THE STRATIGRAPHY AND SEDIMENTOLOGY OF THE MJØSA LIMESTONE (MIDDLE ORDOVICIAN), NORWAY

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy

by

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ABSTRACT

In the north of the Oslo Region, the Middle Ordovician ends in a regression and unconformity between the Mjøsa Limestone (uppermost Caradoc) and Helgøya Quartzite (Middle Llandovery). The 100-120m thick limestone is a sufficiently distinctive unit to warrant the assignation, Mjøsa Limestone Formation. A tripartite subdivision into Members is based on the recognition of three small scale regressive sequences within the limestone, which can be used to effect chronostratigraphical correlation between the outcrop districts.

Facies analysis indicates that, by analogy with Recent carbonates in the Bahamas, Florida and the Persian Gulf, deposition took place in an environment very near mean sea level and of very low relief. Within the six carbonate and three terrigenous clastic dominated facies, environments characteristic of variable energy conditions in the supratidal, intertidal and shallow subtidal (max. depth 5-10m) are recognisable.

The low supratidal - high intertidal facies are represented by mudcracked red beds of highly bioturbated terrigenous mud with interspersed bioclastic stringers, and cryptalgal laminites with spar-filled vugs and dessication polygons, indicative of frequent subaerial exposure, and post-lithification solution. Interbedded peloidal grainstones also contain evidence of very early cementation, probably during periods of exposure as beach rock. In the low-interdal zone, a bioturbated facies, in which the dolomite filled burrows are mostly vertical and the coarser (bioclastic) horizons are frequently cross-bedded, passes laterally into a fossiliferous finer grained subtidal equivalent with inclined, horizontal and vertical burrows. These beds appear at the top of the limestone and are eroded by large channels filled with cross-stratified intraclast rich peloidal grainstones.

The subtidal zone contains both terrigenous and carbonate facies deposited under variable energy conditions. The thinly interbedded siltstones, fine sandstones and bioclastic grainstones represent quiet water deposits with tidally induced movement of coarser sediment. Massive bioclastic grainstones represent prograding shoals, which when sufficiently stabalised are either colonised by Solenopora, or micritized by the activity of endolithic algae. Subtidal deposits in calm waters are represented by micritic mudstones and calcisiltites.

Although benthos are generally restricted by the mobile nature of the substrate a flourishing epifauna appears as small patch reefs composed mostly of stromatoporoids and corals. Within individual reefs a zonation of biotic assemblages allows differentiation of separate development stages. At its height the reef complex extended from the southeast to the west of the area and formed an effective barrier to sediment movement and current activity, allowing differentiation of back reef and fore reef deposits. Contemporaneous ahermatypic stromatoporoids grew in extremely shallow water as evidenced by their lateral equivalence to red beds. The red alga, Solenopora also shows variations in biomass structure which allow differentiation between growth in very shallow and deeper water. Unlike the patch reefs, the Solenopora bioherms are monotypic with the alga acting as builder, binder, domicile, food source, sediment supplier and sediment trapper.

The Mjøsa Limestone was deposited in the northeastern extremity of the Middle Ordovician Baltoscandian epicontinental sea, as part of a circumscribing carbonate shoreline facies traceable through Sweden and in Estonia. Local and regional facies changes indicate a deepening to the south and southwest. During the upper Caradoc it is apparent that the Mjøsa district occupied a marginal position to both the epicontinental sea and geosynclinal ocean, but following exposure in the Ashgillian, circulation between the two was greatly reduced. Local epeirogenic movements of the Baltic Shield are held responsible for the small regressive cycles within the limestone, while the major regression and non deposition of the Tretaspis shale is accorded a glacio-eustatic control.

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CHAPTER ONE

INTRODUCTION

A. GENERAL

The strata to which the present study relates outcrop in the "fylke" of Oppland and Hedmark. All localities examined (with the exception of Torsaeter) can be found on "Topographisk kart over Norge" sheets 25B (Gjøvik) and 26A (Hamar) on the 1:100,000 scale, and sheets 1816 I (Gjøvik), 1816 II (Eina), 1916 III (Østre Toten), and 1916 IV (Hamar) on the 1:50,000 scale. The 1:5,000 scale maps being more recent editions, provide far more accurate siting of localities and place names. All grid-references and locality names cited in the text are taken from the 1:50,000 and 1:5,000 sheets.

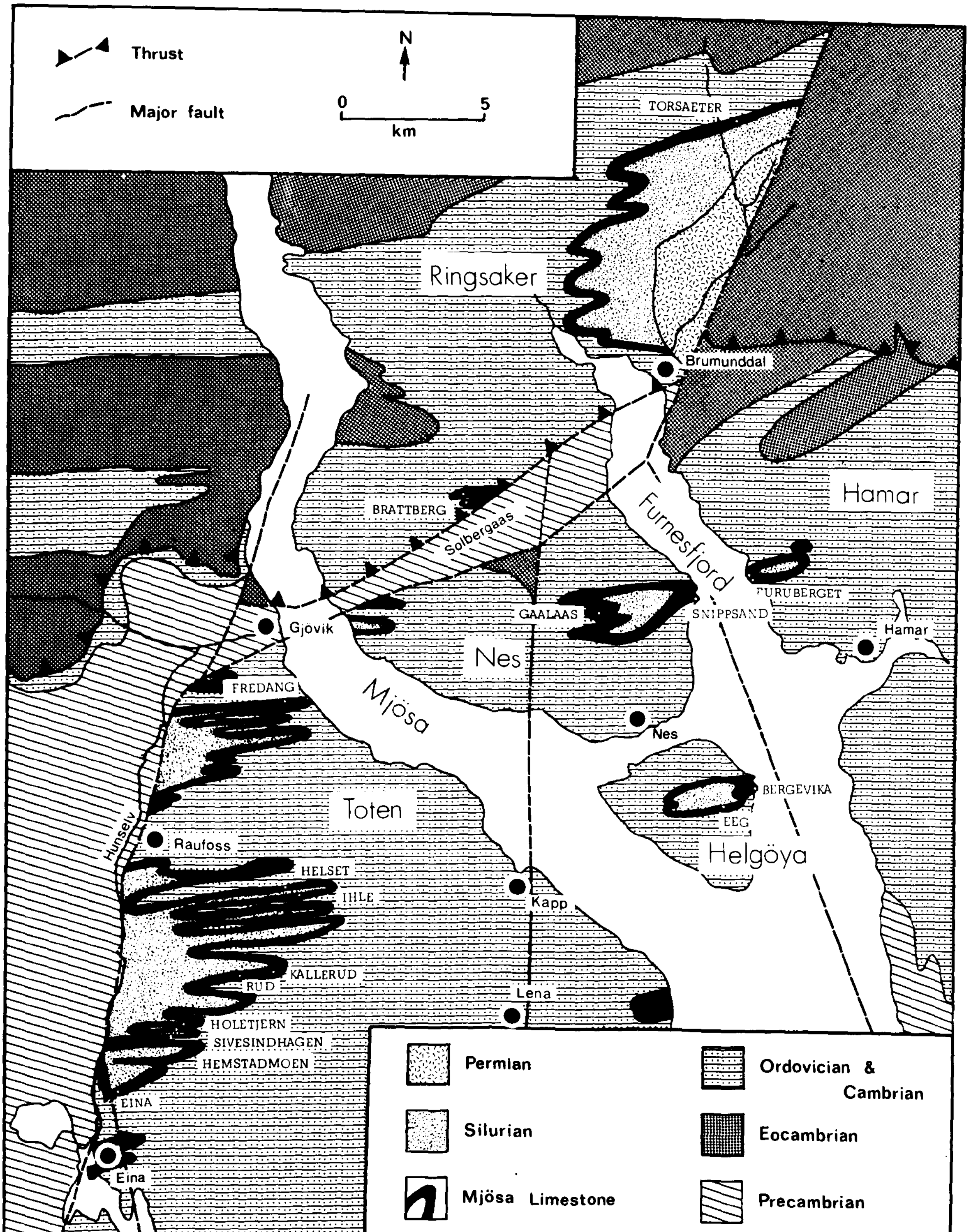
1. Geographical location of the outcrop area.

The Mjøsa Limestone outcrops in the picturesque rolling countryside surrounding the central part of lake Mjøsa, Norway's largest inland lake. Situated approximately 120 km. north of Oslo at the northern extremity of the Oslo graben, the area is one of fairly intensive agricultural use, due partly to the drift cover with its associated rich soils, and partly to the gentle nature of the topography. Consequently, one can distinguish the areas occupied by the Cambro-Silurian rocks from those of the Precambrian, which have thin soil cover, form most of the major upland features, and are generally heavily forested (e.g. the Salbergaas in the Nes peninsula, and the area west of the Hundselv fault in Toten).

The area studied (Fig.1.1) conveniently lends itself to a tripartite division into the Toten, Nes-Hamar, and Ringsaker districts.

a) The Toten district extends from the eastern shore of lake Mjøsa westwards to the Hundselv fault zone, where the Cambro-Silurian succession abuts onto the Precambrian. The Mjøsa limestone occurs in a series of tight almost isoclinal folds from Gjøvik in the north to Eina in the south, although the continuity of this feature is broken in the vicinity of Raufoss by an east-west trending synclinorium which exposes the Orthoceras limestone

Fig.1.1: Simplified geological map of the Mjøsa district (after SKJESETH 1957, 1963). Only those localities which lend their name to formal stratigraphical terminology or are not represented on the detailed locality maps for the Toten and Nes-Hamar districts (Figs I.1,2) are illustrated.



Thrust
Major fault
N
0
5
km
TORSAETER
Ringsaker
Brumunddal
BRATTBERG
Solbergaas
Hamar
Furnesfjord
FURUBERGET
GAALAAS
SNIPPSAND
Hamar
Gjövik
Nes
FREDANG
Mjösa
Nes
BERGEVIKA
EEG
Toten
Helgöya
Hunselv
Raufoss
HELSET
IHLE
Kapp
KALLERUD
RUD
Lena
HOLETJERN
SIVESINDHAGEN
HEMSTADMOEN
EINA
Eina
Permian
Ordovician & Cambrian
Silurian
Eocambrian
Mjösa Limestone
Precambrian

and Ogygiocaris shale (SKJESETH 1963). Good exposures are confined to the area south of Raufoss where the limestone forms a sinuous tautology usually forested, with a series of small lakes occupying the noses of the synclines (SKJESETH 1956). North of Raufoss this distinctive topographic feature is lost in an area of heavy forest and drift cover.

b) The Nes-Hamar district is defined as the tract of countryside occupying the Nes peninsula south of the Precambrian Salbergaas horst, the island of Helgøya, and the area between Hamar and Brumunddal on the east bank of the Furnesfjord. Here the limestone again forms the major topographic features in the generally low lying Cambro-Silurian areas. On the island of Helgøya the limbs of the synclinorium are seen as steep, heavily forested scarps.

c) The Ringsaker district includes the exposures to the north of the Salbergaas and the Veldre region between Brumunddal and the line of the Ringsaker Inversion.

2. Economic importance of the limestone.

Demand for the Mjøsa Limestone as a raw material has fluctuated greatly, a fact witnessed by the abundance of disused quarries and lime-kilns. These supplied the local farmers with lime before the introduction of modern fertilizers, as well as providing building stone for lakeside jetties and domestic foundations. Today the main workings are confined to the Furuberget and Hole localities, the former provides a stable outlet for roadstone, while the latter produces lime and a small amount of roadstone. Some lime is transported to Oslo for cement manufacture, but the majority is now used as a neutralising agent in streams and lakes to combat sulphur dioxide pollution prior to restocking with fish! This demand has led to the reopening of many small disused quarries in the Hole area.

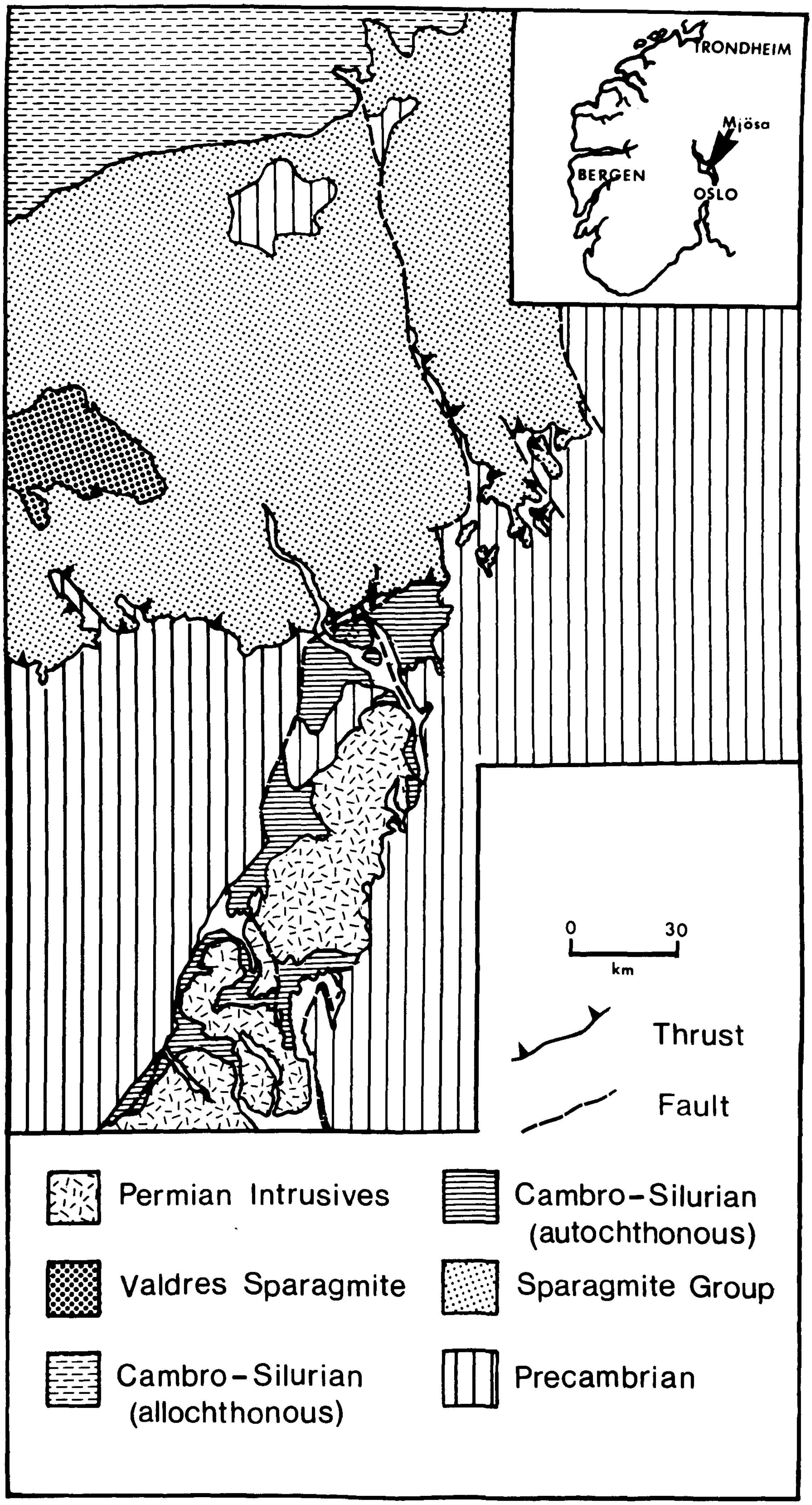
3. Nature of the exposure

In the Toten district quarries provide the main source of exposure, and many of the older ones are further enhanced by the stripping of soil and vegetation cover prior to blasting. This provides a clean weathered surface, sometimes in the form of a limestone pavement, particularly useful where dip sections have been quarried and the beds are almost vertical. In the Nes-Hamar district old quarries are not so abundant, but the lakeside exposures at Bergevika and Snippsand are extremely valuable. Here the limbs of the synclinoria have been eroded to form sheer cliffs up to 20m high and almost 1km in length on the southern side of the bays, which are themselves formed by the breaching of the resistant limestone in the noses of the folds. However access is very limited and examination is best undertaken in Spring when the lake is frozen and the water level fallen by up to 3m, exposing the whole succession and providing extra solution weathered and vegetation free surfaces. (Collecting specimens by boat is a precarious and rather dangerous procedure). Furuberget provides an excellent lakeside section below the main working quarry, where the basal beds can be studied on both limbs of the syncline which are exposed in the railway cuttings. Roadside exposures although generally poor throughout the area, were used to trace the fold limbs from one quarry to another and allow a fuller stratigraphical understanding to emerge.

B. GEOLOGICAL SETTING

The Cambro-Silurian tract of the Mjøsa district is bordered to the west by the upfaulted Precambrian; to the north largely by the thrustline marking the limit of the Sparagmite nappes; to the east by the underlying Precambrian, and to the south chiefly by the igneous rocks of the Feiring district (Fig. 1.2). Major Permian faults divide the region into different

Fig.1.2: The geological setting of the Mjøsa district (after SKJESETH 1963).


TRONDHEIM
Mjösa
BERGEN
OSLO
0
30
km
Thrust
Fault
Permian Intrusives
Cambro-Silurian (autochthonous)
Valdres Sparagmite
Sparagmite Group
Cambro-Silurian (allochthonous)
Precambrian

tectonic units. SKJESETH (1952a, 1963) accredits the preservation of these sediments to their subsidence and slight tilting between the major faults.

Unlike the remainder of the Oslo region, the Cambro-Silurian sediments in the Mjøsa district commence with the lowermost Cambrian (Holmia Series) which overlies the Late Precambrian/Eocambrian sparagmite sequence (Hedmark Group) (BJØRLYKKE et al 1967) and consists mainly of grey and dark shales, siltstones and fine grained sandstones. (A stratigraphical table for the Mjøsa districts is given in Fig. 1.3). The Middle Cambrian (Paradoxides Series) follows conformably, as do beds of the Olenus Series, which are generally grouped together and referred to as Alum shales with stinkstone concretions (HENNINGSMOEN 1960, SKJESETH, 1963 p.36). However, when the Cambrian rests on the Precambrian basement, the sequence commences with beds of Middle Cambrian age (STRAND 1972). The Ordovician begins with Alum Shales and shows no break in sedimentation with the Cambrian. The top of the Ceratopyge Series contains a light coloured limestone which passes up into shales at the base of the Asaphus Series, and into the Orthoceras Limestone, a thick impure nodular limestone in the Mjøsa district. The Ogygiocaris Series is composed of dark shales with occasional dark limestone lenses, passing up into beds of the Chasmops Series. Here, for the first time, distinct facies differences between Mjøsa and Oslo are encountered. The Chasmops Series is composed of the Ceolospheridium Beds (shales and arenaceous limestones with the calcareous algae Coelospheridium and Mastopora as characteristic fossils), the Cyclorinus Beds (arenaceous shales with layers of arenaceous limestones) and finally the massive Mjøsa Limestone. The top of the Mjøsa Limestone marks a break in sedimentation since the overlying Helgøya Quartzite (upper Stricklandia Series) was deposited on a well developed karst surface in places. Sedimentation continued with the Pentamerus Limestone, Monograptus shale and finally the Bruflat Sandstone,

Fig.1.3: The Lower Palaeozoic stratigraphy of the Mjøsa district (after HENNINGSMOEN 1960).

Correlation with Great Britain	RINGSAKER (Northern Mjøsa district)		TOTEN, NES-HAMAR (Central Mjøsa districts)	
Downtonian				
— ? —	10	Not preserved below Permian lavas	10	Not preserved
	9g		9g	
	9f		9f	
Ludlovian	9e		9e	
	9d		9d	
	9c		9c	
— ? —	9b		9b	
	9a		9a	
	8d		8d	
Wenlockian	8c		8c	
	8b	Calcareous sandstone beds	8b	Calcareous sandstone with beds of limestone and shale in upper part
	8a		8a	
— ? —	7c	Monograptus shale	7c	Monograptus shale
	7b	Pentamerus limestone	7b	Pentamerus limestone
	7a		7a	
Llandoverian	6c	Quartzite (Phacops quartzite ?)	6c	Quartzite (Phacops quartzite ?)
	6b		6b	
	6a		6a	
	5b		5b	
	5a		5a	
Ashgillian	4d		4d	
— — — —	$4c\beta$-γ		$4c\beta$-γ	
	$4c\alpha$		$4c\alpha$	
	$4b\delta_2$	Mjøsa limestone, shaly and red	$4b\delta_2$	Mjøsa limestone, with algal and
	$4b\delta_1$	in upper part (c. 100 m)	$4b\delta_1$	reef limestone (c. 100 m)
Caradocian	$4b\gamma$	Cyclocrinus beds	$4b\gamma$	Cyclocrinus beds
	$4b\beta$	Coelosphaeridium beds	$4b\beta$	Coelosphaeridium beds
	$4b\alpha$	Robergia beds	$4b\alpha$	Robergia beds
	$4a\beta$		$4a\beta$	
Llandeilian	$4a\alpha_{3-4}$	Cephalopod shale; Ogygiocaris shale	$4a\alpha_{3-4}$	Cephalopod shale; Ogygiocaris shale
Llanvirnian	$4a\alpha_{1-2}$	Upper Didymograptus shale	$4a\alpha_{1-2}$	Upper Didymograptus shale
	$3c\gamma$		$3c\gamma$	Endoceratid limestone — Orthoceras limestone (10—15 m)
Arenigian	$3c\beta$	Orthoceras limestone (40 m)	$3c\beta$	Asaphus shale
	$3c\alpha$		$3c\alpha$	Megistaspis limestone
	3b	L. Didymograptus shale	3b	Lower Didymograptus shale
	$3a\gamma$	Ceratopyge limestone	$3a\gamma$	Ceratopyge limestone
Tremadocian	$3a\alpha$-β	Ceratopyge shales	$3a\alpha$-β	Ceratopyge shales
	2e	Dictyonema shale	2e	Dictyonema shale
	$2d\varepsilon$	Acerocare	$2d\varepsilon$	?
	$2d\alpha$-δ	Peltura	$2d\alpha$-δ	Peltura
Olenus series	2c	Leptoplastus & Eurycare — Alum shale with stinkstone concretions	2c	Leptoplastus & Eurycare — Alum shale with stinkstone concretions
	2b	Parabolina spinulosa	2b	Parabolina spinulosa
	$2a\beta$	Olenus & Agnostus obesus	$2a\beta$	Olenus & Agnostus obesus
	$2a\alpha$	Agnostus pisiformis	$2a\alpha$	Agnostus pisiformis
	1d	Paradoxides forchhammeri	1d	Paradoxides forchhammeri
Paradoxides series	$1c\beta$-δ	Paradoxides paradoxissimus	$1c\beta$-δ	Paradoxides paradoxissimus — Basal cgl.
	$1c\alpha$	Paradoxides oelandicus; lst., sh., phosph. cgl.	$1c\alpha$	Basal conglomerate
	$1b\beta$	Lst. & green sh. w. Strenuella linnarssoni	$1b\beta$	
Olenellus series	$1b\alpha$	Green shale with Holmia kjerulfi — c. 50 m	$1b\alpha$	Green sh. w. Holmia kjerulfi
	$1a\beta$	Aren. shale with Platysolenites	$1a\beta$	Green sh. w. Volborthella
	$1a\alpha$	Basal cgl., aren. shale with tracks	$1a\alpha$	Sandstone w. Discinella
		Ringsaker quartzite (Sparagmitian)		Ringsaker quartzite (Sparagmitian)

a coarse clastic facies displaying ripples and layers of calcareous sandstones with shales. Permain rhomb porphyries overlie the Cambro-Silurian sediments with a marked angular unconformity.

C. HISTORICAL REVIEW

The Mjøsa Limestone is mentioned in most general accounts of the Mjøsa districts and Oslo region. Consequently an historical review must be considered in this broader regional aspect. Being a classical geological area, a rich and diversified literature has accumulated for the area as a whole comprising tectonic, stratigraphical, palaeontological, and palaeogeographical studies. Works which refer to, or mention, the Mjøsa Limestone specifically are quoted below.

BUCH (1910) who provided one of the earliest general accounts of the area was closely followed by HEYERDAHL (1811), a local priest who for his time, possessed an exceptionally keen insight into geological phenomena. HISINGER (1823, 1828) briefly mentioned the Cambro-Silurian, while KEILHAU (1826, 1850) in a brief description of the geology of the area, stressed the need for geological mapping. This task was undertaken by Th. Kjerulf, Keilhau's successor at the University of Oslo, who published a series of papers based on his investigations carried out in the years between 1857-84. KJERULF'S major publication was in 1862, accompanied by the first geological map of the Mjøsa area and stratigraphic division of the Cambro-Silurian at Mjøsa, based on stratigraphy near Oslo. The culmination of all this work was the publication of the geological map sheets Hamar and Gjøvik (KJERULF, 1884).

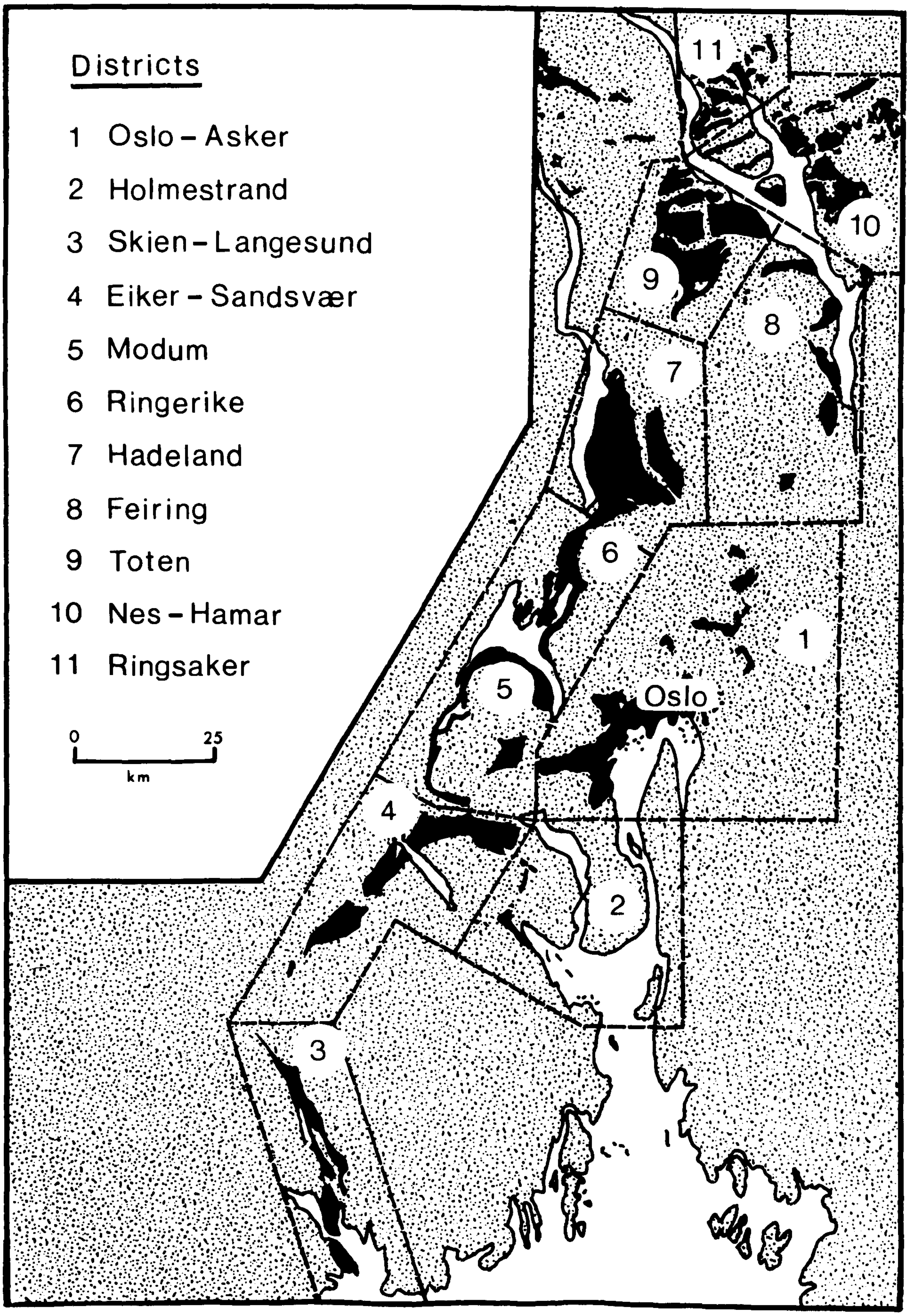
Brøgger (Kjerulf's successor) continued with the detailed investigations, but as his work was mainly confined to the Sparagmites and lower Cambrian, it was not until the turn of the nineteenth century that work pertaining to the Ordovician was published. KIAER (1897) described the Middle Ordovician of the Mjøsa area, and introduced the term "Mjøsakalken" (ibid 1908) for the limestone terminating the Ordovician in this area. HOLTEDAHL (1909) gave an extremely detailed description of the Middle Ordovician strata in the Mjøsa area, and in 1912 discussed the economic importance of the local limestone.

RAYMOND (1916) noticed a hiatus between the Middle and Upper Ordovician in the Oslo area and pointed out that the Mjøsa Limestone was contemporaneous with the Upper Chasmops Limestone of the Oslo region. This view was later supported by KIAER (1920, 1926) and STØRMER (1945, 1953). HOLTEDAHL (1934) in a guide to the Geology of southern Norway gave a brief survey of the geology of the district with a summary of the Eocambrian-Palaeozoic stratigraphy.

More recently, STØRMER (1953) described the Middle Ordovician of the Oslo region making reference to the Mjøsa Limestone and its contemporaneous deposits. A geological map of the Mjøsa district was published by SKJESETH (1953) followed by a preliminary survey of the thrust tectonics (ibid 1954) and water resources (ibid 1956). Brief mention of the geology of the Mjøsa district was made by HOLTEDAHL (1953), BJØRLYKKE (1965, 1974a,b) STRAND (1972). However, the most detailed description of the geological succession and thrust tectonics encountered in the Mjøsa district, has been produced by SKJESETH (1963).

Reference to a few localities in the Mjøsa Limestone and Cyclocrinus Beds are contained in some of the twenty-seven papers so far published in the "Middle Ordovician of the Oslo Region" Series (Published in Norsk Geologisk Tidsskrift). This is a project started in 1953 by Professor Lief Størmer at the University of Oslo to promote a greater understanding of the geological history of the Oslo Region. The whole of the Oslo graben was divided into a series of areas (Fig.1.4) and, at first, groups of areas were assigned to certain geologists to study. Most of the papers in this

Fig.1.4: Cambro-Silurian distribution and constituent districts within the Oslo Region (after STØRMER 1953).


Districts
1 Oslo-Asker
2 Holmestrand
3 Skien-Langesund
4 Eiker-Sandsvær
5 Modum
6 Ringerike
7 Hadeland
8 Feiring
9 Toten
10 Nes-Hamar
11 Ringsaker
0
25
km
Oslo
1
2
3
4
5
6
7
8
9
10
11

series are taxonomic descriptions of fauna found throughout the region and thus provide a valuable (though as yet incomplete) reference collection for subsequent work. Reference to the Mjøsa Limestone is made when fauna found therein are described, but detailed studies of fauna found specifically in this horizon remain, as yet, unpublished (viz. conodont studies by G.Hamar; bryozoa, and the coral stromatoporoid reef complex by N. Spjeldnaes).

D. TECTONICS

Before discussing the nature of folding and faulting in the Mjøsa area, a brief résumé of both the broad depositional environments and the major tectonic events in the Norwegian Caledonides is given. This is considered necessary because of the close association of the sedimentary and tectonic events in the central part of the orogen and their effects on the Ordovician history of the Oslo region. The Mjøsa district was particularly affected as a result of its close proximity to this area of high tectonic activity.

STØRMER (1967) presents an account of the sedimentary environments found in the Caledonian geosyncline, dividing them into a series of belts, each characterised by a distinctive suite of rocks. STRAND (1972), gives a detailed, comprehensive account of stratigraphy and tectonics throughout the Norwegian Caledonides, whilst SKJESETH (1963) deals with the Mjøsa district and BJØRLYKKE (1974a, b) the Oslo Region as a whole. From these works an overall picture of conditions prevailing during Caledonian times can be gained.

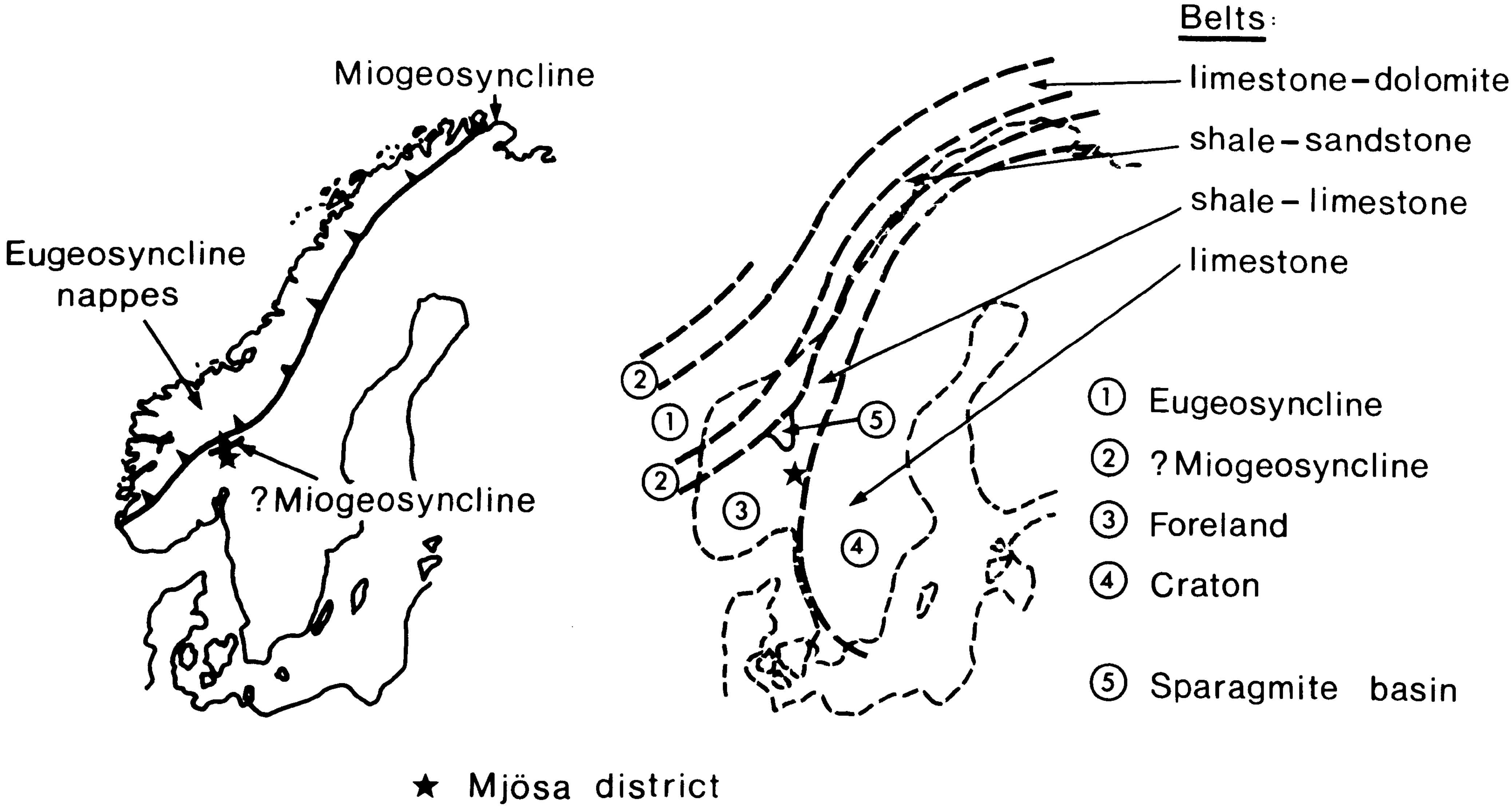
The lithological belts defined by STØRMER (1967), shown in Fig.1.5 are summarised below in a five-fold division:-

(a) western eugeosyncline - limestone and dolomite belt

(b) eastern eugeosyncline - shale, sandstone and lava belt

(c) hypothetical miogeosyncline - shale and sandstone belt

Fig.1.5: Hypothetical geosynclinal pattern. The lower map shows the present position of nappes, while the upper map illustrates the proposed primary position of some lithological belts (after STØRMER 1963).


Miogeosyncline
Eugeosyncline nappes
?Miogeosyncline
Belts:
limestone-dolomite
shale-sandstone
shale-limestone
limestone
1
2
2
3
4
5
① Eugeosyncline
② ?Miogeosyncline
③ Foreland
④ Craton
⑤ Sparagmite basin
★ Mjösa district

(d) foreland - shales and limestones

(e) craton - mainly calcareous sediments

The Cambro-Silurian rocks of the Mjøsa districts are considered a part of the foreland sequence.

STØRMER (1965), concludes that indications of earth movements in the central part of the orogen can be clearly recognised by the introduction of comparatively large amounts of terrigenous material into the Cambro-Silurian of Oslo at several horizons. He (op.cit.) has used this evidence to modify VOGT'S (1928) original sequence of orogenic phases (Fig.1.6) and to propose (STØRMER 1967, Fig.20) their relationship to a series of sedimentary cycles.

Geochemical analyses of Ordovician sediments in the Oslo Region by BJØRLYKKE (1974a,b) have shown increasing Fe, Mg, Ni and Cr contents from the lowermost Ordovician to the top of the Middle Ordovician. These changes first occurred penecontemporaneously with deposition of the Venna (Stokkvola) Conglomerate in the Trondheim Region; a situation Bjørlykke interprets as indicative of an emerging island arc system. The break in sedimentation, and erosion, indicated by the Venna Conglomerate corresponds to an early Ordovician phase of metamorphism (Phase I of Stømer; the Trondheim Phase of Vogt; see Fig.1.6). The thrusting of the Jötun Nappe and the rocks of the Trondheim Region which are regarded by many (e.g. WOLFF 1967; STRAND, 1972) as allocthonous is said by BJØRLYKKE (1974b p.267) to have been "accompanied by shortening of the geosyncline basin due to subduction of parts of the lithospheric plate". The youngest rocks underlying the Jotun Nappe are of early Middle Ordovician (Bjørlykke quotes LOESCHKE 1967 and NICKELSON 1967), thus establishing with reasonable certainty the date of emplacement as Middle to Upper Ordovician. Bjørlykke's hypothesis is that the island arcs of the Trondheim Region and Jotun Nappe

Fig.1.6: Phases of tectonic activity within the Lower Palaeozoic of Norway.

STØRMER (1965)			VOGT (1928)	
Phase	Age	Welsh equivalent	Phase	Age
			Svalbardian	
			Erian	
V	9g-10		Ardennian	Sil-Dev.
IV	7c-8a,b.	Pre-Wenlock		
III	5b,c - 6a,b,c.		Horg (Taconic)	Ord-Sil.
*			Ekne	Middle Ord.
II	4 aα_4 -4aβ	Pre-Bala, Pre-Caradoc		
I	3a-3b		Trondheim	Cam-Ord.

* The Ekne Phase (4b-4cα) is marked by a break in sedimentation but no increase in terrigenous material.

were nearer the epicontinental sea deposits of the Oslo Region and can thus account for the increased chlorite, Fe, Mg. Ni and Cr contents. The maximum contents of chlorite relative to illite achieved in the Upper Ordovician (BJØRLYKKE 1974 b) then correspond to the Taconic phase of metamorphism and folding, or Størmer's Phase III.

Using this chronology, certain conclusions about events in the Mjøsa district can be drawn:

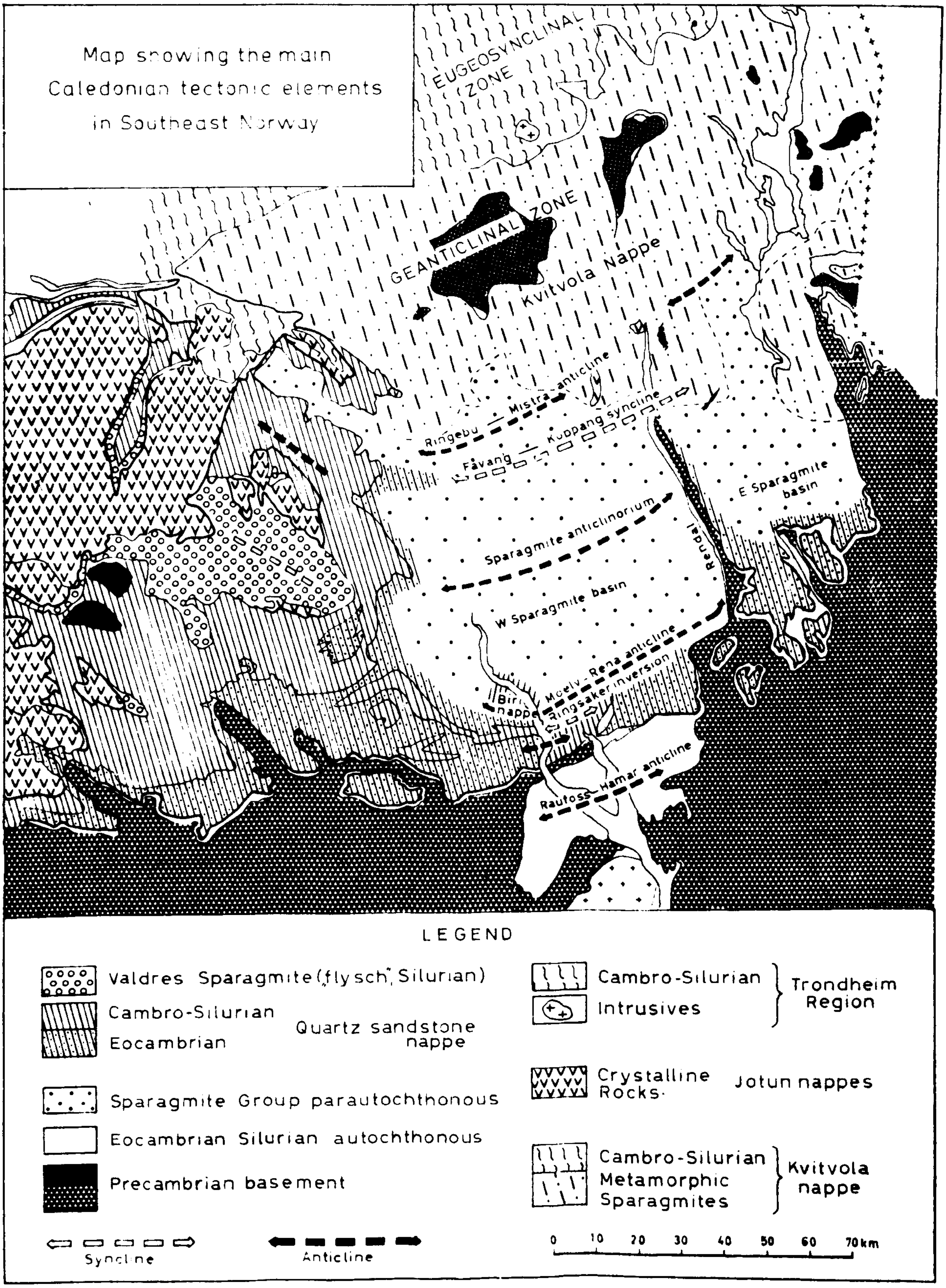
i) The hiatus between the Mjøsa Limestone and Helgøya Quartzite can probably be attributed to epeirogenic uplift during the Ekne Phase (Fig. 1.6). An alternative eustatic mechanism due to glacial control is discussed by BJØRLYKKE (1974a, p.18-19).

ii) The Helgøya Quartzite is derived from the Valdres Sparagmite (hence the mineralogical similarity noted by SKJESETH (1963)). His (op. cit) original proposal was "that the two were contemporaneous, both being derived from the Lower Jotun Nappe". However, from NICKELSON'S (1967) evidence, a true sparagmitian age (STRAND 1972) appears more likely, as does its emplacement with the Jotun Nappe during the late Ordovician. Some supporting evidence is found in BJØRLYKKE'S (1974a p.27) reference to MAJOR'S (1946) hypothesis that the Helgøya Quartzite shows a direction of transportation from the north, although BJØRLYKKE himself (1974a, Fig.12) regards it as the basal facies to a marine transgression out of the Oslo area.

The next major tectonic event to affect the Mjøsa districts was Phase V (Fig.1.6) during which, the folding and thrusting reached the marginal zone of the geosyncline (SKJESETH 1963) - The Upper Jotun Nappe (Fig. 1.7) was thrust over the Valdres Group and metamorphic rocks were thrust as a nappe (the Kvitvola Nappe) over the geanticlinal ridge into the sparagmite area. These thrust movements resulted in the detachment of the Vemdal Sandstone which moved out of the sparagmite basin onto the foreland, causing detachment of the Cambro-Silurian sediments and their folding with dēcollement. STRAND (1972, p.16) points out that the observed and minimum length of thrusting of the Vemdal Sandstone is 25 km., but that the Cambro-Silurian rocks south of Gjøvik may have been moved as far as 100 km. due to the shortening caused by folding. Thus the Cambro-Silurian sediments form one tectonic unit together with the allocthonous Vemdal Sandstone. As the Cambro-Silurian pile of sediments was detached from the basement and folded, the Vemdal Sandstone (Fig.1.7) which was below these sediments in the northern region, was moved at the same time and took a place above the part of the sequence still attached to the basement (HOLTEDAHL 1953). In the northern parts of the district where the Cambro-Silurian was underlain by the Vemdal Sandstone a nappe was formed, whilst in the southern parts there is a parautochthonous Cambro-Silurian sequence folded with dēcollement. Thus the Oslo region represents a rim of dēcollement folded sediments that probably bordered the whole of the Caledonide margin, but has only been preserved here due to Permian downfaulting.

The Mjøsa Limestone has clearly been subjected to dēcollement type folding, which is also more intense than elsewhere in the Oslo Region. In the Nes-Hamar districts there are three large open synclinoria in which the Mjøsa Limestone is relatively undeformed compared to the immediately underlying Cyclocrinus Beds. The latter show folds, slides, small thrusts, and other structures caused by the movements of the rocks above them. SKJESETH (1963, Fig.43) describes Helgøya as the best example of a large synclinorium which has a "coffer shaped north-south cross-section with the limbs converging upwards; a shape typical of dēcollement folding". The tectonics of the sediments below the Mjøsa Limestone mimic, for the most part, those of the limestone as interpreted by HOLTEDAHL (1909, p.38). Along the

Fig.1.7: Distribution of the main Caledonian tectonic elements in southeast Norway (after SKJESETH 1963).


Map showing the main Caledonian tectonic elements in Southeast Norway
EUGEOSYNCLINAL ZONE
GEANTICLINAL ZONE
Kvitvola Nappe
Ringebu — Mistra anticline
Fåvang — Koppang syncline
Sparagmite anticlinorium
E Sparagmite basin
Rendal
W Sparagmite basin
Moelv - Rena anticline
Ringsaker inversion
Biri nappe
Rautoss - Hamar anticline
LEGEND
Valdres Sparagmite („flysch", Silurian)
Cambro-Silurian
Eocambrian
Quartz sandstone nappe
Sparagmite Group parautochthonous
Eocambrian Silurian autochthonous
Precambrian basement
Cambro-Silurian
Intrusives
Trondheim Region
Crystalline Rocks
Jotun nappes
Cambro-Silurian
Metamorphic Sparagmites
Kvitvola nappe
Syncline
Anticline
0 10 20 30 40 50 60 70 km

eastern shoreline of the island, the Robergia Beds exhibit minor folding which SKJESETH (1963, p.97) assumes to be drag folds. In the Toten district the limestone is very tightly folded with limbs becoming vertical in places, but flattening out abruptly towards the cores of the synclines.

The Mjøsa area is traversed by a series of fault zones (see Fig.1.1), mostly of Permian age, which may represent extensions of some of the fault zones of the Oslo region further south. Some of these are briefly outlined below:-

(a) Hundselv Fault Zone - this forms the western margin of the Toten district and may perhaps represent an offshoot of the major Randsfjord Fault Zone, which extends from Røykenvik to Einavann (SKJESETH, 1963). From Einavann the zone is followed by the river Hundselv northwards. A minor fault (the Eina Fault) branches from the fault north of Bruflat and extends south southwest along the Einavann, forming a block of Cambro-Silurian rocks with a general north-east tilt, as opposed to a general westward tilt elsewhere in Østre Toten (SKJESETH 1963).

(b) Nes Fault Zone - this zone bisects the Nes peninsula (Fig.1.1) continues through the Salbergaas as a mylonite zone (SKJESETH 1963) and can be followed from Kapp to Lena in the Toten district.

(c) Brumunddal Fault Zone - the southernmost fault zone of the Salbergaas horst is not seen in the Hamar area; it appears to have converged into the Brumunddal Fault which extends north-northwest, truncating the Mjøsa Limestone in the Ringsaker district, and bringing the Permian against the Vemdal Sandstone (Fig.1.1).

(d) Mjøsa Fault Zone - SKJESETH (1963) has suggested this fault zone which extends down the Furnesfjord and lake Mjøsa, to account for the discrepancies in plunge between the Snippsand and Furuberget synclinoria, and to explain that on the opposite shore from the proposed outcrop of

Mjøsa Limestone at Balke there are Precambrian gneisses (Fig.1.1).

E. THE PROJECT

The Mjøsa Limestone is unique to the Middle Ordovician of the Oslo Region in representing not only a relatively pure carbonate horizon at this stratigraphical level, but also because it is separated by a clearly defined unconformity with the Silurian. As such, a palaeoenvironmental reconstruction of this unit forms the primary objective of this study. Before this was possible, however, a detailed stratigraphical and sedimentological appraisal was necessary to enable both lateral and vertical facies variations to become meaningful. The palaeoecology of the sedentary benthos forming algal and poriferid - coelentrate biomasses has been considered, although more emphasis was placed on their sedimentological and environmental importance.

A study of the penecontemporaneous deposits of the Langesund-Skien districts (Fig. 1.4) is being conducted by T. Harland. By reference to this and the well documented stratigraphy of the remainder of the Oslo Region (e.g. STØRMER 1953, 1967; HENNINGSMOEN 1960; BJØRLYKKE 1974 a, b) the Mjøsa Limestone is considered an important facet in a broader palaeogeographical reconstruction for the Middle Ordovician. In the final synthesis, the spectrum can be broadened to include the Baltic and Caledonides, not only because both are reasonably well documented, but also because the Mjøsa district owes much of its character to the geological influences of both of these important provinces.

CHAPTER TWO

STRATIGRAPHY

I. REGIONAL STRATIGRAPHY

The Mjøsa Limestone occupies the uppermost part of the Norwegian Middle Ordovician. Because of the discrepancies in the definition of the Middle Ordovician in Baltoscandia, a brief review of the wider stratigraphical divisions of the Ordovician are given below, considering firstly the Baltoscandian terminology, and secondly the stratigraphical divisions and nomenclature adopted by Norwegian geologists in the Oslo region. It is from Oslo that all stratigraphical terminology and correlations used in the Mjøsa area are extrapolated.

A. DIVISION OF THE ORDOVICIAN OF BALTOSCANDIA

The Ordovician of this area has been broadly divided into three units, Lower, Middle and Upper, with various authors trying to fix the boundaries to correspond with the international graptolite zones. There is, however, disagreement at present concerning the lower boundary of the Middle Ordovician, although the upper boundary has remained stable at the base of the *Pleurograptus linearis* and top of the *Dicranograptus clingani* zones (Fig.2.1). From this diagram it is clear that discrepancies arise between the divisions for Norway, as proposed by KIAER (1920), STØRMER (1953) and HENNINGSMOEN (1960), those for the U.S.S.R. by ALICHOVA (1957) and those for Estonia, together with the whole of Baltoscandia originally proposed by RAYMOND (1916) and later endorsed by KALJO, ROOMUSOKS, AND MÄNNIL (1958), JAANUSSON (1960) and MÄNNIL (1965). The base of the Middle Ordovician, or Viruan Series (JAANUSSON, 1960), fluctuates across three graptolite zones. STØRMER (1953, p.42-45) presents a cogent argument for placing the boundary (at least in Norway) at the base of the *Didymograptus bifidus* zone, but even he admits (ibid, p.44) that such a decision is not binding and that agreement with other workers is needed. For the purposes of this study, this author follows HENNINGSMOEN

Fig.2.1: The stratigraphical divisions of the Ordovician System in Baltoscandia. Comparison is made with the international graptolite zones and standard British divisions.

British standard graptolite zones	Baltoscandia	Norway	Norway	U.S.S.R.	Baltoscandia	Britain
Dicellograptus anceps						
Decellograptus complanatus	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN (Harjuan Series)	ASHGILL
Pleurograptus linearis						
Dicranograptus clingani						
Climacograptus wilsoni						CARADOC
Climacograptus peltifer						
Nemograptus gracilis	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN (Viruan Series)	
Glyptograptus teretiusculus						LLANDEILO
Didymograptus murchisoni						
Didymograptus bifidus						LLANVIRN
Didymograptus hirundo						
Didymograptus extensus	LOWER ORDOVICIAN	LOWER ORDOVICIAN		LOWER ORDOVICIAN	LOWER ORDOVICIAN (Oelandian Series)	ARENIG
? *Dichograptus*			LOWER ORDOVICIAN			
Tremadocian						
British standard graptolite zones	Raymond (1916)	Kiær (1920)	Størmer (1953) Henningsmoen	Alichova (1957)	Kaljo, Roomusoks & Mannil (1958) Jaanusson (1960) Mannil (1965)	

Fig.2.1: The stratigraphical divisions of the Ordovician System in Baltoscandia. Comparison is made with the international graptolite zones and standard British divisions.

British standard graptolite zones	Baltoscandia	Norway	Norway	U.S.S.R.	Baltoscandia	Britain
Dicellograptus anceps						
Decellograptus complanatus	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN	UPPER ORDOVICIAN (Harjuan Series)	ASHGILL
Pleurograptus linearis						
Dicranograptus clingani						
Climacograptus wilsoni						CARADOC
Climacograptus peltifer	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN	MIDDLE ORDOVICIAN (Viruan Series)	
Nemograptus gracilis						
Glyptograptus teretiusculus						LLANDEILO
Didymograptus murchisoni						LLANVIRN
Didymograptus bifidus						
Didymograptus hirundo	LOWER ORDOVICIAN	LOWER ORDOVICIAN		LOWER ORDOVICIAN	LOWER ORDOVICIAN (Oelandian Series)	
Didymograptus extensus						ARENIG
? Dichograptus			LOWER ORDOVICIAN			
Tremadocian						
British standard graptolite zones	Raymond (1916)	Kiær (1920)	Størmer (1953) Henningsmoen	Alichova (1957)	Kaljo, Roomusoks & Mannil (1958) Jaanusson (1960) Mannil (1965)	

(1960) and adopts Størmer's divisions.

B. DIVISION OF THE LOWER PALAEOZOIC IN THE OSLO REGION.

The Lower Palaeozoic of the Oslo region has been divided into stratigraphical units, or "Etagen", designated by the numbers 1 to 10. KJERULF (1855), proposed the first division and as the original units were split, additional symbols (roman and greek letters together with suffixed numbers) were added. HENNINGSMOEN (1955), points out that the units, which should be regarded as chronostratigraphic, are based partly on lithostratigraphic and partly on biostratigraphic criteria. Those units given numbers only hold the same rank as "Series", while the small units may be regarded as stages or subdivisions of stages, (HENNINGSMOEN 1960). However, not all the series recognised at present correspond with the original units e.g. Ceratopyge Series corresponds to 2e-3a.

Although units such as the Mjøsa Limestone and Upper Chasmops Limestone are lithostratigraphical units (formations or members), actual division into formations has not yet been undertaken. A biostratigraphical division has been carried out in the Cambrian with zones and subzones based chiefly on trilobites. In the Ordovician and Silurian graptolitic shales have been divided into zones and subzones, but the beds with shelly faunas have been biostratigraphically divided only in part, mainly on the basis of trilobites in the Ordovician and brachiopods in the Silurian.

C. DIVISION OF THE ORDOVICIAN IN THE OSLO REGION.

The Ordovician of the Oslo region is divided into five series (Ceratopyge, Asaphus, Ogygiocaris, Chasmops and Tretaspis), but they are usually grouped and more generally referred to as Lower, Middle and Upper Ordovician. The relationship between these series, the international graptolite zones and the standard British stages is given in Fig. 2.2.

Fig.2.2 The stratigraphical division of the Ordovician in southeastern Norway. The relationship between the Series, the international graptolite zones and standard British stages is illustrated.

Dicellograptus anceps	ASHGILL	TRETASPIS SERIES			UPPER ORDOVICIAN
Dicellograptus complanatus					
Pleurograptus linearis	CARADOC		4c	Tretaspis sectiornis	
Dicranograptus clingani		CHASMOPS SERIES	4b	T. iciaeri	MIDDLE ORDOVICIAN
			4b	T. ceriodes Chasmops extensa	
Climacograptus wilsoni			4bγ	Cryptolithus discors	
			4bβ		
Climacograptus peltifer			4bα	Chasmops conicophthalma	
Nemograptus gracilis			4aβ	Reedolithus carinatus	
Glyptograptus teretiusculus	LLANDEILO	OGYGIOCARIS SERIES	4aα	Trinucleus bronni	
			4aα	Trinucleus faveolatus	
Didymograptus murchisoni	LLANVIRN		4aα	Didymograptus geminus	
Didymograptus bifidus			4aα	Didymograptus bifidus	
Didymograptus hirundo	ARENIG	ASAPHUS SERIES			LOWER ORDOVICIAN
Didymograptus extensus			3b		
? Dichograptus					
Bryograptus Dictyonema flabelliforme	TREMADOC	CERATOPYGE SERIES	3a 2e		
B R I T A I N		N O R W A Y			

From this diagram it is apparent that if JAANUSSON'S (1960) division of the Ordovician (Fig. 2.1) is accepted, then the Ogygiocaris series will be split between the Lower and Middle Ordovician, and the traditional Norwegian Ordovician stratigraphy breaks down. (Another reason for accepting STØRMER'S (1953) definition of the Middle Ordovician).

