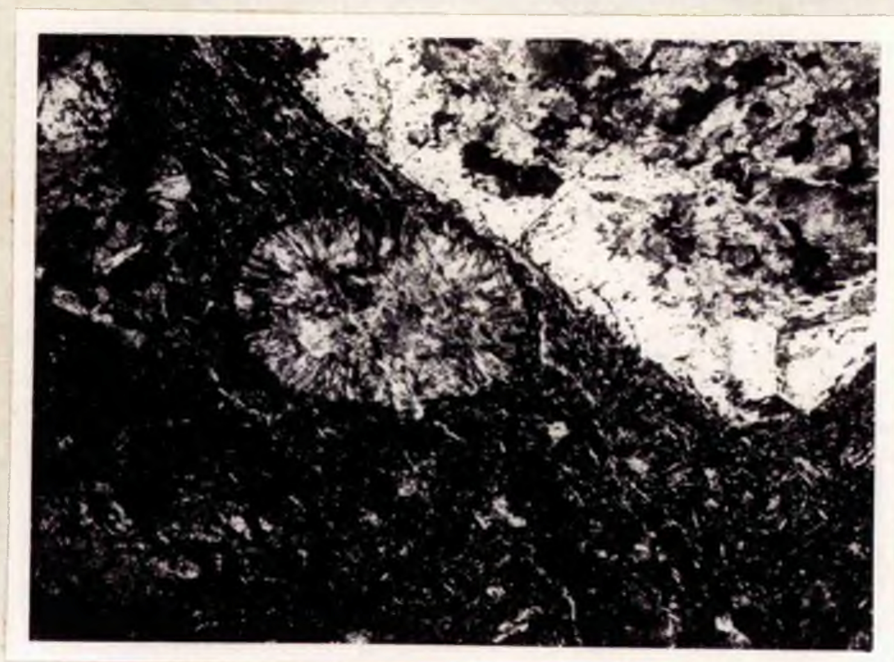


Fig. 141 Pebble of gneiss (specimen B.C.1) from the Balsnes Conglomerate. Crossed nicols. X 15.

Fig. 142 A typical coarse to medium-grained sandstone from Smøla (specimen K.2). Crossed nicols. X 15.

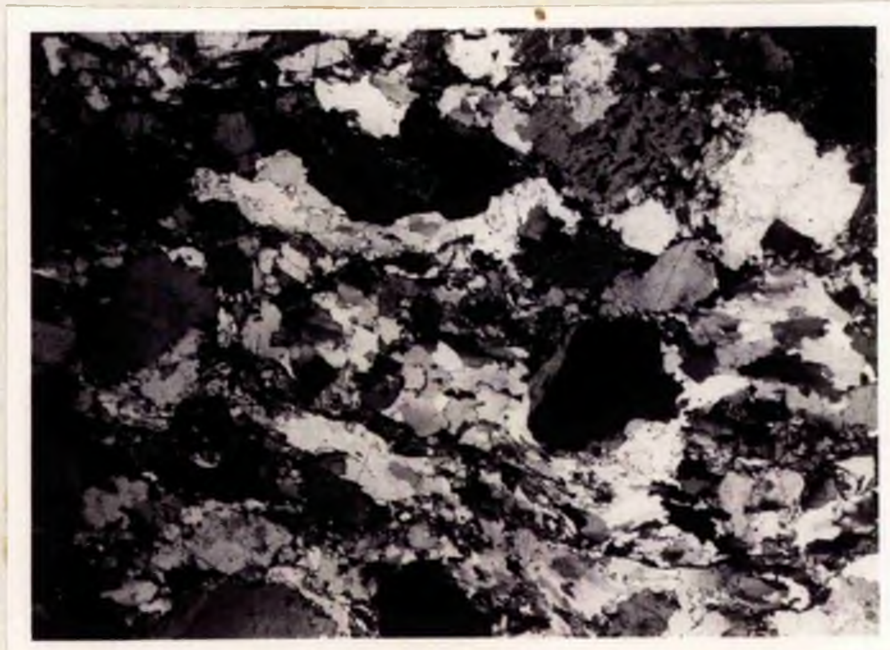
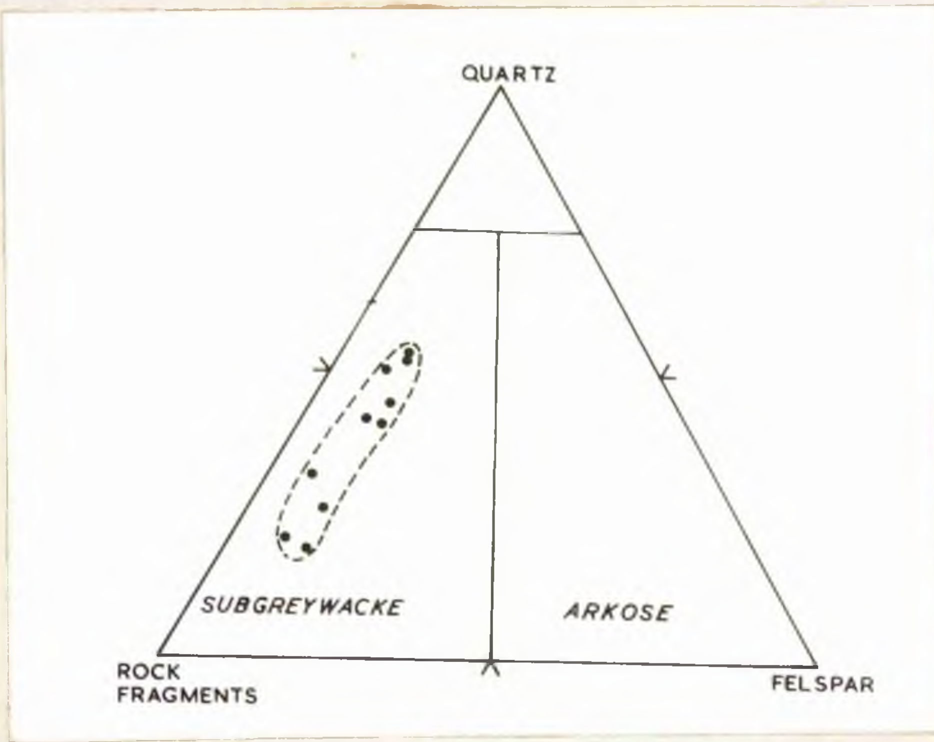


Fig. 143 Ternary diagram showing the mineralogical composition of the Smøla coarse to medium-grained sandstones.

Fig. 144 Ternary diagram showing the proportions of different rock fragments in the Smøla coarse to medium-grained sandstones.