D. THE STRATIGRAPHICAL POSITION OF THE MJØSA LIMESTONE.

The exact stratigraphical position of the Mjøsa Limestone has been in doubt for many years and has fluctuated quite markedly. However, in the absence of conclusive evidence to date, it is regarded by this author as being 4bδ + (c.f. STØRMER, 1953; HENNINGSMOEN, 1960; SKJESETH, 1963; STRAND, 1972). Størmer's proposal is based on a direct correlation with limestones of similar age in the remainder of the Oslo region. The Encrinite Limestone (Langesund-Skien), the Upper Chasmops Limestone (Oslo-Asker) and the Sphaneroid Limestone, together with the Gagnum shale (Hadeland) are shown by STØRMER (1953, pp. 126-129) to be equivalent in age and marking the top of the Middle Ordovician. It is felt by some workers that the limestone may extend into 4c, but apart from some unpublished conodont studies (Hamar), no one has yet worked on the problem and produced the necessary evidence.

II. LOCAL STRATIGRAPHY

Although the Mjøsa Limestone has been regarded by HENNINGSMOEN (1960) and other authors as a distinct lithostratigraphical unit, no formal classification has been previously proposed. Detailed section logging has revealed that within the regional framework outlined above, sufficient characteristic lithological similarities exist at certain horizons throughout the Mjøsa area to permit the erection of formal stratigraphical divisions. In attempting this, this author has, wherever possible, followed the procedure suggested by the International Subcommission on Stratigraphic Classification (Report No. 76, ed HEDBERG) (1972, pp. 305-6).

Name: The unit is herein named the Mjøsa Limestone from the occurrence in the geographical area defined by STØRMER (1953) of this name. This is, in fact, a formalization of informal terminology used by many authors e.g. STØRMER (1953), HENNINGSMOEN (1960), SKJESETH (1963), since KJERULF (1855).

Rank: The unit is assigned the rank of Formation.

General Concept: A prerequisite to the formal definition of a Formation is the possession of certain distinctive characteristics by which it can be differentiated from adjacent units. The Mjøsa Limestone is distinctive as a predominantly carbonate rich formation of approximately 100 m thickness occurring between the quartz siltstone-shale sequence of the Furuberget Formation (SKJESETH, 1963) and the equally distinctive Helgøya Quartzite (op. cit.).

The term "Mjøsa Limestone" is synonymous with earlier Norwegian terms "Mjøskalk", "Mjøsenkalk" or "Mjøskalken", although these have never been employed in a formal stratigraphical sense.

The proposal of a formal stratigraphical unit is considered an essential step in the conception and employment of a dynamic working model for the palaeoenvironmental reconstruction which forms the ultimate goal of this thesis.

Stratotypes: The lack of a clearly defined upper and lower boundary at any one locality, together with the facies variations which occur between the Toten, Nes-Hamar and Ringsaker districts, render it impractical to designate any single exposure or group of exposures, a unit stratotype. Therefore, the upper and lower limits of the formation are defined from various boundary stratotypes while the overall character is obtained from sub-division into small units. "Members" and "Beds" are designated below from a series of component stratotypes within each district and are largely a function of the cyclical nature of deposition. Together these constitute a composite stratotype within the type locality.

Formation boundaries: The upper boundary is marked by an unconformable contact with the Silurian Helgøya Quartzite, 6c. This is particularly spectacular in the Toten district when the upper surface of the Mjøsa Limestone is karstic, but in the Nes-Hamar district it is a more difficult feature to define and appears to lack solution features. By contrast the base of the limestone is poorly exposed in Toten but often visible as a pronounced lithological change from a quartz siltstone-shale sequence into massive carbonates in the Nes-Hamar district. There is also an accompanying faunal change with these basal beds containing a *Chasmops* (particularly *C.extensa*) dominated fauna, compared to the rich asaphid assemblages of the Cyclocrinus Beds (Furuberget Formation).

Procedure: Within each district formal and informal lithostratigraphical divisions were erected and correlation across the Mjøsa area attempted. Detailed stratotype (~~and other locality~~) descriptions are included in Appendix I to which reference is made in the ensuing text by locality name rather than page number. This avoids repetative parenthesis and ultimate fragmentation of the text.

III. THE STRATIGRAPHY OF THE MJØSA LIMESTONE IN THE TOTEN DISTRICT.

A formal tripartite division of the limestone into the Sivesindhagen, Eina and Holetjern Members is proposed for this district (Fig. 2.3). Further subdivisions into formal and informal units is described below and in Fig. 2.3.

A. THE LOWER BOUNDARY.

Sufficient exposure of a quartz siltstone-shale sequence beneath a massive bioclastic limestone to warrant determination of the lower boundary exists at two localities only:-

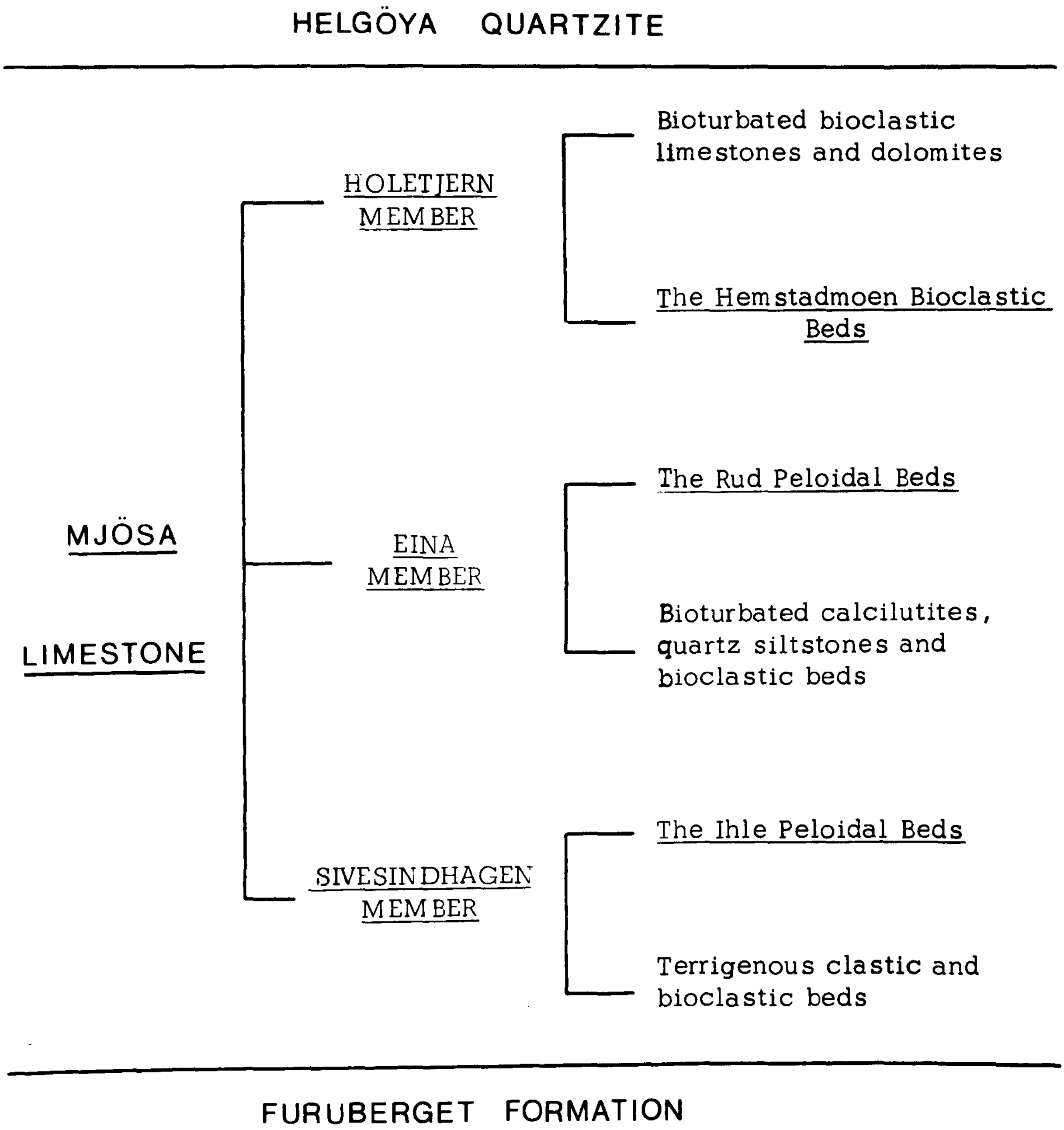
(i) Kallerud: where 20 m or more of siltstones and shales with a very minor carbonate content underlie pelmatozoan bioclastics containing *Solenopora* and *Eoflecheria*.

(ii) Helset: where more than 11m of siltstones and shales with occasional carbonate rich horizons are overlain by a massive unit of coarse pelmatozoan bioclastics with quartz siltstone laminations, which in turn is succeeded by a carbonate sequence representative of the Mjøsa Limestone.

B. THE SIVESINDHAGEN MEMBER.

It is of practical advantage to adopt a two fold division of this member into a lower, terrigenous clastic - bioclastic sequence and an upper, peloidal-bioclastic sequence (Fig. 2.3). The lower sequence, although displaying complex interrelationships is easily distinguished by its dominant coarse to fine pelmatozoan bioclastic limestones and abundance of *Solenopora*. The upper unit is less variable, although local variations are present. Because of this, and its palaeoenvironmental importance, it is attributed formal stratigraphical status as the Ihle Peloidal Beds.

Fig.2.3: The stratigraphy of the Mjøsa Limestone in the Toten district. Formal stratigraphical terms proposed in the text are underlined.


HELGÖYA QUARTZITE
MJÖSA LIMESTONE
HOLETJERN MEMBER
EINA MEMBER
SIVESINDHAGEN MEMBER
Bioturbated bioclastic limestones and dolomites
The Hemstadmoen Bioclastic Beds
The Rud Peloidal Beds
Bioturbated calcilutites, quartz siltstones and bioclastic beds
The Ihle Peloidal Beds
Terrigenous clastic and bioclastic beds
FURUBERGET FORMATION

The stratotype for this member is Sivesindhagen.

1. The terrigenous clastic - bioclastic beds.

A succession of 40m is dominated by pelmatozoan bioclastic grainstones containing *Solenopora*. The basal 13m are entirely of this facies, which also contains *Eoflecheria*. Quartz siltstones containing *Solenopora* overlie this and are themselves overlain by more bioclastic beds. 23m above the base of the exposed sequence a distinctive red and green quartz siltstone unit is seen, which rapidly grades into a pelmatozoan calcirudite with many fragments exhibiting a pink colouration, before reverting to red quartz siltstones. Pelmatozoan bioclastics with *Solenopora* overlie this unit and are, in turn, overlain by more terrigenous siltstones. The final bioclastic beds contain abundant cross-stratification and *Solenopora*, many of which are graded on the foreset beds. The uppermost bed is a dark green quartz siltstone containing scattered pink pelmatozoan fragments.

Some slight variation in facies can be found at certain localities and these are described below:-

In situ Solenopora beds: a well developed boundstone composed of *Solenopora* and *Eoflecheria* is found in isolated exposures at Aannerud and Engøydegaard. It consists of an intergrowth of the above mentioned organisms with ancillary bryozoa, brachiopods and pelmatozoa. By virtue of their position below other recognisable units, these beds are not only regarded as part of the Sivesindhagen Member but may even be a basal facies and represent a similar development to the basal beds at Kallerud. *In situ Solenopora* dominated beds (with rare, or no *Eoflecheria*) occur in both quartz siltstone and bioclastic limestone facies, being particularly well developed at Børsvollen, Eina and Løken. A more detailed consideration of these beds, together with the palaeoecological implications when compared to the *Solenopora* beds at Sivesindhagen, is contained in Chapter 5.

Quartz siltstone rich successions: At Ihle and Granvang a higher percentage of quartz is noticeable. This manifests itself as thicker quartz siltstone-shale sequences, or as red-green quartz siltstones-mudstones at Aannerud, Hole kalverk and Engøydegaard. More detailed descriptions together with a discussion of the palaeoenvironmental significance of these beds is presented in Chapter 3.

2. The Ihle Peloidal Beds.

This sequence of peloid dominated grainstones can be distinguished at many localities of the Mjøsa Limestone in the Toten district. The lower boundary is defined as the first peloidal bed encountered above the *Solenopora* bearing sediments of the terrigenous clastic and bioclastic beds, while the upper boundary is regarded as the last peloid bearing bed in the sequence (e.g. at Sivesindhagen) or the first significant facies change above such a bed (e.g. at Eina). Sometimes this boundary is clearly marked by an erosion surface, but more usually by the influx of coarse pelmatozoan bioclastics with a definite marine biota.

At Sivesindhagen the upper 10m of the Sivesindhagen Member contain a series of bioclastic and peloidal beds. Although some are *Solenopora* rich, the concentration of algae is much less than in the underlying beds. *Ancistrorhyncha* is found in the siltstone/dolomite rich horizons, but no other indigenous biota is evident.

These beds are better exposed at Ihle, which is regarded as a unit stratotype. Here the gradual development of peloidal grainstones from bioclastic grainstones is evident; the former being distinguished by allochemical components, texture, parallel stylolites, a dolomite net and the presence of *Phytopsis*, particularly near the top of each unit. Siltstone/dolomite horizons are few, but where present contain stromatoporoids and *Ancistrorhyncha*.

Peloidal horizons are also well developed at Sellanraa where they are associated with a higher percentage of quartz siltstone; at Eina, where a thinner stratigraphically equivalent unit contains numerous erosion surfaces; and at Løken where horizons rich in Hedstroemia are present.

The Sivesindhagen Member and its subdivision can be distinguished at all localities where it outcrops, although at Bruflat the peloidal horizons appear abnormally thick and Solenopora bearing beds extremely thin. This discrepancy can be explained by thickening due to faulting or original position within the depocentre.

C. THE EINA MEMBER

As illustrated in Fig. 2.3. a two fold division of this member can be made to usefully meet stratigraphical (and palaeoenvironmental) requirements. The lower bioturbated calcilutite, quartz siltstone and bioclastic unit displays great local variability of facies, with small reefoidal bodies, red siltstones, green oncolite rich beds and inter-bedded peloidal horizons appearing as important additions to the succession at various localities. Exposure at this stratigraphical level is very poor compared to the remainder of the Mjøsa Limestone and this can be regarded as a major contributory factor to the complex and incomplete picture which emerges. In contrast, the formally defined Rud Peloidal Beds are extremely well exposed in old quarry workings and display a uniformity of facies throughout the district which exceeds that of the Ihle Peloidal Beds.

The lower boundary of the member is visible at only a few localities where the contact is very sharp due to contrasting lithologies and, occasionally, the presence of an erosion surface. The upper boundary is erosional, very sharply defined and easily traceable throughout the Toten district.

The stratotype for this member is Eina, the only locality where the whole member is both continuously exposed and readily accessible.

1. The bioturbated calcilutite, quartz siltstone and bioclastic beds.

The 34.60m of strata which represent this lower division of the Eina Member commence with a clearly defined erosion surface and an overlying 1.50m of bioclastic (and peloidal) grainstones with abundant small rounded Solenopora. Low angle planar cross-stratification, accentuated by stylolitisation along the forests, represents the only sedimentary structure found in these beds. 9.20m of interbedded quartz siltstones and bioclastic grainstones overlie these basal bioclastic beds and are easily recognisable by the abundance of Chondrites in the terrigenous fraction and the irregular, thin (8cm max.), sharply defined bedding of the bioclastics. Bioturbation by unknown organisms reaches a peak in the upper 2m when the terrigenous and bioclastic fractions become completely mixed. The overlying unit begins as a rapid gradation from fine grained quartz clastic sediments to fine carbonates (calcisiltites and micrites) in the basal 2.30m before developing into 3.70m of nodular looking micritic mudstones. The carbonate beds contain occasional concentrations of rhynchonellids, orthocones and bryozoa but are generally unfossiliferous. The nodular horizons show sparry calcite filled vugs which resemble Phytopsis. The overlying 2.40m mark a transition back to fine quartz siltstones with Chondrites, which occupy 1.50m of the succession before carbonate mud becomes dominant again. The following 1.35m show a transition from micritic mudstones through bioturbated mudstones to nodular mudstones, which show maximum development in the overlying 1.20m. Throughout these latter two units there is a noticeable increase in bioclastic content which manifests itself in the overlying 4m, where the bioclastic horizons appear as very thin discontinuous veneers in a dominantly micritic mudstone. A complex of small faults separates this sequence from an overlying 4m of identical facies which shows an increase in biogenic activity, although the heavily bioturbated fraction is again fault separated. The intensity of bioturbation increases in the uppermost 2.50m, where a small reefoidal body of Eoflechieria and stromatoporoids is developed. The bioherm exhibits a fringing apron of oncolite rich bioclastic grainstone which is in stark contrast to the surrounding sediment. A series of faults separate this lower division of the Eina Member from the overlying Rud Peloidal Beds.

Exposures of equivalent beds bearing identical facies characteristics are seen in the quarries at Bøverbru, Rud, Holetjern and the roadside locality of Slaatsveen. Bruflat rail cuttings contain some stromatoporoid - Ancistrorhyncha bearing horizons beneath well developed peloidal horizons, but any accurate correlation with this locality is doubtful.

Variation from the stratotype is evident within localities in the northwest of the district (and Hole kalkverk), where a distinctive red mudstone is found, often closely associated with green oncolite bearing strata and peloidal horizons. Stratigraphically these facies appear to occur near the base of the member at Hole kalkverk, Aannerud, Engøydegaard and Sellanraa. Bioturbated horizons are evident at Hole kalkverk below the Rud Peloidal Beds and at Aannerud, equivalent horizons contain stromatoporoids, abundant Ancistrorhyncha, dessication cracks and ripple mark. At Eriksrud quarry oncolite rich beds, bioclastic grainstones and Dimorphosiphon rich stromatoporoid horizons underlie a peloidal rich succession.

2. The Rud Peloidal Beds.

In common with the Ihle Peloidal Beds these display a remarkable uniformity throughout the district, but can be distinguished by their lower quartz siltstone and bioclastic content, more abundant Phytopsis, inclusion of much coarser peloidal horizons and interbedded algal mat sequences. The lower boundary is usually a clear lithological transition from the underlying beds while the upper boundary is very sharply defined both by an erosion surface, which is well developed throughout the district, and the associated facies change.

At Eina this unit commences with cross-stratified bioclastic and peloidal grainstones and is represented by 10m of interbedded peloidal grainstones and interbedded algal mats with dolomite horizons. The peloidal beds are characterised by an abundance of Phytopsis, sub-parallel stylolites, some cross-stratification, occasional oncolites and dolomite nets, while the algal mats show evidence of dessication cracks.

The succession is best seen at Rud where peloidal grainstones occupy most of the upper 18m of the Eina Member. Variations in grain size are accentuated by stylolitic boundaries which combine into a characteristic series of parallel or subparallel boundaries, giving the beds the appearance of being thinly bedded. Many beds possess bioturbated upper surfaces while concentrations of bioclasts are often found at the base. Biota are generally absent although occasional pockets of Ancistrorhyncha occur as do the odd ragged stromatoporoid in the non quartz rich horizons. Dolomite nets are poorly developed although they often occur in association with bioturbated beds. Dolomite horizons are rare, but there is evidence of algal mat development in the upper 3m above a coquina of large molluscan shells. Spar filled vugs representing Phytopsis are also present but not in such abundance as at other localities.

Variations from the stratotype are insignificant. More algal mat horizons can be found at the Holetjern localities, while at Aannerud and Eriksrud there appear to be more bioturbated and micritic mudstone beds.

This member and its subdivisions, in particular the Rud Peloidal Beds, can be distinguished at all localities where it outcrops, although some difficulty is experienced in the incomplete sections found in the northwest where facies changes attributed to palaeogeographical position are found.

D. THE HOLETJERN MEMBER

A major feature of this member is the constancy throughout the district. Facies variations are seen in the lower and upper beds, but the sequence is typified by a series of highly bioturbated bioclastic (or in places peloidal) grainstones and dolomites. The lower boundary is clearly defined by an erosion surface cutting into the Rud Peloidal Beds, while the upper boundary is a conspicuoud palaeokarstic surface separating the Mjøsa Limestone and Helgøya Quartzite.

26m of strata representing this member can be observed in the localities adjacent to the southern shore of the Holetjern, which are regarded as the unit stratotype. Within this member only one formal sub-division is proposed, the basal Hemstadmoen Bioclastic Beds. Variations are described by informal terminology.

1. The Hemstadmoen Bioclastic Beds.

Although exposed at the Holetjern localities and recognisable throughout the Toten district as a coarse pelmatozoan bioclastic calcarenite with abundant Solenopora and a high calcisiltite/dolomite content, the beds are most accessible and contain a wider variety of bioclasts at Hemstadmoen.

The beds are characterised by their occurrence immediately above the erosion surface which truncates the Rud Peloidal Beds, as c80cm of pelmatozoan calcarenites, with a high percentage (60%) of bioclasts larger than 2mm. These are mainly rounded Solenopora, although Streptelasma and Grapthodictyon are abundant, with Nyctopora, crinoid stems, broken branching bryozoa and occasional Palaeophyllum-like corals also being present. Other biota represented by a few specimens only include orthocones, gastropods, brachiopods and ragged fragments of Liopora, Eoflecheria and stromatoporoids. A high percentage (40% of total constituent) of fine brown material (dolomite or calcisiltite) may also be evident.

Identical facies can be seen at Gamme, Eina, Holetjern, Rud and Slaatsveen, where ragged oncolites are found among the biotic constituents. The rich diversity of faunal elements decreases northwards, together with a reduction in unit thickness, leaving Solenopora as the dominant ruditic bioclast in an impure pelmatozoan groundmass. In the northernmost exposures of Aannerud and Eriksrud quarry, the only trace of this unit is a thin discontinuous Solenopora - pelmatozoan veneer lining or filling irregularities in the erosion surface.

2. The bioturbated bioclastic limestones and dolomites.

Above the Hemstadmoen Bioclastic Beds at Holetjern are a series of dolomite rich strata with irregular pods of fine bioclastic material displaying a gradual increase in abundance of Vermiporella within them until the unit becomes dominated by irregular lumps of this alga. 4m of this unit are distinguishable before it gradually merges into a 5m bioturbated fine bioclastic/dolomite unit containing stromatoporoid rich horizons. Vermiporella is present throughout, and the biota is supplemented by occasional Liopora together with Solenopora rich horizons. Overlying these are a series of massive bioturbated beds composed, mostly, of fine or coarse, thinly bedded dolomites and bioclastic calcarenites, sometimes with small scale planar cross-stratification. Burrow orientation is mostly vertical, but horizontally orientated specimens can be seen on the underside of many bedding planes. Representation on the surface normal to bedding is either in the form of simple dolomite filled tubes or irregular patches of dolomite. Bedding planes occassionally reveal circular cross sections, which do not appear as matched pairs, although the nature of the exposure rules out definite recognition of a Diplocraterion type ichnofauna. This 9m sequence is overlain by two distinct beds of pink pelmatozoan dominated calcarenite (50cm and 20cm thick) interbedded with dolomite and showing no evidence of bioturbation in its 1.70m thickness. The final 5m of exposure are occupied by a mixture of dolomites, peloidal and bioclastic grainstones with some biomicrites, all of which are bioturbated, although the intensity of activity decreases upwards quite markedly. In places along the quarry wall the Helgøya Quartzite can be seen as bulbous protrusions from the bedding plane indicating the uneven nature of the unconformity.

The main variations within this facies are seen in the northern localities of Aannerud and Eriksrud quarry.

At Aannerud, immediately above the thin veneer which represents the Hemstadmoen Bioclastic Beds is a 5m sequence of massive clean washed pelmatozoan calcarenite. Low angle, oscillatory, planar cross-stratification is extremely well developed, although compaction and subsequent stylolitisation have combined to distort the features quite considerably. 2m of peloidal and bioclastic grainstones overlie this sequence and are themselves followed by 2m of Solenopora rich bioclastic beds. The uppermost 5m is represented by bioturbated or laminated dolomite and biomicrites which contain ostracods, molluscan fragments, Hedstroemia and rare stromatoporoids.

Eriksrud quarry contains another variation. Above the erosion surface and barely perceptible Hemstadmoen Bioclastic Beds are a series of well developed interbedded irregular sheets of bioclastic calcarenite and dolomite/micrite/fine quartz siltstone. A thick (90cm) unit of the latter forms the main basal facies. Sedimentary structures are confined to low angle oscillatory cross-stratification, small channels and parallel laminations in the siltstones while the bioclastics appear structureless. The bioclastic element is composed of pelmatozoan debris, fragmented branching bryozoa, small ragged Solenopora, brachiopods (including Platystrophia, strophomenids and coarse ribbed orthids) together with rare fragments of Liopora and ? Palaeophyllum. Together these sediments comprise a total of 7.20m at the western end of the quarry, while at the eastern end c5.40m of bioturbated bioclastic grainstones, wackstones and dolomite (with a basal 2m rich in bioclastics) are overlain by 1.40m of coarse calcarenites and calcirudites containing abundant small to medium Solenopora, Streptelasma, bryozoa, Eoflecheria and stromatoporoid fragments. The finer grained fractions contain abundant Vermiporella. Small reef like bodies of stromatoporoids, Liopora, Eoflecheria, Conularia and Solenopora are developed as the uppermost units of the succession and interdigitate with both the Vermiporella and bioclastic facies.

Facies variations are most noticeable in the uppermost beds of the member, many of them forming distinctive lithological units:

Peloidal Beds: grain size varies from calcarenite to calcirudite, although commonly they appear completely structureless, even recrystalised in hand specimen. Bioturbation is usually absent with the result that the beds are conspicuous as massive, often white units amongst the brown, rubbly, bioturbated horizons. The most spectacular development of this facies is at Rud, where a massive channel is cut into the bioturbated beds and filled by oscillatory cross-stratified peloidal and bioclastic grainstones. At other localities where this facies occurs the basal junction is both erosive and sharply defined.

Algal mat and dolomite horizons: a variant which is particularly well developed in the Kyset quarries where bioturbated beds undergo a transition to laminated dolomite and micritic mudstone, which bear all the typical characteristics of an algal mat sequence. At Kyset such facies develop into dolomite beds which possess some faint laminations, while at Rud only dolomite beds are found. Stratigraphically these beds appear to be in the upper part of the Holetjerm Member as they underlie peloidal facies and are found within a few metres of the Silurian boundary.

Solenopora - pelmatozoan bioclastic beds: although this is a common facies in the Mjøsa Limestone its position directly below the Helgøya Quartzite at Dølbakken is unusual. The average size range of Solenopora is 2-8cm, but many are larger and bored, while crinoid stems reach a maximum length of 8cm giving the whole unit a coarse calciruditic grainstone texture. Other faunal elements readily discernable include Streptelasma, a thin encrusting stromatoporoid, Nyctopora, molluscan detritus, in particular large planulate gastropods, and large sparry calcite filled spheres (cystoids ?). Unlike the Hemstadmoen Bioclastic Beds this unit contains no fine grained impurities but is clean, well washed and much coarser in grain size.

The Holetjern Member contains a suite of distinctive facies, characterised by bioturbation, which show little variation throughout the district making them easily distinguished from other stratigraphical units.

E. THE UPPER BOUNDARY

Mention has already been made of this phenomena but a full discussion is deferred until the end of this chapter when it can be examined as a stratigraphical feature of the whole Mjøsa area.

IV. THE STRATIGRAPHY OF THE MJØSA LIMESTONE IN THE NES-HAMAR DISTRICT AND ISLAND OF HELGØYA.

Variations of gross lithology within the Mjøsa Limestone of Helgøya and the remainder of the Nes-Hamar district are regarded as sufficiently distinctive to warrant the erection of separate litho-stratigraphical divisions where necessary. These together with formal and informal subdivisions are illustrated in Fig. 2.4 and described below.

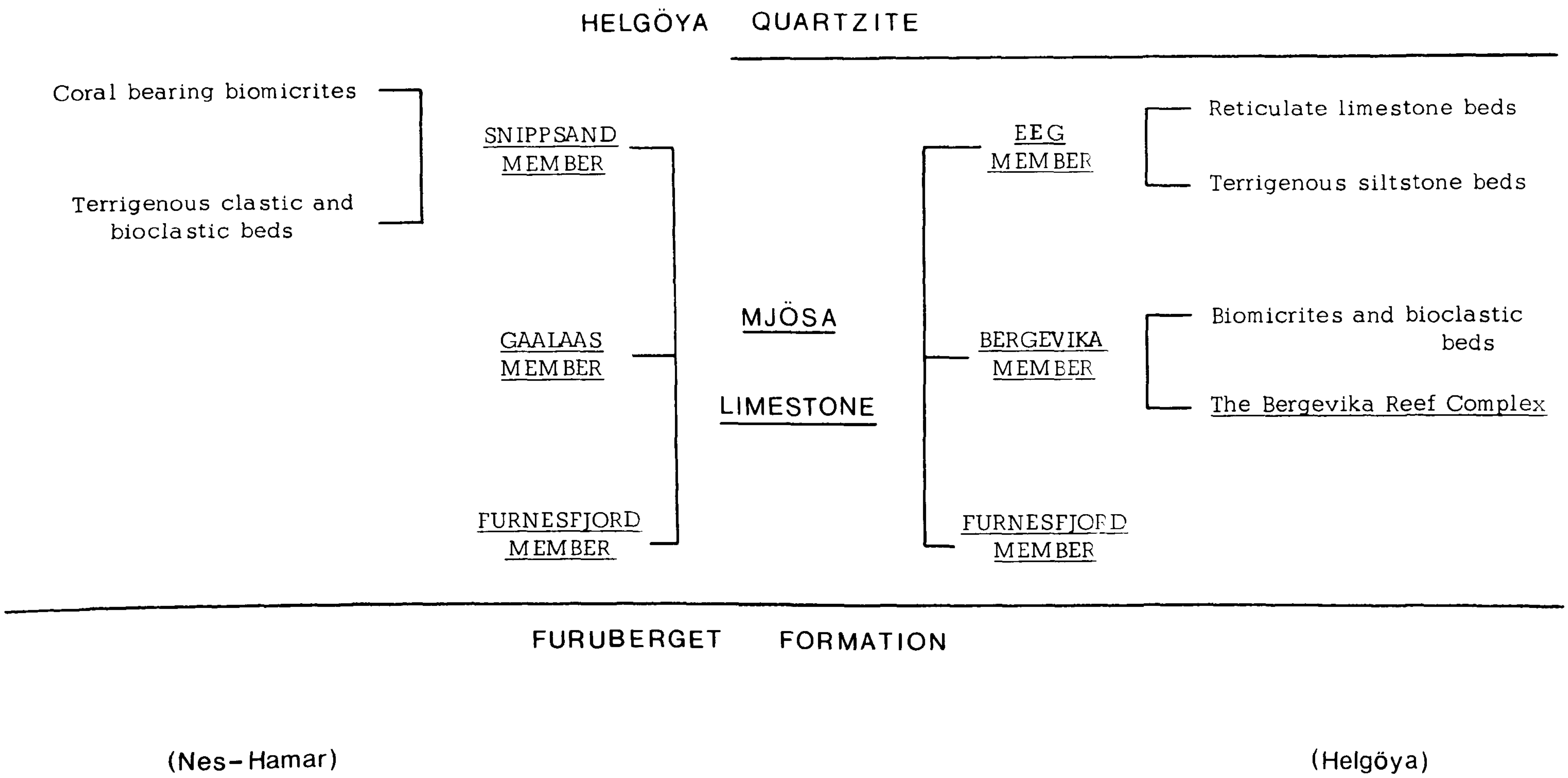
A. THE LOWER BOUNDARY

This is defined by the appearance of the first continuous bio-clastic limestone bed which marks the beginning of a dominantly carbonate rich succession. The excellent exposure afforded to the Furuberget Formation at the lakeside localities of Furuberget, Snippsand and Bergevika allows the base to be drawn with more certainty than in the Toten district. Furuberget is regarded as the boundary stratotype. Here the interbedded quartz siltstones and shales of the Cyclocrinus Beds contain an increasing carbonate content in the form of pods or lenses of bioclastic limestones towards their upper boundary. The first continuous limestone bed is a 74cm (Furuberget North) bioclastic calcarenite/calcirudite containing abundant fragments of Chasmops, branching bryozoa and molluscan material, and is regarded by this author as the basal bed of the Mjøsa Limestone. Identical situations exist at Furuberget South and Bergevika South, although at Snippsand an increased carbonate content within the Cyclocrinus Beds causes minor difficulties, while at Bergevika North an atypical quartz siltstone dominated Furnesfjord Member makes accurate definition impossible.

B. THE FURNESFJORD MEMBER

Although facies variations are present between localities, they are not deemed sufficient to warrant the erection of either formal or

Fig.2.4: The stratigraphy of the Mjøsa Limestone in the Nes-Hamar district and island of Helgøya. Formal terminology proposed in the text is underlined.


HELGÖYA QUARTZITE
Coral bearing biomicrites
Terrigenous clastic and bioclastic beds
SNIPPSAND MEMBER
GAALAAS MEMBER
FURNESFJORD MEMBER
MJÖSA
LIMESTONE
EEG MEMBER
BERGEVIKA MEMBER
FURNESFJORD MEMBER
Reticulate limestone beds
Terrigenous siltstone beds
Biomicrites and bioclastic beds
The Bergevika Reef Complex
FURUBERGET FORMATION
(Nes-Hamar)
(Helgöya)

informal subdivisions of the member. The dominant sedimentation pattern is one of recurring quartz siltstone and bioclastic units with the presence at some localities of Solenopora 'bioherms'.

The locality of Furuberget North is designated the unit stratotype because it contains a complete, accessible section through the member as well as the greatest uniformity of facies. The name is derived from the location of the Furuberget, Snippsand and, to some extent, Bergevika localities on the shore of that part of Lake Mjøsa known as the Furnesfjord. This terminology avoids duplication of nomenclature and confusion with the underlying Furuberget Formation as proposed by SKJESETH (1963).

At Furuberget North the basal 74cm bioclastic limestone is overlain by 3.20m of interbedded coarse quartz siltstones and shales with gutter casts, small scale ripples and parallel laminations. Above a sharply defined base c5m of coarse calcarenitic bioclastic grainstones, with large scale low angle planar, small scale trough cross-bedding and climing ripple lamination, develop. Brachiopods (Strophomena and Zygospira) are abundant, particularly in the uppermost quartz rich layers, which are overlain by the second fine quartz sandstone-fine siltstone unit. This occupies c 7m and contains more laterally extensive (often Solenopora bearing) bioclastic units, ripple and parallel laminations, and well developed Chondrites in the finer grained horizons. The overlying 6m of bioclastic limestone contain a higher percentage of quartz siltstone than normal, usually as laminations along the foresets of low angle planar cross-stratification. Solenopora are common throughout, but particularly abundant at the sharply defined base. With an increase of quartz content more brachiopods become evident and the unit passes upwards into c 3.90m of the third terrigenous clastic unit which contains a varied brachiopod fauna and abundant Chondrites. The uppermost 40-50 cm are particularly fossiliferous and clearly separated from the overlying fourth limestone unit by a sharply defined base. This limestone unit is composed of two separate beds, both c 1.70m thick which are rich in pelmatozoan debris (often pink coloured) at the base, heavily stylolitised throughout, but with a peloidal top showing well developed Phytopsis. Above this unit is c 1m of deeply weathered muddy limestone containing Ancistrorhyncha, patches of sparry calcite, which may be stromatoporoids, and oncolites. This passes into 2.10m of peloidal grainstones with abundant Phytopsis. The sequence continues with a 90cm bed of bioturbated fine peloidal grainstone with a concentration of large Solenopora near the upper bedding plane which separates it from 97cm of Solenopora dominated dolomite - quartz siltstone. Overlying these Solenopora rich beds are 3.36m of dominantly fine quartz siltstones, shales and calcareous mudstones with ripple marks, some channels, a fauna dominated by brachiopods (Ancistrorhyncha, rhynchonellids, Sowerbyella, Strophomena) and abundant Chondrites. Within this unit, 80cm of dark bioclastic grainstone rich in Solenopora can be seen. The total thickness of strata assigned to the Furnesfjord Member at this locality is 40m.

The adjacent exposure of Furuberget South contains only minor variations in thickness of units and can be easily correlated with the unit stratotype.

A greater variation, particularly in the abundance of quartz rich beds, is found at Snippsand, but in spite of them the Furnesfjord Member can be easily recognised. Associated with the increased terrigenous component is a corresponding decrease in bioclastic limestone bed thickness. This causes a minor upset to the clearly defined recurrent limestone-siltstone sequence typified by the stratotype. The most conspicuous variation is the addition of a 15m massive Solenopora biomass and its associated facies, which marks the uppermost unit of the member.

A similar *Solenopora* unit is present in the 28m succession at Bergevika South, but here it is found c 4m above the base of the Mjøsa Limestone and is only 6m thick. Recurrent limestone - quartz siltstone units are present but not as well displayed in this section as in the stratotype.

Bergevika North, however, reveals a particularly quartz rich succession equivalent to the Furnesfjord Member. Limestones here are found in thin discontinuous horizons which often appear as large symmetrical ripple forms with low angle oscillatory cross-stratification accentuated by laminations of quartz siltstone. The terrigenous beds show an abundance of *Chondrites* as well as *Planolites*, *Sinusites* and other ichofauna.

Despite variations due to the inclusion, or omission, of certain facies within the basal beds of the limestone, a simple sequence of calcareous and terrigenous sediments can be recognised. These beds contain sufficient similarities to allow the erection of a basal lithostratigraphic unit, which, although varying in thickness, is readily identifiable throughout the Nes-Hamar district and island of Helgøya.

C. THE GAALAAS MEMBER

Although a greater uniformity of sediments exists between the Snippsand and Furuberget localities, the stratigraphically equivalent beds on the island of Helgøya are deemed sufficiently at variance to warrant the erection of a separate lithostratigraphical unit. The Gaalaas Member is composed of peloidal grainstones, biomicritic wackstones and mudstones with interbedded stromatoporoid horizons.

Snippsand is taken as the unit stratotype and the name derived from occurrence throughout the Gaalaas area.

The basal bed, which overlies the *Solenopora* bioherm is a 2.40m massive, fine bioclastic calcarenite containing occasional *Solenopora* and well developed stylolites which accentuate the small scale, low angle cross-stratification. Above this is the first of the stromatoporoid bearing horizons characteristic of the member. In all, fourteen such horizons can be recognised, interbedded with massive peloidal grainstones and biomicrites, and composed of a quartz siltstone rich, dolomitised biomicrite containing articulated *Ancistrorhyncha*, small 'nodules' of micritic material (which appear to be oncolites) and *Hedstroemia*. The beds are easily distinguished by their contrasting lithology and tendency to weather more easily than adjacent massive beds. The stromatoporoids appear as single coenostea, often with a tendency to spread laterally in sheet like forms, and usually occupy only the lower half of each of these relatively thin (max. 80-90cm.) beds. The peloidal grainstones exhibit a variety of microvariations, usually in the form of a bioclast rich base, sometimes containing stromatoporoids or nests of articulated *Ancistrorhyncha*, which becomes more peloidal with an accompanying increase in dolomite, either as a fine net or concentration in parallel stylolites 10-15cm apart. Peloids tend to amalgamate giving both grapestone rich and micritic units, the latter often show a tendency to bioturbation and, in places, reticulation. Ichnofauna are scarce, but some bifurcating, horizontal dolomite filled forms are present. The uppermost biomicritic beds contain a diverse biota of bryozoa, *Hedstroemia*, *Ancistrorhyncha*, small orthocones and stromatoporoids. Approximately 40m of this member are exposed and although the upper boundary is not visible it can be accurately placed between the above mentioned stromatoporoid horizon and a series of thinly bedded terrigenous clastic and bioclastic limestone beds.

The Furuberget North section shows little variation from the stratotype and apart from containing fewer stromatoporoid bearing horizons any discrepancies are confined to the relative thickness of units.

In Gaalaas quarry, peloidal and bioclastic grainstones are interbedded with purple or green siltstone horizons. Much purple colouration appears to have leached into underlying peloidal beds from siltstones, but there are also small vertical burrows in green siltstone which are filled by sediment of contrasting purple colouration. In this respect the sediments are identical to those described from the Eina Member at Hole kalkverk. Ancistrorhyncha are found scattered throughout the succession, and oncolites concentrated in the green beds, but apart from occassional ragged specimens stromatoporoids appear singularly absent. Many of the peloidal beds (especially those with a purple colouration) contain a heavy dolomite net, Phytopsis and clearly bioturbated tops. The beds of this succession are regarded as stratigraphically equivalent to those described from Snippsand by the position above a well developed Solenopora bioherm at Kvam. Despite patchy exposure between the two localities, this relationship can be established in the field.

D. THE SNIPPSAND MEMBER

The beds which constitute this member are confined in outcrop to the lakeside section at Snippsand, which automatically becomes the unit stratotype. A two fold, informal, division is proposed (Fig. 2.4) to accommodate cross reference in correlation and palaeogeographical reconstruction.

1. Terrigenous clastic and bioclastic beds.

The basal boundary is not exposed, but a sharp facies change from the stromatoporoid bearing biomicrites of the Gaalaas Member to thinly interbedded bioclastic limestones and quartz siltstones is seen across a gap of c 3m. The siltstones contain Chondrites, abundant in some horizons, and evidence of cross-stratification while the limestones appear as pods, lenses or thin beds with sharply defined bases. Bed thickness is rarely more than 20cm for either facies throughout the 2m of exposure. The bioclastic limestones contain an abundant brachiopod fauna with broken branching bryozoa and pelmatozoan fragments.

2. Coral bearing biomicrites

Overlying the terrigenous clastics is a 2.70m massive unit of biomicritic wackstone/packstone which contains small stromatoporoids, Halysites and favositid corals with an associated fauna of orthocones, gastropods and pelmatozoan fragments. Exposure becomes scattered above this massive unit; a gap of 75cm separates 76cm of identical limestone from the main unit, but the next 1m of exposure is found after 5.60m of non exposure. The fauna is dominated by Halysites and a thin encrusting stromatoporoid. If this last horizon is included, the thickness of the unit is c 10m.

Beds belonging to this member have only been recognised at the Snippsand locality where they form a distinctive unit at the top of the Mjøsa Limestone.

Separate consideration is given to the Mjøsa Limestone of Helgøya which above the Furnesfjord Member can be divided into lithostratigraphical units distinct from those described above.

E. THE BERGEVIKA MEMBER

On the island of Helgøya the stratigraphically equivalent beds to the Gaalaas Member contain abundant clean washed, pelmatozoan bioclastic calcarenite and calcirudite on which patch reefs and their associated facies have developed. The reef complex can be recognised throughout the island, and as such, has been designated a formal lithostratigraphical unit, thus allowing a two fold division of the member as illustrated in Fig. 2.4.

The locality of Bergevika South was chosen as the unit stratotype because it contains the greatest detail of reef and associated facies. The total thickness of the member at this locality is c 28m.

1. The Bergevika Reef Complex

The 18.60m of sediments which constitute the Bergevika Reef Complex are dominated in the lower 8.60m by coarse, clean washed pelmatozoan calcirudites and calcarenites. Thin (c 20-30cm) discontinuous beds of dolomite, which contain bioclastic pods of *Eoflecheria* are interspersed within the bioclastics. Small reefoidal bodies composed of stromatoporoids, *Eoflecheria* and *Solenopora* occur throughout, but are poorly developed by comparison with the reefs which occupy the upper 10m. Detailed descriptions of these reefs and their associated sediments are presented in Chapter 4. The major reef builders are stromatoporoids and corals, and the associated sediments are pelmatozoan grainstones, biomicritic wackstones and mudstones, with development of oncolite rich peloidal grainstones at the top of this unit. These uppermost beds are distinctive by the high percentage of *Dimorphosiphon* fragments and their intimate association with small stromatoporoid-coral rich biomasses which appear to be both biostromal accumulations and very poorly developed growth structures. The upper boundary of this unit is sharply defined by a facies change to bioclastic grainstones.

Variations within this unit are confined to thicknesses rather than facies changes. Reefs and pelmatozoan bioclastics are well exposed in the Bergevika quarry, Bergevika North (19.30m), the roadside locality north of Kjelsrud (4.50m), and Helgøya Skole (c 9m). The last mentioned locality shows excellent development of oncolite horizons where the oncolites range in size from 0.5cm to 2.5cm. Bergevika quarry and the locality north of Kjelsrud show fine black calcisiltites which contain trilobite fragments and occasional Dictyonema.

2. Biomicrite and bioclastic beds.

The basal 1.70m of this unit is composed of lenses of highly fossiliferous bioclastic calcarenite containing abundant high spired gastropods, brachiopods, orthocones, crinoid stems, Dimorphosiphon and oncolites. The lenses are usually erosive on immediately underlying strata, but coalesce laterally to give individual thinly bedded (10-15cm) horizons. Channels and cross-stratification are the only sedimentary structures present. With a decrease of biotic content the beds rapidly become micritic mudstones or wackstones. Faunal elements are confined to specimens of Mjøsina mjøsensis and Parallelodus-like bivalves. The upper boundary is defined both by an erosion surface and striking change of facies.

As with beds of the reef complex there is little variation throughout the island and beds of this unit can be easily distinguished.

This member and its subdivisions can be easily recognised at all localities when it outcrops, not only by its distinctive facies, but also by its relative position to contrasting facies types of the Furnesfjord and Eeg members.

F. THE EEG MEMBER.

Although facies variations within this member are significant, a two fold informal division (Fig. 2.4) is proposed for the purposes of correlation and palaeogeographical reconstruction. The basic lithological types present are dominated by quartz siltstones or reticulate limestones and are well exposed at a number of localities.

Bergevika South and Eeg are designated as unit stratotypes; the former gives a readily accessible section through 20m of strata while the latter provides c 35m of discontinuous exposure but reveals a contact with the Helgøya Quartzite.

1. Terrigenous siltstone beds.

The erosional base to this member contains irregular hollows which are filled by a bryozoa dominated bioclastic calcarenite. Overlying this is a 1.15m unit of thinly bedded fine quartz siltstones containing Chondrites, bryozoa and ?Parallelodus. Thin irregular lenses of bioclastic grainstone contain abundant Sowerbyella and Mjøsina, with Rafinesquina, Strophomena, Platystrophia and other brachiopods present. The siltstones display ripple marks and cross-stratification. Bedding becomes more organised in the overlying 2m, the abundance and diversity of brachiopods declines, but the amount of bioturbation increases. The remaining 10m show an increase in finer siltstone concentration and a loss of bioclastic content. Small hemispherical colonies of heavily bored Diplotrypa are seen and the intensity of bioturbation increases, until the uppermost 2m, which show a gradual transition, through an increasing biomicritic content into the overlying beds.

This quartz siltstone rich facies shows almost no variation throughout the island and is easily recognised as a distinct lithostratigraphical subdivision.

2. Reticulate limestone beds.

This unit is distinctive by its three dimensional net of dolomite which gives it a reticulate appearance. This structure is attributed to bioturbation and later modification by diagenetic processes. The transition from the extremely bioturbated upper beds of the terrigenous siltstones is marked by a sudden decrease in quartz content and increase in dolomite. The biomicrites contain bioclasts of trilobites, gastropods, orthocones, some algae and occasional brachiopods. The bedding planes show well developed trace fossils which appear as straight or sinuous, sometimes branching, tubular forms. At Bergevika South this facies accounts for the uppermost 6m of Mjøsa Limestone.

At Eeg the unit can be recognised above a siltstone dominated sequence, but here the amount of reticulation decreases upwards and the structure becomes more representative of bioturbation. Including gaps in the exposure this unit accounts for the uppermost 12m of the Mjøsa Limestone which directly underlie the Helgøya Quartzite.

Variations within the unit are mostly accounted for by differences in the intensity of reticulation/bioturbation or the introduction of a peloidal grainstone facies. The localities at Fjell and, to a limited extent, Helgøya Skole show peloidal grainstone (calcarenites and calcirudites) horizons in the uppermost 3m. These beds usually have a sharply defined base and are conspicuous by their lack of bioturbation (hence dolomite). They are overlain by a biomicritic wackstone which shows a sharp increase in bioturbation towards the top.

The Eeg member contains two distinctive facies, both characterised by bioturbation, which show little variation throughout the island of Helgøya, thus making them distinct from other stratigraphical units.

G. THE UPPER BOUNDARY..

The Helgøya Quartzite is exposed in the three localities east of Fjell, but the contact with the Mjøsa Limestone is obscured. At Eeg a basal wackite conglomerate is visible, but the specimen may not be in situ. Although no information on the nature of the contact can be obtained, the upper boundary of the Mjøsa Limestone can be accurately located and from this the uppermost facies determined.

V. THE STRATIGRAPHY OF THE MJØSA LIMESTONE IN THE RINGSAKER DISTRICT.

North of the Solbergaas and its associated thrust line, limited outcrops of Mjøsa Limestone are concentrated at Brattberg and Torsaeter. Owing to the incomplete nature of the sections and their separation from the main Mjøsa Limestone outcrop, only a tentative correlation can be offered. No formal names are proposed and even the informal terminology must be regarded as 'convenience' nomenclature only.

1. The Brattberg Lille Beds.

A 13m succession exposed in the farmyard at Brattberg Lille consists of interbedded dolomites, quartz siltstones, shales and purplish stained peloidal grainstones. The shales contain gastropods, *Streptelasma*, orthocones, trilobite fragments and other bioclastic material. The central beds are dominated by oncolite rich peloidal grainstones which become increasingly bioturbated. The upper 3.10m are massive pink pelmatozoan calciruditic and calcarenitic grainstones with subparallel stylolites.

2. The Brattberg bioclastic beds.

These beds are a monotonous sequence of fine bioclastic calcarenites, usually dark grey with a purple tinge in places. Red shale is found concentrated along planes of stylolitisation and shows a tendency to increase slightly towards the top of the succession. Faunal elements are scarce and consist of nests of articulated *Rhynchonella*. Parallel to subparallel stylolites are the only structures present. The maximum thickness attained by these beds is 17m.

B. TORSAETER.

Two separately distinct units attributed to the Mjøsa Limestone by SKJESETH (1963) are exposed, but no correlation can be made between them.

1. The Torsaeter shale and limestone beds.

These are a 39m section of interbedded massive shales and biomicrites which contain a high percentage of shale and often give the appearance of tightly packed nodules. The shales contain large orthocones, corals and brachiopods while the limestones display an abundant gastropod fauna with occasional strophomenid and trilobite fragments. The uppermost horizon is overlain by a well sorted quartz sandstone interpreted as the Helgøya Quartzite.

2. The Torsaeter red beds.

These are represented by 6.70m of shales, predominantly red in colour which contain abundant branching bryozoa. Greyer shales are interbedded and these contain large orthocones, corals, branching bryozoa, and brachiopods. The upper part of the succession becomes distinctly nodular.

Correlation between individual outcrops at both Brattberg and Torsaeter is impossible, thus rendering any formal stratigraphical comparisons impossible. The stratigraphical position of these beds with relation to the main outcrop of the Mjøsa Limestone is briefly discussed below.

VI. DISCUSSION

The divisions erected and described above are entirely lithostratigraphical units. For the purposes of a palaeogeographical reconstruction it is desirable to achieve the most accurate correlation possible to avoid misinterpretation of, and confusion between, vertical and lateral facies changes. Therefore a chronostratisgraphical correlation is desirable.

The boundaries of each member can be correlated readily within the district where they were defined, a fact which supports the retention of a three fold formal lithostratigraphical division in each area rather than a broader division as used by HARLAND (1977 verb. comm.). One of the clearest boundaries to define is the erosion surface between the Eina and Holetjern Members of the Toten district. The boundary between the Sivesindhagen and Eina members is more difficult of definition possible because it represents a marine transgression of lesser magnitude. The greater number of localities and the readily identifiable homotaxial development of cyclicity within the Mjøsa Limestone of the Toten district allow more accurate stratigraphical division and correlation. To attempt any meaningful chronostratigraphy other districts are best dealt with by comparison with the stratigraphical succession in the Toten district.

The Furnesfjord Member is easily identified but discrepancies arise as to the recognition of its upper (and to some extent, lower) boundaries. Following the pattern adopted in the Toten district, the upper boundary could be placed at the peloidal horizons occurring above the terrigenous bioclastic sequence at Furuberget. However, no complementary horizons were observed at Snippsand or in any of the Helgøya localities. The boundary must separate the peloidal grainstone/stromatoporoid succession from terrigenous-bioclastic beds and be a readily observable unit at each locality. The only bed which is in accordance with this description is the distinctive bioclastic grainstone with heavy stylolitised planar cross-stratification. This is a doubly useful bed to choose because it occurs directly above the Solenopora bioherms at Snippsand and Kvam. The inclusion of Solenopora bioherms in the Furnesfjord Member is a useful policy as it strengthens the argument for adopting the Furnesfjord Member within Helgøya stratigraphy. The reef bearing strata on Helgøya are sufficiently different and distinct to warrant separation as a formal lithostratigraphical unit. The unit directly above the reefs can then be defined by its position relative to two major stratigraphical divisions.

Although erosion surfaces are not normally taken as time stratigraphic horizons, WILSON (1975 p.53/4) has demonstrated how the flooding of a cratonic area by the transgressive beginning to a regressive carbonate cycle can be regarded as "rapid" and therefore a useful time horizon. The Mjøsa Limestone is representative of sedimentation over a very small period of geological time (only one graptolite zone) and any such transgressive phase can be regarded as a useful horizon about which to attempt a correlation. Corresponding major facies changes which introduce sediments of a more "marine" nature can be found in the terrigenous-bioclastic beds which form basal units to the Snippsand and Eeg Members. At Snippsand these terrigenous and coralliferous biomicrites were assigned by SPJELDNAES (1972 verb. comm) to the Silurian on the basis of the coral fauna. This author, however, regards these coral beds as Ordovician, an assumption based largely on the absence of the Helgøya Quartzite from the Snippsand locality. Throughout Toten and Helgøya, as well as in the forests which cover Furuberget, evidence of the remarkable constancy of this facies (i.e. Helgøya Quartzite) can be found. It is not unreasonable to assume that if the Snippsand Member was Silurian then some manifestation of the Helgøya Quartzite would be present at its base. Although the Holetjerm, Snippsand and Eeg Members are sufficiently different to warrant lithostratigraphical separation within each district they present a general similarity of facies suggestive of contemporaneous deposition. Differences are regarded as being due to palaeogeographical distribution within the depocentre. It is difficult to find the erosion surface at Bergevika as it does not form such a spectacular feature as in Toten, but there is a definite transgressive period at the base of the Eeg Member and this is regarded as contemporaneous.

As a result of this correlation, the biomicrite and bioclastic beds overlying the Bergevika Reef Complex are equivalent to the Rud Peloidal Beds of Toten, but cannot be equated with a similar distinct facies at Snippsand. Credence is given to such a scheme by the position of reefoidal bodies below the Rud Peloidal Beds in the Toten district, which can then be regarded as lateral extensions of the Bergevika Reef Complex.

Correlation of the basal members is almost impossible between Toten, Nes-Hamar and Helgoya. No equivalents of the Ihle Peloidal beds and its overlying facies change exist, unless one regards the lowermost peloidal horizons at Furuberget as equivalents. In this situation it appears that local biofacies development has obscured any time stratigraphical horizons which may have represented the slight transgressive phase suggested by the Toten localities.

The final correlation between the districts is presented in Fig. 2.5. The position of the Torsaeter limestone shale beds as equivalent to the upper three members is a result of its position directly below the Helgøya Quartzite. Any correlation of the Torsaeter red beds or Brattberg localities is purely speculative and not attempted in this formal presentation.

Fig.2.5: Schematic representation of chronostratigraphy in the Mjøsa Limestone.

S I L U R I A N

(Toten)	(Helgöya)	(Nes-Hamar)
HOLETJERN MEMBER	EEG MEMBER	SNIPPSAND MEMBER
EINA MEMBER	BERGEVIKA MEMBER	GAALAAS MEMBER
SIVESINDHAGEN MEMBER	FURNESFJORD MEMBER	FURNESFJORD MEMBER

VII. THE ORDOVICIAN - SILURIAN UNCONFORMITY

An unconformity between Middle Ordovician and Silurian strata has been recognised by many of the authors who have undertaken studies in this area. Exposure of this feature is excellent in the Toten district where a number of localities (e.g. Kyset, Rud and Dølbakken) display a highly irregular plane of contact. The nature of this contact is further accentuated by the contrast in facies (limestone to quartz sandstone) and colour (white to orange-brown) between the Mjøsa Limestone and Helgøya Quartzite. Exposure of this boundary is sparse in the Nes-Hamar district; a thin basal conglomerate has been described by KIAER (1908) and SKJESETH (1963) from the Eksberget on Helgøya, and this author has found evidence of the contact near Fjell, Helgøya Skole and Eeg. In Ringsaker the contact is exposed in the Brumundelv at Torsaeter bru and further upstream, although the nature and accessibility of exposure together with facies changes in the Mjøsa Limestone add to the difficulties of accurately describing it.

At Kyset and Rud, the irregular contact is represented by a series of pipes and cracks filled with sandstone, which penetrate down to 1.5m into the limestone (Fig.2.6a,b). The walls of these pipes are often highly irregular, sometimes exhibiting a serated profile, while the pipes themselves narrow towards the base and attain a maximum width in the order of tens of centimetres. Less common larger bowl-like fills also occur which have smoother, more rounded profiles, attain depths of 70 to 80 cm and widths of 1 to 1.50 m.

Occasionally networks of pipes may coalesce with the result that blocks of limestone (up to 1m diameter) "float" in the surrounding sandstone. In all observed cases these blocks must be attached in the third dimension as they maintain continuity of linear structures (dolomite laminations, stylolites or bedding planes) with the adjacent limestone. No limestone detritus was observed in the bottoms of either pipes, bowls or anywhere in the Helgøya Quartzite. Although the pipes themselves do not penetrate more than 2m from the uppermost surface of the limestone, pockets of sandstone can be found up to 6m below it. These are either ovate in shape or a sinuous linear feature and obviously erosional as they truncate linear depositional fabrics (Fig. 2.6c).

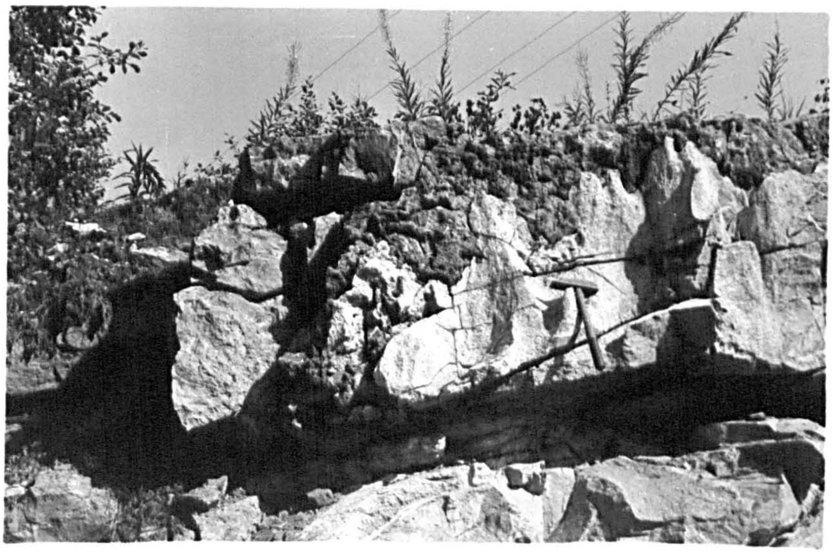
The ragged edges, lack of limestone detritus, floating limestone blocks, depth of penetration of the cavities and highly uneven nature of the contact indicate a chemical rather than physical weathering process to be responsible. This boundary is regarded as representing solution weathering and the production of a palaeokarstic topography prior to the deposition of the Helgøya Quartzite (6c or Middle Llandovery in age).