QUARTZ
SUBGREYWACKE
ARKOSE
ROCK FRAGMENTS
FELSPAR

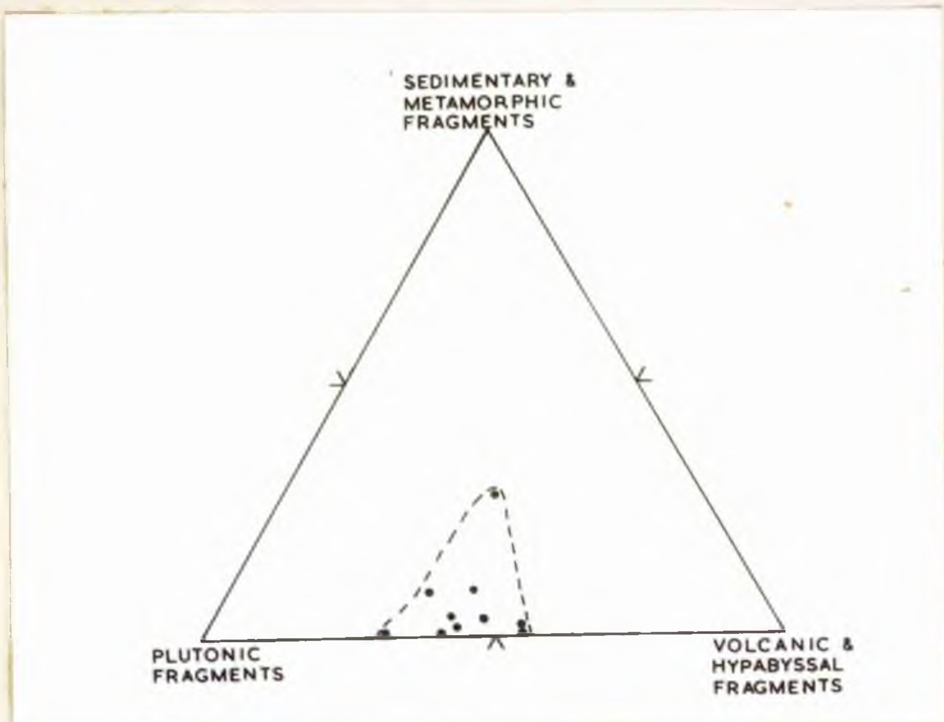

SEDIMENTARY & METAMORPHIC FRAGMENTS
PLUTONIC FRAGMENTS
VOLCANIC & HYPABYSSAL FRAGMENTS

Fig. 145 Pebble of potash rich granite (specimen Gl.C.3) from the Glas~~s~~ Conglomerate, showing the micrographic intergrowth of quartz and felspar. Crossed nicols. X 15.

Fig. 146 Pebble of quartz porphyry (specimen K.6.7) from the Ed~~d~~y Conglomerate. Crossed nicols. X 15.

Fig. 147 Pebble of quartz porphyry (specimen E.G.4) from an Old Red Sandstone Conglomerate, exposed along the river North Esk, Scotland. Crossed nicols. X 15.

Fig. 148 Pebble of dolerite (specimen LH.C.1) from the Glasø Conglomerate on Lille Havrеø. Crossed nicols. X 15.

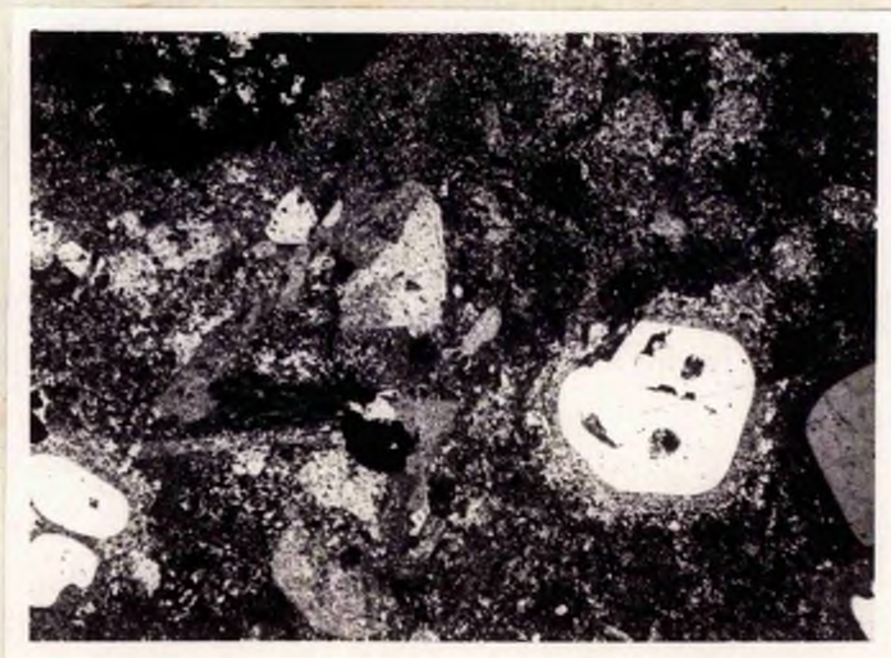


Fig. 149 Pebble of an intermediate rock (specimen Gl.C.8) from the Glasø Conglomerate. Crossed nicols. X 15.

Fig. 150 Pebble of a metamorphic rock (specimen K.14.2) from the Southeast Kyrhaug Conglomerate. Crossed nicols. X 15.

Fig. 151 Pebble of a metamorphic rock (specimen K.14.4) from the Southeast Kyrhaug Conglomerate. Crossed nicols. X 15.

Fig. 152 Pebble of a sandstone (specimen K.6.1) from the ~~Edoy~~ Edøy Conglomerate. Crossed nicols X 15.