Fig.2.6: Palaeokarstic contact between the Mjøsa Limestone and Helgøya Quartzite.

a) general view, the Helgøya Quartzite is the darker lithology at the top of the quarry, the Mjøsa Limestone the lighter coloured rock. Locality Rud. Hammer is 40cm long.

b) close up of 2.6a, note the ragged edges to the solution features and lack of limestone detritus.

c) solution cavities, 6m below the contact, filled with the Helgøya Quartzite. The main cavity is to the left of the hammer at the base of the crack running diagonally across the picture. Locality Rud. Hammer is 40cm long.



CHAPTER THREE

FACIES ANALYSIS

I. INTRODUCTION

The expansion of carbonate sedimentology as a thriving branch of the geological sciences has brought with it a plethora of terminology and a discussion of the nomenclature used in this study is presented as Appendix II.

To supplement the stratigraphical investigations, an analysis of the sediments is necessary to allow the ultimate palaeogeographical reconstruction to be achieved. Sediments were divided into facies, primarily on field characteristics, and subdivided into microfacies after petrographical examination to provide a complete environmental synthesis.

On this basis five basic facies can be recognised:-

i) Terrigenous clastic.

ii) Bioclastic grainstone.

iii) Peloidal grainstone.

iv) Fine grained carbonate.

v) Dolomite.

A further four facies, composed of two or more of the above, are distinct enough to be recognised as separate entities:-

vi) Algal mat.

vii) Red clastic.

viii) Green clastic.

ix) Reticulate/bioturbated.

In addition, two facies containing distinctive biotic constituents, as well as one or more of the five primary sedimentary facies were clearly identifiable:-

x) Stromatoporoid biofacies.

xi) *Solenopora* biofacies.

In view of their palaeoecological significance these two biofacies were accorded a different method of investigation and the results presented as

Chapters 4 and 5 respectively.

Method of study

In the following descriptions each facies is treated separately in terms of its field characteristics, petrographical examination and environmental synthesis; the first two topics being purely descriptive, while the environmental synthesis attempts to place the facies into a distinct sedimentary environment by analogy to modern environments and comparison with other geological studies.

An identical format is adopted for each description. Petrographical subdivision is into separate microfacies distinguished by the facies number and suffixed letter. To avoid duplication, the microfacies regarded as being 'typical' of the facies is given a full description; the subdivisions are compared to this in tabulated form and by a brief description of their different properties.

Finally, a summary of the stratigraphical and environmental distribution is given, prior to the full palaeogeographical reconstruction presented in Chapter 6.

II. FACIES 1. TERRIGENOUS CLASTIC FACIES

A. FIELD CHARACTERISTICS

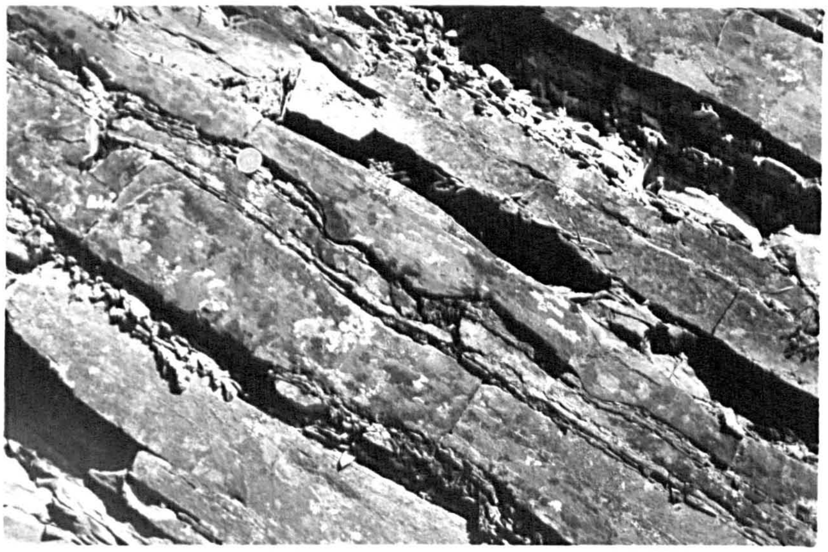
Beds of this facies appear light or dark brown when weathered but grey or grey-green when fresh. Lithologically they are dominated by interbedded fine quartz sandstones/coarse siltstones and fine quartz siltstones, often extremely fissile. Shales are rare. Bioclastic grainstones, composed mostly of pelmatozoan, brachiopod, bryozoa and trilobite fragments, with a high quartz content are also present. Bedding is thin (Fig. 3.1a); fine sandstones range from 3-51cm, fine siltstones 1-20cm and limestones 5-45cm. Total unit thickness varies from 1.40 - 12.50m. Terrigenous clastic beds are often discontinuous laterally, appearing as irregular lenses or sheets (Fig. 3.1a) sometimes composed of amalgamated thinner (2-5cm) horizons and pinch out the finer interbedded layers. Bioclastic grainstones occur as thin beds, lenses, pods, basal layers to coarse siltstone beds, and veneers, filling or lining basal channels. Bases of both the coarse siltstone/ fine sandstone and bioclastic beds are sharply defined, often showing erosional contacts with the underlying horizon (Fig. 3.1a). The tops of the coarser terrigenous beds are also sharply defined but those of the bioclastic beds are gradational into either fine sandstones or fine fissile siltstones. Sedimentary structures include erosive bases, usually displaying asymmetrical channels (Fig. 3.1b) or "gutter casts" (WHITAKER 1973) of variable relief (3-10cm. max 35cm). Within the terrigenous beds, trough cross-stratification, low angle planar cross-stratification, often oscillatory, parallel laminations and out of phase climbing ripple lamination can be seen. The upper surfaces show undulatory current (interference) ripples (Fig. 3.1c) with a polymodal distribution of palaeocurrent directions. The bioclastic beds show some small scale megaripple development and may contain low angle oscillatory planar cross-stratification enhanced by quartz siltstone lamin-

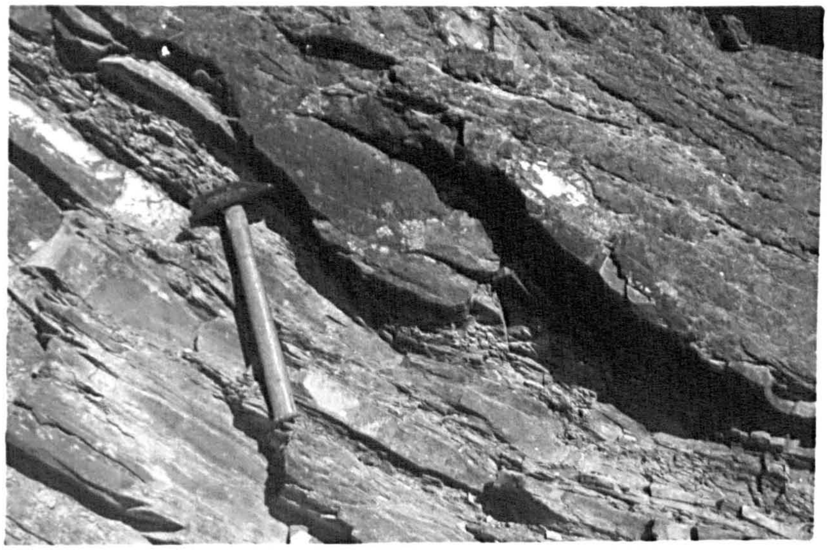
Fig.3.1: Sedimentary structures within the Terrigenous Clastic Facies:

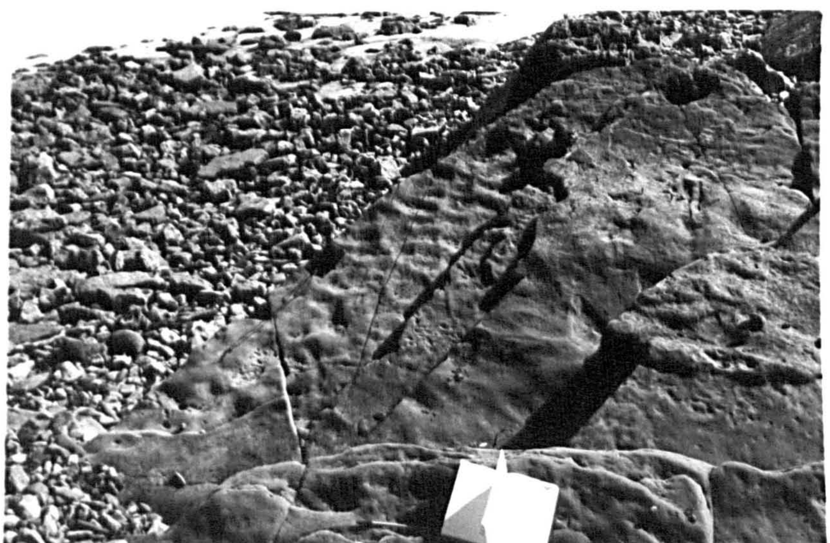
a) thinly interbedded coarse (more massive) and fine siltstones with irregular bedding and small scour structures. Locality, Furuberget North. Coin is 1.6cm diameter.

b) larger scale asymmetrical channel filled with coarse siltstone. Locality, Furuberget North. Hammer is 33cm long.

c) interference ripples on the upper surface of a coarse siltstone bed. Locality. Bergevika South. Notebook is 25cm wide.







ations. *In situ* fauna are rare, most faunal elements (branching bryozoa, brachiopod, trilobite and pelmatozoan debris) appear drifted. Small hemispherical colonies (often heavily bored) of the bryozoan *Diplotrypa* can be found at Bergevika and the finest siltstone horizons have also yielded unbroken ?*Parallelodus*. Biogenic structures are much commoner, especially in the finer lithologies, being dominated by *Chondrites*, with *Planolites*-like and *Scoyenia*-like forms also common. Vertical burrows appear less commonly, although within cross-stratified coarser beds occasional escape structures are visible. Other vertical forms, which may be *Tigillites* rather than *Skolithos* or *Monocraterion* (HARLAND 1976, verb. comm.), are also present. Paired burrow openings (?*Diplocraterion*) were only found at Hole kalkverk.

Although not confined to the lower members of the Mjøsa Limestone (see Figs. 2.3 and 2.4), the terrigenous clastic facies displays its maximum development there, particularly in the Furnesfjord Member.

B. PETROGRAPHICAL DESCRIPTION

In addition to the typical microfacies of the terrigenous clastic facies, three variants can be recognised either by differences in grain size or the allochemical components (bioclasts and pellets). These are illustrated in Table 3.1.

1. Microfacies 1: Fine sandstone/coarse siltstone

i) Texture:

Quartz grains are fabric supported (Fig. 3.2a); small embayments at the points of contact indicate slight pressure solution with adjacent quartz, bioclasts or dolomite crystals during compaction. Most quartz grains are equant and a preferred shape orientation is not immediately apparent. Occasionally lath-like grains may accumulate in a single lamination (60 - 100 μ thick) and exhibit a preferred orientation parallel to bedding.

Chlorite flakes are similarly orientated, but are more frequently buckled or crinkled around quartz grains.

Cementation appears to be by a combination of intergranular dolomite and pressure welding of quartz grains. The small scale interparticular porosity due to fine grain size, precludes detailed observation.

Grain size distribution is that of a well sorted medium to coarse grained siltstone/very fine sandstone (Table 3.1; Fig. 3.2a). Roundness is estimated between 1 and 4 on the Powers scale: angularity may be increased by the effects of grain to grain contact and subsequent pressure solution.

ii) Composition and Mineralogy:

Terrigenous detritus is composed of quartz (39-63%) with some felspar (c 2%) and chlorite (1.7 - 12%). Bioclasts (0-8%) are confined to fragmented echinodermal material, with occasional bryozoan or brachiopod debris.

Diagenetic minerals are represented by dolomite, which occurs mainly as an interparticular fill. Occasionally detrital quartz grains have been replaced by dolomite and sharply defined, ellipsoidal or elongate masses of subhedral crystals, associated with an increased abundance of fine terrigenous grains and bioclasts (Fig. 3.2b) are regarded as burrow fills.

Pyrite appears in a finely disseminated form (Table 3.1).

Small patches of fine grained carbonate are occasionally present, but there is insufficient evidence to establish their origin as allochemical or interparticular filling.

Variants from the type microfacies are shown in Table 3.1.

Microfacies 1A is distinguished by a finer grain size.

Microfacies 1B is distinguished by the addition of a bioclastic (calcirudite) and pellet component (Fig. 3.2b).

Microfacies 1C is distinguished by the increase in bioclastic (calcirudite) content but absence of pellets (Fig. 3.2c).

Table 3.1: Petrographical analyses of the Terrigenous Clastic Facies. Solid circles indicate the diagnostic features of each microfacies compared with the typical microfacies. The Key applies to Tables 3.3 to 3.7 as well.

MICRO FACIES	QUARTZ			CHLORITE	ALLOCHEMS				POROSITY		CEMENT		DOLOMITE			OPAQUES		
	Size	Roundness	%	%	Type	Size	Roundness	%	Type	Abundance	Type	%	Size	Shape	%	Mineral	Form	%
1	20 - 220 (40-80)	1 - 4	39 - 63	1.7 - 12	Bio	20 - 220		0 - 8	-	-	-	-		S - A	29 - 51	P	S	0.3 - 6
1A	20	-	40 - 50	5 - 13	Bio	20	-	4 - 5	-	-	-	-		A	30 - 40	P	S	5 - 7
1B	20 - 150 (40-70)	1 - 4	24 - 39	0.3 - 3	Bio Pellets	30 - 4mm (90-200) 30 - 80 (40-60)	1 - 4 4 - 6	11 - 36 12 - 26	BP WP MO SH	A R - A R - A R - A	V	0 - 15		S - A	12 - 32	P	S	0 - 2
1C	25 - 180 (50-70)	1 - 4	25 - 44	1 - 2	Bios E Br Bz O Pellets	30 - 5cm 30 - 80 (40-60)		 7 - 25 0 - 21 0 - 7 0 - 8 0 - 5	BP WP MO SH	R R - A R - A R - A	V	0 - 10		S - A	12 - 36	P	E.S.	1 - 8

KEY

Grain size is in μ units unless otherwise indicated.

Roundness is on the Powers Scale.

Texture : G = grainstone; P = packstone; W = wackstone; M = mudstone; D = dismicrite; CL = cryptalgal laminite; B = biolithite.

Allochems : Bio = Bioclasts; E = echinodermal; Br = brachiopod; Bz = bryozoan; M = molluscan; T = trilobite; St = stromatoporoid; A = Algal; Os = ostracod; O = others.

Algae : H = Hedstroemia ; Di = Dimorphosiphon; D = Dasycladacean; OK = oncolites ; AC = algal coats; ME = micrite envelopes.

Porosity: BP = interparticle; WP = intraparticle; MO = moldic; SH = shelter; SK = shrinkage; FE = fenestral; DP = disturbed; BU = burrow; GF = growth framework.

Cement: V = void fill; S = syntaxial; Ph = Phytopsis; remainder as for porosity.

Dolomite: Shape, E = euhedral; S = subhedral; A = anhedral.

Opaques: Mineral, P = pyrite; H = Haematite. Shape as for dolomite.

Distribution: L = laminar; S = scattered; remainder as for porosity;

Abundance: C = common; P = present; R = rare; A = absent.

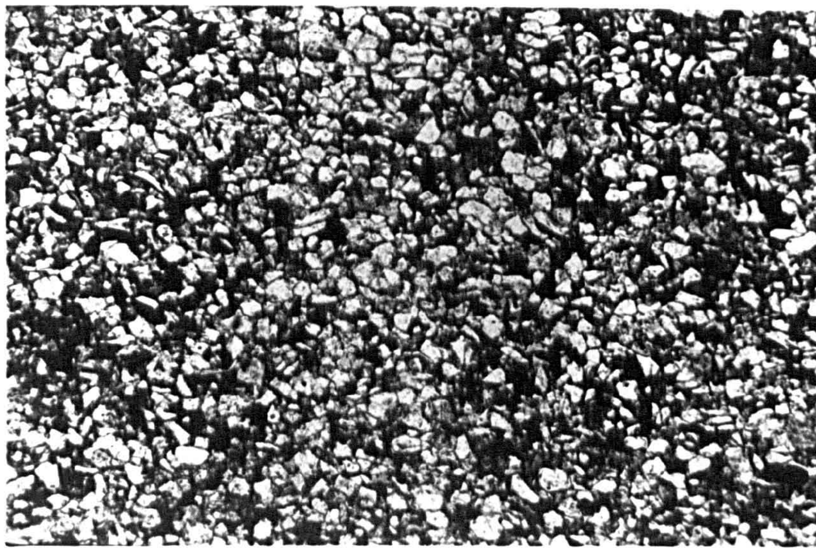
Parentheses indicate a poorly developed feature.

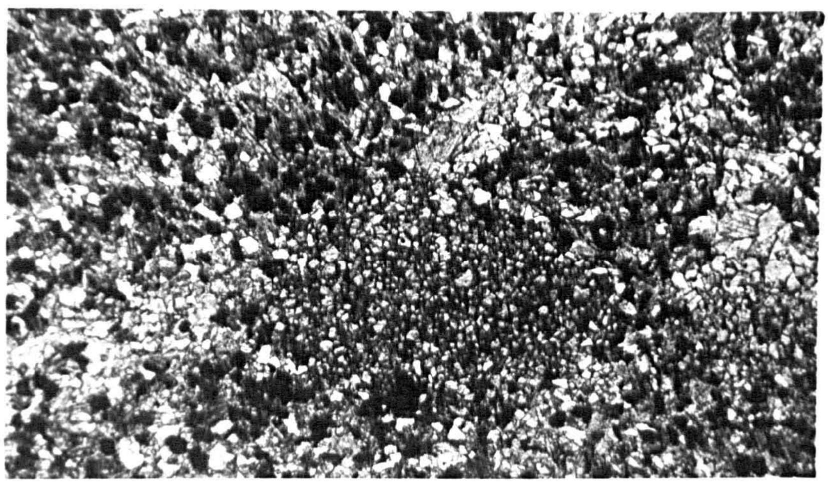
Fig.3.2: Petrographical characteristics of the Terrigenous Clastic Facies.

a) Microfacies 1, note the well sorted nature of the quartz grains, absence of bioclasts and interparticular dolomite (high relief). Slice. Furnesfjord Member. Locality, Furuberget South. x 48.

b) Microfacies 1B, note the inclusion of faecal pellets (black elipsoids), increased bioclastic content and concentration of subhedral to anhedral dolomite in burrow porosity (centre). Slice. Furnesfjord Member. Locality Furuberget South x 30.

c) Microfacies 1C, note calciruditic bioclasts giving a floatstone texture. Bryozoan (top left) has intraparticular pore space filled by sparry calcite and terrigenous mud. Echinodermal fragment (centre) shows partial replacement by authigenic quartz overgrowths to detrital grains. Slice. Furnesfjord South. x 30





Microfacies 1B and 1C are texturally little different than the type microfacies apart from the introduction of intraparticular, moldic and, occasionally, shelter porosity associated with bryozoan, molluscan and brachiopod bioclasts respectively. These pores are commonly filled by sparry calcite cement, although micrite and dolomite can also appear as intraparticular fills. The abundance of bioclasts prevents the development of quartz grain laminations found on the type microfacies, and introduces a floatstone-like texture; bioclasts are sometimes found as stringers, one particle thick.

Four samples were examined which contained a mixture of the type microfacies with variants B and C in proportions which did not allow discrimination into any one category. This was termed a 'mixed' facies.

All four microfacies show no cyclic or rythmic distribution. The bioclastic rich units are often concentrated at the base of a fine sandstone unit, and the pellet rich units are usually associated with the thin bioclastic (pellet rich) limestones. The fine grained siltstones are the thin interbedded material and generally show no gradation with any other microfacies.

C. ENVIRONMENTAL SYNTHESIS

Field relationships between the sediments comprising this facies indicate that the indigenous sedimentation style was that of the finer siltstones, with rapid and short lived periods of higher energy introducing coarser terrigenous clastic and bioclastic microfacies types. The textural and mineralogical maturity of the terrigenous clastic lithologies indicates considerable reworking and deposition in a regime with very efficient winnowing processes. The finest grained sediments are assumed to be the product of deposition under the quietest conditions although the absence of mud-sized particles indicates that sufficient energy existed to retain the finest fractions in suspension or to remove them from the system.

Many of the sedimentary structures observed within beds of this facies indicate transport, deposition and reworking by tidally induced currents (e.g. sharp erosive bases to the fine sandstone beds; oscillatory cross-stratification; interference ripples; sharp tops; asymmetrical (ebb) channels often lined with shell debris. Because such currents are active in both the intertidal and subtidal zones a more detailed consideration of the diagnostic features of both environments is necessary.

In recent years much has been written on modern tidal flats and their ancient analogues (e.g. GINSBURG (1975) presents an extremely valuable collection of short papers on this topic). Perusal of this literature and comparison with the terrigenous clastic facies of the Mjøsa Limestone has led this author to conclude that the lack of certain diagnostic sedimentary structures (e.g. herringbone cross-stratification (REINECK, 1963); mudcracks; mud drapes: B-C sequences (KLIEN, 1970a,b; 1975)) indicate deposition in a subtidal rather than intertidal environment.

A characteristic feature of the terrigenous clastic facies is the abundance of ichnofauna (indicating a thriving infaunal, deposit feeding, soft bodied biota) but virtual absence of benthos. Of the many environmental restrictions usually invoked to account for such paucity, emergence and salinity controls can be disregarded due to the subtidal nature of the environment, as can the lack of food supply by reference to the inferred continuous suspension of mud-sized particles. In an environment subjected to periodic (tidal) currents and intense burrowing activity, a high degree of substrate mobility can be expected due to the resuspension of sediment (RHOADS 1973; Walker in ZEIGLER et al. 1974, p.5.1-5.11). Such mobility precludes attachment and excludes epifaunal suspension feeders. A further control is substrate fluidity, caused by a high water content in level bottom sediments (RHOADS and YOUNG (1971) have recorded values of 80-90%)

giving near fluid properties at the sediment-water interface. This has the effect of severely limiting the epifaunal benthos and increasing the ease of resuspension (Walker in ZEIGLER et al. 1974). An interpretation of original water content by studying burrow boundaries, as proposed by RHOADS (1970) was not possible owing to dolomitization and subsequent obliteration of burrow fabric and burrow-sediment interfaces.

Sediments belonging to the terrigenous clastic facies are therefore regarded as being deposited on a level subtidal substrate where current activity was tidally induced causing the rippling of sand sheet upper surfaces and the constant resuspension of the fine grained siltstones. Periodic higher energy tidal influxes caused the movement of sand sheets or bioclastic material in ebb channels, while the strongest energy (storms?) introduced sheets of bioclastic debris.

A modern analogue which contains many of the features listed above is difficult to find. REINECK and SINGH (1975) in describing various modern clastic depositing environments, discuss work undertaken by REINECK et al (1968) in the Busum Region of the North Sea, and by HOWARD and REINECK (1972) on Sapelo Island, Georgia. The major environmental sub-divisions and their diagnostic characteristics are presented in Fig.3.3, and compared with the terrigenous clastic facies of the Mjøsa Limestone. The Transition Zone of the Busum Region offers the closest analogue, but the scale of bedding and lack of true rhythmites within the Mjøsa Limestone material suggests a shallower depth than the 10-15m proposed. Analogies can be drawn between the Lower Shoreface and Upper Offshore zones of Sapelo Island, where the depths involved would allow a fuller influence by tidally induced currents. A depth range of 2-5m is therefore envisaged for the terrigenous clastic facies.

Fig.3.3: Comparison between the clastic sediments of the Mjösa Limestone and two modern terrigenous clastic environments.

LOCATION / PARAMETERS	BUSUM REGION, NORTH SEA		SAPELO ISLAND, GEORGIA			MJØSA LIMESTONE
	COASTAL SAND	TRANSITION ZONE	UPPER SHOREFACE	LOWER SHOREFACE	UPPER OFFSHORE	Terrigenous clastic Facies
Water depth	0 - 10m	10 - 15m	M.L.W. - 1m	1 - 2m	2 - 5m	
Grain size	Fine sand - silty fine sand	Silty fine sand	Fine sand	Fine sand	Muddy fine sand	Fine sand/coarse silt - Fine silt
Primary Sedimentary Structures	Laminated sand, flaser bedding, ripple bedding.	Flaser and lenticular bedding, sand layers : evenly laminated or ripple bedded, wavey or plain mud layers.	Parallel lamination	Small scale ripple lamination	Parallel lamination, interbedded sand and mud, bioturbation.	Parallel lamination, undulatory ripples, climbing ripples, planar beds, channeled bases and gutter casts.
Ichnofauna	Bioturbation by Echinocardium.	Escape traces of Hydrobia, undifferentiated bioturbation structures. High degree of bioturbation.	No characteristic - Lebensspuren		Callianasa biformis burrow system, High degree of bioturbation	Chondrites, Tigillites, Sinusites, Planites, High degree of bioturbation in fine grained sediments.
Biofacies	Some autochthonous shells.	Autochthonous shell layers and allochthonous Hydrobia layers.	Haustoriidae community. Number of species and individuals are low.		Hemipholis elongata community. Exceptionally high number of species and individuals.	Very low number and diversity of non-drifted biota. Autothonous shell layers at base of units.
	REINECK et al. (1968)		HOWARD AND REINECK (1972)			

III. FACIES 2. BIOCLASTIC GRAINSTONE FACIES

A. FIELD CHARACTERISTICS.

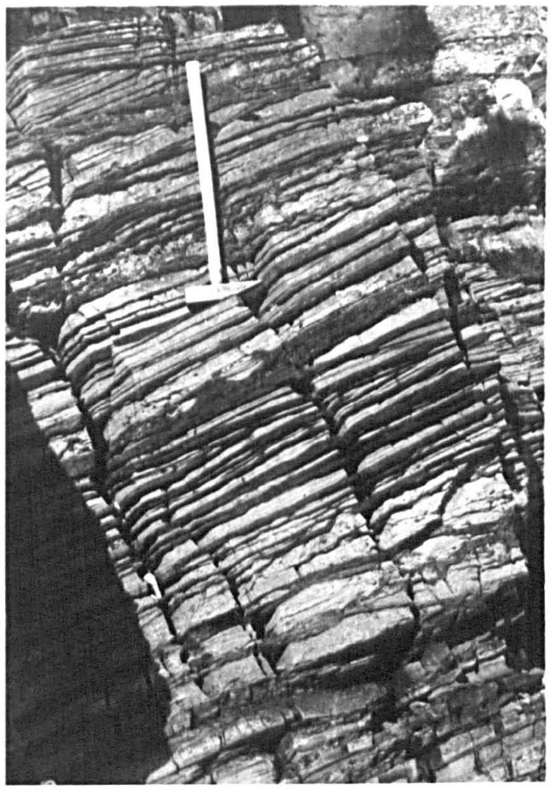
Bioclastic grainstones are usually grey, but can be black when fine grained, and white or white with red flecks when composed predominantly of pelmatozoan detritus. Texturally they are grainstones floatstones or biosparites and any micrite present is usually allochemical rather than matrix or cement. Grain size shows great variability from calcirudites to fine calcarenites and sorting is generally poor. Whole fossils contrast with comminuted material: pelmatozoan fragments are the dominant bioclasts, but local dilutions by Solenopora,brachiopod, bryozoan, trilobite, ostracod and molluscan material occur, the greatest diversity being in the lower members of the limestone. Quartz content is variable, but often shows a gradual increase towards the top of a bed, especially in the Furnesfjord Member, where bioclastic grainstones are overlain by units of terrigenous clastics. Bedding varies from massive (up to 3m thick) to small stringers (less than 1cm thick, as well as pods and lenses or even channel linings in terrigenous clastic beds. Bases are sharp, often erosional and display channels (relief 5-30cm) which are commonly filled by the coarsest material in the unit; bed tops are either sharp or gradational into quartz siltstones or peloidal grainstones. In addition to the asymmetrical channels, sedimentary structures include trough cross-stratification, large and small scale planar cross-stratification, climbing ripple lamination (both in phase (rarely) and out of phase), together with rare symmetrical ripple marks. The planar cross-stratification is often accentuated (especially in the Furnesfjord and Sivesindhagen Members) by quartz siltstone laminations along the foresets (Fig.3.4a) which show the oscillatory nature of current activity. At Bergevika North (Furnesfjord Member), isolated megaripples with amplitude of 11 to 40cm and wavelengths of 50cm to 1.5m can be seen (Fig. 3.4b) which contain siltstone accentuated foresets showing an oscillatory pattern, and

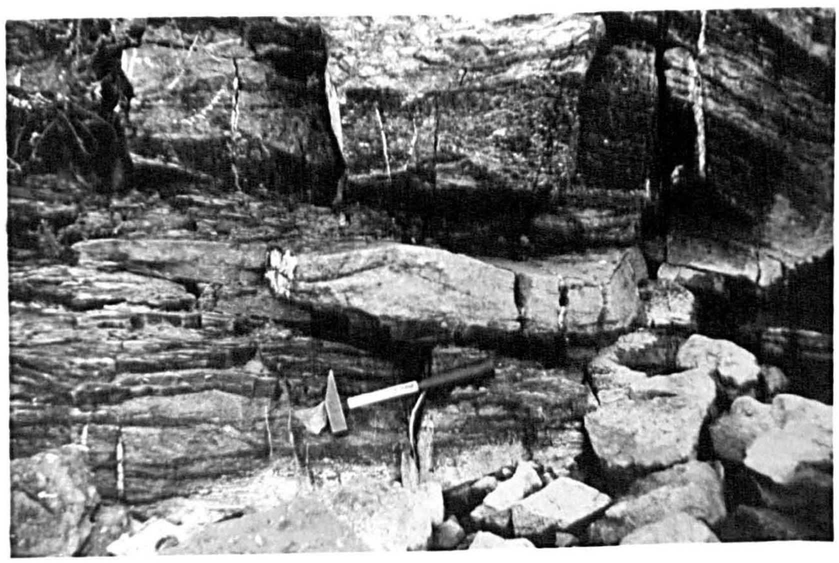
Fig.3.4: Sedimentary characteristics of the Bioclastic Grainstone Facies.

a) large scale planar cross-stratification with siltstone laminations (dark) enhancing foreset beds. Locality. Snippsand. Hammer is 1m long.

b) isolated megaripple of bioclastic grainstone in a predominantly terrigenous clastic sequence. Locality. Bergevika North. Hammer is 40cm long.

c) small scale cross-stratification enhanced by stylolitisation along the foresets. Note concentration of small rounded Solenopora above coin. Locality, Furuberget North. Coin is 2.70cm diameter.





the development of interference ripples in the siltstones on their flanks. Mega ripple bedding can also be distinguished within the more massive beds. Stylolitization often occurs along the foresets (Fig. 3.4c) and this serves to accentuate the feature. In situ biota are difficult to distinguish from drifted whole specimens, but the quartz rich upper horizons of many beds contain a varied brachiopod fauna; pelmatozoa (crinoids in particular) often appear as stems up to 10cm in length and where they are the sole contributors to the sediment they are regarded as being locally derived, breakage being due to oscillatory movement by gentle current activity rather than massive energy surges. Trilobites orthocones and ostracods are regarded as vagrant benthos, but at many horizons they are preserved intact, indicating little movement of the sediment after post mortem settling. Stromatoporoids and Solenopora represent the only definite in situ biota associated with this facies. Biogenic structures are rarely found within the coarse massive beds but the finer calcarenites may show vertical dolomite filled burrows (?Tigillites) on the upper surfaces. The bioclastic horizons immediately above the Bergevika Reef Complex show development of a Thalassinoides like ichnofauna, but this is an isolated case only.

Beds belonging to this facies are found throughout the Mjøsa Limestone, but have their maximum development in the Sivesindhagen and Furnesfjord Members.

B. PETROGRAPHICAL DESCRIPTION

In addition to the typical microfacies, three distinct variants can be distinguished, either by the inclusion of pellets or peloids, or the variation in bioclast size, composition and resultant changes both in texture and cementation style. These differences are presented in Table 3.2.

1. Microfacies 2: Bioclastic grainstone

i) Texture:

Bioclasts are grain supported giving a well developed grainstone texture (Table 3.2); grain edges are often sutured, indicating pressure solution during compaction. Echinoderm fragments appear to suffer preferential dissolution from this feature.

No preferred orientation of grains is apparent even among elongate brachiopod or bryozoan fragments.

Cementation appears to be by pressure welding: syntaxial rim cements to echinoderm debris are very poorly developed in most instances; the interparticular porosity is filled by a dolomite/quartz sediment petrographically identical to the terrigenous facies. Bryozoan fragments contain intraparticular pore space filled by either sparry (void filling) calcite, or micritic mudstone, although occasionally zoanthellae are filled by quartz grains.

Grain size distribution is variable; quartz grains range from 20-100 μ (node 60μ); echinoderm particles from 500μ-5mm with no easily distinguished modal value; bryozoan fragments usually appear in the 1-5mm range, again with no modal value. Roundness of quartz grains is 2-4 on the Powers scale.

ii) Composition and Mineralogy

Terrigenous detritus is composed of quartz (1.5-7%). Bioclasts are dominated by echinoderm fragments (27-65%), with secondary amounts of bryozoan (4-26%) and brachiopod (2-17%) detritus. Solenopora, trilobites ostracod and molluscan bioclasts collectively account for a small (0.3-6%) proportion of the total.

Diagenetic minerals are confined to 60-120 μ dolomite rhombs (6-25%) in intergranular pore spaces. One or two quartz grains show structures resembling authigenic overgrowths, but these are atypical features of this microfacies. Calcite cement (1.7-4%) is limited to cavity fills or rare syntaxial overgrowths. One sample showed a high percentage of pore filling micrite (6%) but this was a singular occurrence.

Pyrite is present as widely scattered small spots (0.3-1%) which are non-fabric selective in distribution.

Variants from the type microfacies generally referred to as a bioclastic grainstone (or bioclastic calcarenite) are illustrated in Table 3.2. There is, however, sufficient dissimilarity between the three to warrant a fuller description than that afforded to the terrigenous clastic facies.

2. Microfacies 2A: this is distinguished by the inclusion of pellets (Fig.3.5b) within the allochemical components and development of syntaxial rim cementation.

i) Textural variations:

Allochems are adjudged to be in three dimensional contact giving a grainstone texture to the calcarenitic fraction. The appearance of calcirudític grains (Table 3.2) introduces a floatstone texture and there is little evidence of grain to grain contacts promoting pressure solution among calcarenites, although the larger grains show slightly serated outlines.

Cementation is by syntaxial rim cements to echinoderm grains of all sizes, but particularly among the calcarenite (a feature which may reduce the pressure solution effects mentioned above and indicate early cementation); pellets and other bioclasts show sparry calcite cement in scalenohedral form. These two forms of calcite account for all interparticular void fills. Intraparticular voids of bryozoan fragments are filled either by sparry calcite or micrite mudstone.

Grain size distribution is similar to microfacies 1B; echinoderm fragments range from 50-500μ, mode 75-150μ, in the calcarenite; calcirudites range from 2mm up to 4cm with no easily defined modal value. Roundness values of both quartz grains and bioclasts are comparable to those of microfacies 1B (Table 3.1).

ii) Compositional and mineralogical differences:

From Table 3.2 it is evident that the major compositional change is the introduction of faecal pellets into the allochemical component.

Dolomite is less common and the higher percentage values are obtained from samples showing a concentration in burrows or body chambers of articulated brachiopods.

Sparry calcite cement occurs as both void filling and syntaxial forms.

Pyrite is commonly non-fabric selective in distribution but the highest concentrations are found where pellets have been selectively replaced.

3. Microfacies 2B: is distinguished by the abundance of echinodermal fragments, greater percentage of bioclasts of calcirudite size, syntaxial and void filling cements and an absence of pellets or peloids. Micrite coats 60-100μ thick (particularly to molluscan bioclasts) are interpreted as being of algal (micrite envelopes) origin (Table 3.2).

4. Microfacies 2C: is distinguished by the abundance of echinodermal fragments and peloids (Fig. 3.5c) as well as exclusive cementation by syntaxial overgrowths; 40-100μ micrite envelopes appear on echinodermal, as well as the occasional, molluscan and bryozoan bioclasts, but are commonly discontinuous around the grain periphery.

A 'mixed' bioclastic subfacies was erected to include bioclast rich samples which contain a mixture of textural and compositional components described above, but cannot be readily accommodated within their

Table 3.2: Petrographical analyses of the Bioclastic Grainstone Facies. Solid circles mark the diagnostic features of each microfacies.

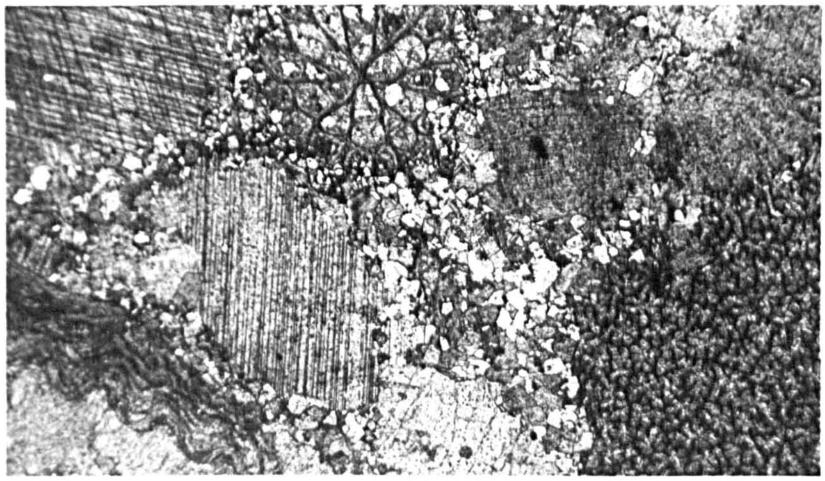
MICRO FACIES	QUARTZ			ALLOCHEMS			POROSITY		MICRITE		CEMENT		DOLOMITE			OPAQUES		
	Size	Round-ness	%	Type	Size	%	Type	Abun-dance	Type	%	Type	%	Size	Shape	%	Mineral	Form	%
2	20 - 100 (60)	2 - 4	1.5 - 7	Bio E Bz Br AC Os	 500 - 5mm 1mm - 5mm	 27 - 65 4 - 26 2 - 17 2 0.3-6%	BP WP	P P - R		6	V(S)	1.7 - 4	50 - 120	E - S	6 - 25%	P	S	0.3 - 1
2A	20 - 150 (40-80)	2 - 4	1 - 6	Bio E Os M Pellets	30 - 5mm 50 - 500 (75-150) 30 - 80 (40-60)	 10 - 64 1 - 12 0 - 6 ● 4 - 50	BP WP MO	R R - A R - A	BP WP	8 - 10 8 - 14	S, V	2 - 21	50 - 120	E - S	1 - 14	P	S	2 - 22
2B	20 - 100 (40-80)	2 - 4	2 - 6	Bio E Bz Br M	02mm - 7mm (1mm- 3mm)	 ● 30 - 52 4 - 12 0 - 6 2	BP WP MO	R R - A R			S	22 - 24	50 - 120	E - S	2 - 16			
2C	20 - 150 (40-80)	2 - 4	2 - 6	Bio E Peloids ME	 40 - 7mm (300 - 4mm) 40 - 800 40 - 100	 52 - 64 ● 32 - 40 4 - 10	BP	R - A			S		50 - 120	S	0 - 2			

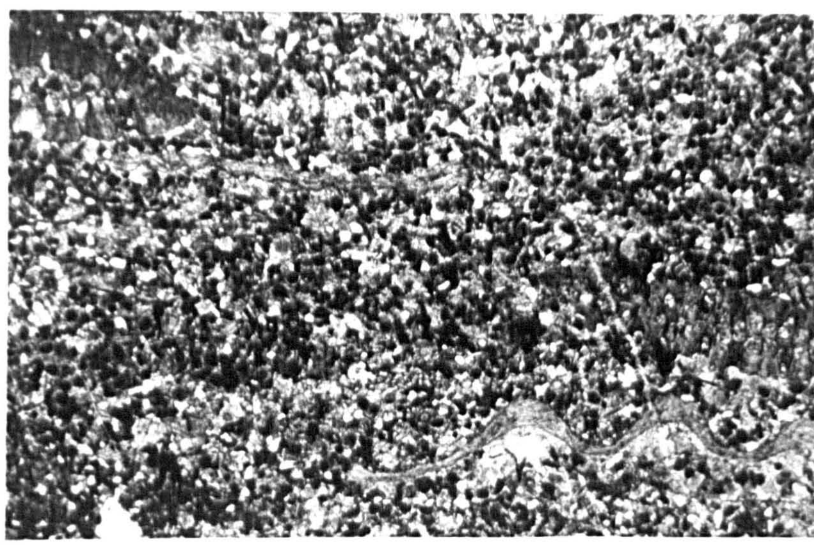
Fig.3.5: Petrographical characteristics of the Bioclastic Grainstone Facies.

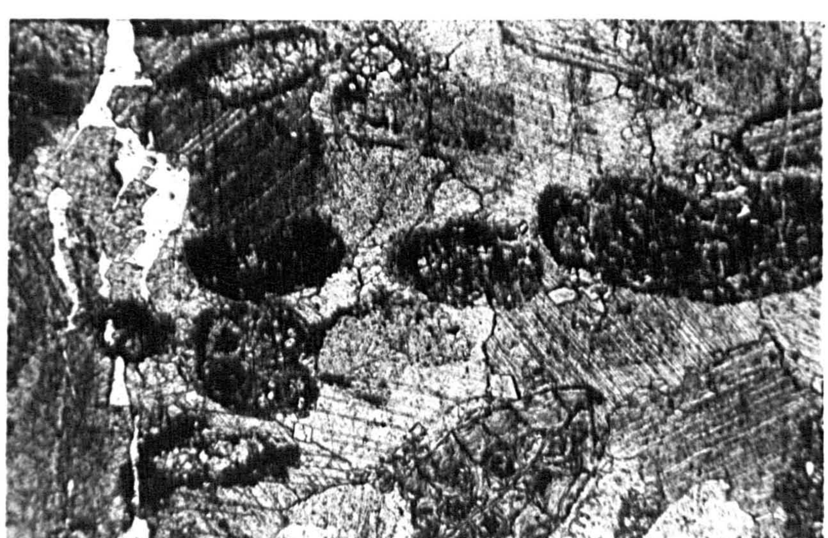
a) Microfacies 2: bioclasts include bryozoa (top centre, Solenopora (bottom right), brachiopod (lower left) - the remainder are echinodermal. Note lack of cement and filling of interparticular porosity by quartz (white) and dolomite. Slice. Furnesfjord Member. Locality. Furuberget South x 30.

b) Microfacies 2A: note the abundance of pellets (black elipsoids) and shelter porosity beneath brachiopod fragment (lower right). Slice. Furnesfjord Member. Locality Furuberget North. x 36

c) Microfacies 2C: note syntaxial rim cement to echinoderm of fragments, peloids (centre), micrite envelope to molluscan grain (upper left) and pressure welding of grains (lower right). Slice. Furnesfjord Member. Locality, Bergevika South. x 30.







limits. Six samples are assigned to this classification and exhibit a range from high peloidal to high quartz content, a high percentage of interparticular micrite, a mixture of peloids, pellets, bioclasts and dolomite, and abundant coated grains, mud filled gastropods, bryozoa and crinoid ossicles. Such specimens are regarded as transgressive (or end members) between the bioclastic and terrigenous, peloidal or micritic facies.

Microfacies distribution is random, the bioclastic grainstone and echinoderm rich beds appearing throughout the Mjøsa Limestone. Pellet rich beds are associated with the terrigenous clastic facies and represent a quartz difficient variant of microfacies 1B. The peloidal rich microfacies is usually associated with peloidal grainstones.

C. ENVIRONMENTAL SYNTHESIS

The general lack of mud within these sediments indicates winnowing by constant wave or current action; dolomite is occasionally found as an interparticular pore fill and if it represents fabric selectivity in favour of micrite, this indicates an original packstone texture. The characteristics displayed by beds of this lithofacies are identical to those given by WILSON (1975, p.358) for winnowed platform edge sands, which can take the form of shoals, beaches, offshore or tidal bars and even eolianite dune sands. These are regarded by Wilson as being deposited within a depth of 0-10m by waves, by tidal or longshore currents in marine waters of normal salinity, where the mobility of the substrate makes colonisation by benthos impossible. Sediments of this type are deposited in Wilson's (op.cit.) 'Facies Belt 6' and belong to his 'Standard Microfacies Type 12'. Sufficient data exists to allow further subdivision of this facies within the broad environmental scheme described above.

Anderson and Pazdersky, (in ZEIGLER et al 1974 p.4.1-4.10) present a brief descriptive account of the six most common types of skeletal sand substrate and the environments in which they are usually deposited. Three of these six can be recognised within the bioclastic grainstone facies.

The basal (Chasmops rich) beds of the Furnesfjord Member show the highest faunal diversity of this facies type in addition to poor sorting, relatively coarse grain size and large scale planar cross-stratification. These characteristics are interpreted as representing a prograding shoal margin in a mosaic environment of migrating bars and siltstone - sandstone substrate. The more massive, coarser grained units of this member (and the Sivesindhagen Member) which are less faunally diverse (pelmatozoa, rhynchonellids, orthids and branching bryozoa) are regarded as the prograding shoals proper whilst many of the thin bioclastic beds within the terrigenous clastic facies can be interpreted as washover fan sands (c.f. SELLEY, 1968). The higher incidence of bioclastic beds in the Sivesindhagen Member, and the related Solenopora colonisation style (p.239) indicates that this may have been the shallower, i.e. low shoreface or beach, environment.

The siltstone laminations which commonly accentuate the foresets (Fig. 3.4a) are interpreted as settling from suspension in periods of relative calm following transport of the bioclastic grainstones. Such a mechanism infers the periodic movement of bioclastic material into an area of dominantly siltstone deposition (i.e. terrigenous clastic facies). The coarse grained nature of the facies and large scale planar cross-stratification indicate that a high energy regime was required for transportation. Storm or tidally induced currents are the most likely causes of such periodic influxes. The bimodal nature of the cross-bedding indicates that oscillatory currents were active, although many of the more massive beds lack the siltstone laminations and appear to represent deposition from one major high energy influx. At Bergevika North a series of rippled bioclastic horizons (Fig. 3.4b) are seen within a particularly terrigenous clastic rich succession of the Furnesfjord Member; these are identical to ripples described from Silurian strata in the Oslofjord by BROADHURST (1968) to which he assigned a tidal origin. Basing his analogy on Recent sediments of the western English Channel and Warts Bank, Broadhurst concluded that these structures were formed on areas of the sea floor swept by strong tidal currents penecontemporaneously with finer terrigenous clastic sediments in areas of calmer conditions, and that these areas migrated giving a vertical interbedded limestone-clastic sequence.

Such a model can be successfully applied to the bioclastic deposits of the Mjøsa Limestone which contain siltstone accentuated foresets. The more massive, silt free units representing prograding shoals may also have moved under tidal influence, although, as with Recent equivalents, storm conditions probably had more effect. The tidally induced currents caused the local redistribution of material.

Beds of the pellet rich grainstones (Microfacies 2A) are found within the terrigenous clastic facies and can be regarded as redistributed washover fan sediments which owe their pelletoidal nature either to infaunal burrowers, vagrant benthos or winnowing from other areas of high organic activity. Of the three explanations a local origin is preferred: the resuspension of silt-grade material would no doubt leave the faecal pellets concentrated on the substrate ready for incorporation with incoming bioclastic material.

The abundance of pelmatozoan material within microfacies 2B and 2C is a reflection of relatively local provenance. The association of pink or red pelmatozoan fragments within these sediments is taken as evidence of a slow rate of sedimentation (FISCHER in MESOLELLA et al. 1974), a conclusion supported by the presence of micrite envelopes on many grains which indicate sufficient exposure for destructive algal attack. The presence of peloids and intraclasts indicates penecontemporaneous deposition within a shallow, stable environment where destructive algal activity and synsedimentary lithification exist. These two microfacies are more common in the middle and upper members of the limestone and their relationship to other facies is more fully discussed in Chapter 6. The basic depositional environment of platform edge sands prograding shorewards is still valid, however, and WILSON (1975, p.65) describes such facies types as being a "special microfacies of SMF 12, requiring winnowing but less strong water movement for their formation".

IV FACIES 3. PELOIDAL GRAINSTONE FACIES

A. FIELD CHARACTERISTICS

Beds belonging to this facies are usually grey or dark grey in colour. Lithologically they are peloidal grainstones. Grains are rounded or ellipsoidal micritic lumps, usually with a smooth outline and size range of less than 1mm to 3cm: amalgamation of grains to give a micritic mudstone is commonly found towards the top of the bed. Bedding is usually massive with bed thickness between 20cm and 3m; boundaries between layers of varying grain size are usually marked by stylolites which are parallel to bedding and 2 to 10cm apart (Fig. 3.6a). Peloidal horizons also occur at the top of some bioclastic grainstone beds through a gradation of grain types. Sedimentary structures are usually confined to occasional cross-stratification accentuated by stylolites; some grading of peloids within an individual horizon is occasionally evident. In the large channel deposits of the uppermost Holetjern Member, oscillatory cross-stratification is accompanied by a weakly developed imbrication of larger, flatter grains. *In situ* fauna are restricted to ragged stromatoporoids and *Ancistrorhyncha*, which often appear concentrated in 'nests'. Biogenic structures other than *Phytopsis*, are generally absent, although occasional small vertical or swirled burrows appear in the amalgamated fractions. Circular or elongate vugs filled with sparry calcite (Fig. 3.6b) are a diagnostic feature of this facies, often appearing concentrated in bands 15 to 20cm thick, especially towards the tops of bed parallel to bedding and match the description given by RAYMOND (1931) and TEXTORIS (1968) of the ichnogenus *Phytopsis*. A dolomite net may develop from parallel stylolites and the intensity of dolomite concentration and fragmentation increases towards the upper bedding plane (Fig. 3.6c) which shows evidence of bioturbation or brecciation.

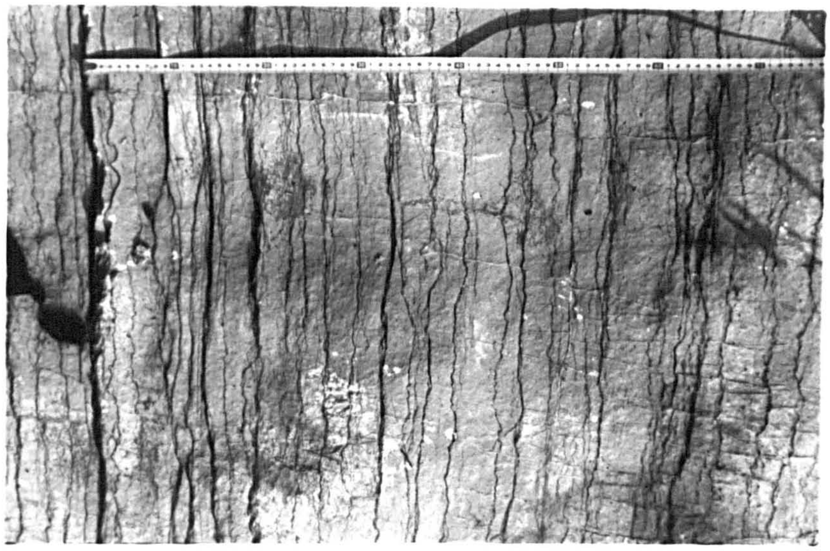
Beds of this facies are found throughout the Mjøsa Limestone but are

Fig.3.6: Sedimentary features of the Peloidal Grainstone Facies:

a) parallel stylolites. Succession youngs to the right. Locality, Dølbakken 2. Tape in cm.

b) parallel stylolites and Phytopsis (small sparry calcite filled burrows - appearing as dark flecks). Locality, Eriksrud quarry. Coin is 2.70cm diameter.

c) dolomite net. Succession youngs to the right. Locality Dølbakken 2. Tape in cm.



particularly abundant in the Eina and Gaalaas Members.

PETROGRAPHICAL DESCRIPTION

The approach to a petrographical analysis of peloidal sediments differs from that adopted for other facies of the Mjøsa Limestone. By their nature, peloids represent the alteration products of algal activity, and reflect the environment in which this process occurred rather than that in which the original grains were created. The polygenetic nature and resultant wide variety of physical parameters of the peloids necessitates the use of a broader classificatory procedure involving:

a) packing of grains - i.e. the reflection of early cementation and preservation of depositional texture prior to grain disintegration,

b) abundance of intraclasts,

c) abundance of relatively unaltered bioclasts.

Such a scheme allowed the recognition of a typical microfacies and three major variants:-

Microfacies 3 - Peloidal grainstone.

Microfacies 3A - Amalgamated peloidal grainstone.

Microfacies 3B - Intraclastic grainstone.

Microfacies 3C - Bioclastic rich grainstone.

1. Microfacies 3: Peloidal grainstone.

i) Texture:

Grains are fabric supported giving a grainstone texture (Fig. 3.7a) characteristic of this facies; pressure solution between grains is absent indicating a lack of compaction, probably due to early cementation. Stylolites occurring between bands of different physical properties show a concentration of quartz grains and clay minerals. Quartz grains occur only within peloids or intraclasts, never as sedimentary particles in their own right. No preferred orientation is shown by any grains; elongate bioclasts or intraclasts appear at random angles to bedding.

Void filling calcite cement occupies the interparticular pore spaces. Intraparticular and molaic porosity is greatly reduced (compared with Microfacies 2) by the lack of bioclastic material. Burrow porosity appears in the form of Phytopsis and is a diagnostic feature of this microfacies. Syntaxial rim cements to echinodermal grains are of minor importance in pore space filling (Table 3.3).

Grain size is variable (Table 3.3.) and sorting is poor, although well sorted samples contain a dominance of peloids in either the 80-125µ range or the 300-800µ range. Grain edges are smooth with a roundness of 4-6 on Powers scale.

ii) Composition and Mineralogy:

Terrigenous material is confined to quartz grains (0-6%) which are included within peloidal grains. In many cases a single grain may be encased by a circular micrite coating (Fig. 3.7a) suggesting an oolithic origin; quartz grains are also concentrated (along with clay minerals) in stylolites. Unaltered bioclasts are comparatively rare and confined to either echinodermal, algal (Rhabdoporella, Dasyporella and Hedstroemia) or more rarely, molluscan fragments; many bioclasts appear as nuclei to some peloids, suggesting an oolitic or accretionary algal (oncolite) origin. Intraclasts are also present within this facies, usually consisting of pellet packstones, mudstones, or dasycladacean wackstones.

Staining of thin sections revealed two generations (at least) of calcite cement, the first consisting of small scalenohedral, non-ferroan calcite binding grains together and confined to the immediate vicinity of grain peripheries; and the second, iron rich, and appearing as large blocky crystals filling the pore spaces.

Dolomite is fabric selective with regard to micrite, appearing only in the peloids or intraclasts, rarely in algal coats and never in the calcite cement; isolated rhombs are euhedral and display a marked variation in concentration (Table 3.3). Overgrowths of authigenic quartz were observed around original detrital quartz grains in three samples only, but none of these attained a euhedral or even anhedral shape.

Pyrite is extremely limited, occurring only as very rare euhedral crystals and filling the tubes vacated by boring algae within the peloids (Appendix II)

2. Microfacies 3A: Amalgamated Peloidal grainstone

This microfacies is easily recognised by the presence of micrite, micritic textures and decreasing percentage of sparry calcite cement (Table 3.3). However, this is only a localised phenomena within any one thin section and appears as large irregular patches (Fig. 3.7b) which occasionally are aligned parallel to bedding, but which are always found within good peloidal grainstone of microfacies 3 type. Examination of these micrite rich areas shows them to be either peloidal packstones or wackstones, rarely mudstones, the peloids often being recognisable only by a discontinuous 10μ rind of clear calcite (?) cement. Many peloids can be distinguished by their darker colouration and these are seen to be more irregular in outline than those in the surrounding grainstone. It appears that such irregular peloids are representative of physical breakdown of the grains to micrite, which acted as an interparticular pore filling. In all other respects, this microfacies is identical to the Peloidal Grainstone described above.

3. Microfacies 3B: Intraclastic grainstones.

The only distinguishing feature of this microfacies is the high content

Table 3.3: Petrographical analyses of the Peloidal Grainstone Facies. Solid circles mark the diagnostic features of each microfacies.

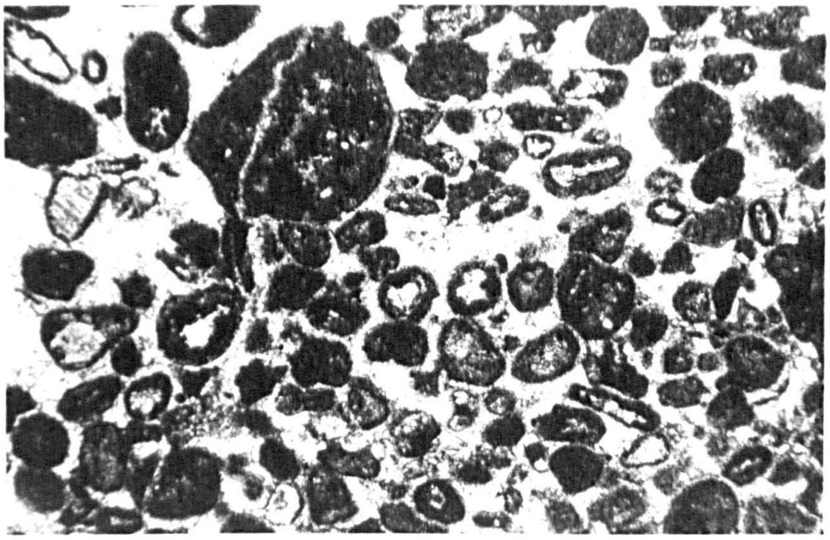
MICRO FACIES	TEXTURE	QUARTZ		ALLOCHEMS			POROSITY		MICRITE		CEMENT		DOLOMITE			OPAQUES		
		Size	%	Type	Size	%	Type	Abundance	Distribution	%	Type	%	Size	Shape	%	Mineral	Form	%
3	G	20 - 100	2 - 4	Bio		0 - 18	BP	C	-	-	V(S)	20 - 60	60 - 240	E	1 - 2	P	within peloids	
				E		0 - 4	MO	R - A			Ph.	0 - 14						
				M	200 - 2mm	0 - 18												
				Algae H		0 - 2												
				Di														
				Peloids	75 - 1mm (80-125 300-800)	26 - 60												
				Ooliths ?	80 - 120	0 - 2												
				Intraclasts	100 - 1.5mm	0 - 4												
				Grapestone	500 - 1mm	0 - 2												
3A	G (P,W,M)	20 - 100	2 - 8	Bio	75 - 1.5 mm	0 - 18	BP	P	Peloid amalgamation	0 - 15	V.S	18 - 38	100 - 280	E	0 - 6	-	-	-
				E		0 - 2	WP	R - A			Ph							
				Br		0 - 4												
				Algae	200 - 800	0 - 6												
				H		0 - 8												
				Di		0 - 10												
				Peloids	40 - 350	52 - 72												
				Intraclasts	100 - 2mm													
				Grapestone	500 - 2mm													
3B	G	20 - 100	2 - 4	Bio	40 - 1.5 mm	0 - 6	BP	P - C	-	-	V(S)	24 - 50	80 - 240	E	0 - 3	-	-	-
				E		0 - 8	WP	R - A										
				M		0 - 12	MO	R - A										
				Algae		0 - 8												
				AC														
				Peloids	60 - 2mm	2 - 38												
				Intraclasts	500 - 2cm	22 - 70												
				Grapestone	500 - 3cm	0 - 8												
3C	G	20 - 200	0 - 2	Bio E	100 - 1mm	20 - 50	-	-	-	-	S(V)	10 - 25	-	-	-	-	-	-
				Peloids	60 - 300	15 - 35												

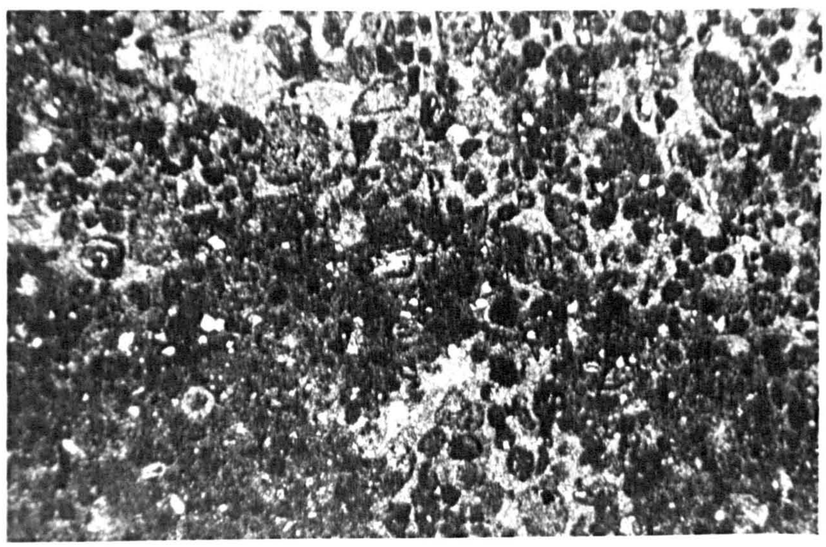
Fig.3.7: Petrographical characteristics of the Peloidal Grainstone Facies.

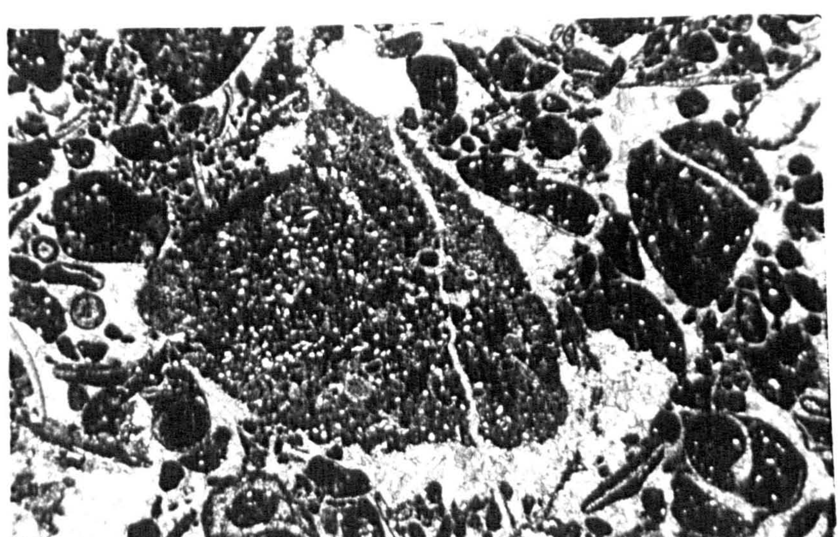
a) Microfacies 3, note the nucleus to peloids (ooids ?), well sorted nature, and micrite envelopes (upper left). Slice. Rud Peloidal Beds. Locality. Eriksrud Quarry. x 30.

b) Microfacies 3A, amalgamation of peloids can be seen in lower left and lower right of the picture. Slice. Rud Peloidal Beds. Locality Rud. x 30.

c) Microfacies 3B, large intraclast of dasycladacean mudstone (centre) eroded gastropods with micrite filling (lower right) and abundance of quartz grains in peloids and intraclasts. Slice. Rud. Peloidal Beds. Locality Rud. x 12.







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of intraclasts (Table 3.3). Compositionally these represent dasycladacean biomicrites, pellet packstones, gastropod rich micrites or micrites with authigenic quartz (Fig. 3.7c).

4. Microfacies 3C: Bioclastic rich grainstones.

The high percentage of echinodermal bioclasts (Table 3.3), resultant abundance of syntaxial rim cements and absence of other allochems makes this a unique microfacies. The petrographical similarity to microfacies 2C implies that this is probably a peloid rich end member of a single mixed bioclastic/peloidal microfacies.

C. ENVIRONMENTAL SYNTHESIS

In his synopsis of the sediments constituting the Great Bahama Bank, BATHURST (1971) describes how attack by boring algae and fungi leads to the development of peloidal grains. The petrographical similarity between these Recent peloids and those of ancient rocks has been noted by BEALES (1958) who invented the term "bahamite" to describe ancient peloidal grainstones. There is little doubt that a direct analogy can be drawn between modern formative processes and those operative in the production of Mjøsa Limestone peloids.

The clean washed, often well sorted nature of the peloidal grainstones typical of this Mjøsa Limestone facies suggests deposition from currents with sufficient energy to winnow out the fine grained carbonate mud and smaller peloids. Further evidence of deposition in a relatively high energy environment is provided by the low angle oscillatory cross-stratification and stylolite separated fractions of variable grain size or composition, each representative of a single depositional episode. Such mobility of grains does not normally occur on the Great Bahama Bank. BATHURST (1967c; 1971) and SCOFFIN (1970) have described the presence of a gelatinous algal mat which acts as a substrate stabalizer and benthonic food source. SCOFFIN (1968) has shown that this mat can withstand current velocities of between three and nine times as high as the maximum tidal currents. From this evidence it would appear that the deposition of the peloidal grainstone facies occurred under conditions of extreme current (storm) activity. A more readily acceptable hypothesis is that either the equivalent of the gelatinous mat was absent, or it was much thinner and less resistant. Bathurst (unpublished data) and GEBELEIN (1969) have both shown that upon removal of the mat, mobility of grains ensued and ripple marks formed after only a few hours exposure to normal tidal currents. Beneath the modern gelatinous mat Bathurst and other workers have found grapestone to be actively forming. The low frequency of occurrence of this allochem within the peloidal grainstone facies can, by inference, be regarded as a testament to the lack of substrate stabilization for a sufficient period of time to allow grain accretion. This in turn, implies the absence of an effective stabilizing gelatinous algal mat. The amalgamated peloidal microfacies is the only analgous lithology to modern grapestones within the Mjøsa Limestone and as such provides the only evidence that an Ordovician equivalent to the modern subtidal gelatinous algal mat may have existed.

WILSON (1971, p.67) assigns similar peloidal grainstones to Facies Belts 7 and 8, proposing formation in areas of restricted marine shoals and classifying them as "typical deposits of very warm, shallow water with only moderate circulation" and citing the beach as one possible environment of deposition. A comparison of the peloidal grainstones with modern Bahamian beach rock revealed many textural similarities. There is ample evidence of syn-sedimentary cementation in the presence of scalenohedral non-ferroan calcite cement, which predates an open burrow system (Phytopsis). These burrows are also filled by early calcite cement and are usually concentrated near the upper boundary of a peloidal bed, less commonly near the top of a constituent layer within the bed. In describing the tidal (beach) sediments from the Burgundy Jurassic, PURSER (1975) concludes that the presence of open burrows and their fill by syn-sedimentary cements is evidence of final deposition above the water table. COLACICCHI et al. (1975) have described identical features of early cementation within peloidal beach rock from the Lower Lias of the Appennines. Further analogies can be drawn from Purser's (op.cit.) description of inclined bedding and coarse textures as evidence of deposition in a prograding beach or coastal spit environment.

Further evidence of syn-sedimentary hardground formation is provided by the development of 'dolomite nets' at the upper surfaces of many peloidal beds. These nets are often associated with bored surfaces and are thought to have formed by solution brecciation (c.f. LUCIA 1972) with later compaction giving the stylolitic margins; modern hardgrounds in identical facies occur at varying depths. TAYLOR and ILLING (1969) and SHINN (1969) from the Persian Gulf, quote a depth range from intertidal to 20m, while TAFT <u>et al</u> (1968), from the Great Bahama Bank, record hardgrounds from the intertidal zone to a depth of 6m. The intimate association of peloidal grainstone facies and intertidal algal mat facies in the Rud Peloidal Beds suggest that formation of hardgrounds occurred towards the shallower end of the depth ranges quoted above i.e. a beach environment.

The association of peloidal grainstones overlying and obviously developing from, bioclastic grainstones, suggests the stabilisation of the prograding shoals of the bioclastic grainstone facies in a nearshore environment where destructive activity by boring algae (and fungi) flourished. Micrite produced by disintegration and decay was removed by tidal currents and in times of strong current activity the peloids were washed up onto the beach. The local development of a subtidal algal mat may have stabilized the substrate long enough to allow development of accretionary textures, but for some reason (absence; exposure and subsequent demises or patchy development) the mat was unable to assert a lasting effect comparable to its Recent equivalent.

The introclast rich microfacies indicate penecontemporaneous syndepositional lithification, and erosion, in a mud depositing environment (shallow subtidal or intertidal). The bioclastic rich microfacies are regarded as shoal sediments which did not attain sufficient stability, or were buried too quickly, to allow peloidal development to the full, or alternatively, as the products of a transition zone between peloidal and bioclastic facies.

V. FACIES 4. FINE GRAINED CARBONATE FACIES

Included in this facies are all micritic rocks together with the calcisiltites of the Eina and Bergevika Members.

A. FIELD CHARACTERISTICS

All members of this facies are either light grey, dark grey or black in colour, although weathering may produce a porcellanous white outer coating. Grain size is indistinguishable, but microclastic carbonates, (calcisiltites/ calcilutites) can be distinguished by their duller lustre, rougher feel and muddy appearance when freshly broken from the high lustre, smooth fracturing microcrystalline carbonates (micrites). Bioclasts may be abundant or absent and the texture varies from packstone to wackstone or mudstone. Bedding varies from thin to massive, although a thinly bedded appearance can be produced by stylolites parallel to bedding and only 10 or 15cm apart. Bases are often gradational into underlying peloidal grainstones but may be sharp above a fine siltstone parting lamination; bed tops are usually sharply defined. Sedimentary structures are generally absent although some ripple marks are evident in the coarser calcisiltite fractions at Rud, while nodular bedding develops at Eina. _In situ_ biota is restricted. The large gastropods of the reef associated facies show little breakage while specimens of _Dictyonema_ have been recovered from the off reef and reef pocket calcilutites on Helgøya. _Parallelodus_ like bivalves, _Lingula_ and branching bryozoa, together with _Strophomena_ are found in similar facies at Rud, while large rhynchonellids appear at Eina. In contrast, the biomicrites of the Snippsand and Gaalaas Members contain _in situ_ stromatoporoids, a variety of algae, unbroken ostracods, articulated _Ancistrorhyncha_ (in the more quartz rich beds), _Halysites_ (two species), favositid corals and small orthocones. The richest biota in this facies occurs in the beds at Torsaeter which are dominated by gastropods and brachiopods, none of which show evidence of transportation. Biogenic structures, which may vary between completely absent, to abundant, in this facies are mainly represented by dolomite filled vertical or swirled burrows and the occasional rhizocorallid structure. The biomicrites are often heavily bioturbated on their uppermost surfaces, the burrows again being mostly vertical and dolomite filled; in the shale partings between beds of micrite, horizontal, bifurcating (Arthrophycos-like) ichnofauna can be found.

Beds attributed to this facies are found throughout the Mjøsa Limestone although they occupy only a small percentage of the Furnesfjord and Sivesindhagen Members.

B. PETROGRAPHICAL DESCRIPTION

Following the definition of a typical microfacies, five variants can be recognised on the basis of changes in texture, allochemical components and quartz content. These are illustrated in Table 3.4.

1. Microfacies 4: Mudstone - Wackstone

i) Texture:

Apart from isolated pockets all bioclasts are mud supported and depending on their relative abundance, a mudstone or wackstone texture results (Fig.3.8a). Grain edges show little evidence of pressure solution with the enclosing micrite.

In most samples, there is no preferred grain orientation among bioclasts. Ostracods, where abundant disarticulated valves occur, appear in a concave up orientation, and may be concentrated into readily detectable layers; elongate grains e.g. brachiopod valves sometimes show a tendency to align parallel with bedding.

Fabric selective void filling calcite is much in evidence. Intraparticular pore spaces of algae, bryozoa, articulated ostracods (which frequently exhibit a calcisiltite floored geopetal structure in correct orientation) and, more rarely, articulated Ancistrorhyncha are filled by sparry calcite cement; gastropod chambers frequently show filling by both sparry and microcrystalline calcite. Moldic porosity is evidenced by calcite cement casts, always between unbroken micrite envelopes, representative of bivalve molluscan bioclasts (gastropods often lack a clearly defined micrite envelope but are represented by void filling calcite). Where molluscan debris is closely packed, the interparticular pore space may be filled by sparry calcite cement. Other sparry calcite-filled voids are also apparent, but are less easily defined. Fenestral porosity sensu stricto is rarely found, although some fabric selective pores show an alignment parallel to bedding; commonly pores which are fabric selective (i.e. possessing outlines which are grain controlled) occur in isolation. Particularly in those samples in which pellets can be distinguished, a disrupted porosity exists, a feature which may be attributable to bioturbation. Non fabric selective porosity is seen in spar filled burrows containing faecal pellets (Fig. 3.8b), shrinkage cracks and vugs; none of these phenomena are ubiquitous within samples of this facies, but tend to appear in isolation.

Grain size distribution is variable; microcrystalline calcite (4-20μ); bioclasts (50μ-2cm); quartz (20-80μ). Apart from quartz (2-4) roundness occurs throughout the range afforded by Powers scale, and is entirely dependent on the original bioclast shape, there being little rounding either by abrasion or micritisation of grain peripheries.

Although compactional and pressure solution features are infrequent, stylolites show a concentration of quartz grains and fine brown material (clay minerals ?); these structures are associated with subfacies or facies boundaries.

ii) Composition and Mineralogy:

Terrigenous detritus consists entirely of monocrystalline quartz (less than 5%). Bioclasts show a restricted range; ostracods are ubiquitous but rarely account for more than 20% total; algae are dominated by the genus Hedstroemia, which again is ubiquitous but varies from 5-20% total, although most of the occurrences are convex upward hemispheres often attached to bioclastic material or forming part of an encrustation. Molluscan detritus, particularly gastropods and bivalves often appear concentrated (40%) in some samples but widely dispersed (0-5%) in others; associated with the molluscan bioclasts are thin micrite envelopes. Echinodermal material is usually absent but may appear as isolated echinoid spines or fragmented plates of uncertain origin. Brachiopods appear as articulated specimens, or as broken (ribbed) valves, probably Ancistrothyncha, but are confined to a small number of samples only. Trilobite bioclasts are small fragments and are only very rarely encountered.

Ferroan calcite is present as cement.

Dolomite is the most abundant diagenetic mineral, appearing in concentrations often associated with bioturbation structures or as isolated rhombs (less than 1%) but is more often completely absent; rhombs are euhedral when isolated but subhedral when concentrated.

Pyrite is occasionally seen as small (less than 150μ) euhedral crystals, but more commonly as 40-60μ spots concentrated in stylolites or areas of stylolitisation.

2. Microfacies 4A: Hedstroemia Biolithite

Although Hedstroemia is ubiquitous throughout the Mudstone-Wackstone microfacies (Table 3.4), the presence of a high percentage of thalli in a convex-upward orientation, an increase in total abundance and the development of a growth framework, make this facies worthy of separate classification. The term "Biolithite" was preferred to the more detailed nomenclature of EMBRY and KLOVAN (1971)(p.360), because none of these terms was in itself satisfactory and the characteristics of the samples examined were identical to those described under the same facies name by TEXTORIS (1968) from the contemporaneous Black River Group (U.S.A.). The development of a crude framework increases the amount of interparticular porosity (Fig. 3.8c) and this is filled either by micrite, sparite or dolomite, with bioclasts and peloids in varying proportions; the increased abundance of Hedstroemia (and in places, a bushy bryozoan) is directly responsible for an increased intraparticular porosity. The grain size distribution is given in Table 3.4.

Compositionally there is little difference between this and the constituents present in the Mudstone-Wackstone microfacies, although in terms of relative abundance the increased percentage of Hedstroemia and sparry calcite cement is accompanied by a decrease in micrite content (Table 3.4). Dolomite shows a marked fluctuation in abundance.

3. Microfacies 4B: Calcisiltites:

This facies is distinctive from other members of the Fine Grained Carbonates by its coarser crystal size, higher quartz content and low percentage (or absence) of bioclasts which combine to give a mudstone texture (Fig. 3.9a; Table 3.4). Calcite cement is restricted to exceedingly rare intraparticular fillings of bryozoan zoanthellae or ostracod corapaces, or even scarcer shelter porosity beneath arcuate (e.g. trilobite) bioclasts. Bioturbation is present and can be recognised by local concentrations of quartz grains, anhedral dolomite rhombs or darker (organic rich) material in an irregular distribution.

Pyrite appears either as disseminated spots, or occasionally replacing sparry calcite, or providing a second generation filling, within the shelter cavities (Fig. 3.9a). Such occurrences are often accompanied by partial replacement of the overlying bioclast.

4. Microfacies 4C: Pellet Packstone

This microfacies is distinguished from the typical microfacies by the dominance of faecal pellets (Fig.3.9b) and more numerous bioclasts which combine to give a packstone (occasionally wackstone) texture (Table 3.4). Bioturbation is common; unlike the calcisiltite facies the bioturbated areas appear lighter in colour, a feature which accentuates the high pellet content. (Fig.3.9b). All samples are poorly sorted in respect of total allochemical components (Table 3.4).

Pellets show a tendency to amalgamate or disintegrate giving a mudstone end member. Bioclasts, particularly of molluscan origin, show local concentrations within samples; ostracods are ubiquitous but Hedstroemia appears only as an encruster on bioclasts.

Dolomite is scattered, with only rare concentrations in areas of bioturbation. Quartz grains occasionally show an authigenic overgrowth with abundant inclusions of micrite sized carbonate crystals; no euhedral forms were observed. Pyrite appears as disseminated spots, but in one sample apparently replaces algal coatings to molluscan fragments.

5. Microfacies 4D: Arenaceous Pellet Packstone

This microfacies is similar in most respects to the Pellet Packstones, but contains a significantly higher percentage of detrital quartz grains (Table 3.4). These together with the allochems, are both grain and mud supported. Quartz grain peripheries show evidence of pressure solution with adjacent micrite, bioclasts or other quartz particles, but unlike microfacies 4C there is no evidence of authigenic overgrowths.

6. Microfacies 4E: Bioclastic Packstones

This microfacies can be easily recognised by the abundance of grain supported bioclasts (Fig.3.9c; c.f. microfacies 4) and lack of faecal

Table 3.4: Petrographical analyses of the Fine Grained Carbonate Facies. Solid circles mark the diagnostic features of each microfacies.

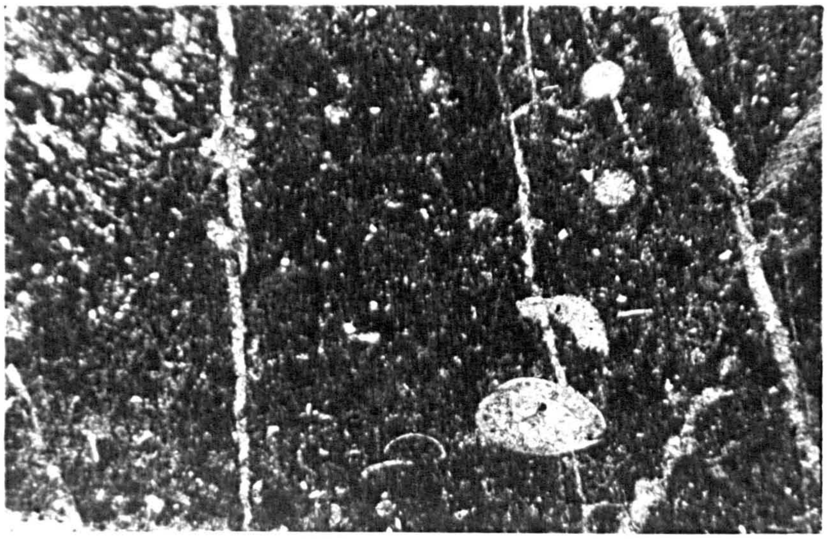
MICRO FACIES	TEXTURE	QUARTZ		ALLOCHEMS			POROSITY		MICRITE		CEMENT		DOLOMITE			OPAQUES		
		Size	%	Type	Size	%	Type	Abun-dance	Distri-bution	%	Distri-bution	%	Size		%	Mineral	Distri-bution	%
4	M - W	20 - 80	5	Bio Os M + ME Algae H	50 - 2cm 200 - 800 100 - 400	5 - 20 0 - 40 (0-5) 5 - 20	BP WP MO SH FE DP BU SK VUG	R - A P - R P - A P - A R - A P - R P - A R - A P - R	BP	25 - 70	WP SH FE BU SK VUG	0 - 5	20 - 100	E - S	0 - 1	P	E.S.	1
4A	B ●			Bio Os Br M Bz Algae H	40 -600 max. 1.5cm (30-7mm) 0.2cm - 0.5cm	0 - 3 0 - 7 ● 25 - 50	BP GF	P P	BP GF	15 - 40	BP GF	0 - 10	40 - 120	S - A * One sample only	0 - 20* (0-5)			
4B	M	125 - 50 (40)	6 - 36	Bio Os T Br Bz	40 - 400 40 - 2mm	0 - 4 0 - 4 0 - 4 1	WP SH	R - A R - A	Matrix grain size:- 2 - 25 (10-25) 125 - 50 (40)	● 50 - 92	WP SH	2	40 - 160	S - A (burrow fills)	0 - 16	P	S	2 - 20
4C	P ●	20 - 60	0 - 6	Bio Os T E Br M Algae H Pellets	 80 - 400 5mm - 4cm 125 - 350 (125-200)	2 - 10 12 0 - 32 0 - 20 ● 20 - 40	WP MO	R - A R - A	BP	14 - 38	WP	2	80 - 120	E - S	4 - 6	P	S	0 - 12
4D	W - P ●	20 - 250 (25)	● 30 - 40	Bio Os E M Pellets	 25 - 750 2mm - 8mm 125-350 (125-200)	 4 - 6 2 - 8 0 - 8 ● 14 - 36	MO	R - A	BP	8 - 30	-	-	50	E - S	0 - 22	-	-	-
4E	P ●	20 - 150	0 - 2	Bio Os E A E Br Bz M St Algae D	 40 - 600 1mm - 5mm	● 2 - 8 30 - 40 0 - 6 8 - 10 0 - 15 0 - 15 0 - 5	WP MO	R R	BP Crystal size: 2.5 - 7.5	24 - 35	WP	0 - 7	40 - 120	S One sample only	0 - 7	-	-	-

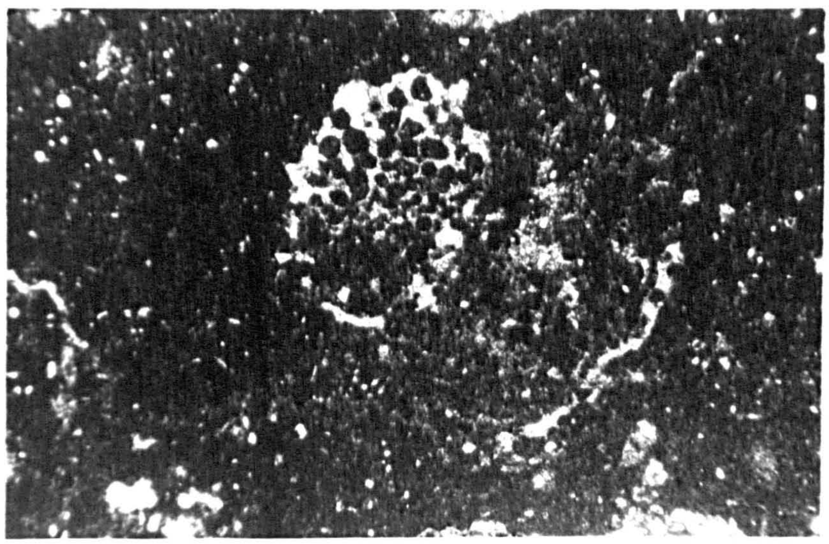
Fig.3.8: Petrographical characteristics of the Fine Grained Carbonate Facies.

a) Microfacies 4, note intraparticular pore filling calcite in ostracod carapace and general lack of other bioclasts. Slice. Rud Peloidal Beds. Locality, Aannerud. x 30.

b) Microfacies 4, sparry calcite cement and faecal pellets filling burrow porosity. Slice. Gaalaas Member. Locality, Snippsand. x 30.

c) Microfacies 4A, note high percentage of interparticular porosity (sparry calcite) between colonies of Hedstroemia. Slice. Rud Peloidal Beds. Locality, Eriksrud quarry. x 30.





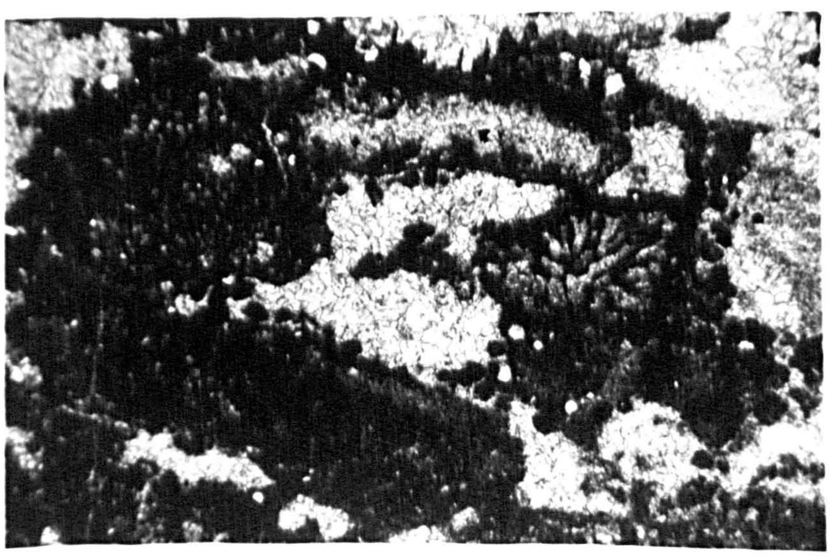
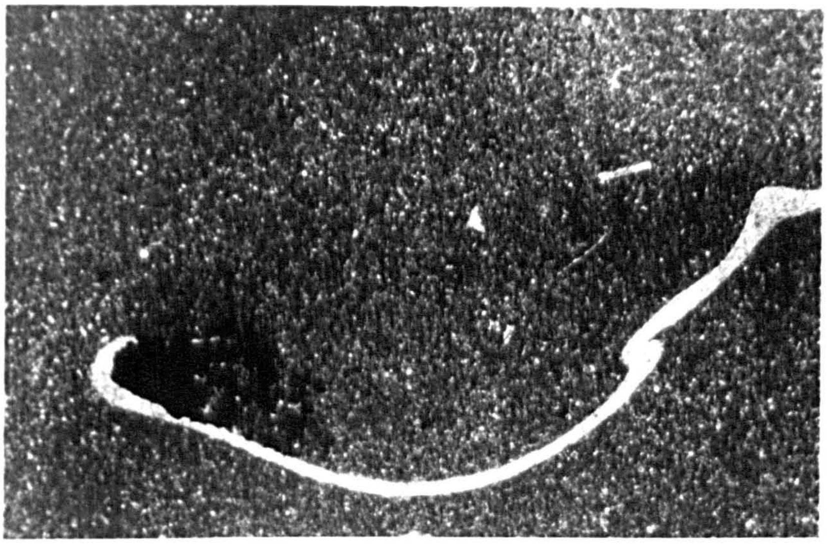
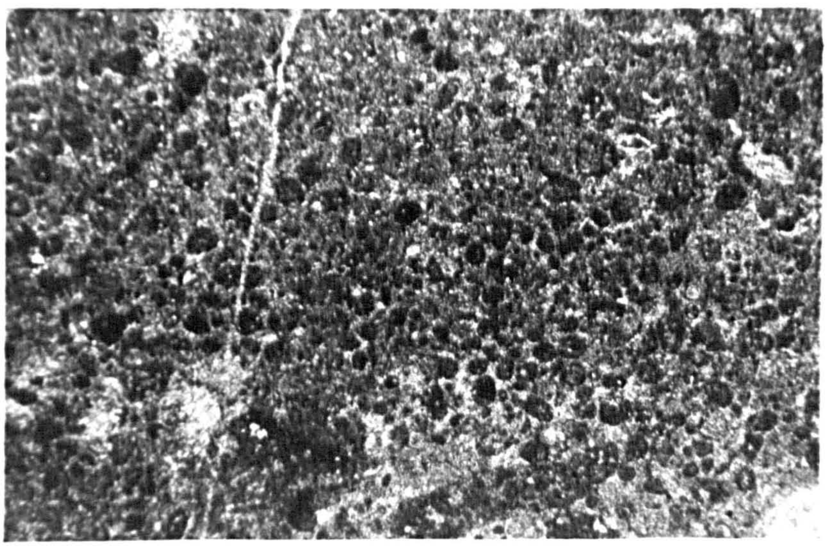
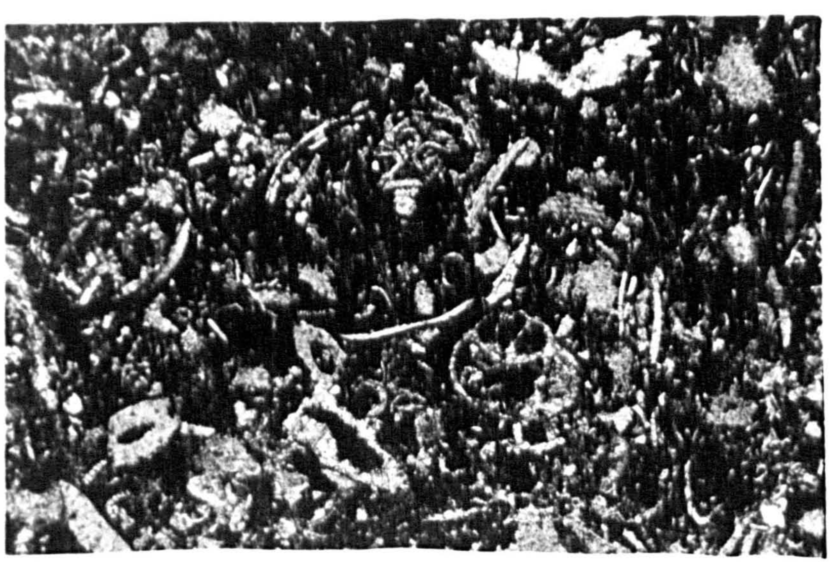


Fig.3.9: Petrographical characteristics of the Fine Grained Carbonate Facies.

a) Microfacies 4B, large trilobite bioclast in calcisiltite with pyrite (black) occupying shelter porosity. Slice. Eina Member. Locality, Eina. x 12.

b) Microfacies 4C, pellets (dark elipsoids) are conspicuous against a lighter (calcisiltite) background. Slice. Eina Member. Locality, Eriksrud quarry. x 30.

c) Microfacies 4E, note the packstone texture and abundance of bioclasts compared to other microfacies. Slice. Snippsand Member. Locality Snippsand. x 12.

pellets (c.f. microfacies 4C, 4D) (Table 3.4). Grains show no evidence of suturing, although some pressure solution embayments are present, and most are distinctly angular with no evidence of abrasive or destructive algal rounding. Bioclasts often show a monotypic concentration in each sample e.g. echinodermal material, dasycladacean algae (Rhabdoporella or Dasyporella), or molluscan debris; ostracod, bryozoan and echinodermal bioclasts are ubiquitous.

Neomorphic sparry calcite appears as a replacement texture in stromatoporoid bioclasts.

Mixed Facies: a number of samples appear either as transitional end members between each microfacies of the Fine Grained Carbonate Facies, as transitions between Peloidal facies and Mudstone-Wackstone microfacies, or between Mudstone-Wackstone and Pelletal Packstones with Algal Mat Facies. Petrographical characteristics were not sufficiently defined to allow allocation to either and these samples were assigned to a "mixed facies" type, although note was taken of their environmental significance within the sequence.

C. ENVIRONMENTAL SYNTHESIS

In discussing the problems of modern carbonate mud on the Great Bahama Bank, BATHURST (1971) points out that the muds accumulating (to a depth of 3m) west of Andros Island are in an area most sheltered from the trade winds and farthest from the strong tidal activity of the Bank edge; faecal pellets are also abundant in this sediment, and represent an undiluted autochthonous carbonate accumulation. PURDY (1964a) attributes the accumulation of carbonate mud in the Bahamas and Caribbean to a supply rate in excess of the removal rate and says that "analogies based on the Bahamian model as to the salinity of the environment or as to the origin of the mud sized constituents are totally unwarrented without evidence additional to the mere occurrence of the calcilutite".

WILSON (1975) attributes deposition of micrite facies to the restricted shelf lagoons (Facies Belts 7 & 8) which edge onto a tidal flat environment. Conditions are extremely variable and constitute a stress environment for organisms. LAPORTE (1967; 1969; 1971), LUCIA (1972) and TEXTORIS (1968) have described similar fine grained carbonate facies and assigned them to shallow subtidal environments of low energy.

By analogy with the observations of the above authors, it would appear that the fine grained carbonates (micrites and pellet rich facies) of the Mjøsa Limestone accumulated in a shallow subtidal (restricted lagoon) environment where the rate of winnowing was far less than the rate of accumulation. By analogy with BATHURST'S (1971) description the softness of the substrate provided the main restriction on benthonic biota (c.f. Laporte who invokes salinity control). The development of a Hedstroemia rich substrate is regarded as directly analagous to TEXTORIS'S (1968) suggestion of growth of this alga in the shallowest subtidal environment, adjacent to the intertidal zone; there is no evidence to suggest growth in tidal pools. The pellet rich muds could be intertidal; the arenaceous rich facies owing its high terrigenous content to wind blown quartz. Calcisiltite appears to be confined to interreef and backreef environments, again envisaged as areas of slack water. The bioclastic rich horizons with the more diverse biota represent the deposits of deeper water and compare favourably with the depth zonations of LAPORTE (1967, Fig.29; 1971, Table 1) and TEXTORIS (1968).

VI. FACIES 5. DOLOMITE

A. FIELD CHARACTERISTICS

Dolomite is distinctive by its weathering colouration of light yellow or deep orange brown, a conspicuous contrast to the adjacent grey limestones; when freshly broken a greenish brown colour, difficult to distinguish from terrigenous clastic facies, is observable. Actual dolomitic horizons are comparatively rare being confined to the Bergevika Reef Complex and Holetjern Member; more usually dolomite appears as concentrates, e.g. burrow fills, in other facies. Sedimentary structures are absent, although at Kyset some faint parallel laminations can be seen. *In situ* fauna found in the Reef Complex consist of *Eoflecheria* colonies, while at the base of the Holetjern Member, *Vermiporella* is associated with dolomitised sediments. Ichnofauna are absent from completely dolomitised units, but in many other facies dolomite is fabric selective in terms of burrows.

B. PETROGRAPHICAL DESCRIPTION

Petrographical descriptions of dolomite are given with each separate occurrence within a microfacies. From these it appears that crystals range from 10-300μ and can be readily divided into two populations:-

i) crystals which are usually subhedral to anhedral, dark brown, often associated with cryptalgal laminites and occupy a 10-60μ size range.

ii) euhedral to subhedral rhombs which are composed of either clear dolomite or appear as clear rims syntaxially overgrowing brown cores; these crystals occupy a 40-300μ size range, but are commonly in a 60-240μ range.

Dolomite always appears fabric selective in terms of micrite both in the subtidal (e.g. reef) and tidal flat deposits; burrows and vugs are also commonly associated with dolomitisation, especially by the larger clear crystals. Bioclasts, however, never appear dolomitised.

C. ENVIRONMENTAL SYNTHESIS

There can be little doubt that the dolomite present in the Mjøsa Limestone is diagenetic in origin. Much of the finer crystal size fraction bears a similarity to the syngenetic dolomites commonly found on modern intertidal and supratidal flats (FRIEDMAN and SANDERS, 1967).

Amongst others, ZENGER (1970) has pointed out that dolomitisation is not necessarily indicative of subaerial exposure; the dolomitised lithologies he describes bear many similarities to the Mjøsa Limestone dolomite facies. In a brief, but succint review of dolomitisation, BLATT et al. (1972, p.491) point out that it is impossible to determine whether this fabric selectivity with regard to micrite reflects a greater surface area for reaction, the availability of more soluable carbonate minerals at the time of dolomitisation, or even the higher permeability for dolomitizing fluid transport at the time of dolomitization. The latter would be true if the micrite free sediments were cemented prior to dolomitisation; there is evidence of early cementation of grainstones in the Mjøsa Limestone and this may well be an important factor.

VII. FACIES 6. ALGAL MAT FACIES

Although a combination of three distinctly separate lithologies, the unique characteristics and palaeogeographical significance of this unit allow classification as a single facies.

A. FIELD CHARACTERISTICS

Units belonging to this facies are distinctive by virtue of the yellow or brown millimetric dolomite laminations in a grey limestone background; weathering may enhance this feature or give the whole unit a brown colouration. Lithologically the facies is composed of interbedded dolomite, micritic mudstones or wackstones, and peloidal grainstones. Bioclasts are rare, being mostly ostracods, molluscs or brachiopods while intraclasts and flake conglomerates appear in many places. Bedding is very thin, most separate limestone beds within an algal mat unit are rarely more than 15cm thick; the thickness of the mat units themselves varies from 10cm to 1m. Apart from isolated occurrences of ripple marks, sedimentary structures are confined to dessication features; on a large scale, polygons are recognisable (Fig. 3.10a) while on a small scale, spar filled cracks normal to bedding (Fig. 3.10b) and fenestral structures parallel to bedding ("birds-eye") are evident. Biogenic activity is mainly confined to immediately underlying beds, although isolated instances of organic destruction of the mat can be found. GEBELEIN and HOFFMAN (1973) have described how millimetric dolomite laminations can be attributed to an algal origin due to concentration of Mg ions in the algal sheath. By analogy the dolomite laminations observed in this facies (Fig. 3.10c) are attributed to an algal origin and can be regarded as representation of the <u>in situ</u> biota. The laminations form a cryptalgal laminite as defined by AITKEN (1966) and a detailed classification is given in Appendix V.

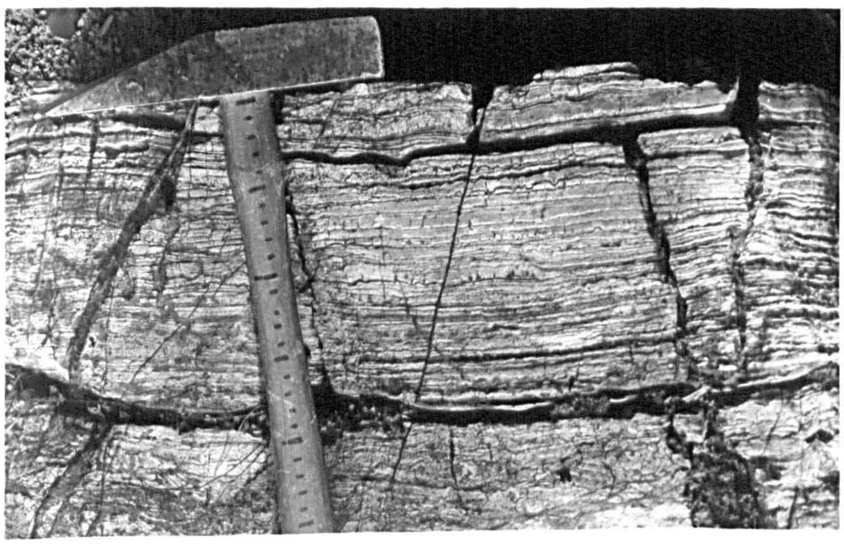
Algal mat facies are best developed in the Rud Peloidal Beds,

Fig.3.10: Sedimentary structures in the Algal Mat Facies.

a) dessication polygons. Locality, Bøverbru kalkverk. Hammer is 40cm long.

b) cryptalgal laminites and vertical sparry calcite filled shinkage cracks. Locality. Rud. Scale on hammer shaft is in cm.

c) cryptalgal laminites developing from a peloidal grainstone (left). Algal mat begins at base of tape and youngs to the right. Locality. Dølbakken. Scale in cm.



although similar structures appear in the overlying Holetjern Member at Kyset.

B. PETROGRAPHICAL DESCRIPTION

A characteristic feature of this facies is the variation of texture and composition, often on a millimetric scale, which exists within an individual thin section. The net result is that facies differentiation is best achieved by a comparison of textural and distributional criteria, rather than rigid percentages obtained through point counting. Table 3.5 contains 'relative abundances' of each constituent rather than 'percentages' and an additional parameter of 'distribution' to record the degree of lamination for quartz and dolomite. Microfacies were erected, therefore, on the basis of quartz abundance, degree of organisation into laminations by quartz and dolomite, presence or absence of fenestral porosity and general compositional or textural changes between samples. Eight distinct petrographic members to the Algal Mat Facies can be recognised:-

1. Well laminated quartz and dolomite
2. Poorly laminated quartz and dolomite
3. Well laminated dolomite
4. Poorly laminated dolomite
5. Intraclastic with disseminated dolomite
6. Bioturbated with dolomite filled burrows
7. Fenestrate mudstone
8. Mixed.

1. Microfacies 6: Well laminated quartz and dolomite

i. Texture:

Grains are in three-dimensional contact to give a fabric supported texture; embayments at the points of contact indicate some pressure solution during compaction.

No preferred orientation is apparent among the finer grain sizes; larger (600-900μ), elongate bioclasts are often parallel to bedding.

Cement appears to be lacking, although bioclast rich laminae with echinodermal particles are often cemented (in part) by syntaxial overgrowths. Fabric selective and non-fabric selective sparry calcite filled pore spaces are generally absent.

Grain size distribution is a function of grain origin (Table 3.5), as is roundness: pellets are 4-6, 40-80μ quartz and echinodermal fragments 1-4, while the smallest quartz grains are splinters.

ii) Composition and Mineralogy:

Terrigenous clastic material is represented by quartz, and to a lesser extent (less than 1%) felspar. Calcium carbonate allochems are confined to uniquitous faecal pellets and echinodermal bioclasts with local additions of brachiopod, ostracod, dasycladacean, codiacean and micritised molluscan bioclasts. Ooliths appear as isolated grains.

Dolomite (Table 3.5) appears as dirty brown crystals which rarely have clear overgrowths; an optically similar microcrystalline carbonate seen between quartz grains is regarded as being dolomite. Quartz grains show no evidence of authigenic overgrowths.

Mineralogically each sample is zoned according to the content of the laminations; (Figs. 3.11a, b); dolomite alone occupies laminations 80-800μ thick; calcium carbonate (bioclasts, pellets etc.) appears in 0.2-2mm laminae; quartz in 0.1-1mm laminae and quartz with dolomite in 100-300μ laminae (Fig. 3.11b). There is no rhythmic or cyclic pattern to the distribution of these microfacies, the sequence of laminae being completely random.

2. Microfacies 6A: Poorly laminated quartz and dolomite

This microfacies is recognised by the higher proportion of micrite which gives a mudstone or wackstone texture, supporting both the bioclastic (echinodermal and ostracod) and terrigenous (quartz) grains. In places, however, the abundance of pellets (often concentrated in laminae; Fig.3.11c) leads to the local development of a grainstone texture (Table 3.5). In addition to the pellet and peloid bearing layers, sparry ferroan calcite cement is found filling shrinkage cracks. Non-fabric selective porosity, with sharply defined cavity walls truncating grain boundaries, is scattered as vugs throughout samples, but is generally scarce and elongate pores with grain controlled boundaries, generally aligned parallel to bedding, and regarded as fenestral porosity, appear in some (but not all) samples. Occasionally pores are dolomite filled and the boundaries become unrecognisable.

Grain size distribution is given in Table 3.5; roundness of grains is similar to microfacies 6.

Dolomite appears as three distinct populations, both in terms of crystal size and distribution within the complex (Table 3.5); the smallest crystals (in the laminae) are usually dark brown and appear dirty, while the disseminated single rhombs contain a cloudy nucleus and clear rim.

Pyrite occurs as widely disseminated spots, and is non-fabric selective in its distribution.

The mineralogical zoning associated with the well laminated microfacies 6 is not a well developed feature; the greater abundance of micrite and appearance of pellet (peloid) grainstone laminae (as well as fenestrate structures) combine with the poorly developed or discontinuous quartz and dolomite laminations and much reduced bioclastic content to give a more diffuse distribution dominated by micrite.

3. Microfacies 6B: Well laminated dolomite

Although texturally and compositionally similar to microfacies 6A (Table 3.5), this variant can be distinguished by the development of laminations composed entirely of dolomite (Fig. 3.12a). Pellets are also more abundant and in extreme cases show a 'fining upwards' into overlying dolomite laminae. Pellets (and peloids) may also exhibit disintegration into micrite which is the third most important constituent, occurring as layers between dolomite and pellet grainstones. Sparry calcite filled fenestrae or other porosity types are extremely rare; a thin (40-80μ) rind of fine sparry, non-ferroan, calcite circumvents most faecal pellets and is regarded as representing a first generation cement.

4. Microfacies 6C: Poorly laminated dolomite

From Table 3.5 it is apparent that this variant can be distinguished by the virtual absence of detrital quartz and bioclasts (ostracods are ubiquitous but are scarce even by their own relatively low standard of abundance), dominance of micrite (giving a mudstone texture) and presence of laminations composed exclusively of dolomite. Where present, pellets and peloids appear in laminations, often with a grainstone texture, and occasionally showing evidence of grading into micrite or dolomite laminae.

Dolomite appears in poorly developed, incomplete laminations and associated with ferroan calcite filled vugs whose boundaries are rarely grain controlled. In extreme cases clear euhedral dolomite rhombs are found within the calcite filled vug, but more usually appear concentrated around the periphery or at the base where micrite may be concentrated in a geopetal-like structure (Fig. 3.12b). Occasionally the vugs are associated with calcisiltite filled swirled burrows and an increased concentration of dolomite results.

Authigenic quartz is ubiquitous throughout samples of this microfacies, appearing as lozenge shaped or hexagonal crystals in the micrite (Fig. 3.12c).

5. Microfacies 6D: Micrite with vugs

Although similar to microfacies 6C, the dominance of micrite (mudstone texture) in conjunction with an abundance of sparry calcite filled dessication and solution features (Table 3.5) justifies the erection of a separate microfacies.

Pellets and peloids are confined to the spar filled areas where they appear concentrated in the base, often with a flat top overlain by sparry calcite or 'floating' within the spar (Fig. 3.13a); laminations of pellet grainstone are absent. The micrite matrix is completely structureless. Shrinkage cracks appear frequently and are often associated with the vug porosity mentioned above; the boundaries to these voids are generally non-fabric selective, and may appear in both a horizontal or vertical orientation through the sample. A variety of origins is proposed for these phenomena (Table 3.5). Dolomite shows a preferential concentration around or in the sediment filled basal areas of these voids. Authigenic quartz is confined to very rare, poorly developed overgrowths to detrital grains.

6. Microfacies 6E: Brecciated facies

The diagnostic feature of this microfacies is the presence of elongate micritic intraclasts (c.1cm long) (Table 3.5) surrounded by a rind of dolomite (Fig. 3.13b). Micrite is dominant, giving a mudstone texture. Pellets and peloids are concentrated in the often irregular dolomitised areas (bioturbation) and are scarce. Quartz grains appear well rounded (4-6 on Powers scale) with little evidence of authigenic overgrowths. Ferroan sparry calcite filled cavities are confined to shrinkage cracks and non-fabric selective vugs which are scattered, irregular and often vaguely triangular in outline. Any cavities with grain controlled boundaries appear confined to the areas between intraclasts.

Table 3.5: Petrographical analyses of the Algal Mat Facies. Solid circles mark the diagnostic characteristics of each microfacies.

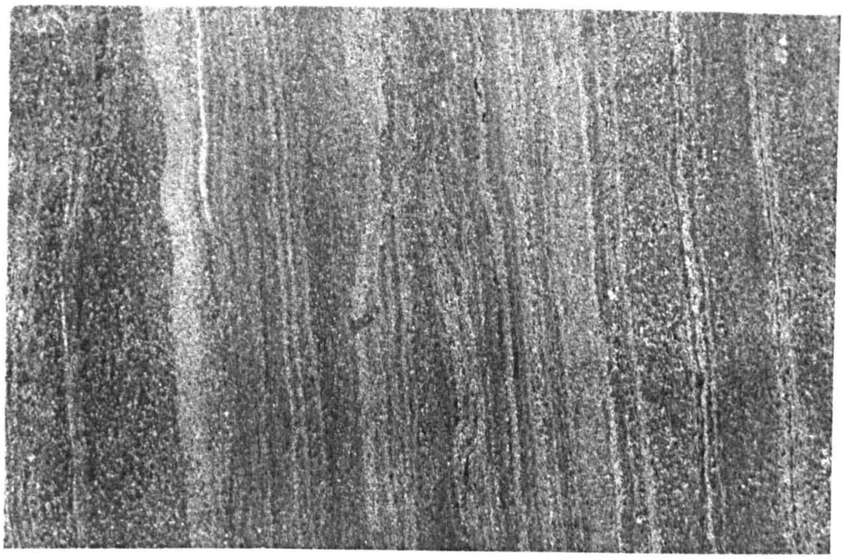
MICRO FACIES	TEXTURE	QUARTZ Size	QUARTZ Distribution	QUARTZ Abundance	ALLOCHEMS Type	ALLOCHEMS Size	ALLOCHEMS Abundance	POROSITY Type	POROSITY	MICRITE Distribution	MICRITE Abundance	SPARITE Distribution	SPARITE Abundance	DOLOMITE Size	DOLOMITE Shape	DOLOMITE Distribution	DOLOMITE Abundance
6	CL	20 - 200 (40-80)	L	C	Bio E Pellet Oolith	20 - 900 (80-120) 40 - 60	P - R P - R R - A	-	-	-	-	(S)	R - A	60 - 240	E - A	L	C
6A	● M,W (D) (G)	20 - 100 (40-60)	(L)	P	Bio E Os M + ME Pellets	50 - 700 40 - 80	R R - A R - A P	SK FE VUG BP	P - R P - R R - A P - A	Matrix -	P - C -	FE SK VUG BP	P - R P - A	10 - 40 40 - 125 (80-100) 25 - 90 (50-80)	S - A E - S E - A	● (L) S P	P - R R R
6B	M (G)	20 - 80 (40)	S	R	Bio E Os Br Pellets	30 - 600 40 - 60	R R - A R - A P	FE SH BP	P R - A P - A	BP Matrix -	C -	FE BU BP	P P	20 - 200 (60-100)	E S	● L (Bu)	AC R - A
6C	M	Detrital 20 - 90 Authi-genic	S S	R - A ● P - R ●	Bio Os Pellets Peloids	40 - 80 40 - 120	R - A ● P - R P - R	FE SK VUG	R R P	Matrix Calcisiltite in BU	C R	FE SK VUG	R	120 - 200 20 - 60	E - S S - A	● (L) VUG BU S	R R R P
6D	M	20 - 80	S	R	Bio Os Br Pellets Peloids	30 - 200 40 - 80 60 - 120	R - A R	MO SK (FE) VUG BU	R - A P ● R P ● R	Matrix	C	MO SK VUG	R - A P - R R	120 - 240 60 - 180	E - S	VUG S	P R
6E	M	10 - 40	S	R	Bio E Os Pellets Intrac-lasts	200 - 600 40 - 80 C. 1cm	R - A R - A R - A C ●	SK VUG	P - R R	Matrix	C	SK VUG	P - R	60 - 180 20 - 80	E - A S - A	Br S	P P - R
6F	M D	20 - 100 (20-60) Authige-nic	S S	R P - R ●	Bio O E M Pellets Peloids	100 - 600 60 - 100 60 - 500	R - A R - A R - A P P - R	VUG FE SK MO	P ● P ● R - A R - A	Matrix	C	(S) VUG FE SK MO	R - A P	40 - 240	E - A	(L) (FE) S	R ●

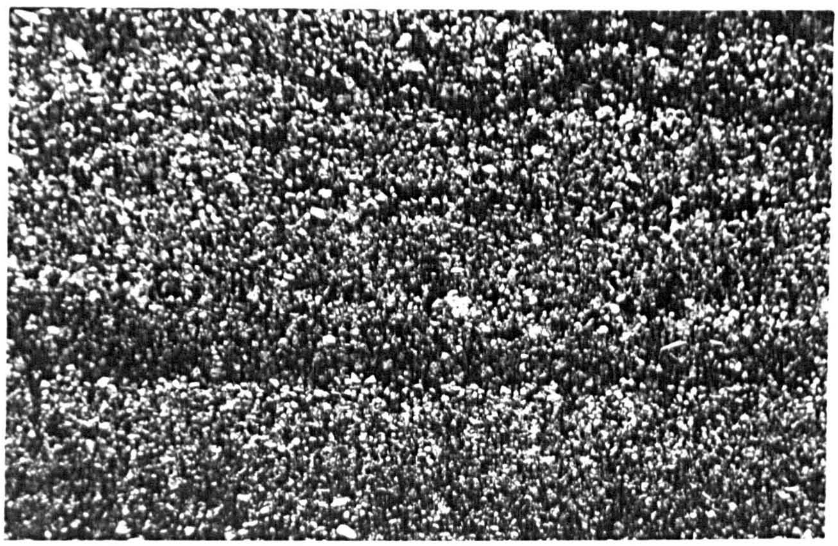
Fig.3.11: Petrographical characteristics of the Algal Mat Facies.

a) Microfacies 6, negative print of slice showing finely interlaminated quartz (dark) and dolomite (light). Younging to the left. Locality, Holetjern. x 5.

b) Microfacies 6, quartz (light), dolomite (dark) and faecal pellet (dark elipsoids) laminations. Slice. Rud Peloidal Beds. Locality, Holetjern. x 30.

c) Microfacies 6A, abundance of faecal pellets gives a grainstone texture to individual laminae. Note dirty nuclei and clear euhedral rims to dolomite rhombs (top left). Slice. Rud Peloidal Beds. Locality, Holetjern. x 30.