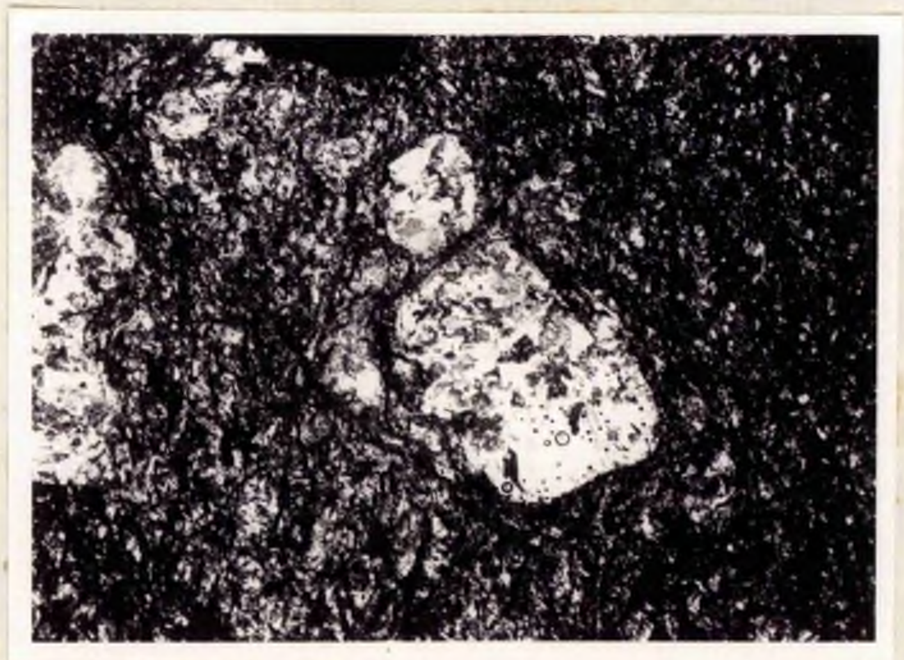
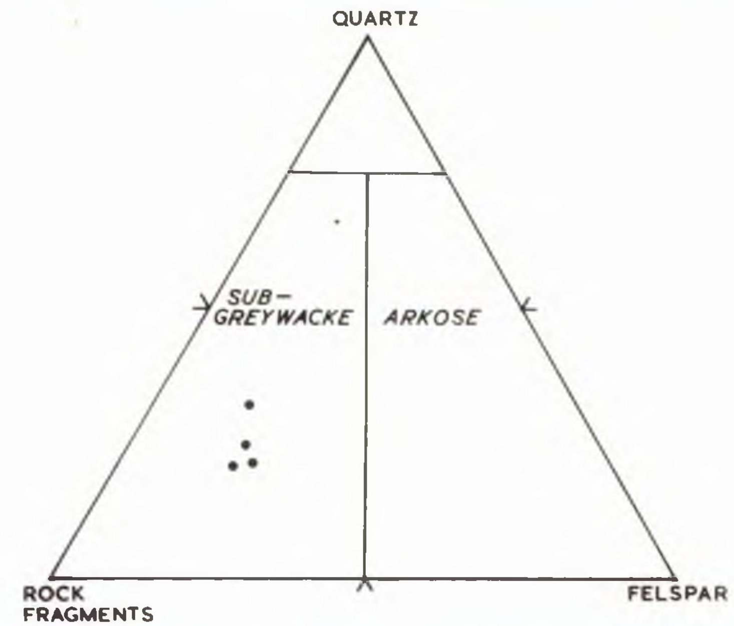


Fig. 153 Ternary diagram showing the mineralogical composition of sandstone pebbles from the Ed~~o~~y Conglomerate.

Fig. 154 Ternary diagram showing the proportion of different rock fragments in the sandstone pebbles from the Ed~~o~~y Conglomerate.


QUARTZ
SUB-
GREYWACKE
ARKOSE
ROCK
FRAGMENTS
FELSPAR

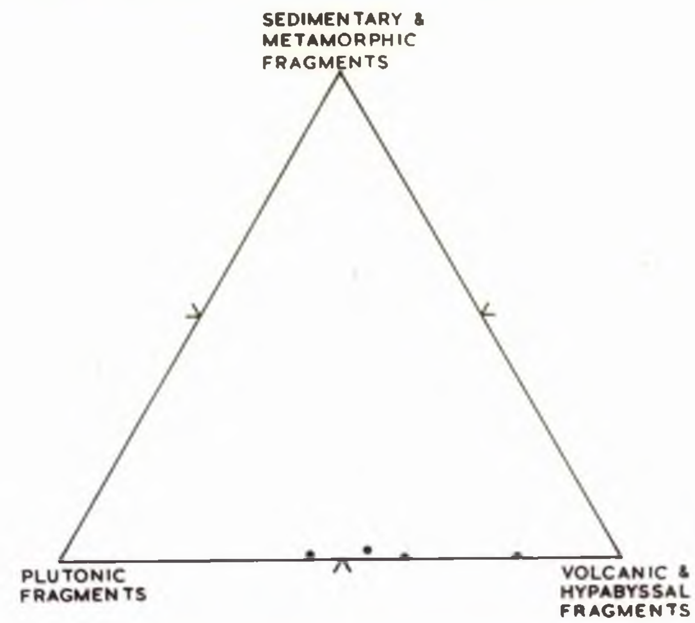
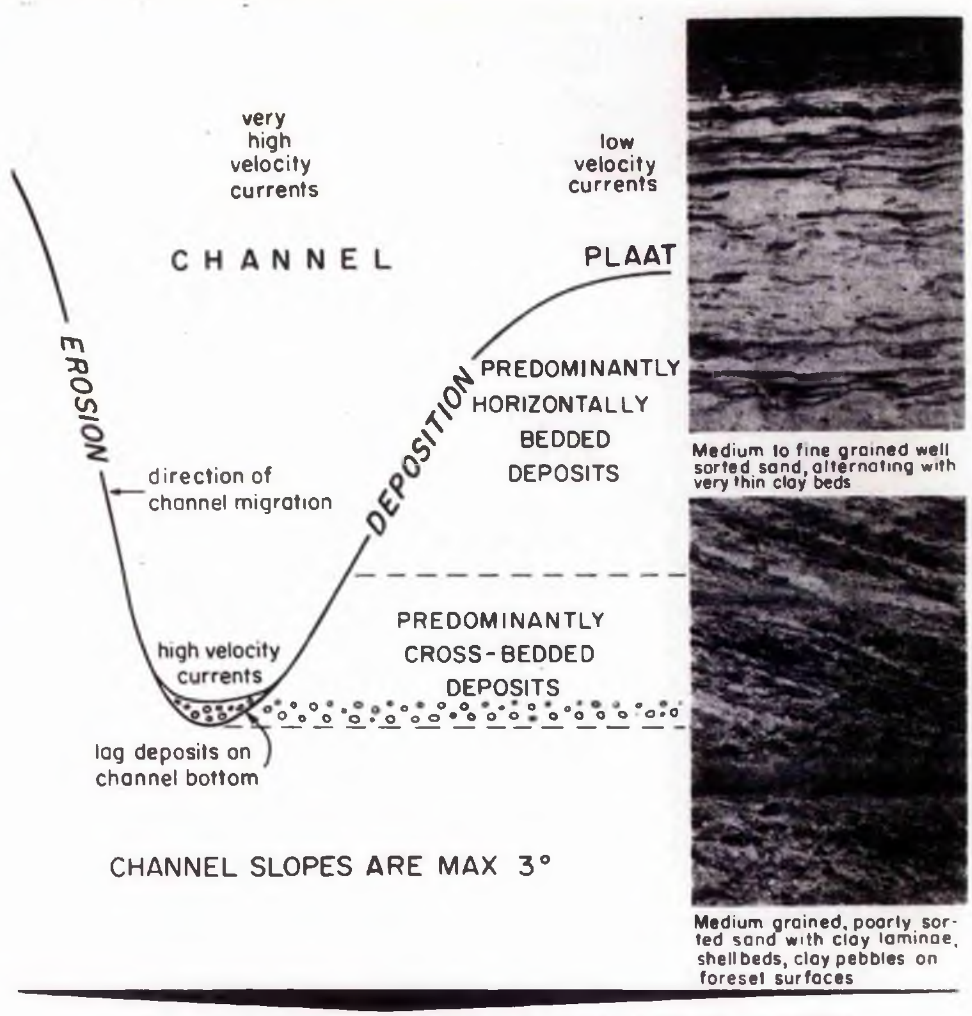

SEDIMENTARY &
METAMORPHIC
FRAGMENTS
PLUTONIC
FRAGMENTS
VOLCANIC &
HYPABYSSAL
FRAGMENTS

Fig. 155 Pebble of grey sandstone (specimen K.14.1) from the Southeast Kyrhaug Conglomerate. Crossed nicols. X 15.

Fig. 156 Diagram to illustrate the mode of deposition of sediments in the Haringvliet estuary. From Oomkens and Terwindt (1960).



Haringvliet channel drawn on natural scale (S-Channel 1901)

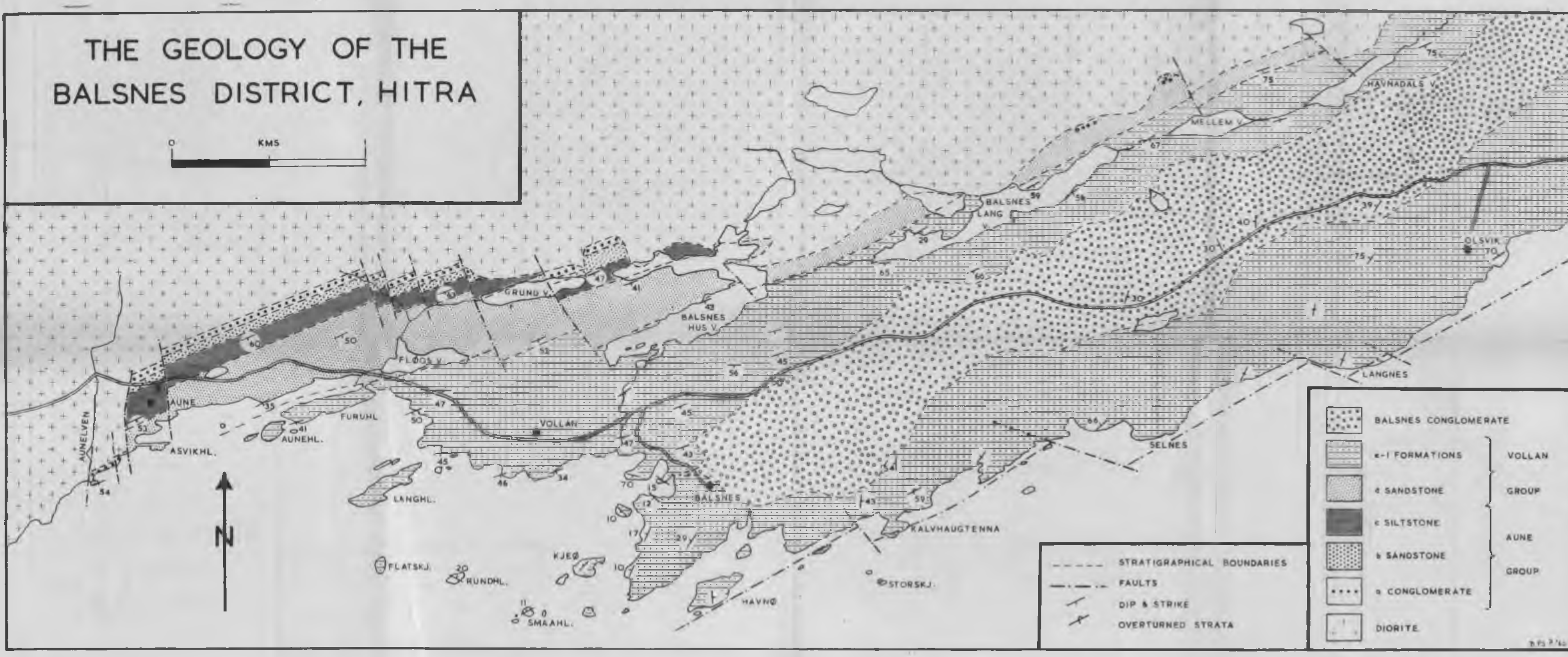
(scale 1 : 5000)

The channel migrates in lateral direction by erosion of one of its banks and deposition on the other.