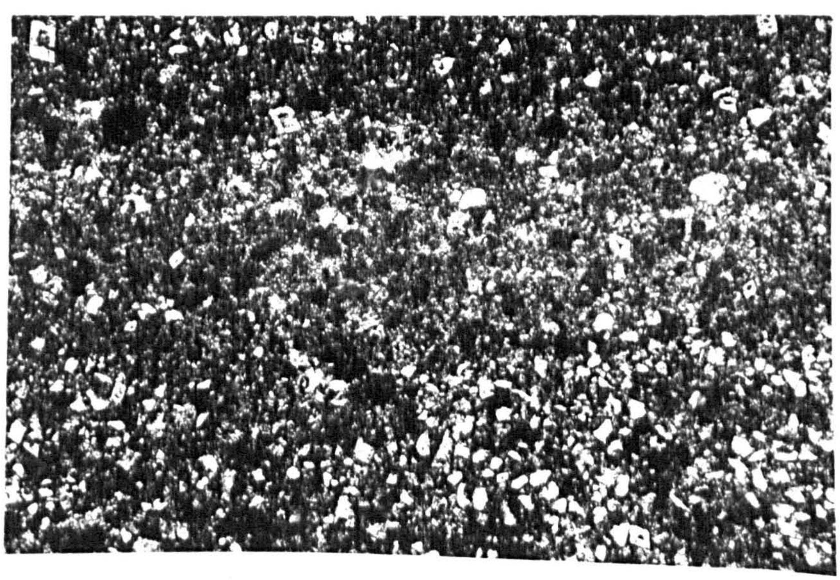
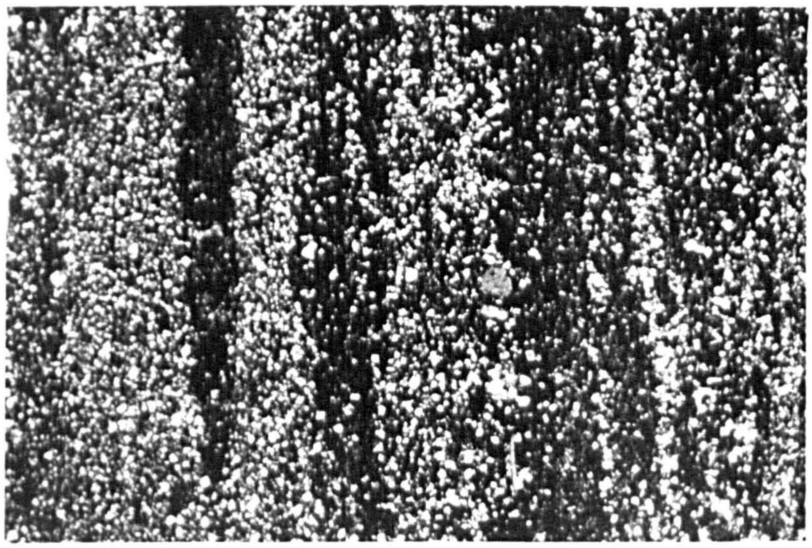


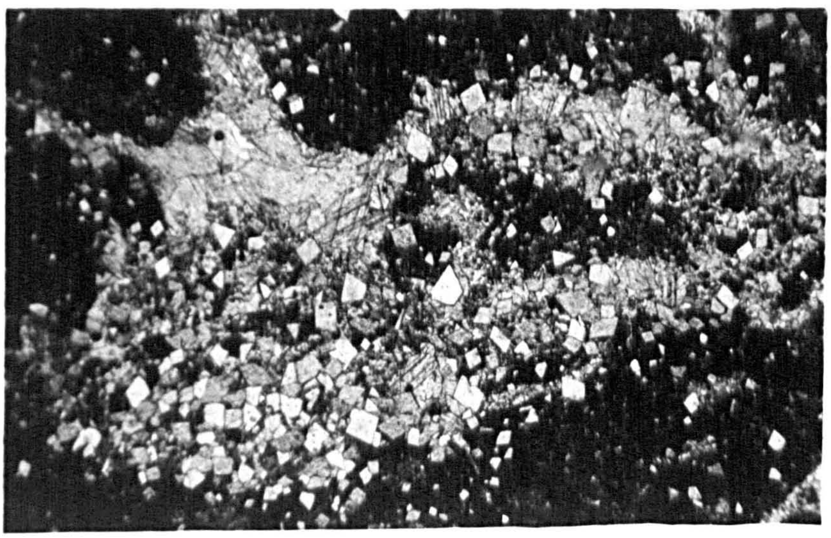
Fig.3.12: Petrographical characteristics of the Algal Mat Facies.

a) Microfacies 6B, laminations composed of sub-hedral dolomite and micrite. Younging to the right. Slice. Rud Peloidal Beds. Locality. Gamme. x 15.

b) Microfacies 6C, concentrations of clear euhedral dolomite in the micrite/calcisiltite which floors the vug. Note the larger crystal size when compared to rhombs in the groundmass. Slice. Holetjern Member. Locality, Kyset. x 30

c) Microfacies 6C, abundance of authigenic quartz crystals (euhedral laths and hexagonal cross sections). Note sparry calcite filled ostracod carapace. Slice. Holetjern Member. Locality, Kyset. x 30.





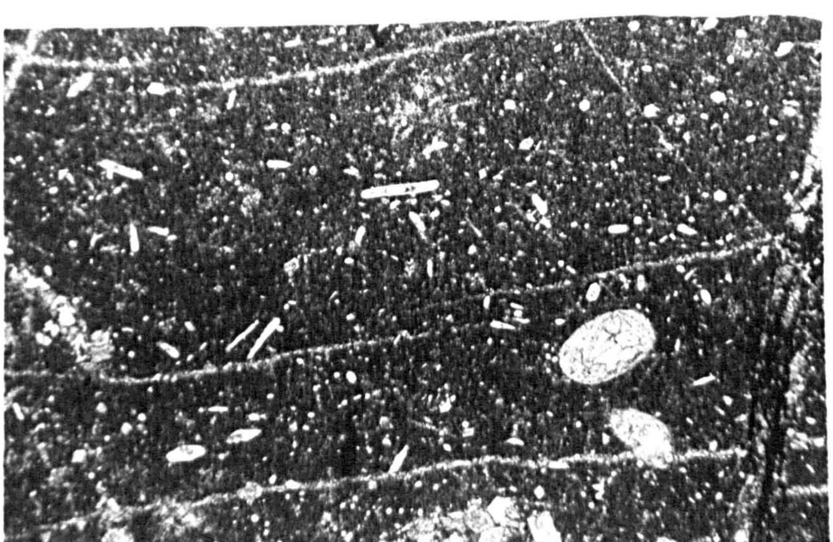
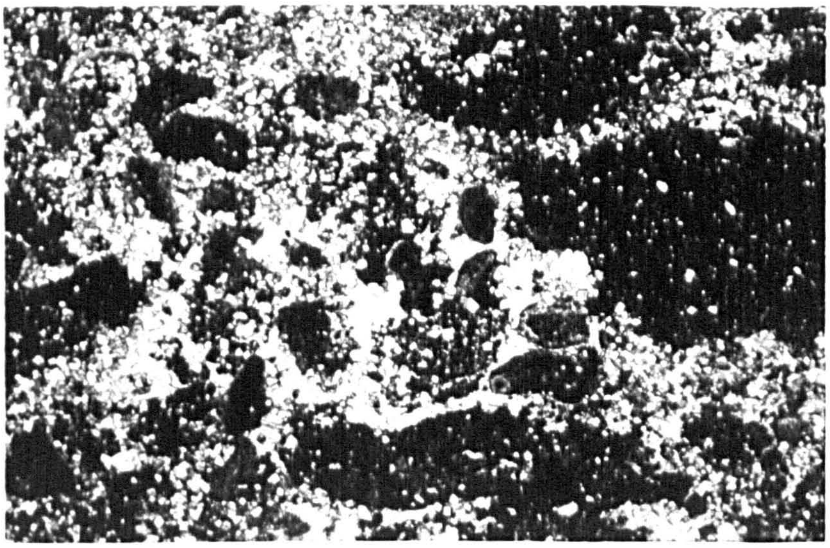


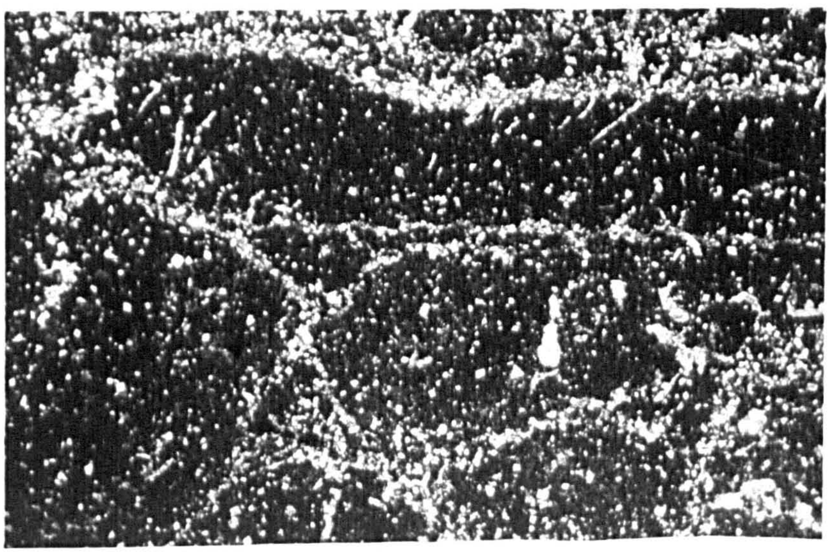
Fig.3.13: Petrographical characteristics of the Algal Mat Facies.

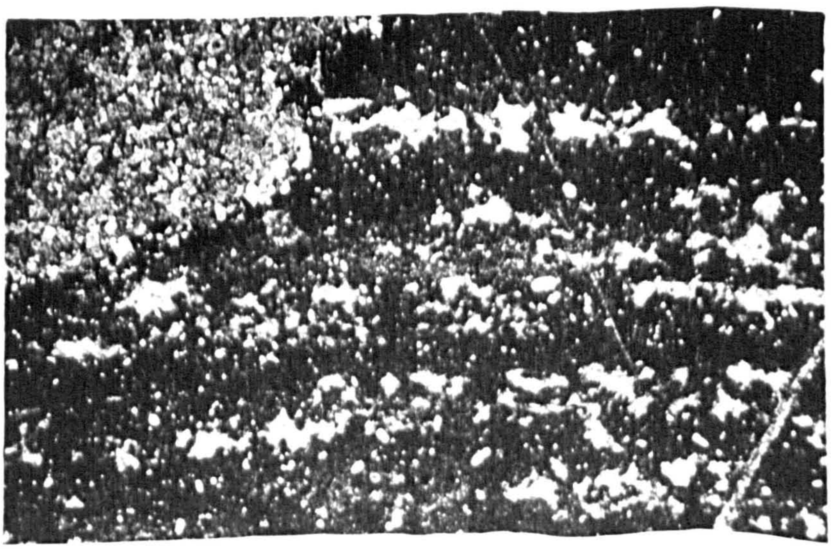
a) Microfacies 6D, pellets and peloids floating in a sparry calcite filled vug. Slice. Rud Peloidal Beds. Locality, Eriksrud quarry. x 15.

b) Microfacies 6E, dolomite rind to quartz rich micritic intraclasts. Slice. Rud Peloidal Beds. Locality, Holetjern. x 15.

c) Microfacies 6F, laminated fenestral porosity truncated by a dolomite filled burrow (upper left). Slice. Holetjern Member. Locality, Kyset. x 19.







7. Microfacies 6F: Fenestrate mudstone

In many respects this microfacies resembles microfacies 6B (Table 3.5) i.e. low bioclastic content and laminae of pellet grainstones (sometimes graded) in a micritic mudstone, but can be distinguished by the presence of well developed authigenic quartz crystals, general paucity of dolomite and development of a true fenestral porosity, which is aligned parallel to bedding (Fig. 3.13c) and regarded as a 'birds-eye' texture. Vugs are also a well developed porosity feature and like microfacies 6D, dolomite is often found in the sediment flooring these cavities.

8. 'Mixed' microfacies

In common with other facies, a number of samples exist which contain diagnostic features of more than one of the above defined microfacies, but which belong to the Algal Mat Facies; these are collectively termed the 'mixed' microfacies.

C. ENVIRONMENTAL SYNTHESIS

The fine interlaminated dolomite and micrite, birds-eye structures, shrinkage cracks, fenestral porosity, absence of fossils, graded pellet laminae, rounded mud intraclasts and dessication cracks, are features identical to those described as diagnostic of modern and ancient algal laminites in a carbonate tidal flat environment (AITKEN, 1967; MATTER, 1967; ROEHL, 1967; SCHENK, 1967; LAPORTE, 1967, 1969; KENDALL and SKIPWITH 1968; BRAUN and FRIEDMAN, 1969; SHINN et al, 1969; LUCIA 1972; GEBELEIN and HOFFMAN, 1973). The term 'tidal flat' refers to a depositional environment where sub-aerial exposure occurred for indeterminate lengths of time (periodicity of flooding unknown) and regarded (for the purposes of this thesis) as occupying the high intertidal to low supratidal environments.

The various microfacies recognised within this facies can be assigned different sub-environments within the tidal flat.

The laminated facies represent the products of periodic algal growth and subsequent trapping of sediment by growth over and around grains or by grain adherence to the sticky mucillagenous sheath (GEBELEN, 1969), the layers of algal filaments being represented by dolomite laminations (GEBELEIN and HOFFMAN 1973). Fluctuations in the sediment supply and growth rate of algae cause the mats to be laminated. The mats show no evidence of relief, (i.e. doming) and by direct analogy with the findings of LOGAN et al. (1974) in Shark Bay, Western Australia, are regarded as forming in an area of low wave energy, probably the high intertidal or low supratidal environment (c.f. DAVIES, 1970; KENDALL and SKIPWITH, 1968; KINSMAN et al. 1971). Periodic inundation introduced a bioclastic element, but more importantly, the sheet flooding gave rise to laminations of graded pellets. Dessication features were not confined to polygonal mud cracks but appear as vertical shrinkage cracks, and fabric selective porosity parallel to bedding. Much of the vug porosity is due to later diagenetic solution giving non-fabric selective voids with geopetals of internal sediment. Their distribution suggests an original fenestrate or open burrow porosity. Syn-sedimentary lithification of the muds is evident from the intraclastic content of both the algal mat and interbedded peloidal grainstone beds. The presence of authigenic (idiomorphic) quartz suggests that some micro-facies may have been deposited under hypersaline conditions (ZAMARRENO, 1975), probably in tidal pools; no cryptalgal laminations are associated with this phenomena, only vugs or sheet cracks.

From the data presented in Appendix V, a sequence of algal mat development can be ascertained. All mat sequences in the Rud Peloidal Beds begin above a peloidal grainstone with a dolomite net although the mats at Kyset (Holetjern Member) develop from bioturbated horizons. The implications of the dolomite net have been previously discussed (p. 97) and the development of tidal flat deposits directly above such horizons lends credence to the proposed hypothesis of sub-aerial exposure and subsequent solution or dessication. The development of a laminar aspect to the nets and their evolution into truly laminated facies indicates that this microfacies should be regarded as the basal unit of a mat cycle. The appearance of micrite, peloidal or bioclastic horizons within the nets is evidence of sediment incursions through inundation of the tidal flat, suggesting that nets may develop in the lower zones of the intertidal facies.

The zones of discontinuous laminae are regarded as an intermediate stage between the start of a cycle and its culmination in a laminated zone. The discontinuous nature of the laminae could be due to immature development, dessication, bioturbation or erosion; this can best be determined by the relationship to beds above and below i.e. whether the sequence is progressive or retrogressive, although the effects of short lived, unfavourable conditions cannot be overlooked. In general, these discontinuous laminae are succeeded by a laminated unit; they never terminate a mat cycle and are not regarded as the final phase; broken laminae (B3 zones) do not succeed laminated zones.

The laminated zones mark the optimum conditions of growth in planar sheets of algae which very rarely attain a domical structure, indicating a constancy of environment not recorded in Recent analogues (c.f. KENDALL and SKIPWITH 1968). Laminated zones frequently terminate the mat cycle, being overlain by dolomite nets or other (more 'marine') facies upon which development restarted.

The dolomite zones which terminate the mats development may represent supratidal conditions and the formation of a dolomite crust above the mat sequence.

VIII. FACIES 7. RED CLASTIC FACIES

A. FIELD CHARACTERISTICS

Beds belonging to this facies are immediately recognisable by their distinctive deep red colouration. Lithologically they are represented by fine quartz siltstones or mudstones which contain a variable bioclastic component. Bioclasts are often concentrated in small stringers less than 1cm thick and are predominantly pelmatozoan in origin. The finer horizons show a high percentage of micaceous material. Bedding is variable, generally thin (less than 50cm). Determination of exact thickness is hampered by the gradation into underlying beds through an increase in siltstone content and the staining of these beds by leaching. Thus, the maximum thickness obtained (c.4m) represents a combination of true red clastic facies and peloidal or bioclastic grainstones. Sedimentary structures are mostly fine parallel laminations, ripples and well developed polygonal dessication cracks. (Fig. 3.14a,b). Some indentations on a surface at Hole kalkverk are interpreted as rain pits. No _in situ_ biota was found. Bioturbation is often intense, concentrated in the finer non-bioclastic fraction, and represented by both vertical and sub-horizontal, single, non branching burrows, which are made more conspicuous where red clastic facies overlies green clastic facies, by their fill of fine red material.

Representatives of this facies are found mainly in the Eina Member although they do occur in the Gaalaas and Sivesindhagen Members.

B. PETROGRAPHICAL DESCRIPTION

Because of the interlayering of terrigenous clastic and bioclastic horizons, samples belonging to this facies display affinities to the bioclastic rich microfacies of Facies 1. A distinction can easily be made by the high percentage of haematite and presence of ooliths in samples of the Red Clastic Facies.

i) Texture:

Grains are generally in three-dimensional contact to give a fabric supported texture (Fig. 3.14c); the bioclastic rich layers attain agrainstone texture; small embayments at the points of contact indicate slight pressure solution during compaction. Grains show no preferred orientation.

Cementation appears to be by haematite in the quartz rich portions and by a combination of syntaxial rim cements to echinodermal grains and pressure welding in the carbonate rich layers.

Grain size distribution is variable (Table 3.6) but within each sample sorting is generally good.

ii) Composition and Mineralogy:

The terrigenous clastic fractions are dominated by quartz (28-50%), although felspar and chlorite (less than 1%) can also be detected. The bioclastic layers are composed mostly of echinodermal particles (22-38%), although a typical feature is the concentration of one of the other allochemical components in a single horizon. Pellets (8-17%) and ooliths (2-14%) are uniquitous; the pellets commonly form the nuclei around which a strongly radial (20-80μ) coating of calcium carbonate has formed (Fig.3.14c)

Sparry calcite cement (0-3%) is generally absent from interparticular pore spaces and is only found in the rare instances of moldic or intraparticular void fillings associated with molluscan and bryozoan bioclasts respectively.

Dolomite (0-6%) appears as scattered subhedral rhombs.

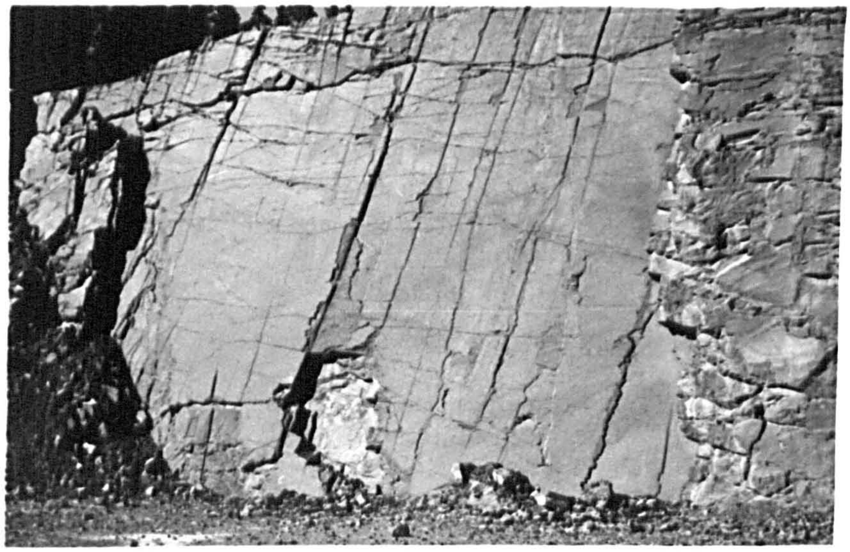
Haematite (4-16%) appears concentrated in the quartz rich layers (Fig. 3.14c) where it occurs admixed with the mud acting as an intergranular fill, many quartz grains are texturally supported by it (Fig.3.14c). Occasionally haematite fills the pores of echinodermal particles.

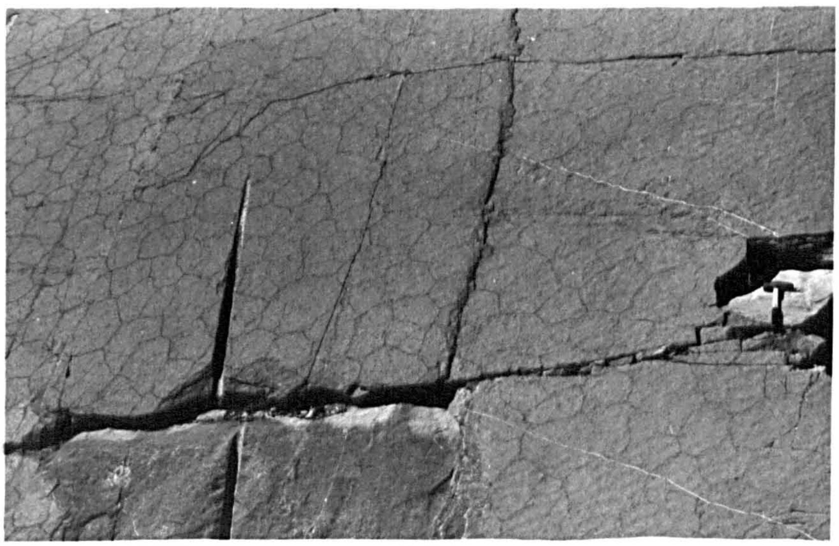
Fig.3.14: Characteristics of the Red Clastic Facies.

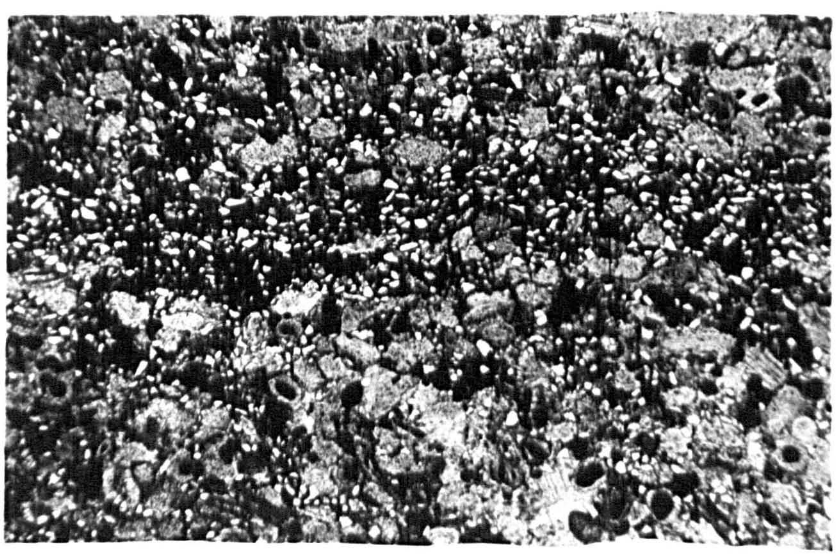
a) General view of bedding plane. Note dessication polygons. Locality. Hole kalkverk.

b) close up of 3.14a. Note dessication polygons and straight crested wave ripples (above hammer). Locality, Hole kalkverk. Hammer is 40cm long.

c) photomicrograph of Facies 7. Note the quartz-haematite rich and oolitic - echinodermal layers. Slice. Ihle Peloidal Beds. Locality, Hole kalkverk. x 30.







C. ENVIRONMENTAL SYNTHESIS

The combination of dessication cracks, haematite rich mudstones, stringers of bioclastic material, high biogenic activity and ripple marks indicate deposition in area prone to periodic exposure, but with sheet flooding bringing in material of marine origin, considerable deposition from suspension in time of slack water and bottom traction by oscillatory currents. This implies that beds of this facies belong to the high intertidal or supratidal environment.

The association of red colouration with beds containing a high quartz content, both as silt or mud sized particles, is a result of these particles being coated by the hydrated ferric iron oxides (limonite or goethite), or in the case of the mud rocks in the form of phyllosilicates (illite, chlorite and biotite). Upon exposure, these hydrated oxides turn to haematite giving a distinctive red colouration. WALKER (1967) has shown that as little as 0.1% of haematite is sufficient to cause a bright red colour in red beds.

Stratigraphically the red beds of the Toten district appear at the top of the Sivesindhagen and bottom of the Eina Members, and are laterally equivalent to terrigenous clastic facies in Nes-Hamar and Eina. It has already been noted that no mudstones are associated with the terrigenous clastic facies, a fact explained by water agitation. By inference, the muds of the red clastic facies must have been deposited in very quiet water and may represent the suspension load of fine particles winnowed from the terrigenous clastic facies. The association with peloidal grainstones (shoal or beach deposits) implies that large shallow ponds may have formed behind the shoals, muds and clays settled from suspension, the water evaporated and haematite formed during the ensuing dessication.

The red beds of the Gaalaas Member are laterally equivalent to stromatoporoid horizons (p.197) in which the micritic sediment contains a high quartz content. Exposure would again allow the production of haematite from goethite or limonite.

IX. FACIES 8. GREEN CLASTIC FACIES

A. FIELD CHARACTERISTICS

The beds of this facies can be distinguished by their green or yellow green colouration, particularly when intimately associated with the red clastic facies. Lithologically they are composed of a fine quartz siltstone, mud or clay and a variable carbonate content. Bioclasts are not always easily distinguished, due to solution, but appear to be of pelmatozoan, bryozoan and brachiopod or molluscan origin. A diagnostic feature of this facies is the presence of oncolites, which are particularly abundant in some beds, range in size from 0.2 to 4cm diameter and are usually extremely ragged in outline, with no obvious preference of nuclei. Bedding is variable from 40cm to 2m and unlike the red clastic facies the boundaries are well defined with little gradation into adjacent beds: the upper surfaces are heavily bioturbated when these beds underlie red clastic facies with a subsequent mottling effect still recognisable up to 30cm below the contact. In situ biota appears to be confined to the algae which construct the oncolites and occasional articulated Ancistrorhyncha

Beds of this facies occur in the Sivesindhagen, Eina and Gaalaas Members, associated with red clastic facies horizons.

B. PETROGRAPHICAL DESCRIPTION

This facies is distinct by the inclusion of clay with micrite in the matrix, abundance of quartz and large calciruditic oncolites.

i) Texture:

The range in grain sizes gives a variety of textures: calciruditic grains exhibit a floatstone texture; the calcarenitic bioclasts and quartz grains are mud-supported (wackstone); concentrations of quartz grains, stylolitised areas adjacent to oncolites, show deeply sutured edges.

There is no preferred orientation of grains.

Sparry calcite cement is found in voids of moldic porosity (molluscs), intraparticle (Hedstroemia and articulated ostracods) and in elongate, sometimes sinuous non fabric selective voids peripheral to oncolites.

Grain size distribution is extreme: oncolites 0.5cm-1.5cm; bioclasts (not including oncolite nuclei) 40μ - 800μ, with disarticulated ostracod valves attaining a max. of 1.6mm; quartz grains 20-80μ. Roundness of quartz grains was estimated at 2-4 on Powers scale; allochems occupied the whole range.

ii) Composition and Mineralogy:

Terrigenous material is represented by monocrystalline quartz (18-34%) and clay (6-17%). Carbonate allochems include oncolites (6-56%) in which molluscan fragments are encrusted by algae which show either a spongiostrome or Hedstroemia type texture. The calcarenitic bioclasts (2-9%) include ostracod, trilobite, dasycladacean algal, echinoderm and brachiopod fragments, together with a variable (0-6%) molluscan component. All molluscan bioclasts exhibit evidence of attack by boring algae, either as micrite envelopes or micrite filled indentations on the periphery; it is difficult to estimate the importance of such attack on other bioclasts due to the effects of pressure solution with adjacent grains and micrite matrix giving rise to a similar effect. Other allochems include isolated ooliths (0-2%), pellets 0-2%) and intraclasts (0-8%), (Table 3.6).

Ferroan calcite cement (4-6%) fills shrinkage cracks circumventing oncolites. Dolomite (0-1%) occurs as subhedral to anhedral crystals apparently as a burrow fill in one sample only.

C. ENVIRONMENTAL SYNTHESIS

LOGAN et al (1964) have proposed that oncolites (or SS stromatolites) form in the low intertidal or shallow subtidal zones where sufficient

Table 3.6: Comparison of the petrographical characteristics of Facies 7 (Red Clastic) and 8 (Green Clastic).

FACIES	QUARTZ			ALLOCHEMS			POROSITY		MICRITE		CEMENT		DOLOMITE			OPAQUES		
	Size	Roundness	%	Type	Size	%	Type	Abundance	Distribution	%	Distribution	%	Size	Shape	%	Mineral	Distribution	%
7	40 - 200 (80-160)	1 - 4	28 - 50	Bio	40 - 2mm		WP MO	R - A	BP	4 - 9	(S)	0 - 3	40 - 120	S - A	0 - 6	H ●	BP D	4 - 16
				E	40 - 500	22 - 38												
				Os	40 - 300	0 - 2												
				M	200 - 2mm	0 - 28												
				Bz		0 - 8												
				Br		0 - 4												
				Algae														
				D	100 - 300	0 - 6												
				OK	200 - 800	0 - 6												
				Pellets	60 - 100	8 - 17												
				Intra-clasts	0.1 - 1mm	0 - 10												
				Ooliths	80 - 360	2 - 14												
8	20 - 160	1 - 4	18 - 24	Bio		0 - 18	WP MO SK	P P R	Matrix	10 - 26	MO SK	4 - 12	60 - 240	S - A	0 - 2	P ●	S	0 - 2
				M		0 - 6												
	Clay ●	-	8 - 20	Algae ● (OK)	1cm-2cm	6 - 48												
				Pellets	60 - 100	0 - 4												
				Intra-clasts	0.5mm-1mm	0 - 10												
				Ooliths	120 - 250	0 - 3												

agitation exists to periodically turn the grains. The deposition of a fine grained carbonate-clay matrix is apparently paradoxical to this situation, although WILSON (1975, p.69) describing SMF 22 (micrite with large onkoids) attributes its formation to the shallow back reef environment 'typically at the edges of ponds or channels'. The biotic components of this facies indicate a marine origin, and the interbedding with red, dessicated sediments suggests an alternation between marine and sub-aerial conditions. By inference, the marine conditions must be very shallow.

X. FACIES 9: BIOTURBATED / RETICULATE FACIES

This facies was erected to explain and recognise the distinctive bioturbated and reticulate (STØRMER, 1953; SKJESETH, 1963) limestones which constitute the bulk of the Holetjern and Eeg Members. It does not include any other bioturbated beds and, as such, is defined both lithologically and lithostratigraphically.

A. FIELD CHARACTERISTICS

Beds of this facies show yellow or brown dolomite in a sharp contrast to grey, black or in places, white limestone. Lithologically the limestones occupy a range of biomicrites (wackstones and mudstones but very few packstones) in the Eeg Member but both bioclastic grainstones and biomicrites in the Holetjern Member. Bioclastic grainstones are mostly composed of well sorted pelmatozoan calcarenite with few other biotic components; the biomicrites contain whole gastropods, brachiopods and orthocones together with fragments of branching bryozoa, trilobites and molluscs. Bedding is usually massive; the bioclastics appear as either massive units (Fig.3.15a) or thin layers between dolomite horizons (Fig.3.15b); biomicritic facies are massive. Sedimentary structures are confined to the bioclastic beds and consist of low angle planar cross-stratification; occasional load casting and possible scouring appears at the base where bioclastics overlie a dolomite horizon; the biomicrites lack any visible sedimentary structures. Ichnofauna are present as simple vertical tubes (Fig. 3.15b) which manifest themselves on bedding planes as circular or elongate dolomite patches (Fig. 3.16a); horizontal burrows can be small straight and non-branching (Fig. 3.16b), large feeding burrows (Fig. 3.16c) or small bifurcating trails crowded onto the major bedding planes.

Fig.3.15: Characteristic features of the Bioturbated/Reticulate Facies. Sections young to the left. Hammer is 40cm long.

a) cross-stratified bioclastic grainstones and dolomite. Holetjern Member. Locality Rud 3.

b) vertical burrows with some horizontal linking to give a partly reticulate (left). Holetjern Member. Locality, Holetjern.

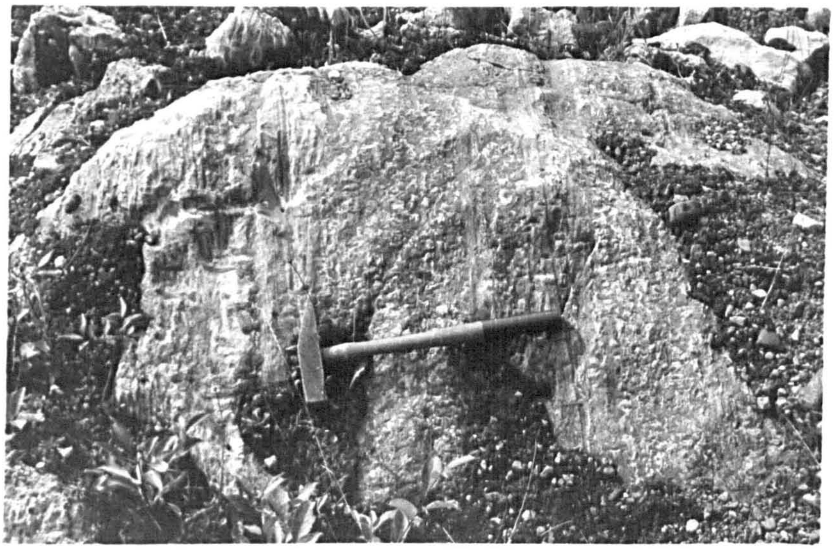
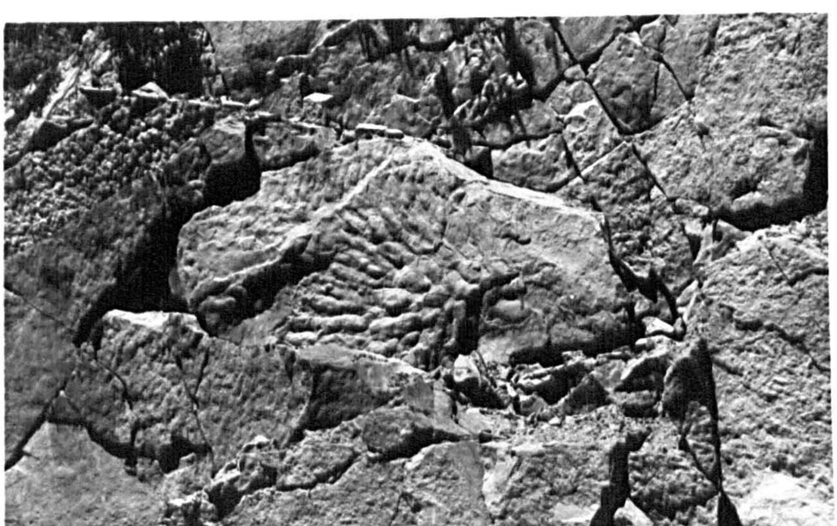


Fig.3.16: Ichnofauna from the Bioturbated/Reticulate Facies.

a) bedding plane exposure of dolomite filled burrows. Holetjern Member, Locality. Rud 3. Penknife is 7cm long.

b) densely packed small straight burrows on the underside of the bed. Holetjern Member. Locality, Bøverbru kaklverk.

c) large fodinichnia resembling Phycodes. Holetjern Member. Locality, Bøverbru kalkverk. Structure is 1.20m max. length.



B. PETROGRAPHICAL DESCRIPTION

Although thin sections of this facies were examined no extra environmental information could be obtained beyond that yielded by field descriptions.

C. ENVIRONMENTAL SYNTHESIS

The three dimensional network of dolomite, i.e. reticulation, is associated with an increase in bioturbation and the change of burrow attitude from dominantly vertical in the Toten district, to horizontal and vertical in the Nes-Hamar district. All recognisable burrows in this facies are dolomite filled, and as dolomite shows a preference for burrow porosity it is reasonable to assume that the reticulated limestones represent heavily burrowed deposits, which probably underwent an early lithification, thus preventing dolomitisation of the whole rock.

LAPORTE (1967) has described a similar increase in burrow intensity from the Manlius Formation and interprets it as a change from intertidal to subtidal environments. A direct analogy can also be drawn from SEILACHER'S (1964; 1967) depth zonations based on burrow orientation i.e. Scolithos facies (vertical) to Cruziana facies (oblique or horizontal).

The association of vertical burrows with thin beds of oscillatory (sometimes herring-bone) cross-stratified, coarse calcarenite, indicates that in the Toten district this facies probably represents low intertidal or high subtidal deposits which pass into true low energy subtidal deposits in the Nes-Hamar district.

XI. CONCLUSIONS

The nine distinct lithofacies (together with their constituent microfacies) of the Mjøsa Limestone indicate that deposition occurred in the supratidal, intertidal and shallow subtidal environments. A summary of the facies types, their major characteristics and environments of deposition is presented as Table 3.7.

The sediments of the Mjøsa Limestone represent the deposits of a shallow carbonate platform and shoreline, and mark a regressive phase at the close of the Middle Ordovician in this area of southeastern Norway.

A stratigraphical arrangement of facies distribution (Fig. 3.17) shows that within the Toten district there is greatest depth variation, and that the lithostratigraphical divisions proposed in Chapter 2 are related to three regressive episodes. In the more "marine" sequences of Nes-Hamar and Helgøya the regressions are not clearly recognised but are inferred by correlation: regression is evident towards the top of the Eeg Member, although the Snippsand Member contains a well developed marine sequence.

Table 3.7: The sedimentological and palaeontological characteristics of Facies within the Mjøsa Limestone. An environmental interpretation is given below showing the depositional zone and inferred energy levels for each Facies. More than one of the above characteristics implies a range of conditions.

INHERENT CHARACTERISTICS \ FACIES	7	6	9	3	8	4	2	1
Dessication cracks	typical	typical	-	-	-	-	-	-
Wave ripples	typical	typical	-	-	-	-	-	-
Current ripples	-	-	-	-	-	-	present	typical
Interference ripples	-	-	-	-	-	in calcisiltite only	-	typical
Oscillatory cross-stratification	present	-	present	present	-	-	typical	typical
Herring-bone cross-stratification	-	-	present	-	-	-	-	-
Megaripples	-	-	-	-	-	-	typical	-
Channels	-	-	-	-	-	-	present	typical
Erosional bases	-	-	-	-	-	-	typical	typical
Bioturbation	intense	-	intense	-	-	variable	present	typical
Burrow orientation/type	vertical	-	vertical, oblique, horizontal	Phytopsis	-	swirled	vertical	Chondrites, horizontal
Fossil diversity	low	low	low-moderate	low	low	low-high	high	low
Fossil abundance	low	low	low-moderate	low	low	low-moderate	high	low
Invertebrate fauna	ostracods palmatozoan	ostracods	gastropods, trilobites, orthocones, brachiopods	Ancystrorhyncha Stromatoporoids	Molluscan fragments Ancystrorhyncha	ostracods, bivalves, gastropods, trilobites, corals, Ancistrorhyncha, orthocones	palmatozoans, brachiopods, bryozoa, trilobites, gastropods, molluscs, corals	bivalves, bryozoa
Algae	-	laminites	-	evidence of gelatinous algal mats and boring algae	Hedstroemia, Spongiostroma	Hedstroemia, Dasycladaceans	Solenopora	-
Oncolites	-	-	-	-	typical	-	rare	-
Birds-eye	-	typical	-	-	-	-	-	-
Red beds	typical	-	-	-	-	-	-	-
Solution features	-	present	-	present	-	present	-	-
Early cement	-	present	-	typical	-	-	present	-
Early dolomite	-	typical	-	-	-	-	-	-
Sparry calcite cement	-	rare	-	typical	-	-	typical	-

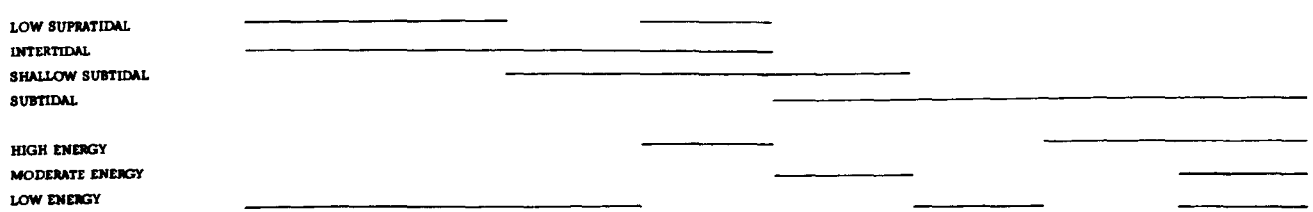
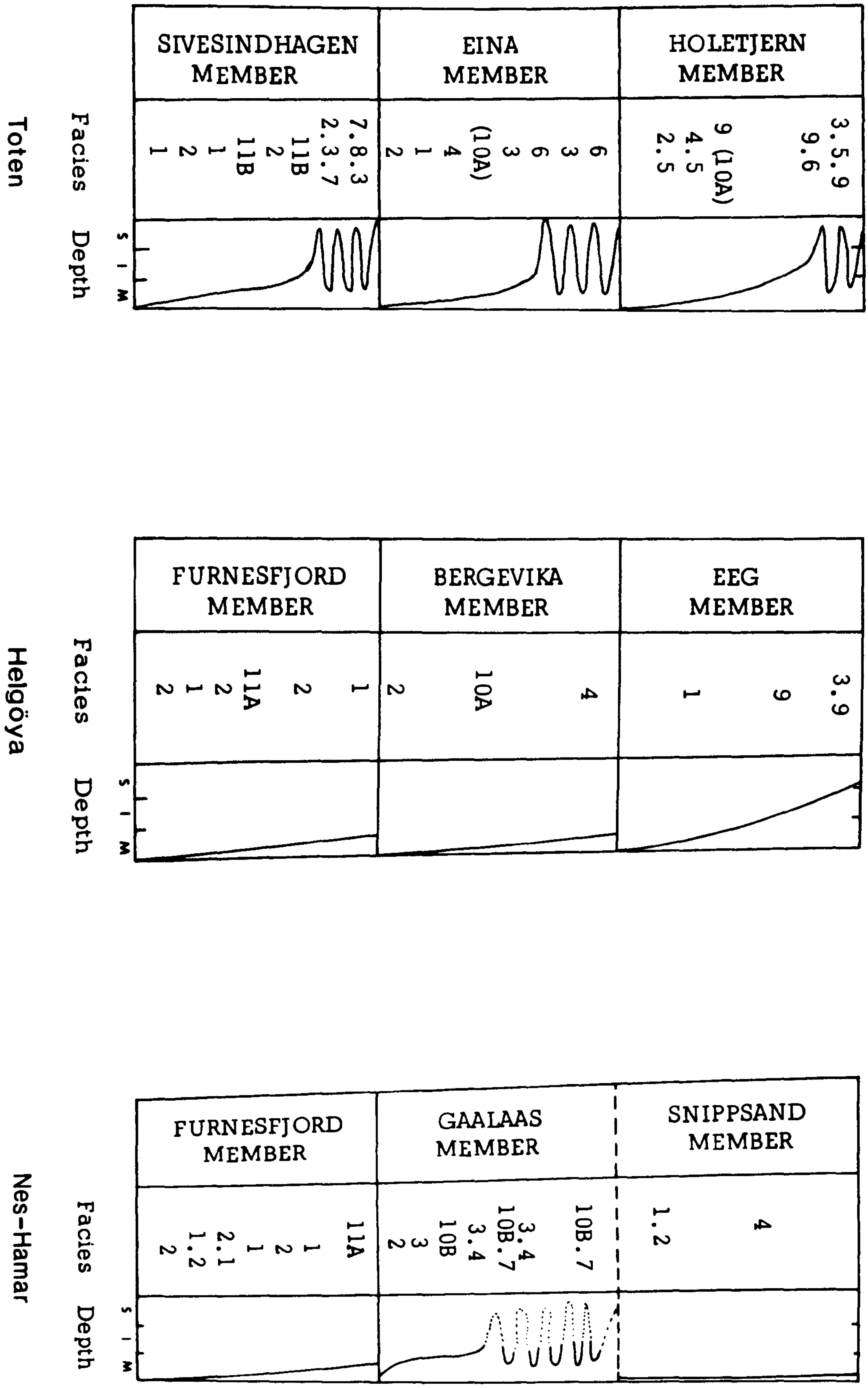


Fig.3.17: Stratigraphical and environmental distribution of Facies in the Mjøsa Limestone. Facies are as numbered in the text; depth zones are, S - supratidal, I - intertidal, M - subtidal (marine).



Toten
Facies
Depth
SIVESINDHAGEN MEMBER
EINA MEMBER
HOLETJERN MEMBER
Helgöya
FURNESFJORD MEMBER
BERGEVIKA MEMBER
EEG MEMBER
Nes-Hamar
FURNESFJORD MEMBER
GAALAAS MEMBER
SNIPPSAND MEMBER

CHAPTER FOUR

STROMATOPOROID PALAEOECOLOGY:

REEF AND NON-REEF HABITATS

I. INTRODUCTION.

Stromatoporoid bearing horizons are present at a number of localities in the Nes-Hamar and Toten districts, occurring both as localised small reefoidal features or laminar sheets (rarely more than one coenosteum thick) with no evidence of a build up or framework formation. In view of this localised abundance, a study of these organisms and the surrounding sediment was undertaken to assess their suitability as palaeoenvironmental indicators. To assist in this aim a series of simple parameters were chosen and tested in the hope of obtaining data relevant to stromatoporoid palaeoecology in the Mjøsa Limestone.

For the purposes of this study a "reef" is regarded as an underbedded mass of limestone consisting predominantly of *in situ* colonial skeletons, as defined by SCOFFIN (1971). The term is regarded as synonymous with DUNHAM'S (1970) 'ecologic reef', HECKEL'S (1974) 'encrusted skeletal build up' and WILSON'S (1975) 'organic framework reef'. A 'reef complex' is regarded as an aggregate of reef limestones and genetically related carbonate rocks, after HENSON'S (1950) original definition. Such a term can be successfully employed to describe the Bergevika Reef Complex, while the smaller organic buildups at Bøverbru, Eina and Eriksrud can be regarded as reefs.

II. STROMATOPOROID PALAEOECOLOGY

A. TAXONOMIC CONSIDERATION.

The systematic position of stromatoporoids has remained a controversial topic since their discovery over 150yr ago. Since then they have been variously assigned to the foraminifera, sponges, hydrozoa and algae. LECOMPTE (1956) presents a comprehensive review of various classifications and systematic considerations which were proposed prior to that time, and in common with GALLOWAY (1957) regards stromatoporoids as hydrozoa. Since then, discoveries by HARTMAN and GOREAU (1970) of a new class of modern sponge, the Sclerospongia, has led to suggestions, by them and STEARN (1972; 1975), that stromatoporoids are, in fact, ancient examples of the Porifera rather than Coelenterata. The most recent suggestion by KAZMIERCZAK (1976) that stromatoporoids are not even animals but algae (Cyanophyta), is bound to cause a revival of arguments in this already controversial subject.

Perusal of the above mentioned literature in conjunction with contemporaneous studies of Mjøsa Limestone algal and stromatoporoid microstructures leads this author to conclude that stromatoporoids were more akin to animals than plants. The strength of Stearn's detailed arguments together with the completely non-corraline appearance of the organisms overides, in this author's mind, the somewhat tenuous associative evidence produced by the proponants of an anthozoan origin. Therefore for the purposes of this thesis stromatoporoids are regarded as being members of the Porifera.

Taxonomic studies were based on consideration of coenostal morphology together with relationships of pillars to laminae and other internal structures as proposed by LECOMPTE (1956) and GALLOWAY (1957). Various authors have referred to the detailed study of microstructures in stromatoporoid taxonomy and reviews of the proposals are discussed by FISCHBUCH (1968 pp.516-7) and BATHURST (1971 pp.31-33). However, the recrystallisation of the microstructures, which can be regarded as at the 'moderate' or 'advanced' stage in RIDING'S (1974) classification, prohibits the fruitful pursuance of the detailed scheme proposed by STEARN (1963). Specimens were therefore cut tangentially and horizontally, polished and examined by binocular microscope, using secondary microstructures to effect a tentative classification, often at Family level only.

B. PALAEOECOLOGICAL CONSIDERATIONS.

A detailed analysis of the problems, relevant literature, parameters chosen, method of determination together with a full discussion of the nomenclature employed in this study and its suitability to studies of stromatoporoid palaeoecology is presented in Appendix III. By way of introduction to the detailed study comprising this chapter, a brief summary of the three main categories adopted and their subdivisions, is given below.

i) Coenosteal shape:- (a) Domical - a length/height ratio less than 4.
(b) Laminar - a length/height ratio greater than 4.
(c) Tubular - a length height ratio less than 1.
(d) Rounded.

Coenosteal size - recorded in actual measurements where necessary.

ii) Coenosteal orientation:- expressed as the attitude of the growth surfaces:

(a) Convex upward.
(b) Convex downward.
(c) Convex sideways.

iii) Coenosteum periphery:- (a) Smooth.

(b) Ragged.

(c) Bored.

(d) Encrusted.

In addition to the above morphological parameters the associated sediments and biota were also considered.

III. THE BERGEVIKA REEF COMPLEX.

A. INTRODUCTION

Due to the concentration of reefal exposure around the hamlet of Bergevika, most information pertaining to the palaeoecology and sedimentology of the Mjøsa Limestone reefs was obtained here rather than in the Toten exposures. However, other localities containing reefs or reef complex beds were investigated and reference to them is made by way of comparison. Detailed descriptions of the general succession, above and below the reefs, are contained in the appropriate locality descriptions within Appendix I.

The following account represents only a brief review of all aspects of the reefs examined. Detailed palaeontological studies have been undertaken by Spjeldnaes and Lecompte and latterly Spjeldnaes and Webby, but these remain, as yet, unpublished.

Stratigraphical distribution

Detailed consideration of this is given in Chapter 2, but it appears from the correlation of the Bergevika Member and Eina Member, that the reefs at Eina, Bøverbru and on Helgøya may be regarded as contemporaneous in their development. The small localised growth at Eriksrud appears to be younger belonging to the Holetjern Member, and, as such, is described in a separate section.

Method of study

Due to problems of exposure and accessibility a semi-qualitative approach, as advocated by SCOFFIN (1971), was adopted. This took the form of examining exposures of reef, interreef and forereef beds inside a $1m^2$ area and recording the relative percentages of organisms in a growth position, in addition to the parameters previously outlined (p.145), which are relevant to stromatoporoid (and coral) palaeoecology. These sites were arranged in such a way that a stratified sample through the reef complex could be obtained and lateral or vertical variations in organic constitution or sediment types would become apparent. Specimens of organisms and sediments were collected for thin section and peel analysis.

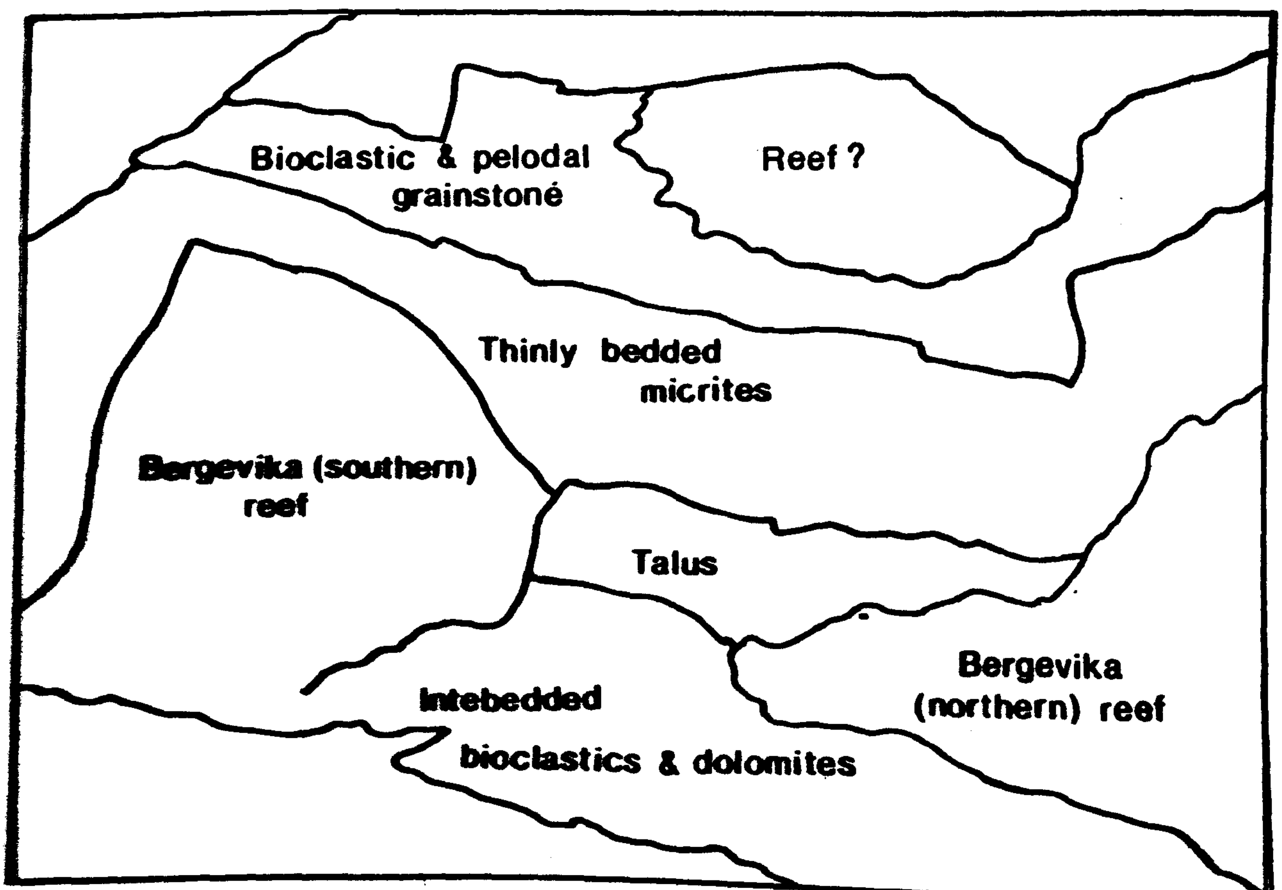
The interreef sediments and their relationship to the biomass were investigated to obtain information pertinent to the relative growth rates and topography of the reefs, in addition to general environmental conditions (particularly energy) prevailing at that time.

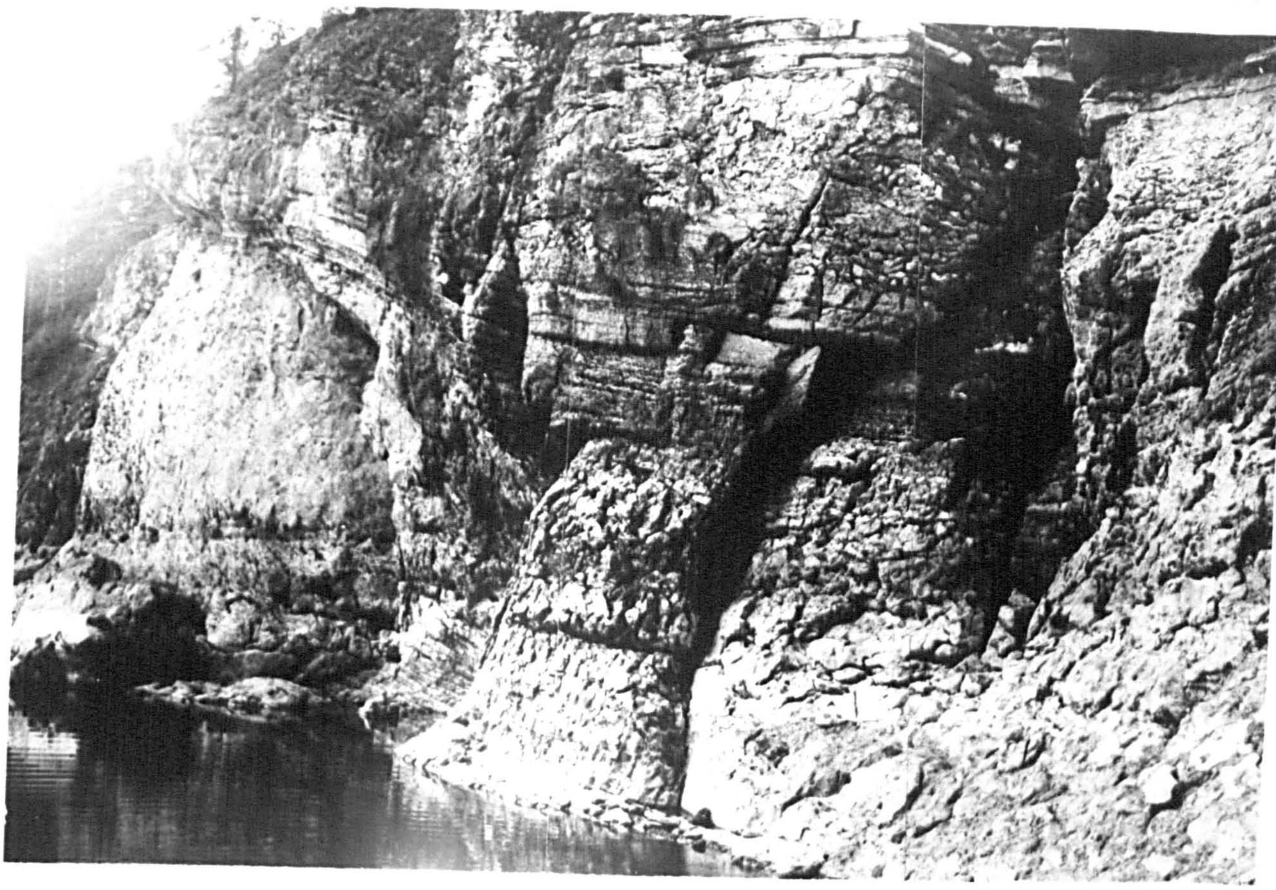
B. GENERAL OBSERVATIONS.

The thickness of the reef bearing strata decreases sharply from 21m at Bergevika South (Fig. 4.1), (19m at Bergevika North), to 3.40m at a small roadside locality north of Kjelsrud, Helgøya (Fig. 4.2). In all cases the succession is similar; pelmatozoan bioclastic grainstones overlie interbedded quartz siltstones and shales. The bioclastic beds contain the reefs and are equivalent to interreef micrites, calcilutites or interbedded reef detritus and dolomites. The uppermost bed is usually an oncolite bearing grainstone underlying flaggy, gastropod rich, grainstones and packstones. The oncolite bed together with the previously mentioned beds are grouped together and collectively termed the bedded interreef sediments to distinguish them from the sequences above and below the reef complex (flaggy packstones and wackstones above, quartz siltstones and shales below) as well as from the sediments contained within the reefs themselves.

The Spring shoreline section at Bergevika South reveals a complex series of reef and reef beds, but the two main reef bodies which can easily be distinguished (Fig. 4.1) are termed the Bergevika (southern) and Bergevika (northern) reefs respectively. (The use of parentheses is to avoid confusion between the localities of Bergevika North and Bergevika

Fig.4.1: Spring shoreline exposure of the Bergevika Reef Complex. The overlay shows the relative positions of the units described in the ensuing text.