Map 2

The Geology of the Balsnes

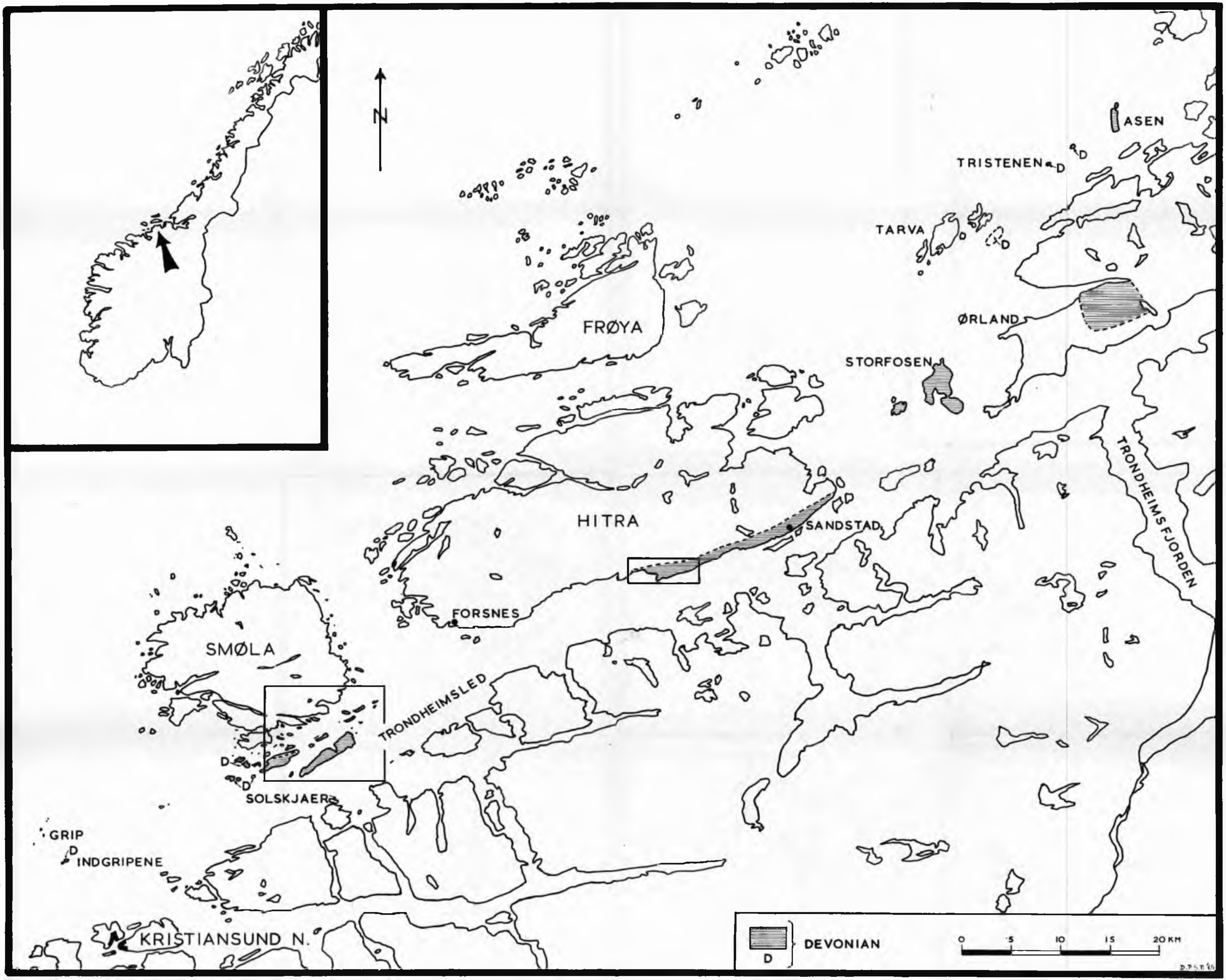
District, Hitra.



THE GEOLOGY OF THE
BALSNES DISTRICT, HITRA
0
KMS
BALSNES CONGLOMERATE
e-i FORMATIONS
d SANDSTONE
c SILTSTONE
b SANDSTONE
a CONGLOMERATE
DIORITE
VOLLAN GROUP
AUNE GROUP
STRATIGRAPHICAL BOUNDARIES
FAULTS
DIP & STRIKE
OVERTURNED STRATA
AUNELVEN
AUNE
ASVIKHL.
AUNEHL.
FURUHL.
FLOOS V.
GRUND V.
VOLLAN
LANGHL.
FLATSKJ.
RUNDHL.
SMAAHL.
KJEØ
BALSNES
BALSNES HUS V.
BALSNES LANG V.
MELLEM V.
HAVNADALS V.
OLSVIK
LANGNES
SELNES
KALVHAUGTENNA
STORSKJ.
HAVNØ

Map 1

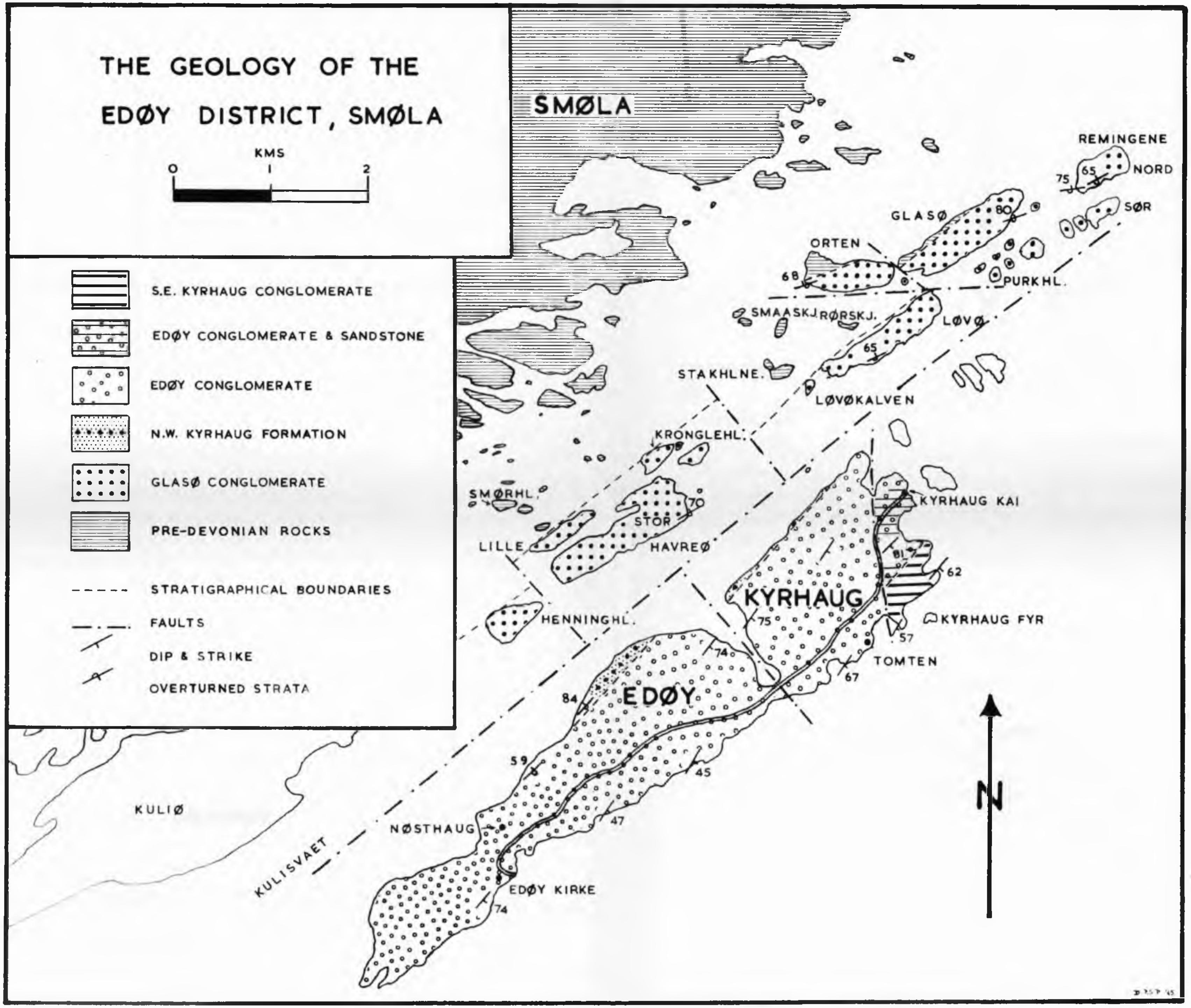
The distribution of Devonian rocks in the Trondheimsled district.


N
ASEN
TRISTENEN
D
TARVA
FRØYA
ØRLAND
STORFOSEN
HITRA
SANDSTAD
TRONDHEIMSFJORDEN
FORSNES
SMØLA
TRONDHEIMSLED
SOLSKJAER
GRIP
INDGRIPENE
KRISTIANSUND N.
DEVONIAN
0
5
10
15
20 KM

Map 3

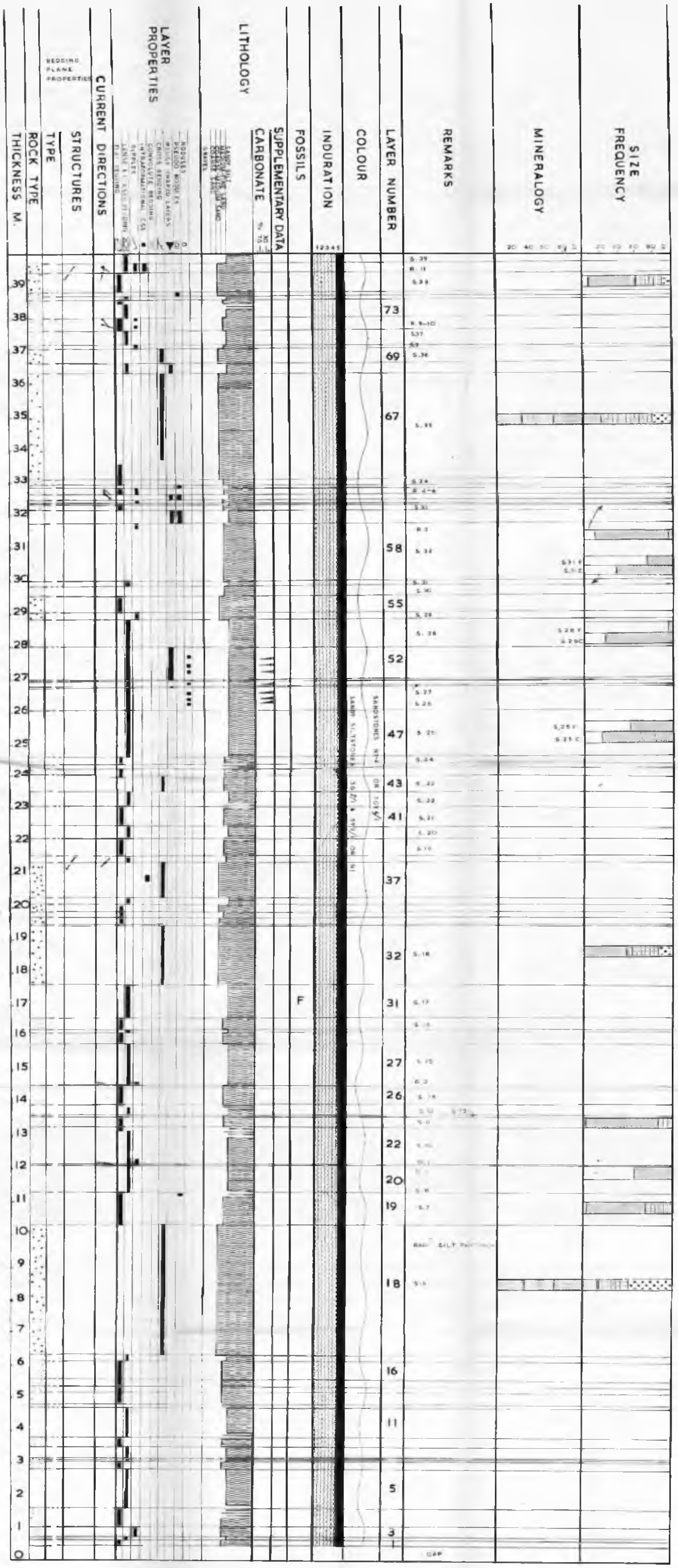
The Geology of the Edøy

District, Smøla.



THE GEOLOGY OF THE
EDØY DISTRICT, SMØLA
KMS
0
1
2
S.E. KYRHAUG CONGLOMERATE
EDØY CONGLOMERATE & SANDSTONE
EDØY CONGLOMERATE
N.W. KYRHAUG FORMATION
GLASØ CONGLOMERATE
PRE-DEVONIAN ROCKS
STRATIGRAPHICAL BOUNDARIES
FAULTS
DIP & STRIKE
OVERTURNED STRATA
SMØLA
REMINGENE
NORD
SØR
GLASØ
ORTEN
PURKHL.
SMAASKJ
RØRSKJ.
LØVØ
STAKHLNE.
LØVØKALVEN
KRONGLEHL.
SMØRHL.
STOR
HAVREØ
LILLE
HENNINGHL.
KYRHAUG KAI
KYRHAUG
KYRHAUG FYR
TOMTEN
EDØY
KULIØ
NØSTHAUG
KULISVAET
EDØY KIRKE
N
75
65
80
68
65
70
81
62
75
57
74
67
84
59
45
47
74