Bioclastic & pelodal
grainstoné
Reef ?
Thinly bedded
micrites
Bergevika (southern)
reef
Talus
Bergevika
(northern) reef
Intebedded
bioclastics & dolomites



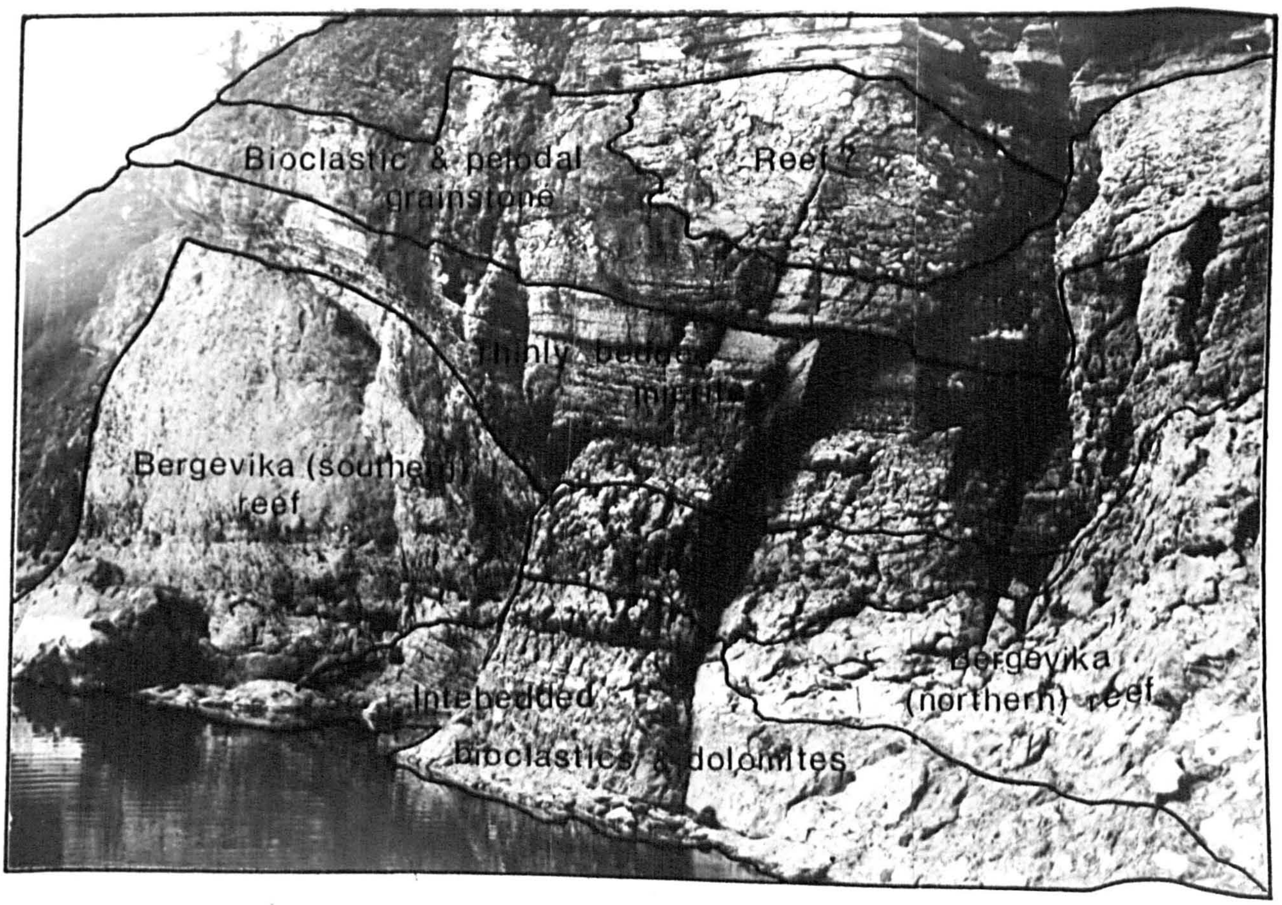
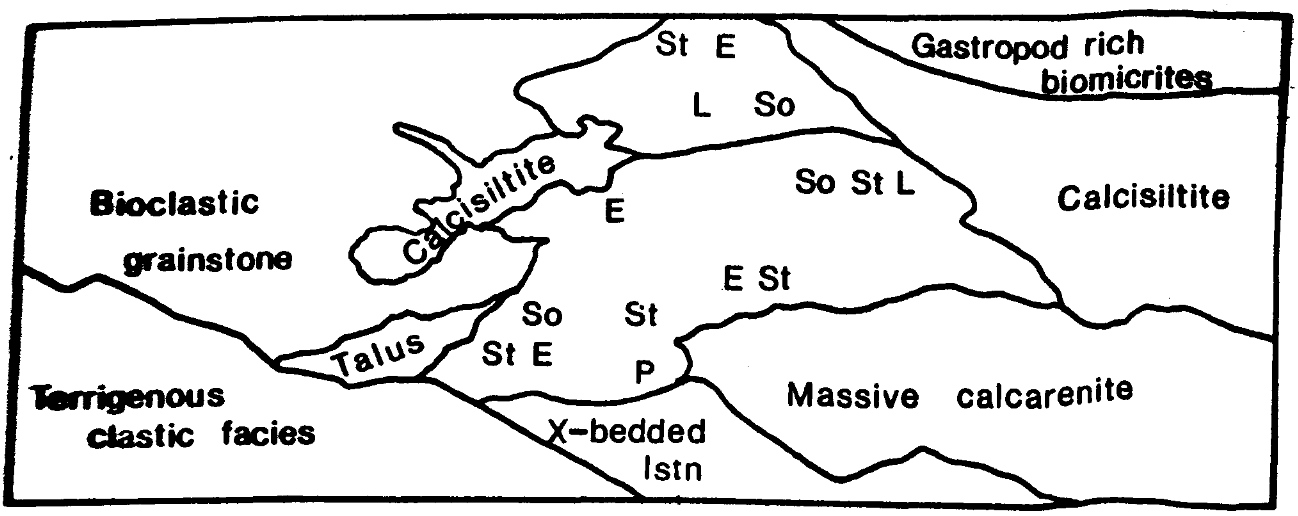
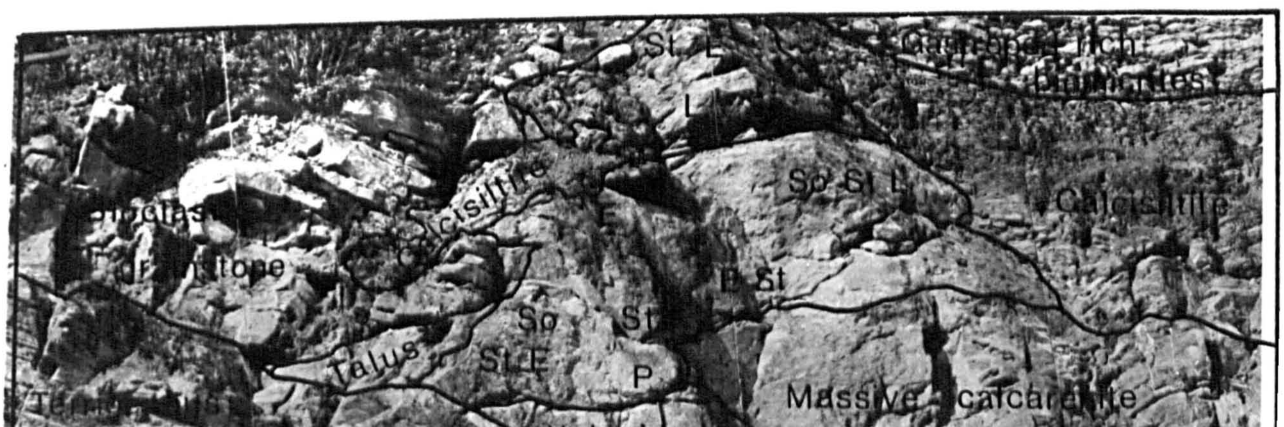

Bioclastic & pelodal
grainstone
Reef ?
Bergevika (southern)
reef
Intebedded
bioclastics & dolomites
Bergevika
(northern) reef

Fig.4.2: Small bioherm at Kjelsrud. The overlay shows the main lithological units present in a NNE-SSW section. The letters in the reef itself refer to the main faunal and floral components: St - stromatoporoid; So - Solenopora; E - Eoflecheria; L - Liopora; P - ?Palaeophyllum. Hammer (in x - bedded lstn) is 1m long.


St E
Gastropod rich
biomicrites
L So
Calcisiltite
So St L
Bioclastic
grainstone
Calcisiltite
E
E St
So
St
Talus
St E
P
Terrigenous
clastic facies
Massive calcarenite
X-bedded
lstn


St
L
L
So St L
Talus
So
St
St E
P
E St
Massive
X-bedded
lstn

South). Other reef bodies are referred to by their position relative to these two main reefs or by locality names. The distribution of reefs and bedded interreef sediment is shown in Figs. 4.1 and 4.2.

The reef mass can be conveniently divided into the organic framework and cavity systems. The latter is a compound term and includes primary organic and sedimentary features together with later diagenetic effects.

Each aspect of reef morphology and composition is described below, with the main emphasis on the exposures at Bergevika.

C. THE BEDDED INTERREEF SEDIMENTS.

Four distinctly separate groups of sediments constitute the interreef beds. These are defined and described below:

(1) Pelmatozoan calcirudites and calcarenites.

(2) Interbedded dolomites and bioclastic grainstones.

(3) Thinly bedded biomicrites.

(4) Bioclastic and peloidal grainstones with oncolites.

1. Pelmatozoan calcirudites and calcarenites.

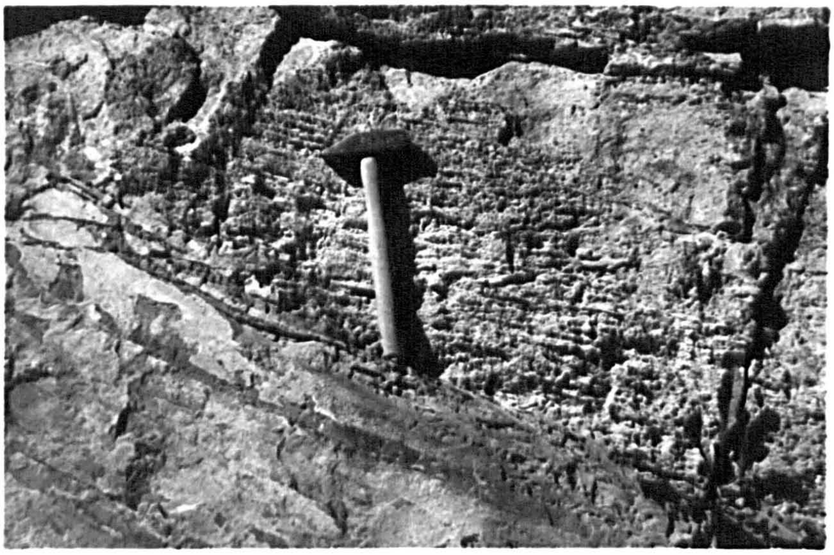
This is dominantly a bioclastic grainstone composed of crinoidal remains, which are frequently seen as broken stems up to 10cm long and 1 to 1.5cm diameter. There appears, however, to be a singular lack of roots and calyces. Associated with these are small to medium rounded Solenopora together with specimens of Streptelasma, both of which are well dispersed throughout the sediment, remain fairly common, and give every indication of having been transported to the site of deposition. (Fig. 4.3b,c.). Minor associates, mostly present as broken material only, are Chasmops, strophomenid brachiopods, unidentifiable molluscs, Nyctopora (occasionally still attached to a skeletal fragment), branching bryozoa,

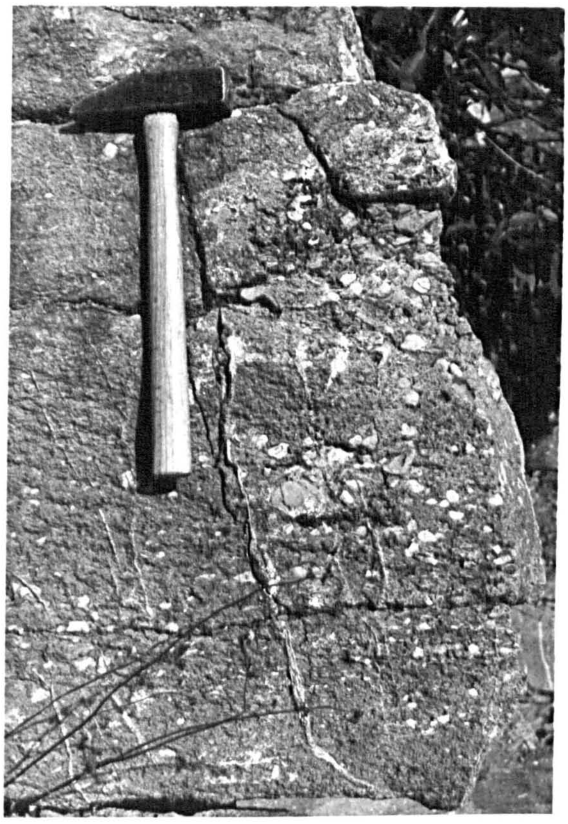
Fig.4.3: The intereef pelmatozoan calcirudites and calcarenites. Locality, Kjelsrud. Hammer is 33cm long. These beds are directly beneath the bioherm in Fig.4.2.

a) cross-stratified limestone. Note the sharp junction (at base of hammer shaft) with the terrigenous clastic beds.

b) small rounded Solenopora (white) and crudely developed cross-stratification.

c) Solenopora and stromatoporoid (darker bioclasts; bottom right).





and in the vicinity of the reef, some stromatoporoid, coral or bryozoan bioclasts. The coarse grained nature of the rock gives it a distinctively rough surface, and clearly defines the local development of large scale planar cross-stratification (Fig. 4.3a).

Petrographic analysis indicates an average composition of:

Echinodermal	70%
Solenopora	12
Brachiopod	5
Coral	3
Dolomite	5
Micrite	2
Mollusc	2
Bryozoa	1

Although representing the complete range of components present in the rock, the percentages of corals and Solenopora are probably lower than a surface count would reveal. The high percentage of echinodermal material is both a function of its abundance, and the "grain growth" phenomenon of ORME and BROWN (1963) effected by the syntaxial rim cement apparently enlarging the original grains. Counts of bioclasts undertaken at the exposure face give the following percentages for recogniseable bioclasts with a diameter larger than 2mm:

Pelmatozoa	48%
Solenopora	30
Streptelasma	16
Bryozoa	8
Nyctopora	4

Petrographically this unit is similar to the Bioclastic Grainstones (Facies 2), with the syntaxial sparry calcite cement giving a grainstone texture. Pressure solution is evident between these enlarged grains with the intergranular cavities containing micrite, dolomite or a mixture of the two. Molluscan bioclasts possess micrite envelopes, and a geopetal structure within such a skeletal grain is seen to be inverted.

Geographically beds belonging to this facies are found on the southeast flanks of the reefs both at Bergevika South, Bergevika quarry, and the small roadside exposure north of Kjelsrud (Fig. 4.2).

2. Interbedded dolomites and bioclastic grainstones.

Beds belonging to this group of sediments occur at two different sites within the reef complex and can be distinguished by their contrasting style of bedding and fauna.

a) Massive Beds: these are situated directly above the main pelmatozoan calcirudites to the south-west of the main (southern) reef on the Bergevika shoreline. Stratigraphically they appear to be below the reef, and discontinuous towards the southwest. They are composed of interbedded pelmatozoan calcarenites and dolomites, the bed thickness ranging from 40 to 110cm. The dolomites contain a limited fauna of corals (*Eoflecheria irregularis* (Hill) and ?*Palaeophyllum*) near the base, but laminar and domical stromatoporoids in the upper 2m. The domical forms have obviously been transported as the coenostea occur in a variety of orientations; many show abrasion and fragmentation. Boundaries with the adjacent bioclastic beds are stylolitised. Petrographically the limestone beds are dominated (95%) by echinoderm debris with syntaxial rim cements and contain less than 5% of other bioclasts, including molluscan fragments with micrite envelopes, ?*Hedstroemia*, bryozoa and one stromatoporoid.

The dolomite beds are dominated by corals (c 50-60%) and contain lesser amounts (c 10%) of echinoderm, molluscan, brachiopod or algal fragments in a dolomite groundmass (40%). Micrite is present in two distinct forms:-

i) as fills to the axial sections of corallites, and irregular patches throughout the dolomite groundmass. The patches are small and generally uncommon, but contain bioclasts in a wackstone texture, indicating this to be the primary depositional texture which has become replaced by dolomite.

ii) as peripheral rinds to the corallites, which, unlike the micrites described above, contain no bioclasts and almost no dolomite. The boundary with the dolomite groundmass is always stylolitised and the contact with the corallite generally smooth or only slightly irregular. One or two specimens display small irregular spar filled vugs which give a texture very similar to that of spongiostrome algae, and in one instance organisation into tubules could be recognised. From the above evidence it was concluded that these micrite rinds were similar to WOOD'S (1941a) 'algal dust', and represent encrustation of the corallites by an indeterminate species of alga.

b) Thin interbeds: these are situated between the two reefs exposed on the Spring shoreline (Fig. 4.1) and consist of thinly (3 to 6cm) interbedded bioclastic calcarenites and dolomites (Fig. 4.4). These overlie more massive dolomites which in turn may overlie a reefoidal unit which is below water level. If this is the case, these beds are occupying a large shallow depression on the reef surface rather than being true interreef beds i.e. occupying an area between two separate reefs. Bioclastic limestones appear more abundant nearer the edge of the (southern) reef as a result of thickening and, in places, amalgamation of beds.

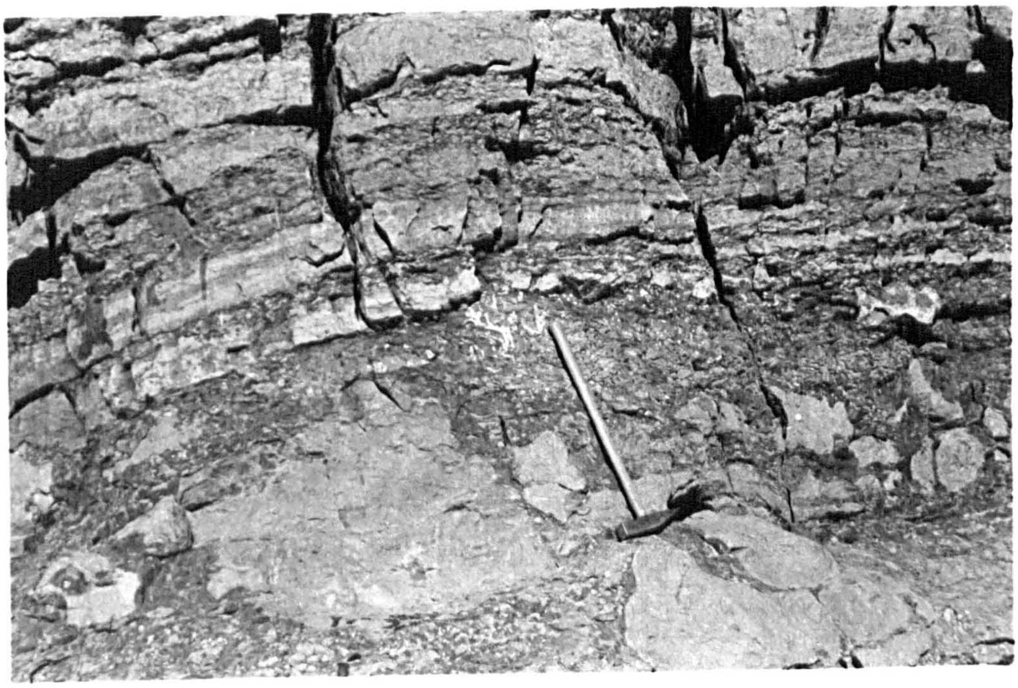
The bioclastic calcarenites contain a predominance of pelmatozoan bioclasts, although trilobite, bryozoan, molluscan, brachiopod and ostracod fragments are all readily visible. Corals too are common, Streptelasma in particular, but their abundance and diversity is greater in the dolomite horizons which also show a zonation of fauna away from the reef edge (Fig. 4.5). This is discussed in greater detail below.

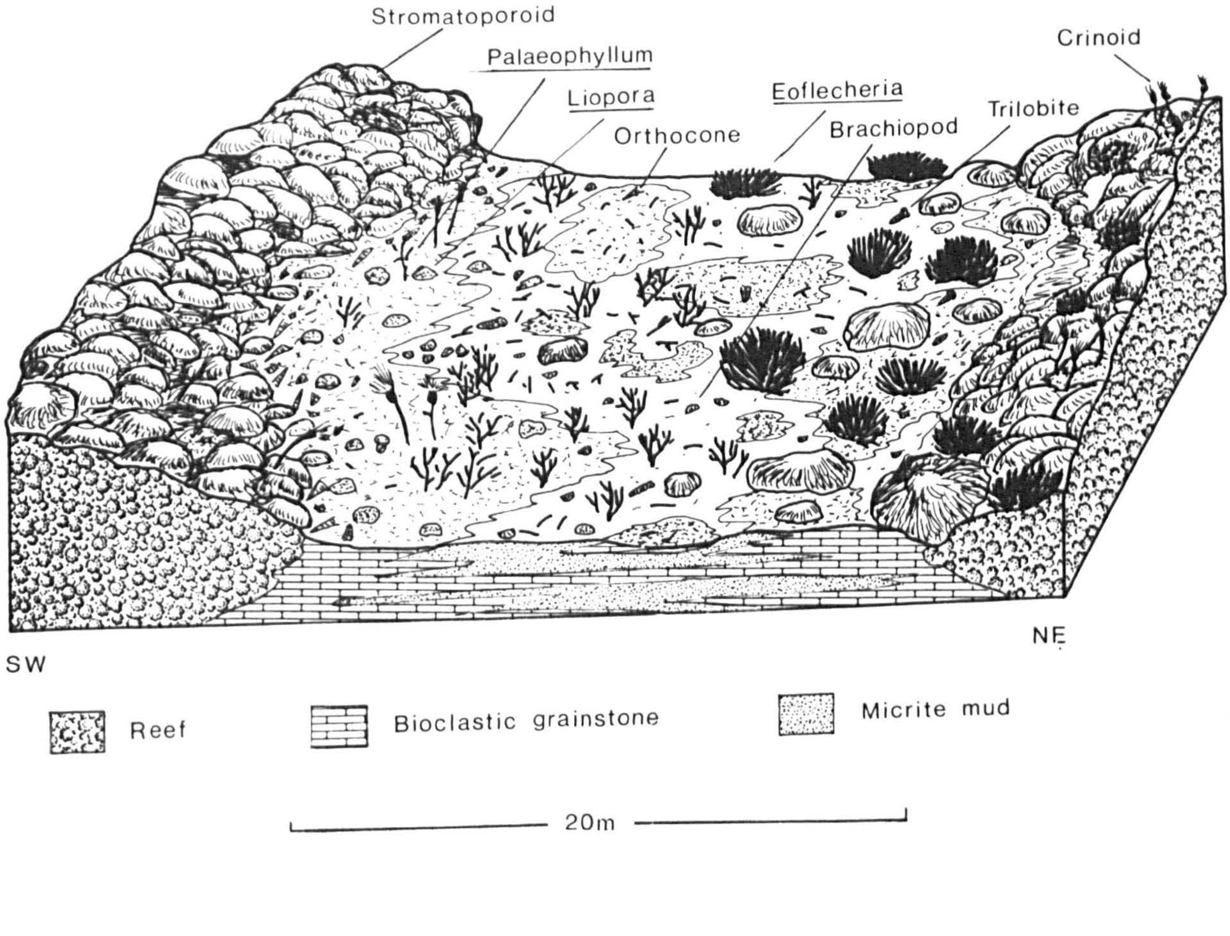
Petrographically the dolomite is similar to that in the massive beds, with pelmatozoan fragments more abundant and containing appreciable amounts of brachiopod, bryozoan, trilobite, molluscan and algal (micrite envelopes; 'spongy' textured encrusters; Dimorphosiphon rectangularis) bioclasts. Dolomite replacement of both micrite and bioclasts is evident with subhedral crystals falling into the 50-60 μ and 150-200 μ size ranges. The development of authigenic quartz adds another event to the diagenetic history. Subhedral crystals have grown around detrital grains which were apparently trapped in the original aragonite tissue (Fig. 4.12). As well as these crystals, authigenic quartz also fills small cracks within the corallite. Boundaries between dolomitised areas and micritic areas are always stylolitised.

The fauna present in the dolomite beds show a marked zonation away from the reef edge (Fig. 4.5). Orthocones are less abundant than at the reef edge, although there is little difference biometrically between the two populations. Liopora is more common in a convex upwards position near the edge of the reef, but its abundance gradually decreases northwards. (Its apparent abundance in these beds may be due to the easier observation of colonial organisms once the dominance of stromatoporoids has declined, or a palaeoecological preference for the reef edge by corals). Brachiopod and trilobite remains also appear more abundant at the reef edge. The Liopora are gradually replaced by ?Palaeophyllum, which in turn give way to large stromatoporoids and massive Eoflecheria subparallela (Hill) which form the basal unit of the (northern) reef. The majority of these organisms (with the exception of ?Palaeophyllum) are in a growth orientation indicating an original benthic assemblage, probably developed on a fine grained carbonate substrate.

Fig.4.4: Thinly bedded dolomites and bioclastic grainstones. Intereef beds overlying a dolomite unit which contains massive stromatoporoids (hammer head) and _in situ_ ?_Palaeophyllum_ (end of shaft). Fragmented remains of this coral are the dominant bioclasts (white dots). Locality. Bergevika South. Hammer is 1m long.

Fig.4.5: Schematic representation of the faunal zonation in the intereef dolomites and bioclastic grainstones. The reef on the S.W. side represents the Bergevika (southern) reef.




Stromatoporoid
Palaeophyllum
Liopora
Orthocone
Eoflecheria
Brachiopod
Trilobite
Crinoid
SW
NE
Reef
Bioclastic grainstone
Micrite mud
20m

3. Thinly bedded biomicrites

Directly above the (northern) reef and thinly bedded bioclastic limestones with dolomites, is a succession of biomicrites which are themselves thinly bedded (4-6cm), stylolitised along the bedding planes and of variable thickness. The beds immediately above the reef surface contain abundant specimens of Vermiporella (Fig. 4.7a) and above this is a local concentration of sparry calcite filled bivalves, usually in the lower 50cm of the unit, but extending across the entire surface of the reef. Scattered individuals, often displaying local concentrations, occur throughout the unit, although their irregular outlines make identification impossible in some samples.

As a whole, the unit shows a definite thickening to the southwest and a thinning to the northeast, until at its northern extremity it becomes a discontinuous veneer (less than 20cm) over the reef surface, but still contains an abundance of the spar filled objects (Fig. 4.6).

4. Bioclastic calcarenites with oncolites.

These beds appear as lateral equivalents of the bedded biomicrites, and contain distinctive biotic constituents, the most noticeable being patches of reefoidal material. The most abundant bioclasts appear to be pelmatozoan fragments, although the finer grain size makes distinction of the calcarenite fraction difficult. The calciruditic component is dominated by oncolites, which may reach up to 2.5cm diameter, Solenopora, stromatoporoid and coral fragments. Beds of this facies show particularly good development at Helgøya Skole where the oncolites decrease in size and grade upwards into peloidal horizons. The intimate association of oncolite bearing bioclastic beds and the reefoidal masses is discussed at greater length below.

Overlying this sequence is a bed of oncolitic grainstone (Fig.4.7b)

Fig.4.6: Section through part of the Bergevika (northern) reef.

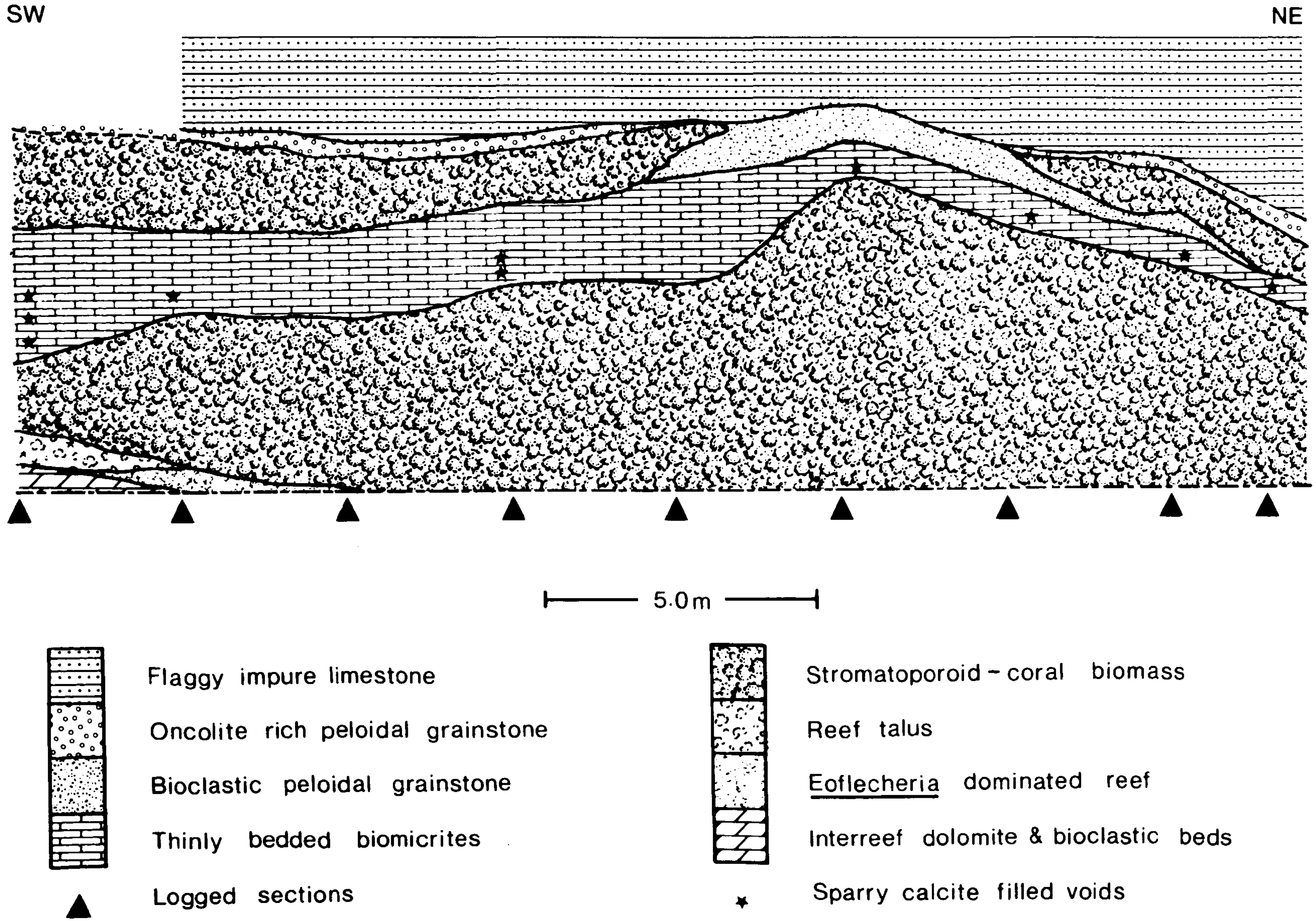

SW
NE
5.0m
Flaggy impure limestone
Oncolite rich peloidal grainstone
Bioclastic peloidal grainstone
Thinly bedded biomicrites
Logged sections
Stromatoporoid - coral biomass
Reef talus
Eoflecheria dominated reef
Interreef dolomite & bioclastic beds
Sparry calcite filled voids

Fig.4.7: Algal dominated interreef sediments, Bergevika South.

a) _Vermiporella_ biomicrite. The algae grow in a three dimensional chain like network. Note the later diagenetic solution cavities and their geopetal fills by (vadose?) calcisiltite. Slice: Bergevika (northern) reef. x 10

b) Algal dominated grainstone. _Girvanella_ oncolites are common throughout (e.g. lower right). _Dimorphosiphon_ is the dominant algal bioclast (e.g. lower left) often forming the oncolite nucleus. Other algae include _Rhabdoporella_ (top centre) and micrite envelopes. Note also the variety of well rounded bioclasts, echinodermal, brachiopod, molluscan (e.g. eroded mud filled gastropods). Negative print of slice. Oncolite grainstone above Bergevika (northern) reef. x 6.5.

which varies in thickness from 10 to 30cm but appears to be a virtually continuous horizon (Fig. 4.6) forming the uppermost bed of the reef complex. The oncolites are generally well rounded (c.f. to more ragged outlines in the Green Clastic Facies) and are dominated by Girvanella. The commonest nuclei are fragments of Dimorphosiphon rectangularis which are often bored at the periphery. Molluscan and brachiopod bioclasts may also act as nuclei. The coatings of algal material are generally concentric layers of micrite and sparite giving an overall "spongiostrome texture" and may incorporate quartz grains and (up to 80µ) bioclasts. Broken fragments of Vermiporella are also included in the bioclastic component.

The resemblance of D.rectangularis to the modern Halimeda is striking and has been previously noted by HØEG (1927; 1961) who concluded that the segments, so commonly found in this horizon, were probably linked together in similar fashion to Halimeda. The similarities between the two algae extend further. D.rectangularis is only found associated with reefoidal facies, usually towards the uppermost parts of each reef or in immediately overlying debris beds. Halimeda is found on the upper surfaces of modern reefs and it seems reasonable to assume that D.rectangularis occupied a similar niche in the Mjøsa Limestone.

D. GENERAL CHARACTERISTICS OF THE REEFS.

1. Distribution, size and shape.

On the island of Helgøya, a decrease in the thickness of the reef complex and apparent abundance of reefs is noticed between the localities of Bergevika South and Kjelsrud. An overall pattern of decreasing reef numbers and size, with associated absence of typical reef complex facies, emerges if the area under consideration is broadened to include the equivalent stratigraphical horizons of the Toten district

(Fig. 4.8). Within the 21m thick reef complex at Bergevika, reefs develop at different horizons and attain different orders of magnitude. The dimensions of the reefs vary greatly from a maximum of 15m high by 60m long at Bergevika South, to a minimum of 50cm high by 1.5m long at Eina. Consequently reef shape varies accordingly; most having irregular outlines in cross section, but the smaller reefs are nearer to being bilaterally symmetrical than the larger ones.

2. Reef margins.

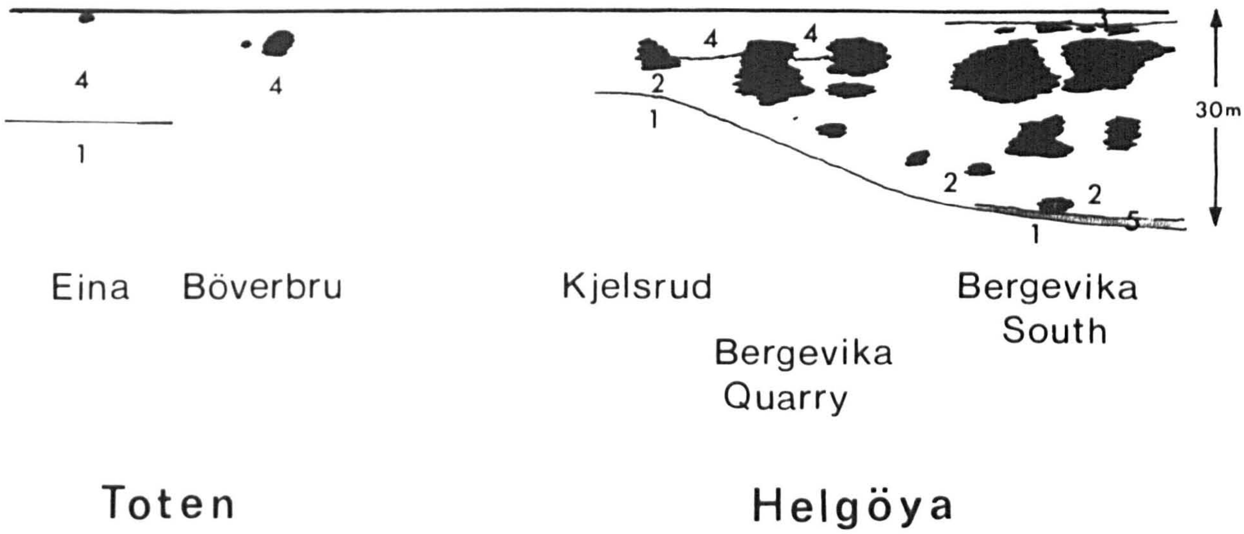
Margins of the larger reefs appear as irregular, but clearly defined, features with only localised incursions of sediment (Fig. 4.9). In contrast, the smaller reefs, particularly those at the base of the reef complex, display indistinct boundaries due to a poorly developed organic framework and abundance of included sediment. The smaller reefoidal masses above the main Bergevika reef, together with those of the Toten district, contain a comparatively high sediment content, but display reef edges which are more organised with interdigitations of framework and surrounding sediment.

3. Flanking and Talus beds.

At Eina, the small reefoidal body is surrounded by a fringing apron of oncolite rich grainstone within a sequence of bioturbated calcisiltites and micrites (Fig. 4.10a). Similar oncolite rich facies are seen above, and, to some extent, flanking the small reefoidal masses above the Bergevika main reefs (Fig. 4.11). The most spectacular developments of this facies are at Helgøya Skole and Velt Malterud, although the relationships between reefs and oncolite beds at the latter locality are obscured by faulting. The occurrence of such beds in sediments indicative of quiet water conditions appears contradictory. Their close

Fig.4.8: Schematic representation of reef abundance in the Mjøsa Limestone Reef Complex. Numbers refer to Facies types. The solid upper line marks the upper boundary of the Bergevika Reef Complex and lower boundary of the Rud Peloidal Beds (Toten).

Fig.4.9: The Bergevika (southern) reef margin. Reef growth was upward and outward over the thinly bedded dolomites and bioclastic grainstones of the intereef beds with frequent incursions of sediment causing temporary retreats. Hammer is 1m long.


30m
4
4
1
4
4
4
2
1
2
2
5
1
Eina
Böverbru
Kjelsrud
Bergevika South
Bergevika Quarry
Toten
Helgöya

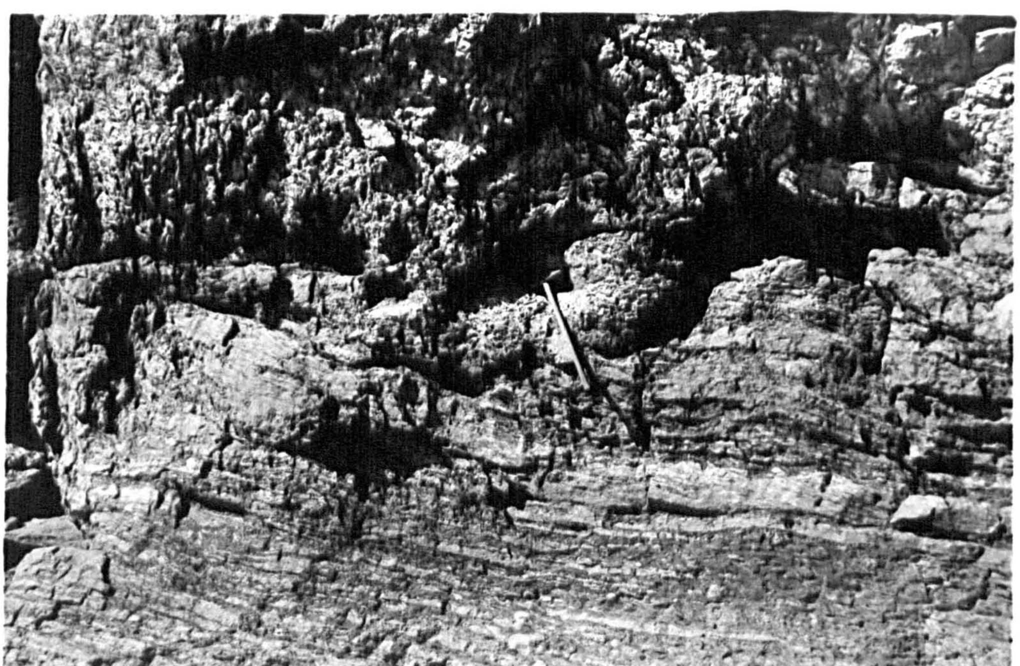
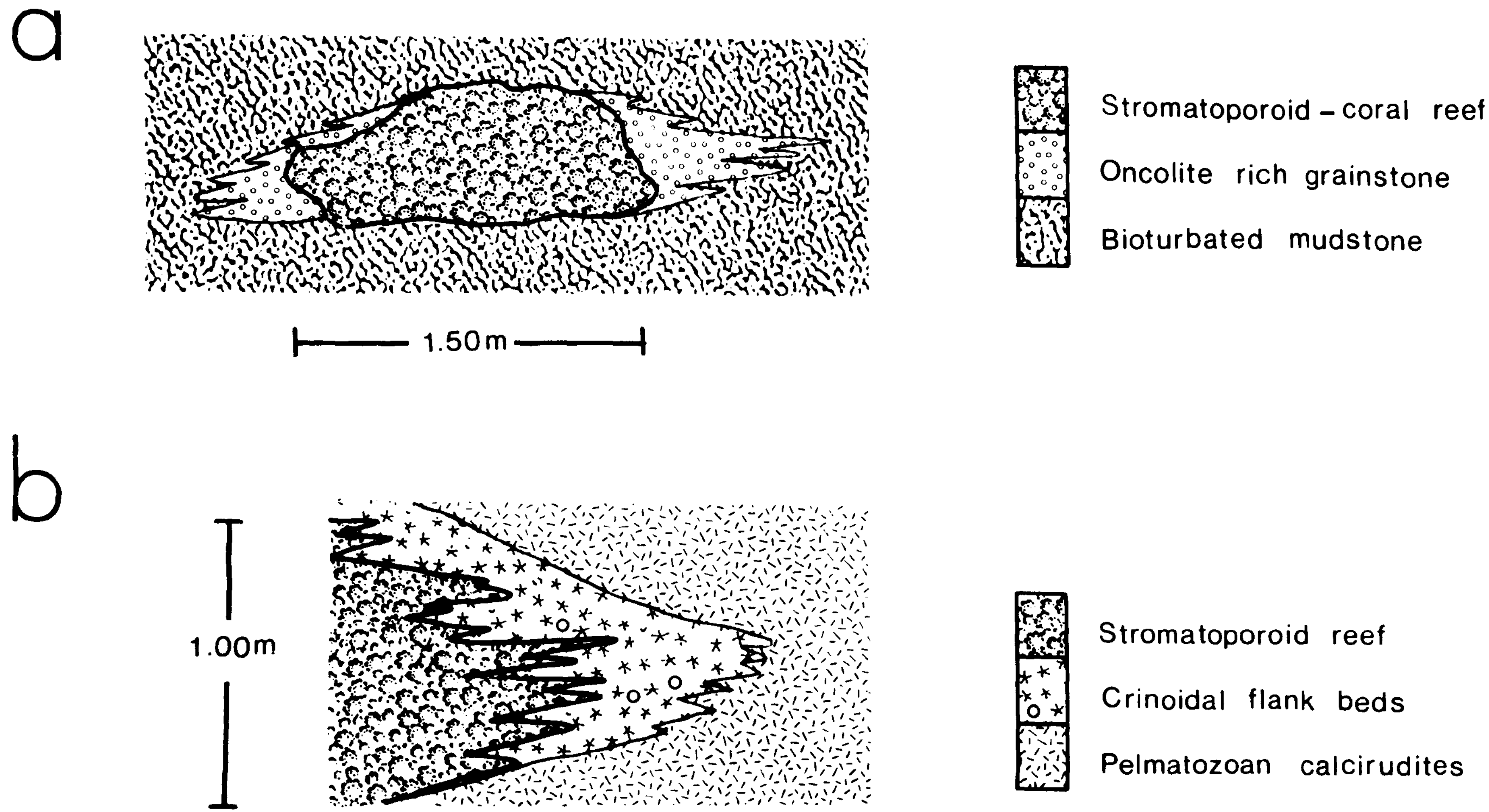


Fig.4.10: The localised development of flank beds around small reefs.

a) Eina

b) Bergevika South, base of the Reef Complex. The interdigitation of flank bed and reef suggests poor framework development, low relief or high energy and sedimentation rates.


a
1.50m
Stromatoporoid - coral reef
Oncolite rich grainstone
Bioturbated mudstone
b
1.00m
Stromatoporoid reef
Crinoidal flank beds
Pelmatozoan calcirudites

association with the reefoidal masses, however, suggests that they developed in pockets of turbulent water caused by the effects of the local irregularities (i.e. reefs) on the flow regime.

The crinoidal flanking beds of the small reefs at the base of the Bergevika reef complex (Fig. 4.10b) appear to represent the remains of an original flanking crinoid community. This is implied by the coarse nature of the material and higher incidence of stems which are both larger and less broken than in the adjacent pelmatozoan calcirudite and calcarenite.

Reef talus beds are developed locally on the southwest flanks of the two main Bergevika reefs (Fig. 4.6), and contain disoriented, together with fragmented, stromatoporoids and Liopora. A similar development is apparent in the reefs of the Bergevika quarry.

4. The upper surfaces.

At Bergevika South the upper surfaces of all but the (northern) reef are seen to be convex or irregular (Fig. 4.6), a phenomenon repeated at most other reef bearing localities in the limestone. The (northern) reef displays a generally flat, sharply defined upper surface for most of its length (Figs. 4.6; 4.11), and is associated with 60cm of disoriented stromatoporoids and Liopora, suggestive of a talus or reworked deposit. (It is interesting to note that Eoflecheria subparallela colonies can be found along the reef top in what appears to be their growth position). A similar sharp junction between reef and overlying sediments exists in the Bergevika quarry. There the junction appears erosional and the overlying beds have been deposited parallel with this surface.

5. Reef topography and relief.

The presence of talus beds and oncolite rich flanking beds imply that the reefs attained sufficient relief to allow destruction and cause local turbulent flow. The lack of beds dipping off the reefs at angles significant enough to overule the effects of compaction and the number of sediment incursions into the biomass, suggest that any relief present was very slight indeed, or that the reef front possessed a very gentle gradient. The relationships of the smaller reefs to the surrounding sediment, particularly those at the base of the reef complex suggests that relative to the main reefs they possessed a much lower relief and were therefore frequently inundated with sediment. The poor development of the framework suggests this may be due to growth near the tolerance limit of the organisms.

E. THE PRESERVATION OF REEF ORGANISMS.

Alteration of framebuilders and cavity filling material appears to have been post burial in age. Most organisms display evidence of quiet burial and there is no evidence of destruction by boring organisms. Micritisation of some grains, following attack by filamentous algae, is evident but of minor significance only.

The major diagenetic changes involve the replacement of aragonite, or high Mg calcite, by low Mg calcite, with an ensuing obliteration of skeletal microstructure in both stromatoporoids and corals. The type of replacement differs in these two groups of organisms. The former display a granular (neomorphic) mosaic, while the latter exhibit a radial fibrous structure, thus allowing petrographical distinction between them. Replacement of skeletal material by dissolution and reprecipirication in the void (e.g. mollusca) is described below (p.182).

Dolomitisation has also aided the destruction of the original fabrics although this process has been mainly confined to the finer grained sediments. Small scale secondary fabric destruction by the growth of authigenic quartz occurs on a local scale (p.156) and is illustrated in

Figs. 4.12a,b.

All skeletons comprising the framework are accentuated peripherally by a stylolitic boundary with the adjacent organism or sediment. In their turn, the stylolites are made more conspicuous by the inclusion of a brown residue of clay minerals, quartz silt and dolomite, which represents the concentration of insolubles from dissolution of adjacent carbonates during compaction.

F. THE FRAMEBUILDING ORGANISMS.

All reefs in the Mjøsa Limestone are constructed by in situ framework builders (corals and stromatoporoids with small localised concentrations of Solenopora) which appear in a matrix of micrite, dolomite or calcarenitic grainstone. These sediments are regarded as having been deposited after the framework has been build and therefore most likely represent cavity fillings. Binders appear to be absent, although this may be a function of a lack of more detailed faunal investigations.

1. Stromatoporoids.

Labechiid stromatoporoids are the dominant framebuilders in all the reefs, although their numerical superiority may be locally reduced (Fig. 4.16).

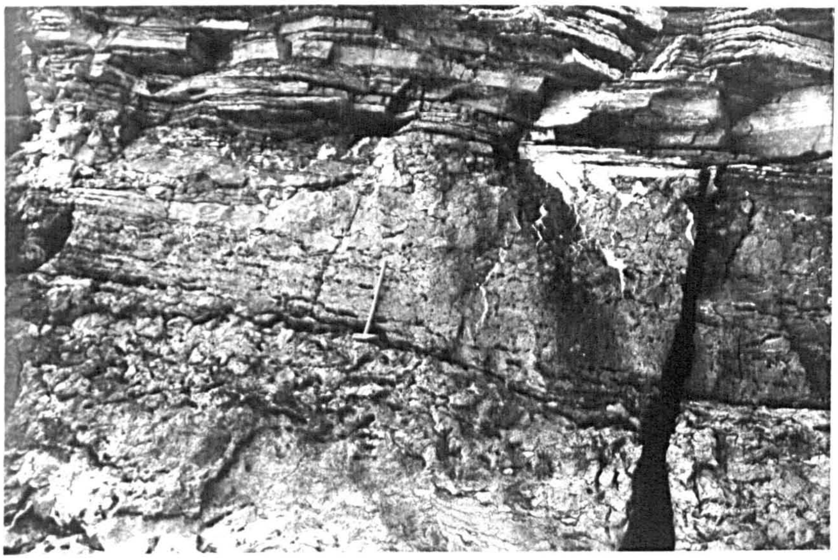
Thin section examination reveals little except a mass of neomorphic sparry calcite with crystal sizes varying from 40 μ to 900 μ, although the great majority occur in the 220-450 μ range. Within this sparry calcite are irregular patches of micrite which often have two distinct quartz grain contents, viz. less than 5% and 20-50%. Although the quartz is 40-80 μ diameter and often lath like it displays little evidence of an authigenic origin (e.g. inclusions). It is, therefore, regarded as fine sediment trapped along with the carbonate mud on the surface of the stromatoporoid. Other detrital particles are confined to rare 50 μ diameter echinodermal

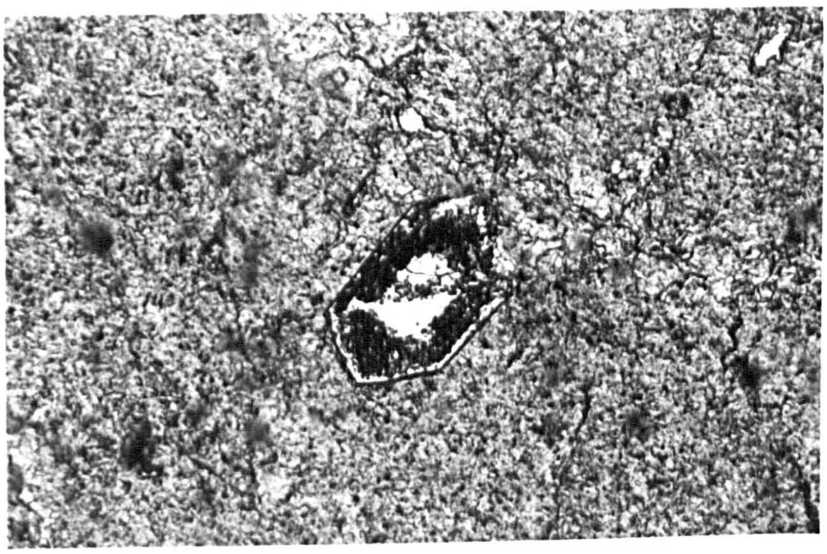
Fig.4.11: Features of the upper boundary of the Bergevika Reef Complex. Note the sharp junction with the overlying flaggy gastropod beds, flank beds developed around a small biohermal unit (top of hammer shaft) and sharply defined upper boundary of the Bergevika (northern) reef. Hammer is 1m long.

Fig.4.12: Authigenic quartz within a coral wall. Both crystals appear to have grown around an original detrital quartz grain trapped in the tissue. Slice. Bergevika (northern) reef.

a) Crystal width is 190μ. x 48

b) Crystal width is 380μ. x 30





grains. Some examples of 'spongy' textured micrite remeniscent of an algal origin, were also found, but there was insufficient detail to make any meaningful conclusions. KAPP (1975) however, has described a spontaneous association of Solenopora embrunensis with stromatoporoids in a Middle Ordovician mound. Dolomite also occurs within the coenosteum, accentuating the convexity of the growth surface and from petrographical analysis appears to be a replacement of the micrite mentioned above.

Stromatoporoid shape varies both within the larger reefs as well as between them and the smaller organic buildups. The (southern) reef at Bergevika shows a development from laminar to domical forms at the base, the domical forms encrust ?Palaeophyllum rich biomicrites. Passing towards the centre of the reef, thinner laminar forms are encountered (Fig. 4.13a) which gradually develop into a compound laminar-domical form (Fig. 4.13b, c; c.f. Fig. III.1) before apparently grading into the ragged domical form often quoted as being typical of stromatoporoids (Fig. 4. 14a) and described by BROADHURST (1966) as a direct result of sedimentation rates. Approaching the reef margin a noticeable steepening of dip is observed (Fig. 4. 14b) which is more than can be attributed to local tectonic effects and must be related to an original dip at the reef front. Such an hypothesis is given credence by the shape and orientation of coenostea, which can only be achieved by the organism draping itself over a sloping irregular surface i.e. the reef front.

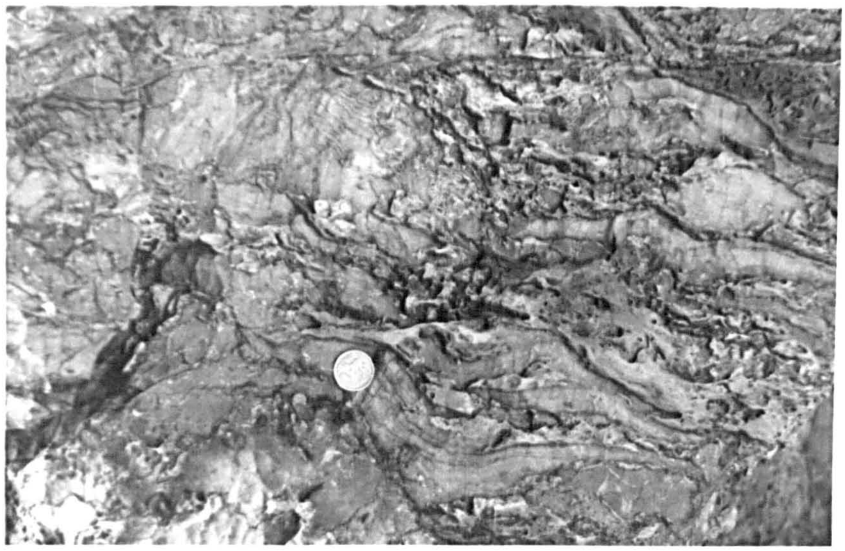
Laminar stromatoporoids are also common in the bioclastic calcarenites underlying the main (southern) reef, where they are small (10-12cm in length; 3 or 4cm high) and ragged. Concentrations of these occur throughout the beds but are well developed around the margins of some of the smaller reefoidal units, where they are associated with a particularly high percentage of sediment (c. 60%). From this, and other evidence cited previously (p.162) a possible relationship between the laminar

Fig.4.13: Stromatoporoid shapes from the Bergevika (southern) reef. Coin is 2.70cm diameter.

a) laminar coenostea

b) laminar-domical coenosteum

c) ragged laminar-domical coenosteum



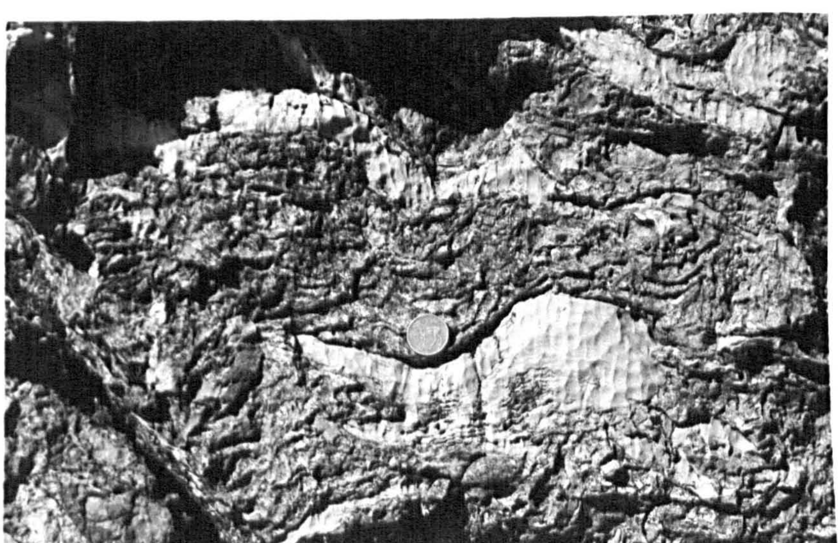
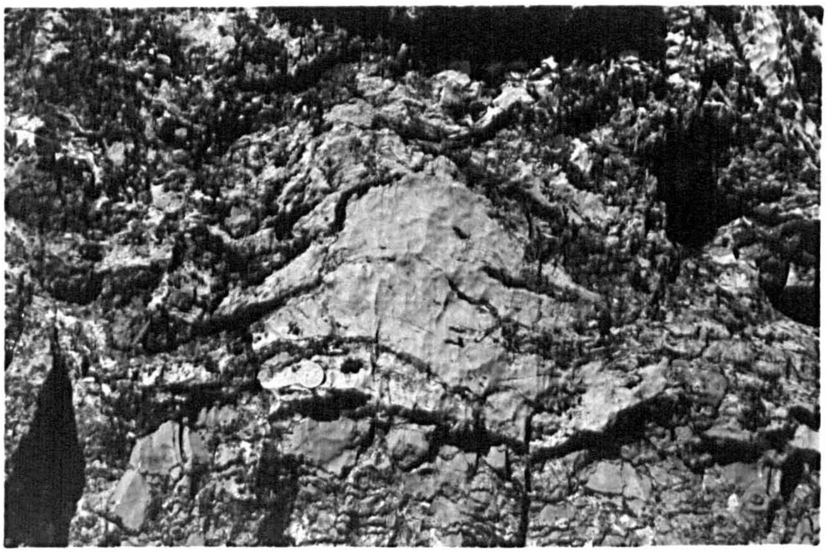


Fig.4.14: Stromatoporoid shapes from the Bergevika (southern) reef. Coin is 2.70cm diameter

a) "pine tree" type of domical coenosteum

b) inclined coenosteum on the northeastern margin of the reef. The dip of the latilaminae (centre) is 18 or 20° steeper than the surrounding sediments, suggesting growth, and possible overhang, at the reef margin.



and domical forms in the reef can be deduced. Laminar forms appear to indicate high energy and high sedimentation rate, while domical forms can be produced by a lessening of the sedimentation rate, so that only the peripheral areas are gradually inundated. However, consideration of a coenosteum such as that illustrated in Fig. 4.13b) shows that it is composed of a series of superimposed laminar forms. The only difference between it and those in Fig. 4.13a is that growth has remained steady at a fixed site. It appears therefore that, at least within the reef, the production of laminar or domical forms depends solely on sedimentation rate, although high energy will prevent superposition of coenostea by removal of the first growth form, thus giving rise to laminar rather than ragged domical or compound laminar-domical forms.