HITRA, LOG 1

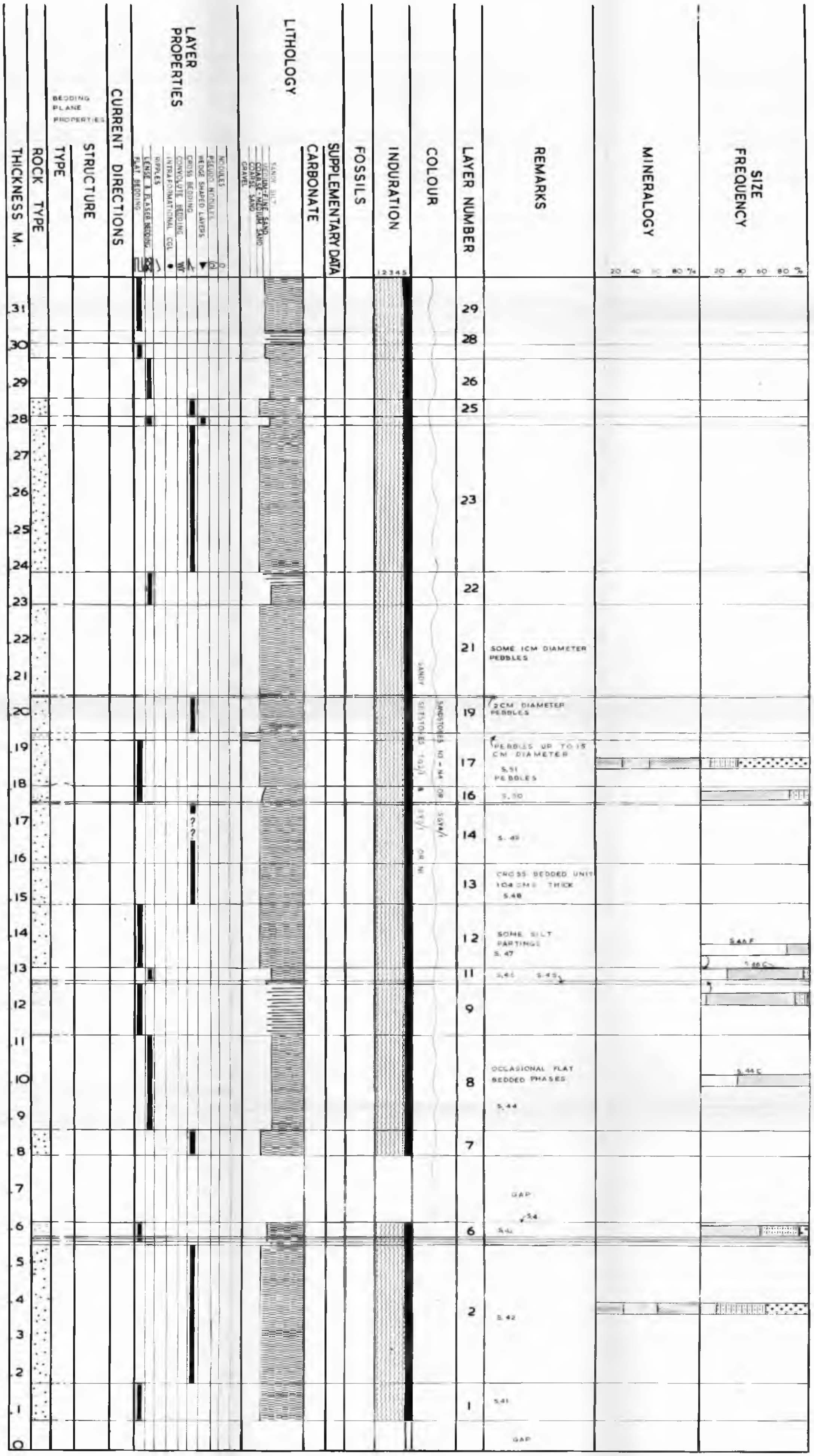


BEDDING PLANE PROPERTIES
LAYER PROPERTIES
LITHOLOGY
THICKNESS M.
ROCK TYPE
TYPE
STRUCTURES
CURRENT DIRECTIONS
CARBONATE
SUPPLEMENTARY DATA
FOSSILS
INDURATION
COLOUR
LAYER NUMBER
REMARKS
MINERALOGY
SIZE FREQUENCY
73
69
67
58
55
52
47
43
41
37
32
31
27
26
22
20
19
18
16
11
5
3
1
F