The effects of competition with neighbouring organisms on the shape of coenostea is discussed in Appendix III. Within the Bergevika (northern) reef it is well displayed (two examples are illustrated in Fig. 4.15) and may be the most important shape determining factor of all, although until the effects of compaction and ensuing rotation of organisms can be identified, it is not easily recognised.

The small reefs above the main Bergevika reefs contain small ragged and rounded stromatoporoids which appear to represent a combination of reef talus and poorly developed framework builders in a sediment dominated environment.

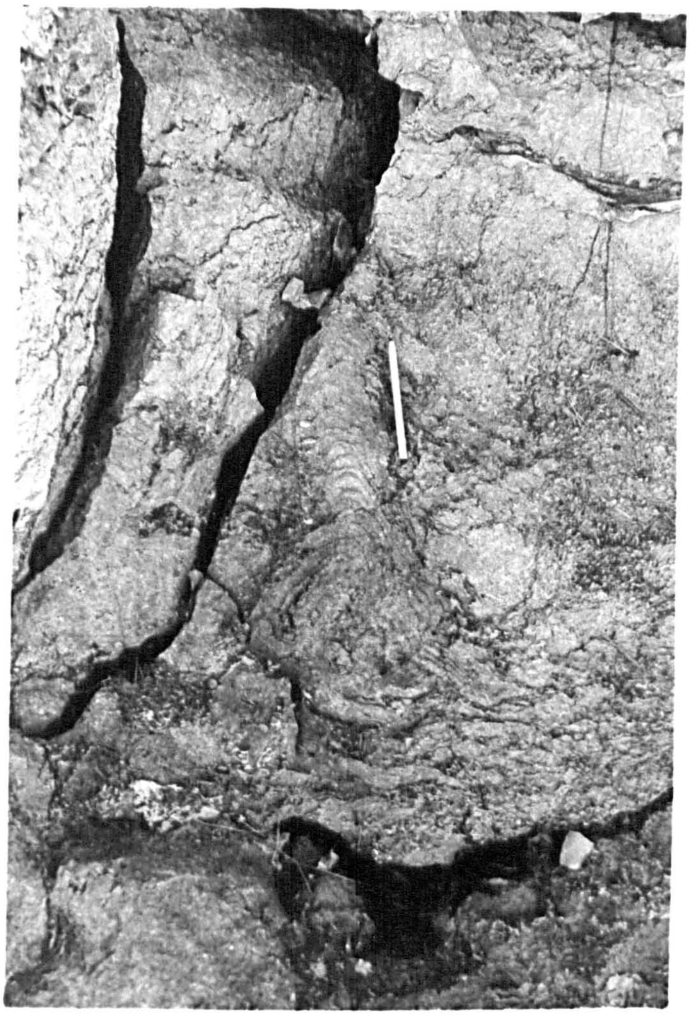
2. Corals.

Two major genera of corals were active as framework builders alongside the stromatoporoids. HILL (1953) has described L.favosa, (McCoy), L. tenuis, (Hill), and E.subparallela (Hill). Distinction between Liopora species was not attempted due to the poorly preserved nature of the material. The recognition of Eoflecheria subparallela, as

Fig.4.15: The effects of niche restriction on coenosteal shape. Bergevika (northern) reef.

a) stromatoporoid (immediately left of biro) changes from a domical to tubular form due to competition with surrounding colony of Eoflecheria subparallela until its ultimate demise (biro point). Biro is 14.5cm long.

b) removal of niche restriction allowed the change from a tubular to domical coenosteum. Coin is 2.70cm diameter.



opposed to E.irregularis (Hill) was both easy and essential due to their different growth forms and niche utilisation. The former is a framebuilder and the latter a cavity dweller. Distinctions within the framework are made only between Liopora spp. and E.subparallela.

Of the two, E.subparallela is the more conspicuous being generally much larger in size and occurring as a shapeless mass of tubular corallites which billow up to and around the other framebuilders. Liopora is more compact and occurs as small subhemispherical to conical shaped colonies. Both are also encountered ahermatypically in sediments outside the reefs, where of the two, E.subparallela is more abundant.

3. Solenopora and uncertain ?organisms.

Although common in the pelmatozoan bioclastics and the small reefs therein, very few Solenopora are found in the main reefs. Micritic masses bearing some dolomite enhanced structure were observed, but proved impossible to identify.

Solenopora, are, however, more conspicuous in the small reef at Bøverbru where they account for a variable percentage of the reef building biota.

4. Variations within the framework.

From the data presented in Fig. 4.16, it can be seen that there is little compositional variation among framebuilders within all the reefs; stromatoporoids are dominant but subject to local variations. The percentages of organisms to spaces (i.e. cavities) is recorded by the organism-sediment percentage in column I, which shows a random variation throughoüt each reef. The total percentage of sediment is probably higher in the smalle: than the larger reefs. In the Bergevika (northern) reef, there is a tendency for E.subparallela to be concentrated near the basal and upper surfaces.

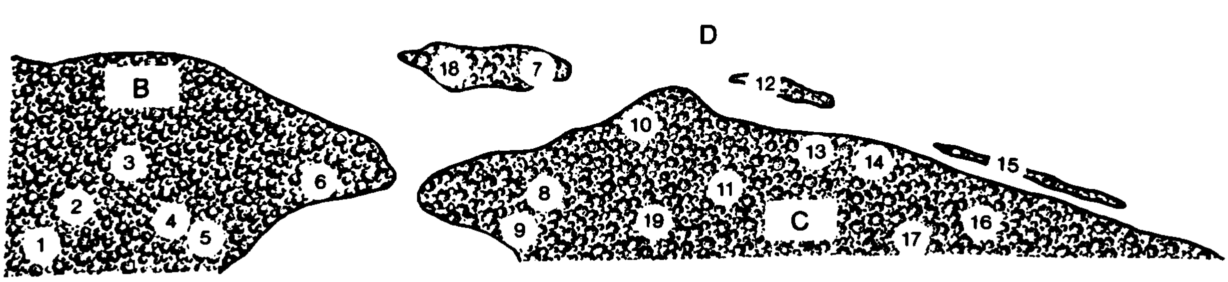
Fig.4.16: Reef composition, Bergevika Reef Complex. The letters refer to relevant reefs: A - small reef at the base of the Complex. B - Bergevika (southern) reef, C - Bergevika (northern) reef, D - small 'reefs' above the main reefs.

	I				II					III			
	PERCENTAGE OF FRAME BUILDERS AND SEDIMENT				MAJOR REEF FORMING BIOTA					STROMATOPOROID SHAPES			
	Stromatoporoids	Eoflecheria	Liopora	Sediment	Stromatoporoid	Eoflecheria	Liopora	Palaeophyllum	Others	Domical	Laminar	Tubular	Rounded
A 1	20	15	10	55									
B 3	25	-	-	25	28(22)	-	-	-	-				
6	60	-	5	35*									
2	25	20	5	50	15( )	8(1)	7(2)	19	3*				
4	45	5		50	12(11)	-	-	-	-	4	6	-	1
5	60	-	-	40	7(6)	-	-	-	-				
1	60	-	-	40	39(24)	-	-	-	-	5	2	-	-
C 10	30	5	15	50	21(4)	7(7)	11(6)	-	-				
13	30	15	25	30	23(8)	12(12)	22(14)	-	-				
14	40	30	5	25	20(13)	5(5)	3(1)	-	-				
16	30	5	20	45	20(5)	3(3)	23(3)	-	-				
11	30	20	10	40									
8	40	10	15	25	24(13)	5(5)	16(5)	-	-	14(9)	5(4)	5	-
17	60	4	1	35	28(21)	2(2)	3(2)	-	-	18(13)	7(6)	3(2)	-
19	20	15	10	55									
9	40	30	-	80	14(8)	13(13)	-	-	-	5(1)		4(1)	5(3)**
D 18	30	5	5	60									
7	45	15	-	40	41(16)	3(1)	-	-	-	15(5)	8(8)	11(3)	7
12	55	5	5	35	20(7)	2(2)	5(2)	-	***6(6)				
15	30	10	20	40	39(6)	12(8)	26(8)	-	-	2	-	18	6

* Including 15% orthocones

** Massive forms

*** ? Solenopora



This abundance is shown only in column I which represents the percentage of total area occupied by each organism, whereas column II, which expresses total number of individuals present, shows a low figure. This is a direct function of the size of this organism. Towards its northern extremity, the (northern) reef becomes dominated by this coral which appears to be in direct competition with the stromatoporoids for niche dominance.

The orientation of organisms is represented in column II and indicates that a relatively small proportion of the reef stromatoporoids occupy a convex upwards position. Whether this is a palaeoecological reflection or the result of compactional reorientation is uncertain. However, this criterion provides a major distinction between the main reef and the small overlying reef bodies, where an even smaller percentage of organisms occupy this position. The difference in coenosteal shapes also indicates a higher energy environment and one which probably bordered on the survival threshold for these organisms.

G. ASSOCIATED ORGANISMS.

Grouped in this category are the vagrant benthos, trilobites, ostracod , gastropods (Fig. 4.17a) and in particular orthocones (Fig. 4. 17b, c) whose skeletal remains are found in both reef pockets or encrusted by (even incorporated into) framebuilders' skeletons. Orthocones show a definite concentration on the northern edge of the (southern) reef where a faunal count reveals 28 in $0.5m^2$ of reef and only 3 in the same area of the interbedded bioclastics and dolomites.

H. THE REEF CAVITIES, THEIR FILLS AND BIOTA.

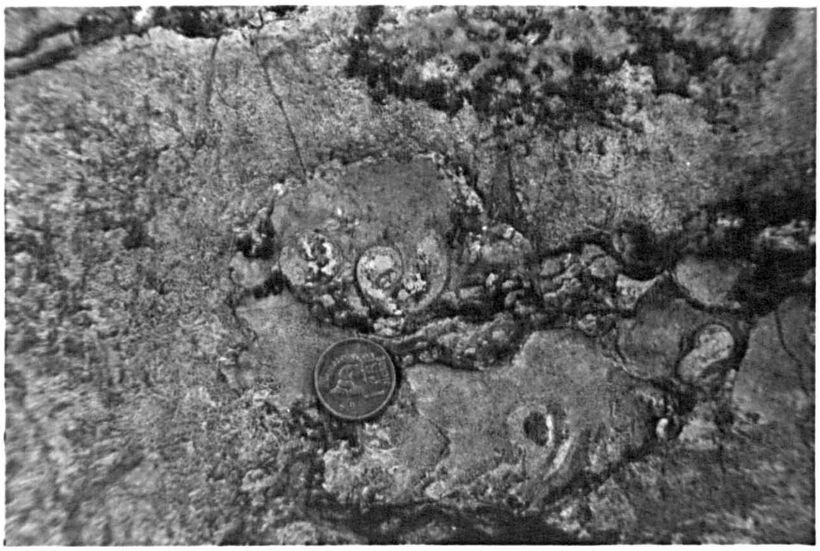
For the purposes of this investigation, this author has followed SCOFFIN'S (1972) definition of a cavity as "any part of the reef rock which

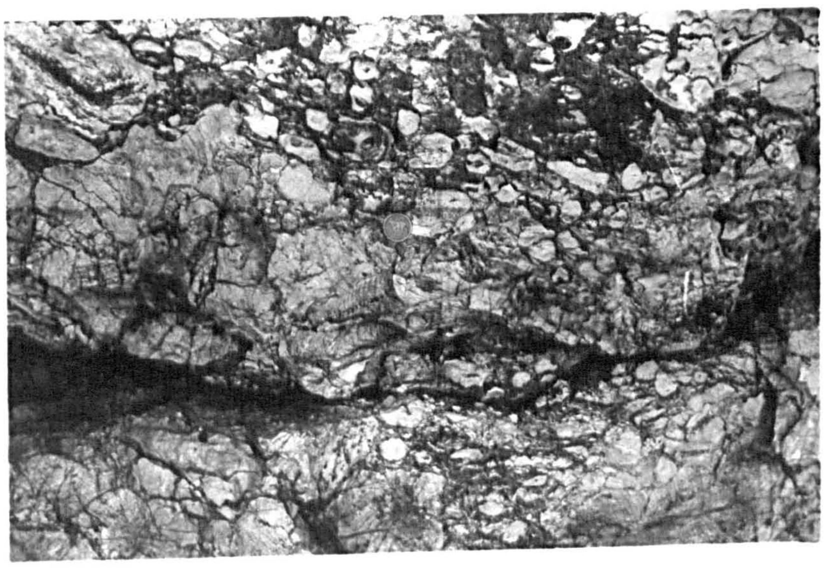
Fig.4.17: Associated reef organisms. Bergevika (southern) reef.

a) gastropods (centre). Coin is 1.60cm diameter.

b) orthocones. Coin is 2.70cm diameter

c) orthocones. Note concentration and orientation parallel to reef edge. Coin is 2.70cm diameter





was at some time a fluid filled void in the solid reef structure". A division can be made into growth cavities, interskeletal cavities and diagenetic cavities, each of which is described below:

1. Growth cavities.

These are synonymous with SCOFFIN'S (1972) "between knobs" of reef builders and are representative of depressions on the reef surface which became sediment filled and finally overgrown by the reef organisms. Examples are found in the small reefs of sediment lenses overgrown by organisms, but, because of the low relief of these reef bodies, such phenomena probably represent sediment washed onto the biomass rather than that generated on it. Roofing over of such cavities is well displayed in the Bergevika (southern) reef, where larger lenses (up to 1.50m in length and 1m thick) of pelmatozoan calcarenite occur within the reef core. Directly overlying the sediment are stromatoporoids, which, from their growth habit and relationship to the sediment, appear to have overgrown it.

This echinodermal sediment is characterised by its almost monotypic origin, white colouration, excellent sorting and position within the reef. Petrographically it is 90% echinoderm fragments with syntaxial rim cements. The remaining 10% is intergranular dolomite and micrite, with rare intraclasts of algal or molluscan origin. Dolomite crystals are anhedral, range from 20-300 μ diameter (modal value 100 μ), and appear to replace the micrite. The micrite contains nothing except occasional lozenge shaped crystals of authigenic quartz with a length of 10-100 μ and width of 10-40 μ. Pressure solution is obvious between all grains and probably accounts for the anhedral outlines of the dolomite crystals.

Lenses of calcisiltite occupy a similar position in the reefs of the Bergevika quarry and roadside locality north of Kjelsrud. If the observation of reef material underlying the interbedded dolomites and grainstones between the two main reefs is correct (p.155), then technically these sediments become growth cavity fills.

2. Interskeletal cavities

These refer to the cavities existing between organisms which form the reef framework, and all are filled by a variety of sediments:

(a) Brown argillaceous material: this occurs both in stylolitic partings and in interskeletal cavities near the base of the (southern) reef, where it is frequently typified by a coquina of smooth trilobite (? Isotelus) skeletal remains.

(b) Black calcisiltite: cavity fills of this material are frequent in the reefs of the Bergevika quarry and roadside locality near Kjelsrud. Faunal remains include Dictyonema, ?Hillophyllum, ?Palaeophyllum and indeterminate trilobite fragments.

(c) Dolomite: conspicuous by its brown colouration, dolomite is present as an interskeletal and intraskeletal cavity filling. Petrographically this occurrence of dolomite is similar to all other dolomites in the Mjøsa Limestone, with euhedral to subhedral 30-80 μ crystals. Relicts of micrite are present and their 2-5% content of medium silt sized angular quartz grains indicates a primary sediment which has been replaced by dolomite. Bioclastic content is similar to the biomicrite filled cavities and is described below. Pressure solution has accentuated the boundary with the micritic areas and has, in places, modified crystal boundaries.

(d) Biomicrite: sediments of this facies show a variety of textures from packstone to mudstone but all appear as light grey carbonate mud-fills between the main reefbuilders and are rich in biotic constituents.

The percentage of biota to sediment varies widely, as does the composition of the total biota, with concentrations of specific organisms in one pocket and no visible representatives in others. Despite this variability, however, the dominant faunal element is the coral Eoflecheria irregularis, closely followed by pelmatozoan bioclasts, often represented by 10cm crinoid stems, but no apparent roots or cups. Also common are large branching corals (?Palaeophyllum) which appear to be in a growth position. Less common throughout the reef, although they may be dominant in any one population, are gastropods, bivalves, brachiopods, orthocones, trilobites and bryozoans (Fig. 4.18a).

Petrographical analysis reveals a wealth of algal structures within these cavities. All cavities contain some bioclastic grains which have a micrite envelope or 'spongy' textured coating. Many of these coatings are irregularly distributed around the periphery, commonly being thicker on one side than the other, which suggests little movement of water through the cavities, an hypothesis consistent with the evidence for quiet conditions provided by the in situ corals and fine sediment fill. Recognisable algal-remains include clumps of Hedstroemia, Halysis and phylloidal grains which may be algal or molluscan in origin. Around the walls of the cavity and present throughout it, is a clotted micrite - sparite texture which is best described as "gremeleuse". In places the sparry calcite develops gradually into laminations, and the whole structure resembles Mallacostroma as figured by JOHNSON (1961, plate 99). Stromatolitic algae have been reported from the Wenlock reefs of Shropshire by SCOFFIN (1971; 1972) who has also indicated to this author (verb. comm. 1976) that this is the most likely cause of such a structure. A mechanism of production as described by SCOFFIN (1972, p.575) has been discounted due to the absence of bryozoa or similar organisms to produce lumps of micrite in the cavities, as has a faecal origin due to the siting of these textures along the walls and roofs of many cavities. Spherical areas of sparry calcite, ranging in diameter from 60-300 μ, are present in cavities which contain this spongiostrome structure and could represent calcispheres or the sporangia of algae.

In addition to the biotic component, the micrite typically contains from 2-15% of subrounded (3-4 on the Powers scale) 0.2mm diameter quartz grains scattered throughout. Occasionally grains appear to possess an authigenic overgrowth, but most appear to be detrital in origin. Dolomite is also found in varying degrees of concentration, and is petrographically identical to that described previously.

3. Intraskeletal cavities.

The association of dolomite with E.subparallela (Fig. 4.18b) has been noted on several previous occasions, and is attributed to a high intercorallite porosity. Micrite mud is assumed to have collected in much the same way as in the interskeletal cavities, although in this instance the corallites may have acted as a baffle and micrite collected before the colony became overgrown. The original cavity was also utilised by encrusting algae, whose decay may have contributed to the fine sediment accumulation.

All corals possess an intraskeletal cavity in their axial portion (Fig. 4.18a,b) and this has become variously filled by micrite, sparry calcite or dolomite; crinoid ossicles display a similar phenomena.

Gastropod skeletons frequently provide a cavity which is both sediment and sparry calcite filled (Fig. 4.18a) while overturned brachiopod or bivalve shells produce umbrella structures for the subsequent precipitation of cavity filling sparry calcite.

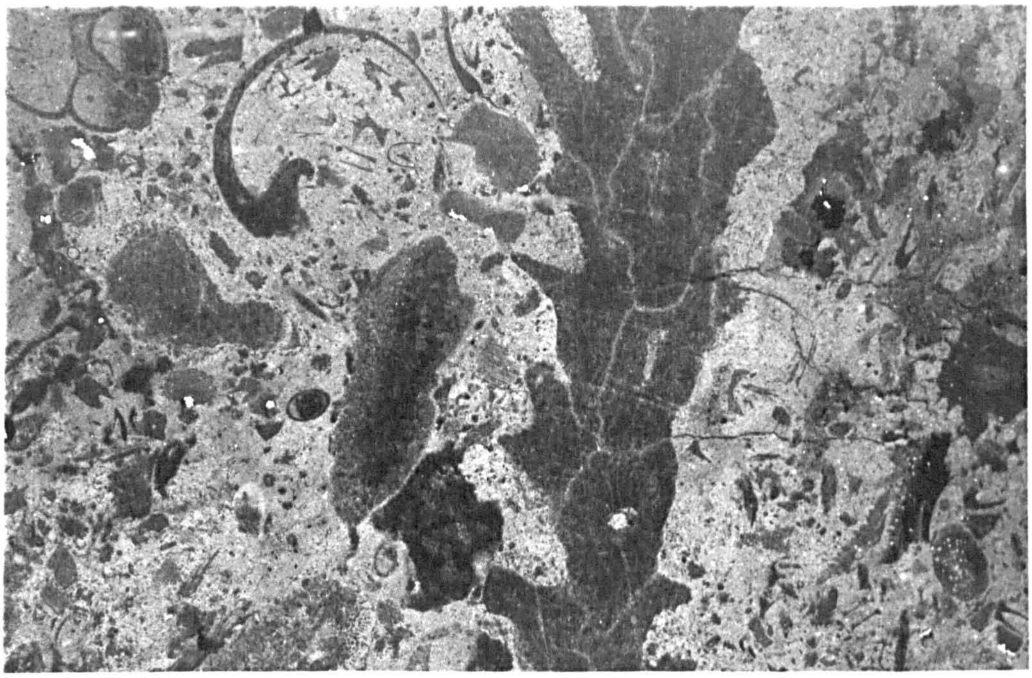
4. Diagenetic cavities

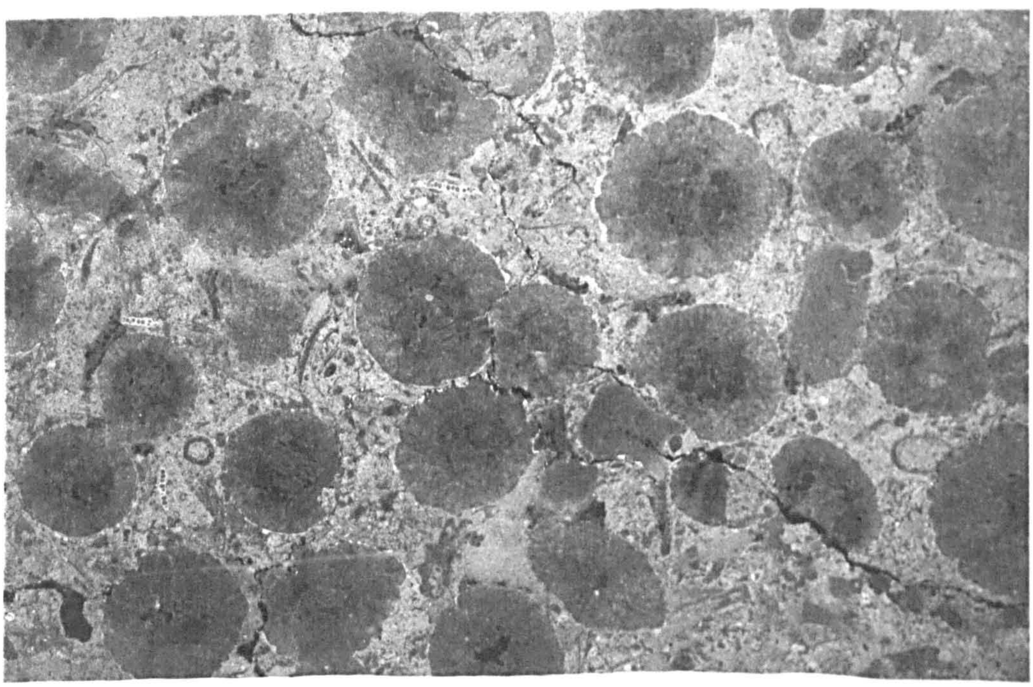
After reef burial, diagenetic processes opened new cavities by

Fig.4.18: Reef cavities. Bergevika (northern) reef. Negative prints of slices. x 7.5

a) interskeletal cavity containing abundant bioclasts, gastropod, echinodermal, coral, algal, ostracod, trilobite and brachiopod in a micrite mud matrix.

b) intraskeletal cavity (Eoflecheria subparallela) Between the corallites micrite mud and small bioclasts are trapped. Note the small alga, Halysis, (white chain-like feature).





dissolution of original skeletal material. Molluscan bioclasts were particularly susceptible to such attack as evidenced by their present representation by void filling sparry calcite (Fig. 4.18a).

Evidence of non-fabric selective diagenetic destruction and subsequent filling of the cavity was not found, although rare examples of material closely resembling vadose calcisiltite were encountered. However, in view of the paucity of this evidence in a brief study of the reefs, comment on such features is deferred at this stage.

I. DISCUSSION

Energy conditions during reef growth appear to have been relatively quiet as witnessed by the preservation _in situ_ of delicate branching corals and the general abundance of carbonate mud (mostly dolomitised) in the surrounding sediments. The pelmatozoan calcirudites and calcarenites contain little evidence of high energy depositional conditions apart from the occasional instance of high angle cross-stratification or major innundation into a reefoidal body, both of which can be regarded as the products of occasional high energy catastrophic events (storms?). The comminution of faunal elements, together with the thin ragged nature of stromatoporoids and high sediment content giving small irregularly shaped reef masses, can be adequately explained by a mobile substrate in gentle current conditions rather than invoking high energy environments. The interparticular micrite is, in itself a poor indicator of quiet water deposition (cf. FOLK 1959) as the texture of the sediment could allow for introduction after deposition and early lithification, which as shown by EVAMY and SHEARMAN (1965; 1969) can be extremely early in echinoderm dominated calcarenites. Petrographical analysis of this micrite and its constituent grains indicates that it is probably primary in origin, but its confinement to small intergranular cavities is a function of both the original sediment texture and later diagenetic phenomena. The occurrence of such pelmatozoan rich deposits in association with reefs has been noted by many authors, among them INGELS (1963) and MANTEN (1971) who both proposed that crinoidal flank beds represent deposition on the windward side of a reef body. The reefs of the Bergevika reef complex all show a concentration of pelmatozoan dominated sediments to the south and southeast, and mostly micritic sediments to the north. Such a distribution is possible if the reef tract acted as a form of barrier or baffle zone, causing an energy reduction which allowed the deposition of fine grained carbonate sediments in the quiet (and by inference, back reef) areas. Even in the relatively calm conditions proposed for the fore reef areas, the reefs would have to be topographically significant features to prevent large scale mixing of pelmatozoan and micritic sediments. The apparent lack of topography discussed on p.166 appears more likely to be due to a gentle reef slope rather than complete lack of relief. Palaeogeographically the above hypothesis allows distinction of a seaward and landward side to the reefs, and infers that the Toten area was a back reef, quiet water mud accreting area with limited organic development. The seaward side is represented by the pelmatozoan rich deposits and poorly developed reefal bodies of the lower reef complex.

The depth at which these reefs grew is uncertain. SCOFFIN (1971) quotes a maximum of 30m for the Wenlock reefs, although he based this figure on the occurrence of *Girvanella*. RIDING (1975) has shown *Girvanella* to be present throughout a considerable depth range and specifically quotes Scoffin's conclusions as erroneous. The reef biota show no community zonation equivalent to that described by LOWENSTAM (1950; 1957) as indicative of reef growth from quiet into rough water. However, evidence of higher energy conditions prevailing towards the top of the Bergevika reefs is afforded by the planar nature of the reef top and underlying c.50cm stromatoporoid and coral talus bed. Both these occurrences are regarded as indicating growth into a zone of water energy high enough to cause active erosion of the reef framework i.e. at a depth where wave, even surf, action was dominant.

GARRETT et al (1971) have described two lagoonal patch reefs from Bermuda which have characteristics pertinent to the study of Ordovician patch reefs developed in an epicontinental setting. Although differing from the Bergevika reefs in that these modern analogues are composed mostly of coral, those reefs which are within 1 or 2m of the surfaces are built of massive forms whereas reefs with tops 4 to 5m below the surface are covered by branching corals. ALBERSTADT et al. (1974) have implied that the assemblage of massive corals is a high energy assemblage. Such a model would lend itself ideally to the faunal associations seen in the Bergevika reef complex. The sediments around the base of the reef contain abundant branching corals, many preserved _in situ_, while below the eroded top are massive stromatoporoids and corals. The Bermuda reefs also show a decrease in coral species diversity as the degree of exposure increases, although reefs subjected to the greatest exposure have the greatest coral biomass and are therefore probably the largest and most massive reefs. ALBERSTADT et al. (1974) draw analogies to Ordovician patch reefs in the United States which show a dominance of one or a few taxa in their upper parts. Such dominance is certainly evident in the Bergevika reefs, where the upper parts are composed almost solely of _Eoflecheria_ and stromatoporoids. Indeed, as far as taxa are concerned, the framework of the reefs is composed almost exclusively of corals and stromatoporoids. The implication of this is that the Bergevika reefs developed in shallow water, probably no more than 5 or 6m depth, and grew rapidly upwards into 1 or 2m of water when the main reef development took place prior to destruction and erosion in the surf area. A lowering of sea level to obtain a similar situation is discounted on the grounds that the reef bodies show no evidence of increasing width towards the top, a criterion regarded by SCOFFIN (1971) as indicative of steadily decreasing water depth.

ALBERSTADT and WALKER (1973), ALBERSTADT et al (1974) and WALKER and ALBERSTADT (1975) have described four vertical development stages from both Ordovician and younger reefs, which they have termed (in order of progression):

i) stabilization (pioneer) stage

ii) colonization stage

iii) diversification stage

iv) domination stage

Equivalent developments can be recognised in the Bergevika reef complex, where the stabilization stage or pioneer community is represented by the pelmatozoan calcarenites and calcirudites previously described (p.151). A detailed reconstruction similar to that presented by ALBERSTADT and WALKER (1976) is not possible at this stage, but certain similarities can be drawn. The bioclasts are pelmatozoan dominated, contain algal remains (Solenopora, Hedstroemia and ?Girvanella) and have encrusting ectoproct bryozoa, as well as thin laminar stromatoporoids, which may well act in an encrusting manner, locally stabilizing the mobile substrate.

Such stromatoporoids could be recognised as belonging both to the pioneer and colonizing communities, as they often appear in the latter role at the base of the small ragged reefs contained within these pelmatozoan beds. The main Bergevika reefs have a colonization community dominated by Eoflecheria subparallela or ?Palaeophyllum, upon which the domical stromatoporoids have established themselves.

Diversification is represented by the inclusion of Liopora and other corals together with Solenopora into the stromatoporoid dominated framework. The growth of the flora and fauna in the reef pockets can also be included in this stage (see pp.177-181).

Alberstadt and Walker's final, or domination, stage is more difficult to recognise and distinguish as a separate entity, although it is probably represented by the Eoflecheria - stromatoporoid rich upper parts of the reefs. It could equally well be argued that the whole of the reef biomass is stromatoporoid dominated and therefore represents a domination rather than diversification and domination stage. However, it appears that changes in the overall community structure of the Bergevika reefs take place in a vertical sense, even if represented by the addition or subtraction of "in reef" dwellers within a low diversity framework. This situation can be directly related to reef development in a shallow high energy environment (ALBERSTADT et al., 1974).

From the above descriptions and conclusions it would appear that Eoflecheria subparallela represents a coral which flourished in high energy conditions, often at the expense of the stromatoporoids. However, E.subparallela also occurs in abundance at the base of the reef in relatively quiet conditions and appears absent from the central part of the reef where stromatoporoids and Liopora are the dominant framebuilders. The role of E.subparallela as a member of the pioneer community has been described above, and it appears that as soon as the corals grew above a soft muddy substrate, they were colonised by stromatoporoids which flourished. Competition for niches at the top of the reef was reduced by the high energy environment which limited the stromatoporoids but allowed the Eoflecheria to once again establish themselves. In the central parts of the reef where diversity and niche competition was greatest, Eoflecheria irregularis is found inhabiting pockets within the framework. The question then arises as to whether this is indeed a different species or an adaptation of growth form to the new conditions, which represents a degree of niche specialisation, a criterion regarded by WALKER and ALBERSTADT (1975, p.243) as diagnostic of the autogenic stages (in particular the diversification stage) of community evolution. If this is true then the changes in form of *Eoflecheria* may provide useful guidelines in the recognition and definition of the colonization, diversification and domination stages of reef development in the Mjøsa Limestone.

IV. THE ERIKSRUD REEFOIDAL UNITS

Scattered exposures in the quarry at Eriksrud reveal stromatoporoid dominated reefoidal masses, which because of overall morphological and stratigraphical differences with the Bergevika reefs are briefly described below.

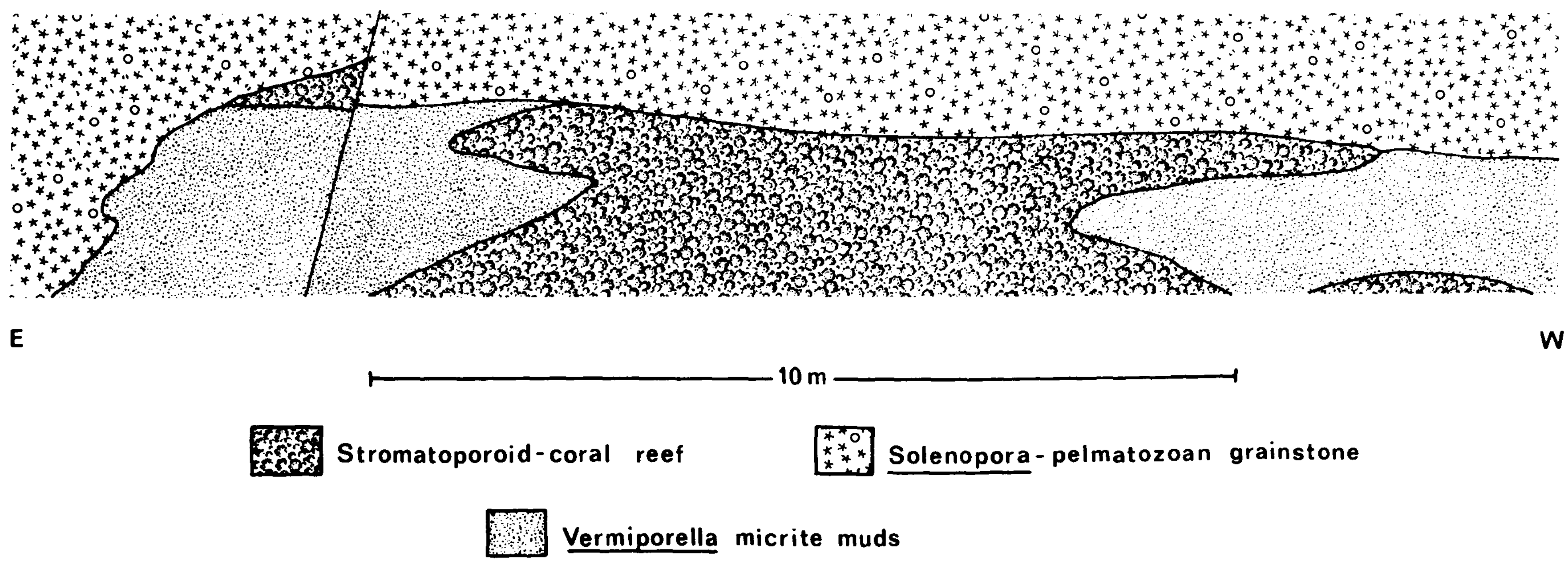
The reefoidal units are composed of pink stromatoporoids (containing much dolomite within the coenostea), Liopora, Eoflecheria and occasional Solenopora. Stromatoporoids are by far the most abundant, often accounting for the complete biota at any sample site. A crudely developed framework is present (although most of the stromatoporoids are not in a convex upward orientation). In the pockets, Conularia and Vermiporella are frequently found.

The relationship of this biomass to the surrounding sediments is given in Fig. 4.19. The boundary between the reefoidal mass and the Vermiporella micrite is often difficult to determine precisely due to the considerable interdigitation and loose skeletal framework involved. However, an intimate association between the two exists, with the Vermiporella micrites occupying a strictly interreef position.

The third rock type is a pelmatozoan-Solenopora-Bioclastic grainstone, which appears both above and below the reefoidal units as well as laterally equivalent to them and the Vermiporella micrites. In addition to the above mentioned bioclasts, these beds contain Liopora and Conularia fragments also, together with occasional patches (clasts?) of Vermiporella micrite.

The shape of these reefoidal masses and their relationship to the surrounding sediment indicates development as a series of flat sheets in equilibrium with the surrounding sedimentary regime. Optimum periods of growth resulted in marked lateral spreading and vice versa. No topography is envisaged, although the constituent organisms must have presented relief on the substrate sufficient to allow a fall in energy and deposition

Fig.4.19: The Eriksrud reefoidal beds. Field sketch.


E
W
10 m
Stromatoporoid-coral reef
Solenopora-pelmatozoan grainstone
Vermiporella micrite muds

of mud between areas of colonisation. The bioclastic grainstones represent an equivalent area of different biotic constituents (surrounding pelmatozoan thickets?) which eventually overran this localised development. As in the Bergevika reefs, there is no evidence of high energy conditions causing comminution or disruption of faunal elements, although some energy conditions capable of dislodging and disorientating stromatoporoids must be envisaged. It is possible that such disruption could be a direct expression of the baffling action these organisms performed.

Stratigraphically these beds are equivalent to the Vermiporella beds of the Holetjern Member and the Favositid-Halysitid beds of the Snippsand Member.

V. THE NON-REEFBUILDING STROMATOPOROIDS.

Non-reef building stromatoporoids are found throughout the Mjøsa Limestone in thin (20-70cm) beds of micritic mudstone with a variable quartz and/or dolomite content. Quartz rich beds tend to be greyer and more fissile, while dolomite rich beds are yellow or green depending on the degree of weathering.

Stratigraphically, these beds show their optimum development in the Gaalaas and Eina Members, which are regarded as lateral equivalents of the Bergevika Reef Member. Apart from local occurrences above the *Solenopora* and *Eoflecheria* units at Eina and Kallerud respectively, stromatoporoids appear singularly absent from the lowest members of the limestone. The Holetjern and Snippsand Members both contain non-reef stromatoporoids, but their occurrences are scattered and only briefly described below.

Preservation of the internal structures is little better than in reef dwelling stromatoporoids, but a series of curved cyst plates suggests that most may belong to the Labechiidae. At the top of the Gaalaas Member (at Snippsand) ?*Cystostroma* may be present, and in the Snippsand Member ?*Clathrodictyon* appears. These distinctions are only generalised and based upon a relatively small percentage of specimens where preservation of microskeletal architecture has been sufficient to allow any identification. More meaningful divisions were obtained by considering the physical parameters defined earlier in the chapter, and by making special reference of the Snippsand locality where its distinct stromatoporoid horizons can be recognised within the Gaalaas Member.

Size and Shape

A variety of shapes exist, but a tendency towards domical forms is noticeable especially in the Toten district. At Aannerud and Rud discrete domical coenostea are present in a highly dolomitised unit, while at Eriksrud a thin micrite mud bed forms the main quarry face and exhibits an abundance of domical shapes which, although spread randomly, appear by their relationship to one another to represent the optimum non-reef development (Fig. 4,20a). Other developments are present in the Toten area but are mostly small, isolated, ragged or fragmented individuals.

The Snippsand exposure of the Gaalaas Member provides a degree of shape variation, with compound forms displaying both sheet and domical affinities, and also domical and rounded coenostea (Fig. 4.20b). At the top of this succession a series of broad, dominantly conical, forms exist (plan views are presented in Fig. 4.21), with maximum diameters of 10 to 80cm, but with a height of only 8 or 10cm.

Specimens from Furuberget exhibit a variety of shapes, but those in the lower part of the Gaalaas Member are extremely ragged, small (8 to 10cm. max. width and 3 or 4cm in height), encrust orthocone shells with little evidence of spreading onto the adjacent substrate (Fig. 4.22a) and are themselves encrusted by algae (Fig. 4.22b).

The upper members of the limestone contain sheet-like or ragged specimens at Snippsand, domical forms which may be both scattered or closely packed at Fredang, and scattered ragged to rounded individuals among the Vermiporella bearing dolomites of Toten. With the exception of the Fredang fauna, all specimens are small (less than 15cm wide). Some bizarre thin sheet-like forms are also evident at Snippsand (Fig. 4.20c).

Orientation

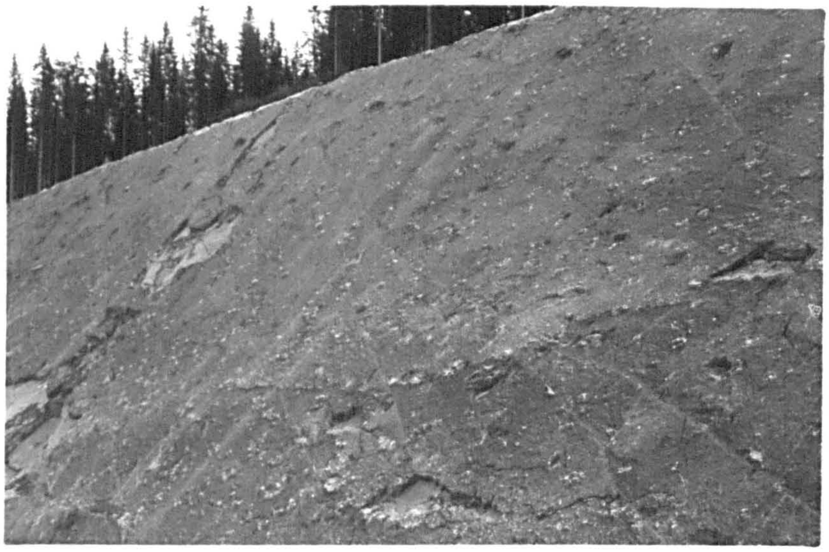
More than 90% of stromatoporoids in this category are in a convex-upward orientation, the anomalies being the small ragged or rounded individuals. Orientation criteria cannot be applied to the bizzare sheet like forms at Snippsand but, because of their branching form and intimate relationship with the sediment they are regarded as in situ growth phenomena.

Fig.4.20: Non-reef stromatoporoids.

a) distribution on a bedding plane (stromatoporoids are the white spots) Eina Member. Eriksrud quarry.

b) thin laminar growth forms with immediately overlying oncolite horizon (base of hammer shaft) in a peloidal grainstone sequence. Gaalaas Member. Locality. Snippsand. Hammer is 33cm long.

c) bizarre growth form (centre). Snippsand Member. Locality, Snippsand. Coin is 2.70cm diameter.



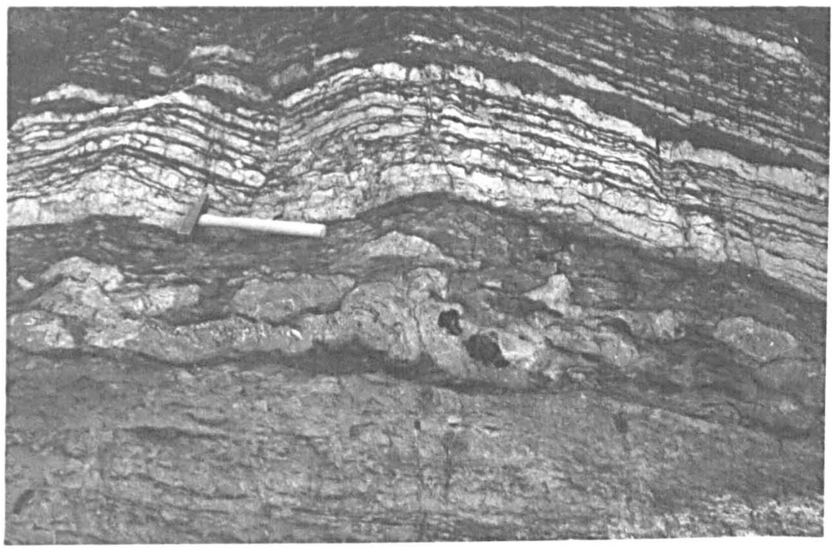


Fig.4.21: Non-reef stromatoporoids. Plan view of coenostea in the uppermost bed of the Gaalaas Member. Snippsand. Black represents dolomite.

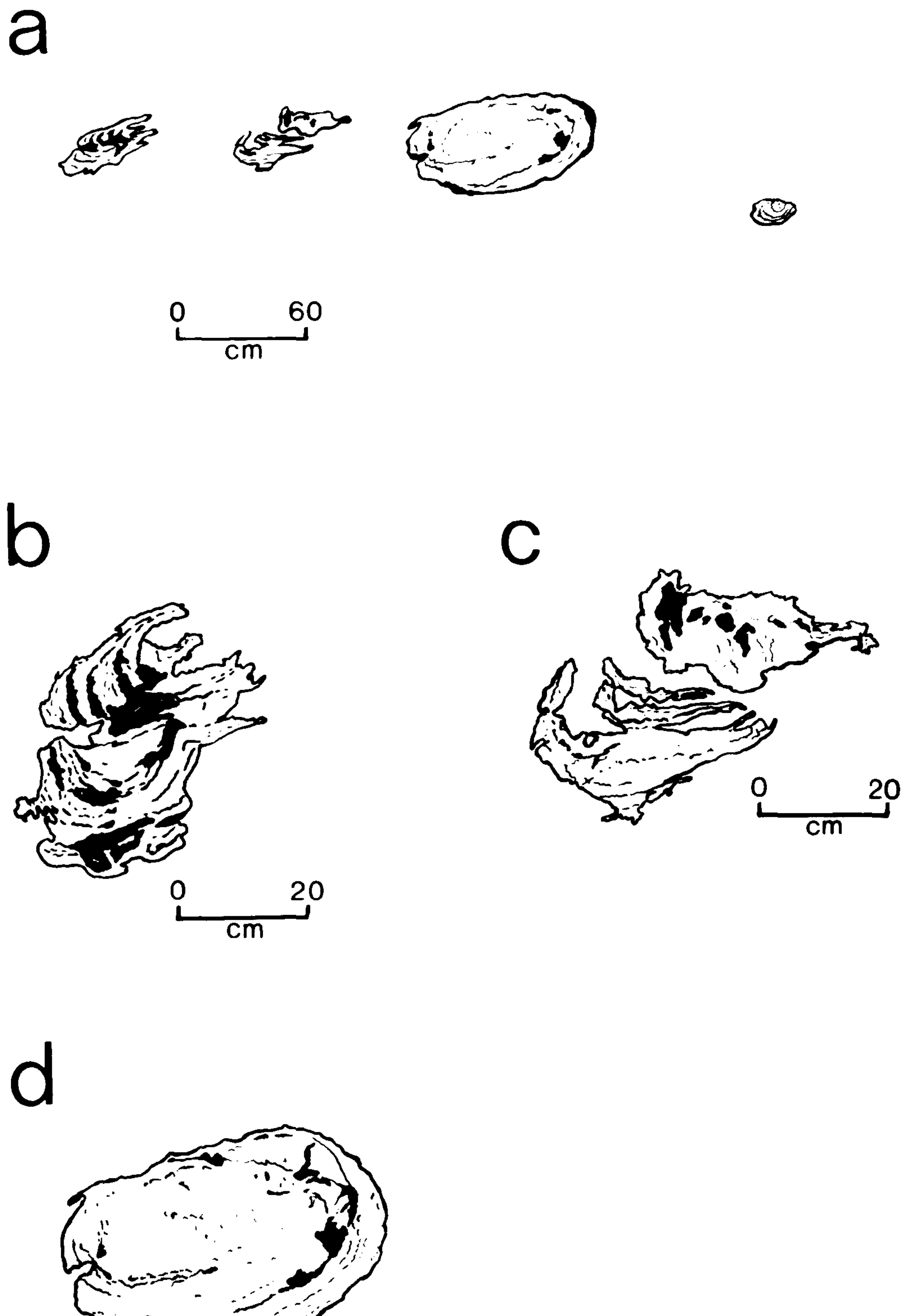
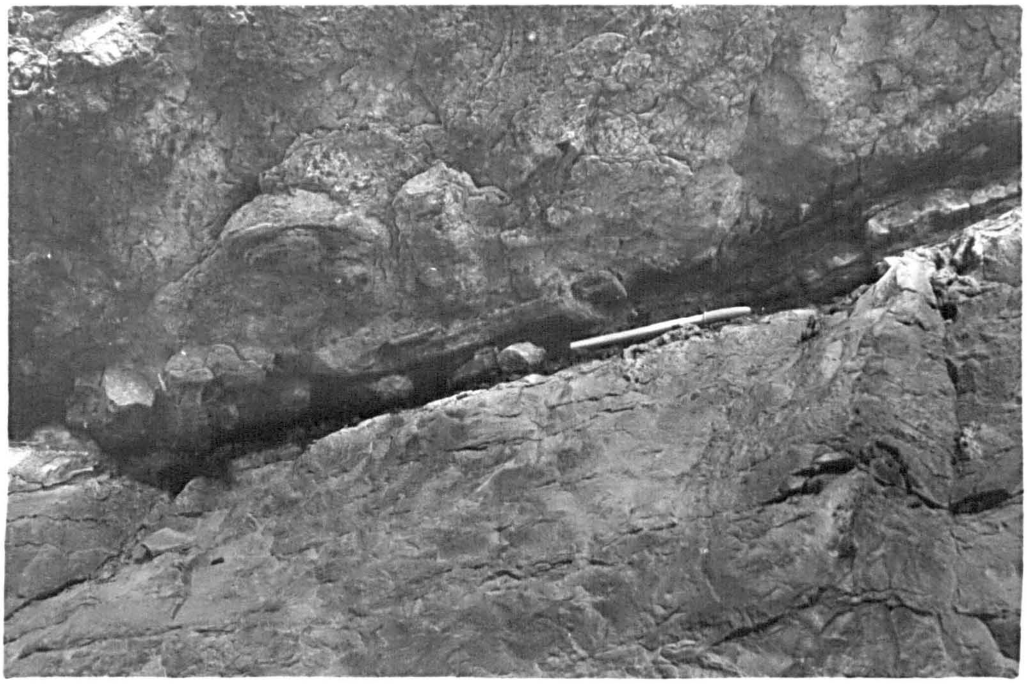
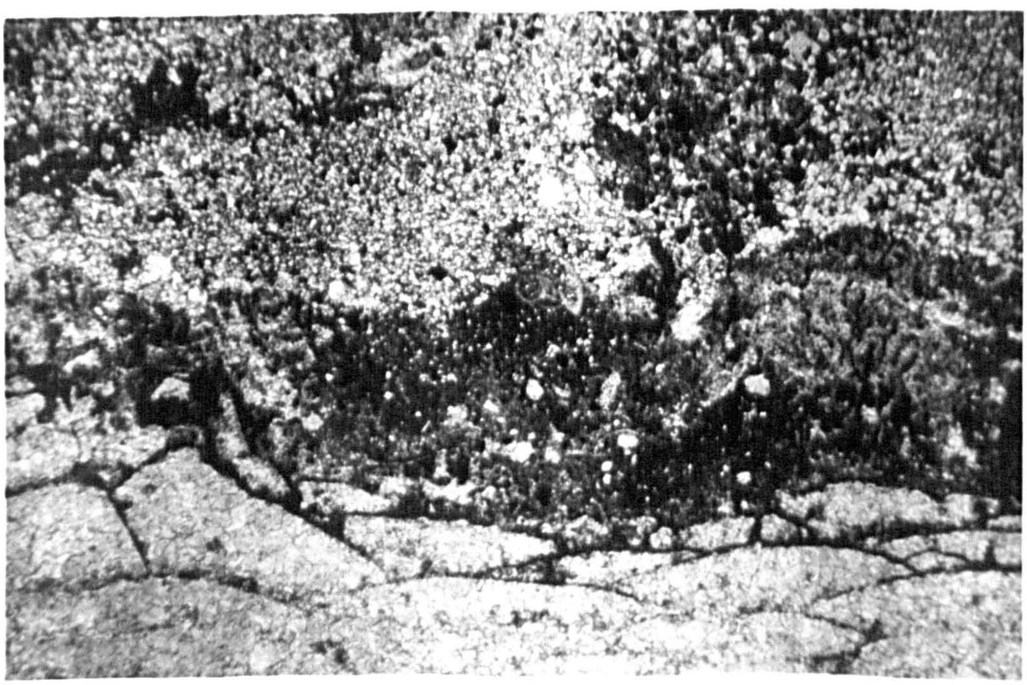

a
0
60
cm
b
0
20
cm
c
0
20
cm
d
0
35
cm

Fig.4.22: Non-reef stromatoporoids. Gaalaas Member. Locality, Furuberget South.

a) basal view of bedding plane showing small irregularly shaped coenostea. The elongate form immediately above the biro encrusted an orthocone which has been removed to leave a mould. Biro is 14.5cm long.

b) stromatoporoid coenosteum (note replacement by neomorphic sparry calcite) encrusted by algae (dark band) which have trapped quartz grains and small bioclasts. Enclosing sediment is highly dolomitised. Slice. Gaalaas Member. Locality. Furuberget South. x 12.





Associated sediments and biota

This is the only parameter to show any significant variation and allow an environmental significance to be attached to the stromatoporoid horizons. The background sedimentation was at all times carbonate mud but this contains a variable percentage of quartz, bioclasts or dolomite, in addition to differing sedimentary structures and non-drifted biotic constituents.

At Snippsand the majority of stromatoporoid beds are micrite dominated, dark brown to black in colour and contain a variable quartz (5 to 40%) content. This is mostly silt grade material, but many horizons exist which display a fissility typical of argillaceous grain sizes. Dolomitised beds are not common, although dolomite is present in most beds. Associated biota are mainly confined to specimens of articulated Ancystrorhyncha, which are often found in small "nests" as well as scattered throughout the beds. Oncolites are also present, although in varying percentages and usually concentrated above the stromatoporoids, near the boundary with, and in the basal parts of, the overlying bed. Lateral equivalents of these beds in Gaalaas quarry, although containing no stromatoporoids, often contain articulated Ancystrorhyncha and lie between peloidal units. The major difference between the two localities is colouration. The beds in the quarry are either purple, or green, and contain vertical bioturbation features identical to those in the beds at Hole kalkverk, which contain well developed dessication cracks. Some evidence of similar structures is present but the distinction of dessication and bioturbation marks in a vertical section alone is always tenuous. The relationship between sediment and coenostea at Snippsand suggests equilibrium between growth and sedimentation rates. Incursions of fine sediment onto the coenosteum resulted in the demise of the affected portion of the organism (Fig. 4.20b), prior to periods of regeneration and lateral expansion. Such a relationship suggests growth under quiet, very shallow conditions.

At Aannerud, dolomite is more abundant, as are Ancystrorhyncha rich beds, but the main sedimentological feature is the presence of straight assymetrical ripples, dessication cracks and both horizontal and vertical bioturbation features. Other Toten localities display a lack of sedimentary structures, although some poorly developed ripples, both large and small scale, can be seen at Rud in stromatoporoid bearing horizons. Sediments are micrite dominated throughout, while articulated Ancystrorhyncha are the only other fauna present, and these vary from common to extremely rare.

The uppermost beds of the Gaalaas Member at Snippsand display a totally different petrography; they are dark brown micrites, probably faecal in origin, contain little quartz and only local concentrations of dolomite in what appears to be burrows. Biota is dominated by bushy ectoproct bryozoa and Hedstroemia, both of which appear as in situ occurrences. Associated elements include articulated ostracods, trilobite fragments, small orthocones, rare articulated Ancystrorhyncha and occasional echinoderm spines.

The Snippsand Member stromatoporoid bearing beds are pelmatozoan dominated packstones and wackstones with a variety of bioclasts including trilobites, ostracods, brachiopods, molluscs, faecal pellets, algae, coral and stromatoporoid. Quartz grains are angular, silt grade, but relatively scarce (less than 5%), while dolomite is even less evident. Associated macrofauna in growth position is represented by sheet or small domical stromatoporoids, Halysitid and saucer like Favositid corals. In Toten, equivalent beds are almost entirely dolomites with abundant Vermiporella, some ?Liopora, occasional Eoflecheria and rare Solenopora, none of which appear to represent an in situ growth assemblage.

Discussion

From the evidence above it appears that the ahermatypic stromatoporoids flourished in an area of quiet shallow water. Although depth may have varied, it is possible that periodic exposure to subaerial environments may have occurred. The prevailing shallowness is regarded as the prime factor in preventing an otherwise flourishing group of potential reef building organisms from constructing a 'framework' at least two coenostea in thickness, when similar organisms were active in producing reefs simultaneously in a more southerly palaeogeographical location. Other factors could have influenced growth rates, among which sedimentation rates, or substrate are the most often cited. The stromatoporoids in question appear to have coped most efficiently with the apparently slow sedimentation rate and periodic coenosteal innundations. Most had apparently died before deposition of the overlying sediment. The growth of stromatoporoids on a soft substrate is a question which has aroused some controversy in the past. One would expect an organism growing on a soft mud to assume a thin encrusting form as a means of support (ST. JEAN, 1969 p.1406). Thus the thin sheets of the bizarre forms seen in the Snippsand Member are more likely to occur under such conditions than the larger more massive forms considered here. It is possible that stromatoporoids found it difficult to grow on a soft muddy substrate. The specimens from the lower part of the Gaalaas Member may be a testament to this, as indeed may the growth of the reef builders on Eoflecheria rather than directly on a muddy bottom. If this is the case then the carbonate muds which form the substrate to these stromatoporoids must have been semi-lithified to allow such profuse growth. A warm, quiet, very shallow environment would provide an ideal site for early lithification processes to act.

Comparisons with the stromatoporoid bearing grainstone horizon of

Eriksrud (described in Appendix III) show some marked differences. This horizon is regarded as a lateral equivalent of the Bergevika reefs, and represents growth in deeper, more agitated water conditions over a harder substrate. Vertical growth is more pronounced in this horizon; stromatoporoids are often found one atop the other and bear a closer resemblance to the reefoidal growth forms than those in the horizons described above. Such evidence implies that the stromatoporoid growth forms are influenced by depth of water and energy of the system, rather than substrate or taxonomic differences.

VI. CONCLUSIONS

Stromatoporoids within the Mjøsa Limestone are poor indicators of sedimentary environments as they are tolerant of a wide range of conditions. Generally, they appear to have developed in relatively shallow waters and depth appears to have been the most important physical parameter influencing reef or non-reef growth. Growth forms are varied and appear directly related to niche restrictions, which are both palaeobiological and sedimentological. In non-reef environments, restrictions on growth form were applied by depth of water, rate of sediment incursion onto the coenosteum and (possibly) hardness of substrate. Within the reefal environments, biological competition appears to have been the major factor, although mobility of substrate and rates of sedimentation, together with hydraulic energy were also important. Although forming the dominant frame-builder, stromatoporoids rarely formed a major constituent in the pioneer community but tended to flourish once this had been established. Tolerance of mud or turbidity of water (c.f. MANTEN 1971) is difficult to ascertain as most stromatoporoids are found associated with carbonate mud, but it appears that a preference for development on a hard substrate was shown. Water turbulence (c.f. LECOMPTE 1956, 1959) may have restricted development, especially in the surf zone, although here again depth of water (and periodic exposure) was probably a more important factor.