Hitra, Log 1

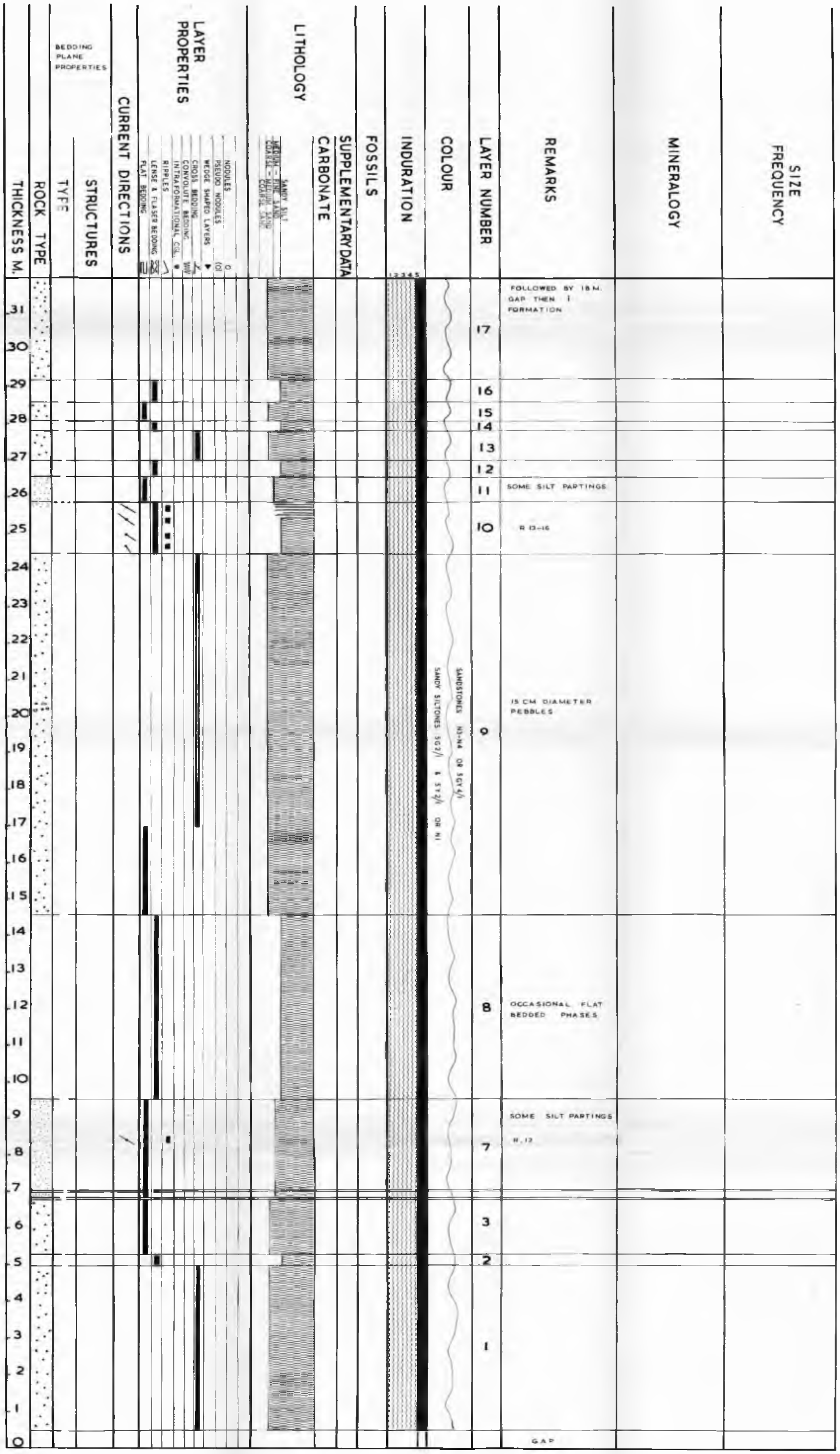
Hitra, Log 2

HITRA, LOG 2


THICKNESS M.
ROCK TYPE
TYPE
STRUCTURE
BEDDING PLANE PROPERTIES
CURRENT DIRECTIONS
LAYER PROPERTIES
LITHOLOGY
CARBONATE
SUPPLEMENTARY DATA
FOSSILS
INDURATION
COLOUR
LAYER NUMBER
REMARKS
MINERALOGY
SIZE FREQUENCY
SOME 1CM DIAMETER PEBBLES
2CM DIAMETER PEBBLES
PEBBLES UP TO 15 CM DIAMETER
PEBBLES
CROSS BEDDED UNIT 104 CMS THICK
SOME SILT PARTINGS
OCCASIONAL FLAT BEDDED PHASES
GAP

Hitra, Log 3

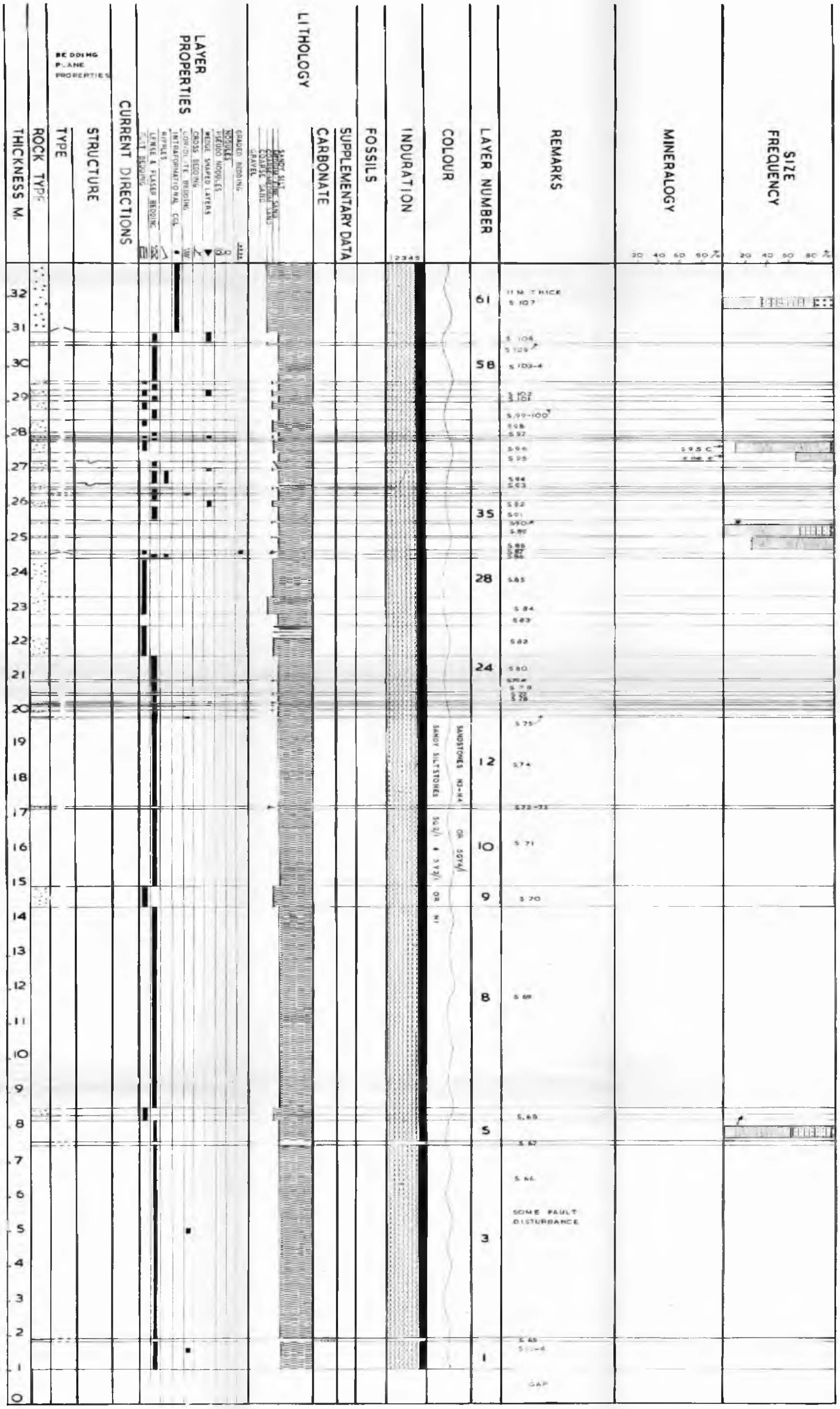
HITRA, LOG 3



THICKNESS M.
ROCK TYPE
BEDDING PLANE PROPERTIES
TYPE
STRUCTURES
CURRENT DIRECTIONS
LAYER PROPERTIES
NODULES
PSEUDO NODULES
WEDGE SHAPED LAYERS
CROSS BEDDING
CONVOLUTE BEDDING
INTRAFORMATIONAL CGL
RIPPLES
LENSE & FLASER BEDDING
FLAT BEDDING
LITHOLOGY
SANDY SILT
CARBONATE
SUPPLEMENTARY DATA
FOSSILS
INDURATION
12345
COLOUR
LAYER NUMBER
REMARKS
MINERALOGY
SIZE FREQUENCY
FOLLOWED BY 18 M. GAP THEN I FORMATION
SOME SILT PARTINGS
R 13-16
15 CM DIAMETER PEBBLES
SANDSTONES N3-N4 OR 5GY4/1
SANDY SILTONES 5G2/1 & 5Y2/1 OR N1
OCCASIONAL FLAT BEDDED PHASES
SOME SILT PARTINGS
R. 12
GAP
17
16
15
14
13
12
11
10
9
8
7
3
2
1
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0

Hitra, Log 4

HITRA, LOG 4



THICKNESS M.
ROCK TYPE
BEDDING PLANE PROPERTIES
TYPE
STRUCTURE
CURRENT DIRECTIONS
LAYER PROPERTIES
LITHOLOGY
CARBONATE
SUPPLEMENTARY DATA
FOSSILS
INDURATION
COLOUR
LAYER NUMBER
REMARKS
MINERALOGY
SIZE FREQUENCY
SANDSTONES N3-N4 OR 5GY4/1
SANDY SILTSTONES 5G2/1 + 5Y3/1 OR N1
SOME FAULT DISTURBANCE
GAP