Both reef and non-reef stromatoporoids constitute distinct sedimentological as well as palaeoecological units, and can, therefore, be regarded as distinct facies types. Thus it is proposed to assign both units to Facies 10 (p.63) and subdivide as shown below:

Facies 10A - Stromatoporoid reef facies

Facies 10B - Non-reef stromatoporoid facies

CHAPTER FIVE

Solenopora PALAEOECOLOGY

I. INTRODUCTION

A. GENERAL.

Specimens attributed to the genus *Solenopora* occur almost ubiquitously throughout the Mjøsa Limestone, but their great abundance at certain horizons allows of their study from both a palaeoecological and sedimentological standpoint. Individuals are easily distinguished by their colour (light grey when weathered, black when freshly broken) and lack of macrostructures.

JOHNSON (1961, p. 73) gives the geological range of the Solenoporaceae as Cambrian to Cretaceous (with probable survivors into the Paleocene) and presents a series of maps in which he (1960, pp. 29-35) outlines their world wide distribution in the Palaeozoic.

B. HISTORICAL NOTE.

The genus *Solenopora* was created by DYBOWSKI (1877) on the basis of a specimen from the Ordovician of Estonia, which he described under the name *Solenopora spongiodes* and regarded as a monticuloporid coral. The systematic position of this and other similar organisms was uncertain for many years until BROWN (1894), describing all known and several new species of *Solenopora*, proposed that they be considered as algae rather than invertebrates, and placed them close to coralline algae. PIA (1927) erected the Solenoporaceae, discussed the included genera and suggested various features, particularly wall pores and cross partitions, as basic criteria for classification. Pia's classification was endorsed by other authors, among them HØEG (1932), although there was disagreement from MASLOV (1935, 1956) who suggested they be considered a separate sub-family, not a separate family within the Corallinaceae. JOHNSON (1960, pp.14-15) modified both Pia's and Maslov's classifications, proposing that the differences between the coralline and red algae are great enough to warrant classification as separate families.

A detailed review of Palaeozoic Solenoporaceae is given by JOHNSON (1960) while some Norwegian species have been described by HØEG (1932; 1961 pp. 112-113).

C. PALAEOECOLOGICAL CONSIDERATIONS.

A full discussion of the problems involved in palaeoecological studies of Solenopora together with a review and definition of the criteria selected as being most meaningful is presented in Appendix III. These parameters can be successfully classified by a four fold division:-

i) Shape and size

ii) Orientation

iii) Form

iv) Peripheral condition

Observations based on these criteria were combined to produce a rapid classificatory system for field analysis (Fig. III.6).

II SOLENOPORA BIOHERMS

WILSON (1975, p.23) gives the definition of a bioherm as a "build up whose internal composition shows it to be largely derived from in situ production of organisms or as a framework of encrusting growth as opposed to mainly mechanical (hydrodynamical) piling". Solenopora units which accord to such a definition are recognised at various localities within the Mjøsa Limestone and are described below. The most accessible is at Snippsand where the bioherm is distinctive by virtue of its restricted biota and high percentage of sediment.

A. GEOMETRY

A series of vertical transects of the cliff face were undertaken during Spring low water to enable construction of a northeast-southwest profile. The bioherm emerges as a strongly asymmetrical body with an apparently sharp, steeply inclined southwestern margin, but with finger-like extensions to the northeast (Fig. 5.1). The base is not exposed but the minimum dimensions of height and length obtained were 15m and 60m respectively.

From the absence of sediments dipping off the biomass edges, it is apparent that the Solenopora did not construct a topographically significant feature. Indeed, the geometry of the biomass (Fig. 5.1) and the algae-sediment relationship suggests that the unit accumulated as a series of sheets which may only have been one or two thalli in thickness, giving a maximum relief of 70cm. Major sediment incursions can be seen occurring at a single horizon effectively smothering growth; this again points to the biomass achieving low relief during growth.

B. SOLENOPORA PALAEOECOLOGY.

Because Solenopora occurs to the exclusion of all other mound building organisms, it performs a complex series of functions (Fig. 5.2).

Fig.5.1: Cross section of the Solenopora bioherm. Snippsand.
Vertical lines represent logged sections.

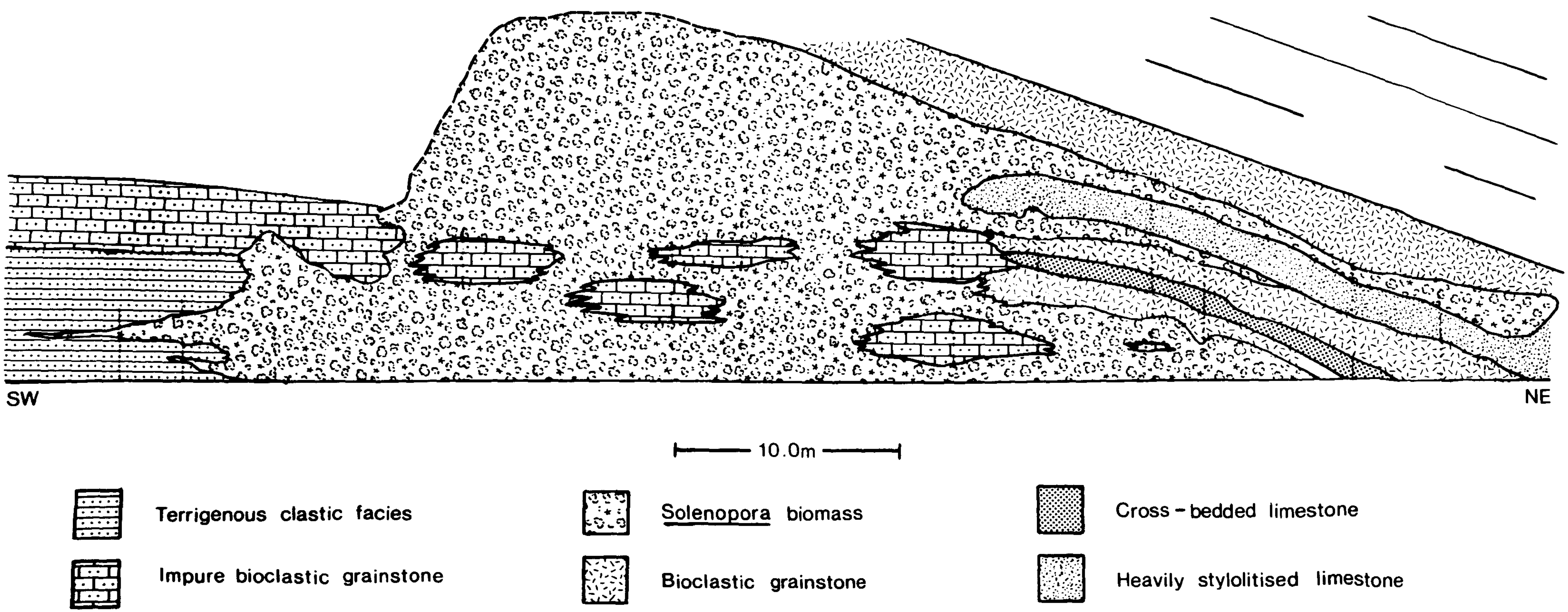

SW
NE
10.0m
Terrigenous clastic facies
Impure bioclastic grainstone
Solenopora biomass
Bioclastic grainstone
Cross-bedded limestone
Heavily stylolitised limestone

Fig.5.2: Biotic composition and functional palaeoecology within the Snippsand *Solenopora* bioherm.

Function	Organisms
Mound builder Sediment trapper Food source Domicile Sediment supplier	Rhodophyta { *Solenopora compacta* *S. compacta var. norvegica* *S. filiformis*
Fodinichnia Domichnia	Unknown borers
Encruster	Bryozoa
Accessory organisms	Brachiopods Bryozoa Echinoderms Trilobites

Each of these is examined in more detail below.

1. Mound building *Solenopora*.

Approximately 20% of *Solenopora* examined possessed clearly defined, simple formed, shapes classifiable as hemispherical, cabbage head or inverted bell (see Fig. III.6), and among these, 40% have a maximum diameter of 20cm or more, while only 15% have a diameter of less than 10cm. These growth forms tended to be concentrated in sheets (e.g. the extensions of the biomass illustrated in Fig. 5.1) where the majority of thalli appeared in a convex-upward orientation, i.e. growth position. From this evidence it was concluded that large or very large *Solenopora* with the aforementioned shapes were most likely to represent *in situ* individuals, especially as only 8% were found in a convex-downward orientation (Fig. 5.3a). 60% of *Solenopora* within the biomass, however, were found to have divided or irregular shape categories, the two often merging to give thalli with a complex form (Fig. 5. 3b). Irregular forms appear in a variety of orientations (Fig. 5.3c) and occupy a small to large (rarely very large) size range. Branching forms (Fig. 5.3c) are extremely rare and account for less than 3% total. The remainder of the *Solenopora* appear as small rounded, simple, forms (Fig. 5.3c) between the larger thalli.

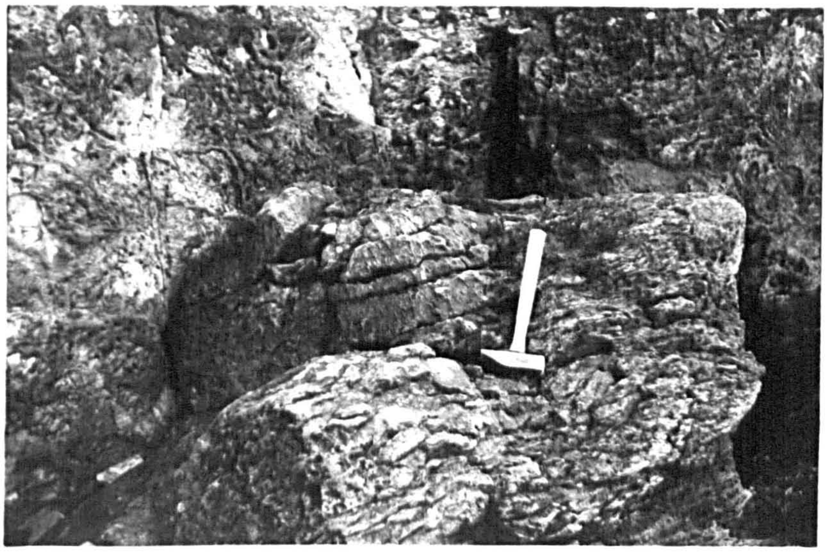
Many of the thalli appear to have suffered shape distortion through the introduction of increasing amounts of sediment (Fig. 5.3b). Taken as a whole, the ratio of sediment to algae varies locally from 10-80%,but is usually between 40-60%. This indicates biomass development in an area where the rate of sedimentation was high relative to growth rate. This is illustrated by Fig. 5.3b, where the thallus edge (lower left) shows contemporaneous growth with a high rate of sedimentation. Towards the crown sediment interdigitates with the thallus edge indicating synchronous growth, before a final influx almost causes its demise. The rapidity of sedimentation can be used to account for the apparent splitting of a simple

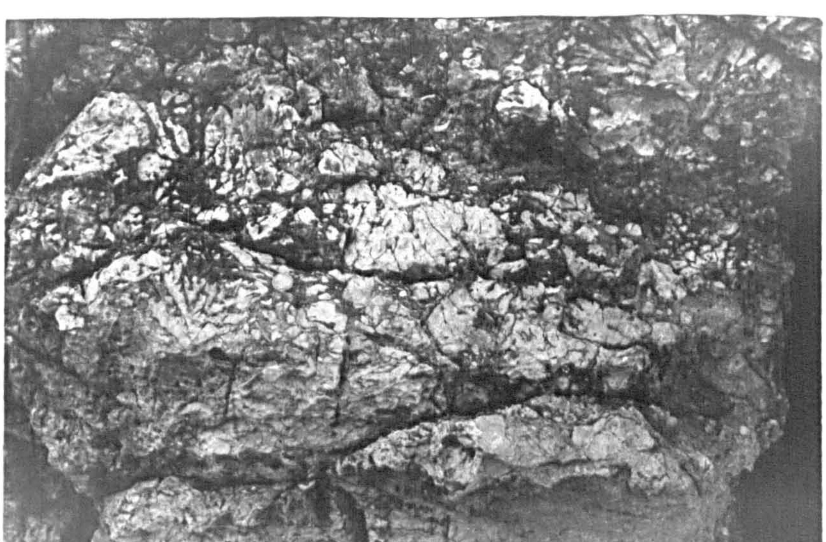
Fig.5.3: Variations in biohermal *Solenopora* shape. Snippsand.

a) bell shaped thallus (convex down). Hammer is 23cm long.

b) hemispherical thallus with a high sediment content which shows regeneration (upper right). Hammer is 33cm long.

c) variable forms; branching, split, bored, small and large. Coin is 2.70cm diameter.





formed thallus into a complex form. In many cases parts of the plant must have remained above the enveloping sediment and acted as separate regeneration points (Fig. 5.3b).

A regeneration process is observable on a microscale within individual Solenopora thalli. Inundation of the thallus periphery by carbonate mud appears to have killed certain areas, but the unaffected parts show regenerative processes; this is determined by changes of tube alignment which in many instances indicate an uneven nodular upper surface to the Solenopora. Regeneration proceeded from a series of separate nuclei producing tufts which later coalesced to give the familiar uninterrupted, parallel tubed, growth pattern associated with this alga (Fig. 5.4a). The commonest effect of these sediment films was a slight refraction of tube orientation (Fig. 5.4b), while the occasional single coarse particle (e.g. an echinodermal bioclast) could be incorporated into the thallus by tube growth around the foreign body (Fig. 5.4c).

2. Solenopora as a host.

Attack by unidentifiable boring organisms upon these algae was particularly severe. Almost every specimen examined showed some effects. These borers exhibit a high degree of selectivity in their actions, being restricted to Solenopora and Diplotrypa. Borings are dolomite or dolomite-quartz siltstone filled with additional bioclastic material (mainly echinodermal) in the larger cavities. The morphology of the borings varies, but two distinct groups can be recognised:-

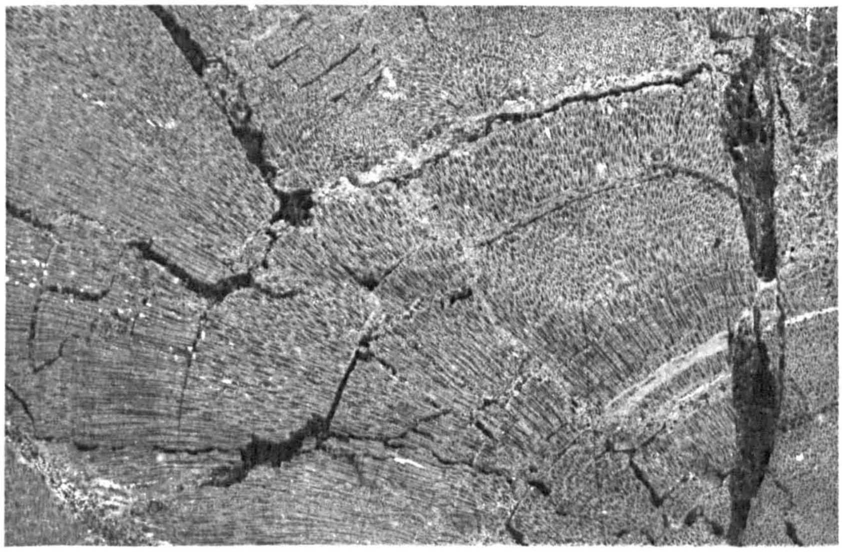
i) small straight sided punctures rarely more than 5mm wide (commonly 2mm) but of variable length (1cm being common) and concentrated around the periphery of the Solenopora. These are regarded as domichnia, and from their position in the thallus may be a post mortem or late life phenomena.

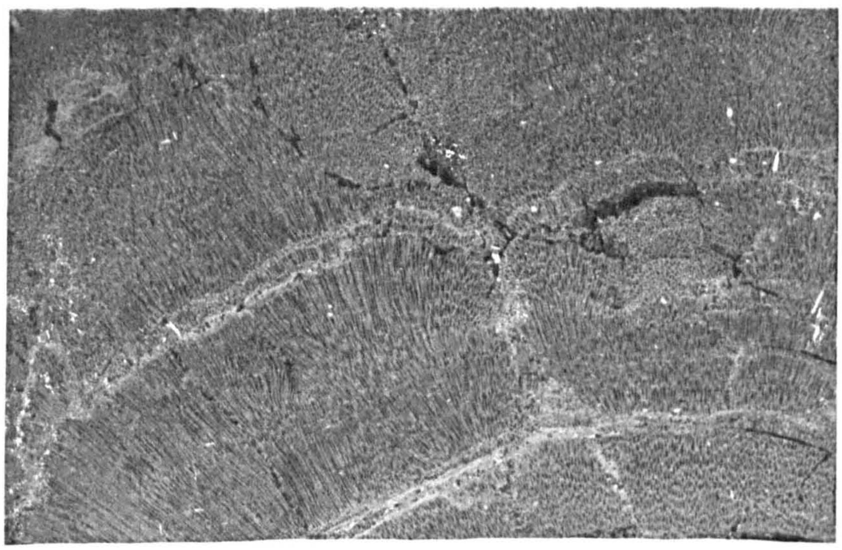
Fig.5.4: Variations in Solenopora internal structure due to incorporated sediment.

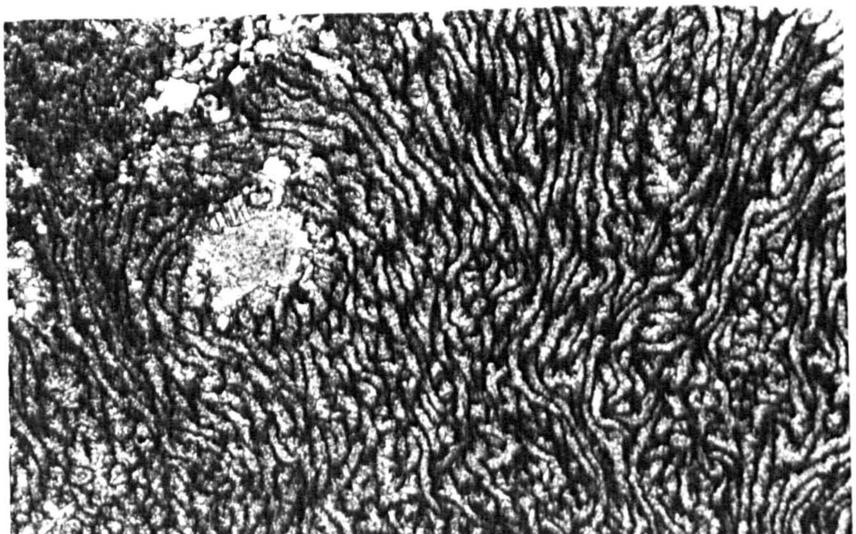
a) fine grained carbonate band caused a realignment of tubes and growth of 'tufts' before normal orientation is obtained. Negative print of slice. Snippsand bioherm. x 8.5.

b) fine grained carbonate band causing only mild refraction of tube alignment. Negative print of slice. Snippsand bioherm. x 8.5.

c) incorporation of an echinodermal fragment into the thallus. Slice. Sivesindhagen Member. Eina. x 48.







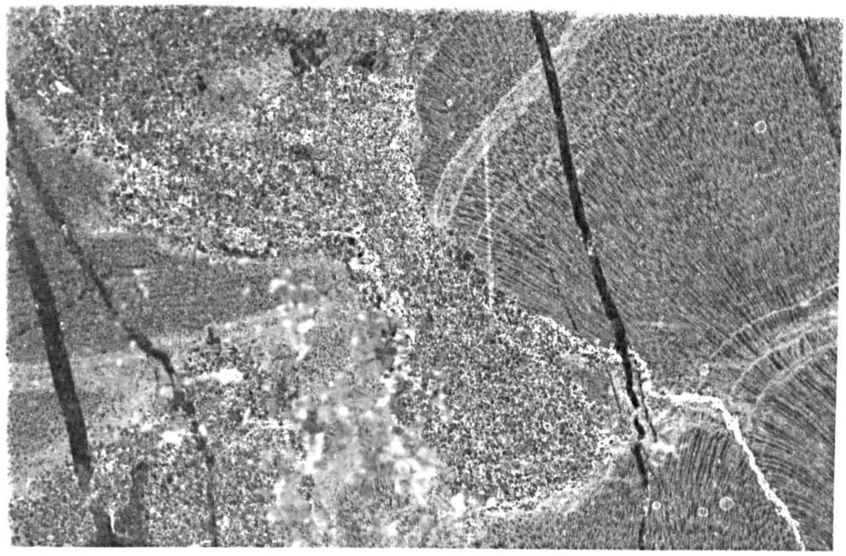
ii) large irregular areas of sediment within the thallus (Fig. 5.5a,b) which often break it up into apparently separate growing units where most abundant. From later annealing and resumption of normal tube orientation (Fig. 5.5b) it is apparent that these features were being formed while the plant was actively growing. Two possible explanations exist; firstly, the uneven growth surface of the Solenopora would allow sediment to accumulate between the knobs, which could then grow over and cover it in a manner similar to incorporation of bioclasts; or, secondly, such structures represent organic destruction (domichnia or fodinichnia) of an unknown organism, which became sediment filled following vacation. The irregular shape and large size favour an organic, probably fodinichnial origin (c.f. KAPP 1975 who describes similar structures as due to grazing by the gastropod Maclurites). Many of these structures contain evidence of habitation by bryozoa, which either line walls (Fig. 5.5b) or, in extreme cases, occupy the whole cavity (Fig. 5.5c). There is no apparent evidence of a symbiotic or preferred relationship as the same bryozoa encrusts echinoderm debris in the flanking sediments. A similar two fold explanation for the origin of the cavities arises if the bryozoa are considered; firstly, it is possible that encrustation was on dead surfaces of a growing Solenopora, which later enveloped the bryozoa, cutting off nutrient supply and causing death; or, secondly, the bryozoa encrusted the walls of vacated borings. The first of these hypotheses appears the least likely because one has to invoke as initial method of killing local areas of the Solenopora surface, and the mechanism of causing death to the bryozoa should also cut off the open circulation existing, hence stopping the supply of any sediment to the cavity; no bryozoa bearing cavities filled with sparry calcite cement were found. Destruction of the thallus by organic activity would expose the dead tissue of the thallus interior, thus providing a relatively hard substrate

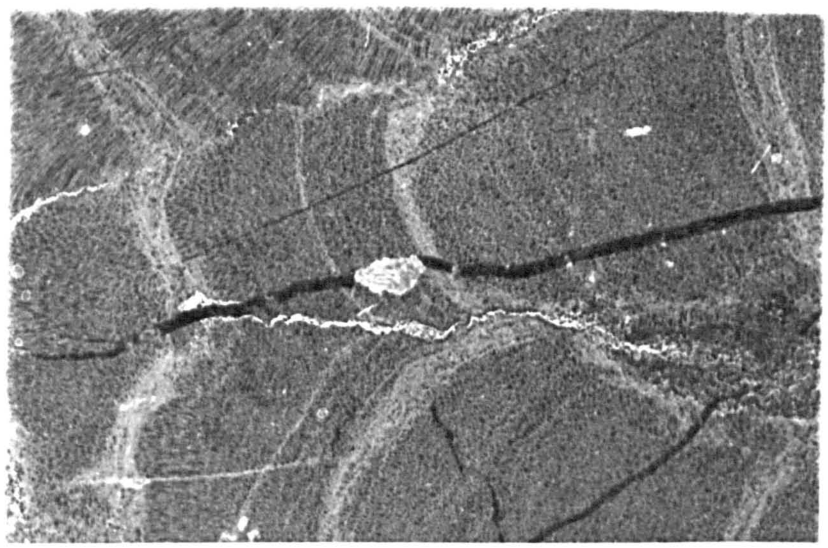
Fig.5.5: Variations in *Solenopora* internal structure due to biogenic activity. Negative prints of slices. Snippsand bioherm. x 8.

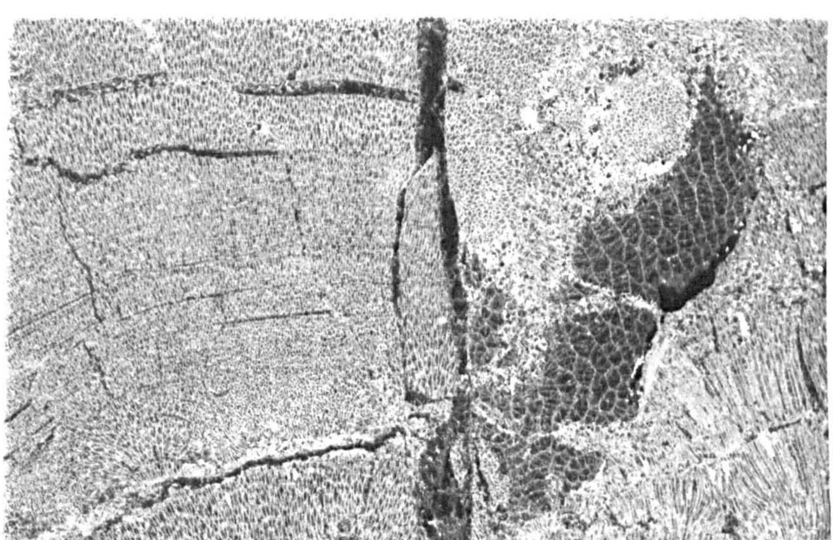
a) fodinichnial burrow filled with dolomite and terrigenous siltstone.

b) regeneration and healing of thallus. The dolomite siltstone filled cavity (extreme right) progressively becomes 'healed' with minor disorientation of tubes until normal growth and alignment occurs (left).

c) occupation of internal cavities (bores) by bryozoa.







for encrustation, an open circulation for nutrient supply and the terminal mechanism of sediment influx with subsequent smothering. The position of many bryozoa as thin encrustations only on the walls of cavities and the relatively sharp truncation of cellular structure at these margins, indicates a destructive organic origin to these cavities.

3. Solenopora as a sediment supplier.

The dislodgement of sedentary Solenopora and their subsequent transport to a site of deposition qualifies them both as sedimentary particles and a potential sediment source. From the physical condition of many small Solenopora (see p.233 for a detailed discussion) it appears that they are derived from the mechanical break up of larger individuals.

The disintegration of algae to aragonite needles has been regarded by many (see BATHURST 1971, p.276 for a full discussion) as an origin for modern aragonite muds. Petrographic analysis of the inter-thallic and intrathallic sediments has revealed a dominance of dolomite, which manifests itself in hand specimen as a yellow rind, cavity or burrow fill, and is distinct from other enclosing sediment types. Dolomite appears as subhedral, 20-40 μ rhombs which often contain a dirty crystal as a nucleus. Local concentrations of angular quartz fragments, 20-60 μ diameter, appear in the dolomite groundmass. Also within these cavities are isolated patches of micrite, which are neither peloidal nor intra-clastic in origin and often display a rapid decrease of dolomite towards the centre. Here, if as elsewhere in the Mjøsa Limestone dolomite is fabric selective in respect of micrite, the micrite can be regarded as a primary sediment fill which may have escaped dolomitisation by early lith-ification. The origin of this primary carbonate mud is debatable. Was it derived from breakdown of the Solenopora thallus, or does it represent sediment trapped from suspension by the baffle action of a sheet of algae?

An answer to such a question is bound to effect some form of compromise, but the general high energy prevailing at the time, the lack of micrite in other sediments and the concentration between algal thalli, suggest a local (i.e. algal) origin and deposition in a sheltered (i.e. inter- or intrathallic cavities) microenvironment, where contaminants (quartz silt or bioclasts) occasionally filtered through the protective Solenopora canopy.

4. Solenopora as a sediment trapper.

The possibilities of Solenopora acting as a trap for locally derived fine carbonate sediment has been mentioned above. No doubt exists about the ability of this alga to retain quantities of quartz silt or even bioclastic calcarenite in the larger interthallic cavities. Quartz silt accumulation in borings has been previously mentioned, but the bulk of this sediment (and all the calcarenites) accumulated between areas rich in Solenopora. Thus it appears that Solenopora was acting as an energy reducing agent in the system, causing the rapid dumping of sediment between groups of individuals.

C. SEDIMENTS WITHIN THE BIOHERM.

A diagnostic feature of the Solenopora bioherm is its high sediment content (in excess of 40%). A simple four-fold division can be affected:-

i) dolomite (micrite)

ii) calcisiltite

iii) terrigenous siltstone

iv) impure bioclastic grainstone

1. Dolomite

This has been described on p.214, and is regarded as representing a diagenetic alteration of micrite (aragonite) primarily derived from in situ disintegration of Solenopora thalli.

2. Calcisiltite

A fine grained black carbonate found as small pockets between thalli or groups of thalli. Hand specimen and petrographical analysis show it to be identical to variant B of the fine grained carbonate facies (Facies 4), although it lacks any bioclastic component.

3. Terrigenous siltstones

In contrast to the thin interbeds of the terrigenous clastic facies (Facies 1), quartz siltstones within the Solenopora bioherm are irregularly distributed, possess poorly defined bedding, no ichnofauna, a paucity of sedimentary structures (some high angle, small scale, planar and trough cross-stratification is present) and display a higher percentage of bioclasts concentrated in stringers parallel to any bedding structures which may be present. Echinodermal bioclasts (0.25-5mm) are dominant; bryozoa (often encrusting other bioclasts) and disarticulated brachiopod valves are common. Micrite is present as an intraparticular fill to some bryozoa and crinoid ossicles, as well as relict patches of original matrix in the dolomitised areas of the samples. Quartz is present as 40-100 μ angular detrital grains.

4. Impure bioclastic grainstones.

Sediments pertaining to this facies occupy the largest interthallic cavities between groups of thalli (Fig. 5.1). High and low angle cross-stratification is common with the smaller bioclasts aligned along the foresets. Variation of bioclastic components is locally at a maximum, with concentrations of Solenopora, rhynchonellid, orthid and dalmanellid brachiopods, stick branching bryozoa, and pelmatozoan fragments, although the latter form a background sediment type on which abundances of the others are overprinted.

Petrographic analysis reveals a texture identical with Facies 2, viz. a grain supported calcarenite/calcirudite, with quartz and dolomite in the intergranular cavities. Bioclasts are dominated by echinoderm fragments (size range, 0.5mm to 1.6mm; mode, 1mm), many of which are crinoid ossicles with a micrite fill to the axial canal. Where other bioclasts dominate, the size range of the echinoderm fragments decreases e.g. in a section with 70% Solenopora, the interparticular cavities are filled by an echinoderm wackstone (dolomitised) with the bioclasts exhibiting a 200-800 μ size range and a mode of 600 μ. The echinoderm fragments only rarely exhibit syntaxial rim cements or pitting of the grain boundaries due to pressure solution effects with adjacent grains.

Quartz is present as angular fragments with a 40-100 μ size range (mode 60 μ), although grains as small as 10 μ have been recorded. The only difference between quartz in these sediments and in terrigenous siltstone beds is abundance (less than 10% compared to 50 or 70%).

Dolomite is present as subhedral to euhedral rhombs, ranging in size from 20 to 100 μ; the smaller (40 μ) being more anhedral and dirty while the larger rhombs are clearer, often with a dirty nucleus to a euhedral form. Small relict patches of micrite are occasionally found in areas of heavy dolomitisation, indicating that early lithification may have prevented the fabric selective dolomitisation process, and, more importantly, much of the original interparticular cavities were occupied by primary carbonate mud.

5. The Sedimentary Environment.

The bioclastic grainstones represent deposits from high energy conditions which acted on the Solenopora biomass, while the finer quartz siltstones indicate settling from suspension in times of quiescence or within sheltered inter- or intrathallic cavities. The question of whether these sediments are derived from the immediate vicinity of the bioherm and are deposited by high energy conditions representing periodic influences of storms or tides is uncertain. Consideration of the sedimentological properties of the beds which form lateral equivalents to the bioherm is presented below in order to elucidate the situation.

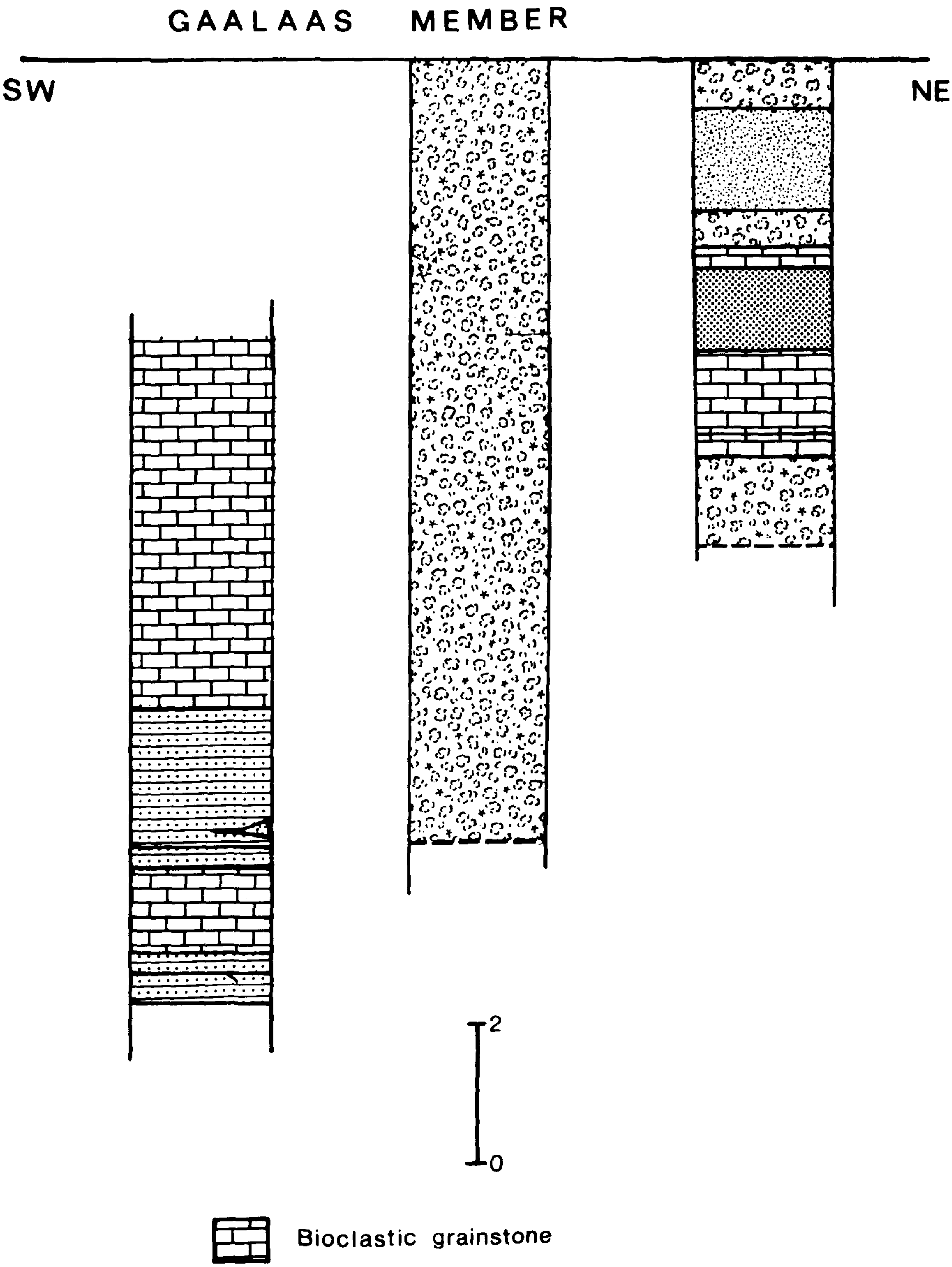
D. ASSOCIATED LATERAL SEDIMENTS.

The lateral equivalents of the bioherm differ markedly in their geometry and composition between the northeast and southwest flanks. Due to the regional dip of the beds (Fig. 5.1) the sediments to the southwest are slightly older than those to the northeast, and a useful starting point for an appraisal of environmental conditions at the time of Solenopora growth.

The oldest beds equivalent to the Solenopora bioherm are bioclastic calcarenites and calcirudites (Fig. 5.6) dominated by a rhynchonellid orthid brachiopod assemblage in a pelmatozoan groundmass. Other faunal elements include bryozoa, trilobite fragments and occasional small rounded Solenopora. Quartz content increases towards the top of each bed to give a siltstone before the next limestone unit begins. The basal 5 or 6cm frequently contain pebbles of siltstone up to 5cm (max.) diameter. Overlying this sequence are a series of coarse quartz siltstones, with typical terrigenous clastic (Facies 1) characteristics, and interdigitating thin lateral extensions of the Solenopora bioherm. These two clastic units and the overlying bioclastic limestone are distinguished by a lack of Solenopora. The dominant palaeocurrent trends based on ripples and small channels (Table 1.5) are NW - SE with a secondary mode at NE - SW (Fig. 5.6).

The northeast flank contrasts with the southwest and has four vertically distinct, bioclastic grainstones (Fig. 5.1); these are assigned a convenience nomenclature and briefly described below:

Fig.5.6: Section logs of lateral sediments to the Snippsand <u>Solenopora</u> bioherm (Vertical scale in metres).



Other lithologies as in Fig.5.1

i) Lower bioclastic grainstones

ii) Cross-bedded bioclastic grainstones

iii) Upper bioclastic grainstones

iv) Stylolitised bioclastic grainstones

i) Lower bioclastic grainstones: these are approx. 1.5m thick, (min. of 0.5m); contain a brachiopod (strophomenid, orthid, rhynchonellid) dominated fauna with fairly common *Streptelasma*, pelmatozoan debris, and near the periphery of the biomass, small, rounded *Solenopora*. Quartz rich horizons are limited to thin (c. 1cm.) bands near the top of the grainstone unit. The contact with the underlying biomass is sharply defined, distinctly irregular, and in many places appears erosional. This lithofacies is identical to the beds overlying the Bergevika *Solenopora* bioherm.

ii) Cross-bedded bioclastic grainstone: this consists of a pelmatozoan dominated bioclastic grainstone which is easily distinguished by well developed, dark brown, quartz siltstone accentuated, low angle (10-14°) planar cross-stratification. Total thickness of this lithofacies is 75-90cm, but it contains several poorly developed sub-units within it, each displaying a poorly imbricated pebble conglomerate (quartz sandstone/siltstone pebbles) at the base. Towards the periphery of the bioherm, the cross-stratification gradually dies out until it eventually becomes unrecognisable and is replaced by an impure quartz rich limestone, almost identical to the impure bioclastic grainstone on the southwest flank. Palaeocurrent directions taken from foreset azimuths indicate a flow direction towards the northwest.

iii) Upper bioclastic grainstones: these differ from the lower bioclastic grainstones by a higher quartz content, bands of imbricate sandstone pebble conglomerate (diameter 3-5cm by 2-3cm) and lack of corals, bryozoa and algae from the faunal element, which is dominated by pelmatozoan material, coarse ribbed orthids, rhynchonellids and strophomenids, with fragments of trilobites (?Chasmops) and occasional Kokenspira-like gastropods. In contrast to the cross-bedded facies, there is a marked increase in quartz and pebble content together with small rounded Solenopora towards the bioherm periphery. The bedding within this unit is thin (c. 20-30cm), with the basal parts of each bed showing poorly developed low angle planar cross-stratification above a pebble conglomerate. Unit thickness increases from 50cm at the bioherm edge to 3m at the northeastern extremity of exposure.

iv) Stylolitised bioclastic grainstone: stylolites are the dominant structure found in this 1.5-2m unit, and are picked out by black weathering of the insoluable residues; they occur at vertical intervals of 2-3cm and display a max. thickness of 2mm; this gives the whole unit the appearance of being thinly bedded. In places, the stylolites show an inclination resembling cross-stratification. Pelmatozoan material is the dominant biotic constituent; small rounded Solenopora appear in isolated pockets and are probably derived from the bioherm. Quartz (siltstone) content increases substantially in the upper 20cm of the unit, giving a calcareous quartz siltstone-fine sandstone bed directly underlying the uppermost finger extension of the biomass (Fig. 5.1): This horizon contains a well developed ichofauna; dichotomously branching forms (?Arthrophycos); sinuous, often discontinuous forms, (?Sinusites); incomplete, straight horizontal forms, (?Planolites), and Scoyenia-like forms are apparent. In places the bedding within this unit runs directly into the flank of the bioherm or into protrusions from the surface of the lateral extension. As a whole the unit gradually wedges out to the southwest, passing laterally into a bed of small rounded Solenopora which abutt directly against the main biomass.

E. DISCUSSION.

The Solenopora established themselves on a dominantly quartz sand/silt substrate as a series of discrete patches in which a delicate balance between organic growth and sedimentation rate existed, both in respect to the bioherm and to individual Solenopora. For example, the northwestern extension represents periodic quiescence of sedimentation and a resultant flourishing of organic activity while the steeper south-western margin indicates a more even balance, a compromise between equal growth and sedimentation rates. Such a situation would require a slight topography of the biomass, but there is no evidence of this feature attaining a substantial relief on the sea floor. The growing biomass may have attained a height of one or two Solenopora only (max. specimen height measured was 40cm), and development is envisaged as a series of laterally spreading sheets. Restriction was placed upon expansion to the southwest; the most likely cause being a combination of prevailing current directions, mobility of substrate and rapid sedimentation rates; the incursions of impure bioclastic grainstones into the biomass from this direction can be regarded as supporting evidence.

Within the bioherm a complex sedimentary regime appears to have been dominated by high energy conditions, producing a system whereby local quartz silts and bioclastic sediments were spread over the Solenopora. The turbulence created winnowed the micrite muds from around the colonies causing the particles to go into suspension along with the other finer grains, until a rapid energy decrease caused dumping of the mixed sediment over the biomass, between the colonies and in the sediment dominated areas separating organic patches. The periodic nature of these events and the alignment of many of the larger areas of sediment incursion within the bioherm suggest a particularly vigorous influx which almost destroyed the biomass. Such occurrences are adequately explained by storm conditions, although it appears that the sedimentary environment was one of moderately high energy, high sedimentation rate and localised mobile substrate, all of which placed restrictions on the growth of Solenopora.

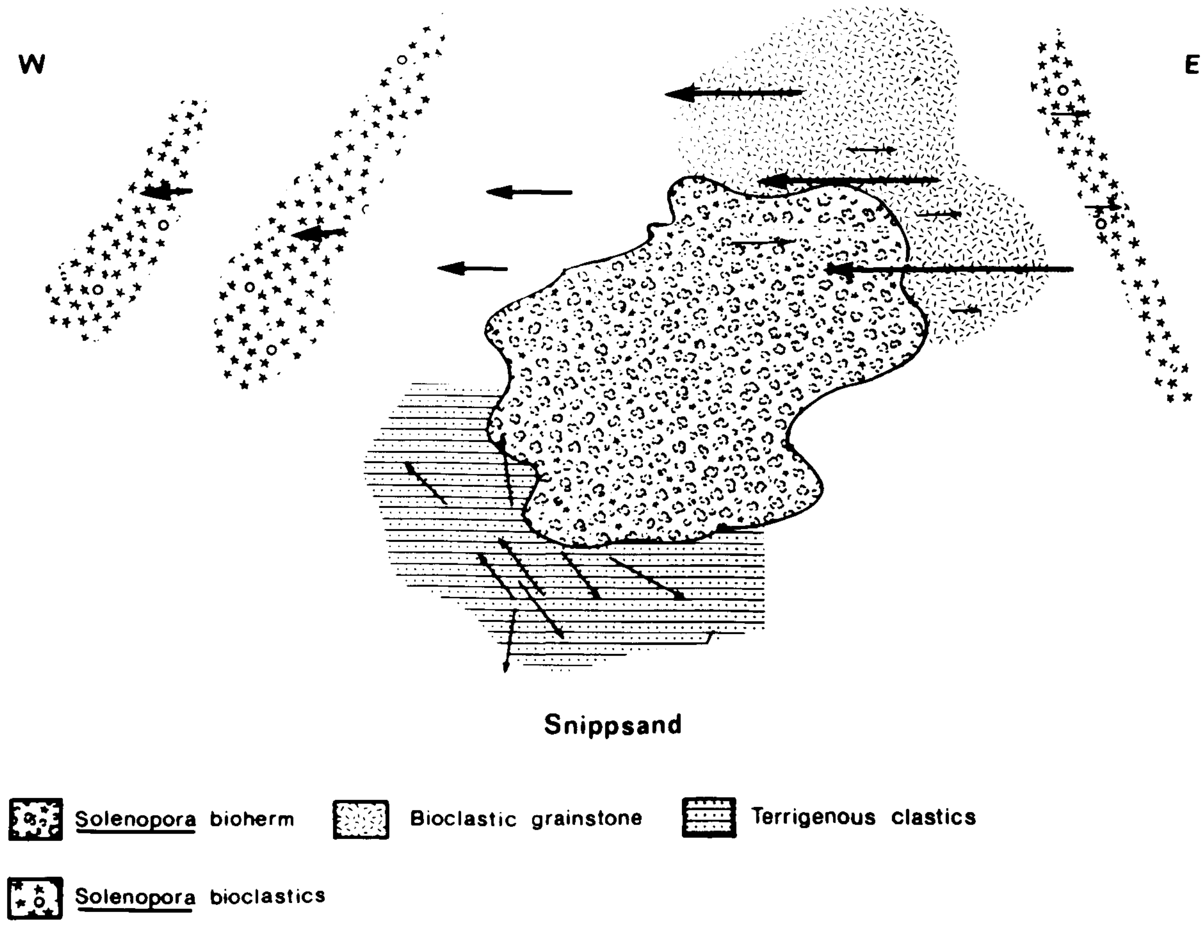
Palaeocurrent analysis indicates that the sediments associated with the northeastern flank of the bioherm were derived from a source to the east while those at the southwestern flank show a northwest-southeast trend with a secondary northeast-southwest direction. The lack of Solenopora in these flanking beds indicates that, either conditions were not severe enough to dislodge the growing algae, or that conditions were so severe as to completely remove them from the area. A low energy system is envisaged for the terrigenous clastic sediments on the southwest margin, while those on the northeast are regarded as high energy (storm) deposits. Solenopora would have been carried by these currents off the bioherm and to the west (Toten) or pulled by the ensuing backwash to the east (Furuberget) as illustrated in Fig. 5.7a. An hypothesis of this nature invokes a series of questions regarding stratigraphically equivalent horizons and the recognition not only of drifted Solenopora, but the distinction of algae which suffered removal and rapid deposition from those which have undergone transport over a longer period. Solenopora rich horizons exist both in the Toten district and at Furuberget in a stratigraphically equivalent position (Fig. 5.7b) and a consideration of the palaeoecological characteristics of these horizons is discussed below.

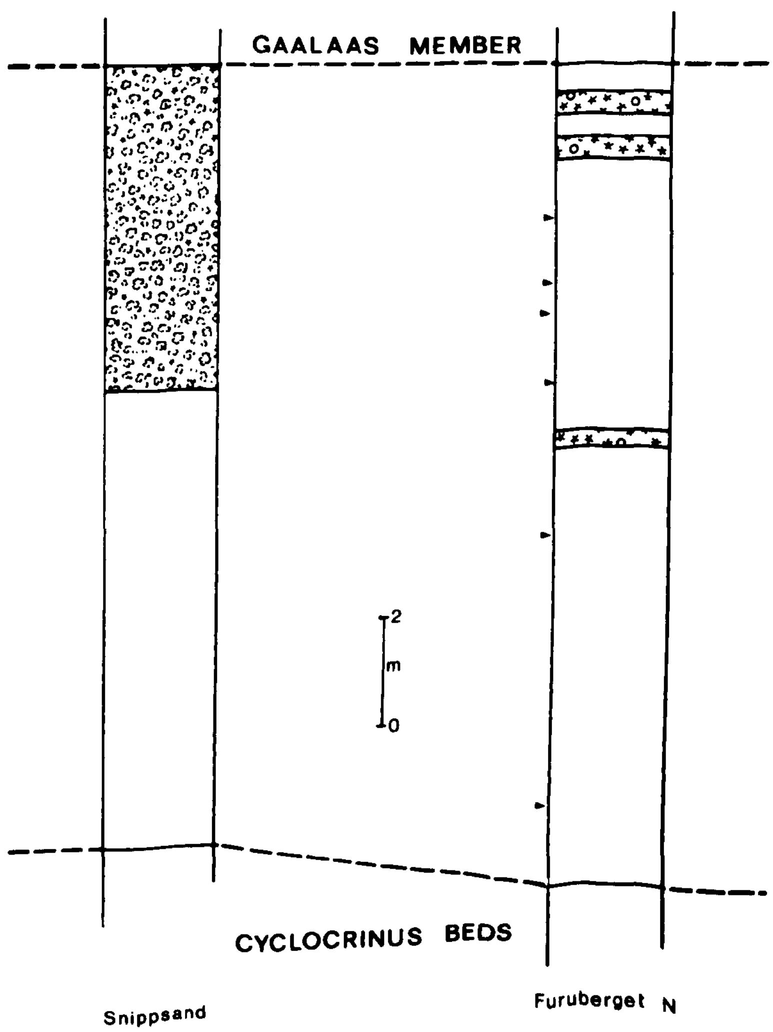
From observations on the bioherm flora it appears that a general distinction exists between drifted and non-drifted Solenopora in respect of the latter's larger size, tendency towards a conical or hemispherical outline (i.e. a convex-upward top surface), closer packing of individuals and high degree of attack by unknown boring organisms. However, only 30%

Fig.5.7: Schematic representation of the Snippsand bioherm as a source for <u>Solenopora</u> bioclasts.

a) bioclastic grainstones are washed over the bioherm by high energy tidal (or storm currents), gain uprooted <u>Solenopora</u> and are then carried to the west or east (by the backwash).

b) <u>Solenopora</u> bioclastic grainstones, and horizons of drifted algae (arrowed), in the Furuberget North succession and penecontemporaneous development of a bioherm at Snippsand.


W
E
Snippsand
Solenopora bioherm
Bioclastic grainstone
Terrigenous clastics
Solenopora bioclastics


GAALAAS MEMBER
2
m
0
CYCLOCRINUS BEDS
Snippsand
Furuberget N

or less of such algae examined showed a clearly defined outline; the main characteristic appeared as a complex interrelationship with the surrounding sediment which destroyed any sharpness of outline. In order to allow distinctions between thetwo to be accurately drawn (and hence elucidate the origin of many horizons in Toten and Furuberget), it was decided to examine in detail beds where the Solenopora had acted as sedimentological, rather than biological (in situ), components and obviously represented a drifted assemblage.

Before detailed discussions on this topic are embarked upon, a brief description of other Solenopora bioherms is included to indicate their similarity to the Snippsand model.

F. OTHER SOLENOPORA BIOHERMS.

At Bergevika South, a Solenopora bioherm exists which in all respects is almost identical to that described from Snippsand. The overall geometry and relationship to surrounding sediments (Fig. 5.8) indicates that growth here was also in a series of patches, probably discrete, with an equilibrium between sedimentation and organic growth. The surrounding sediments are also similar, although the biomass established itself on an oncolite rich bioclastic grainstone which displays a marked abundance of coarse ribbed brachiopods. Within the bioherm size and shape (Fig. 5.9a) classes are similar to Snippsand although a higher percentage of large forms appear to be present; boring of specimens is extremely common, and, in addition, many of the larger colonies which immediately underlie sediment dominated areas, display an abundance of small encrusting Halysitid corals (Fig. 5.9b). BAIRD (1976) has described Halysitid encrustations on concretions protruding from an erosion surface in a Devonian shale sequence from New York, and a parallel can be drawn with this situation. The Solenopora are substituted for the concretions, while

Fig.5.8: Cross section through the Bergevika South Solenopora bioherm. Redrawn from photographs by T. Harland.

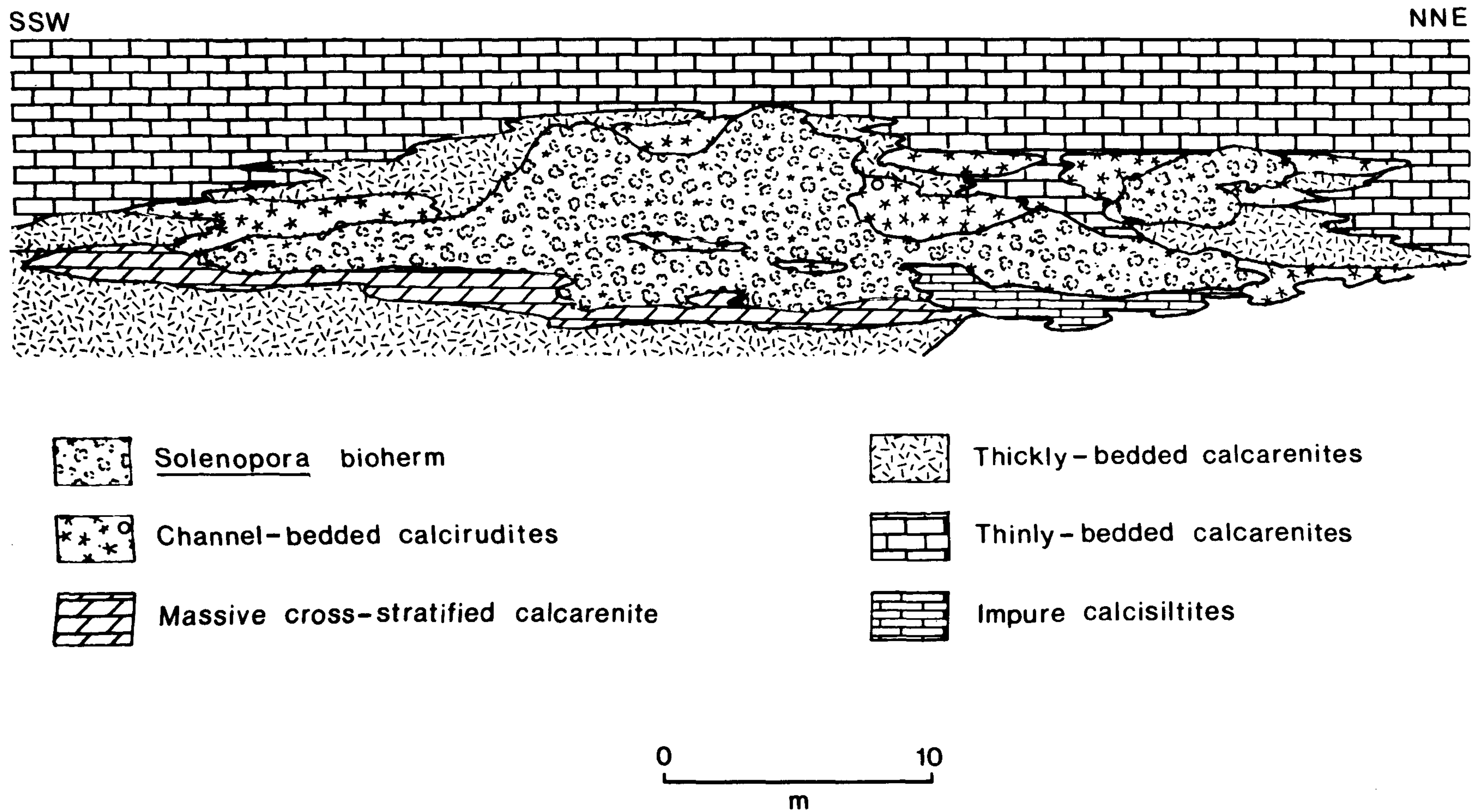
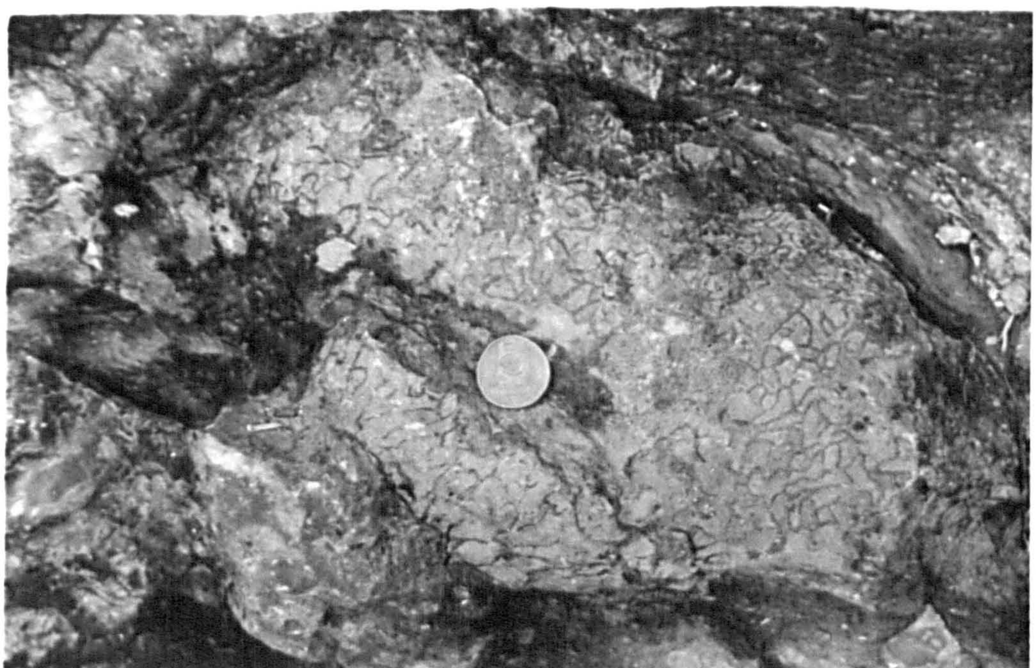

SSW
NNE
Solenopora bioherm
Channel-bedded calcirudites
Massive cross-stratified calcarenite
Thickly-bedded calcarenites
Thinly-bedded calcarenites
Impure calcisiltites
0
10
m

Fig.5.9: Solenopora in the Bergevika bioherm.

a) size and shape range. Tape case is 7cm long.

b) encrusting Halysites on Solenopora thallus.
Coin is 1.5cm diameter.



the erosion surface is replaced by a pause in deposition during a period of relatively high sedimentation. If such reasoning is correct, the presence of Halysitid encrustations assumes importance as an indicator of relatively quiet or sporadic sedimentation and should be associated with lateral expansion of the biomass. The surrounding Streptelasma rich bioclastic grainstones (c.f. the lower bioclastic grainstones of Snippsand) have increased local dips of up to 20° against the bioherm edge; an indication of a significant topographical feature.

At Kvam, the biohermal development also resembles that at Snippsand in all respects, although the weathered exposure and inaccessibility hinder any detailed comparisons.

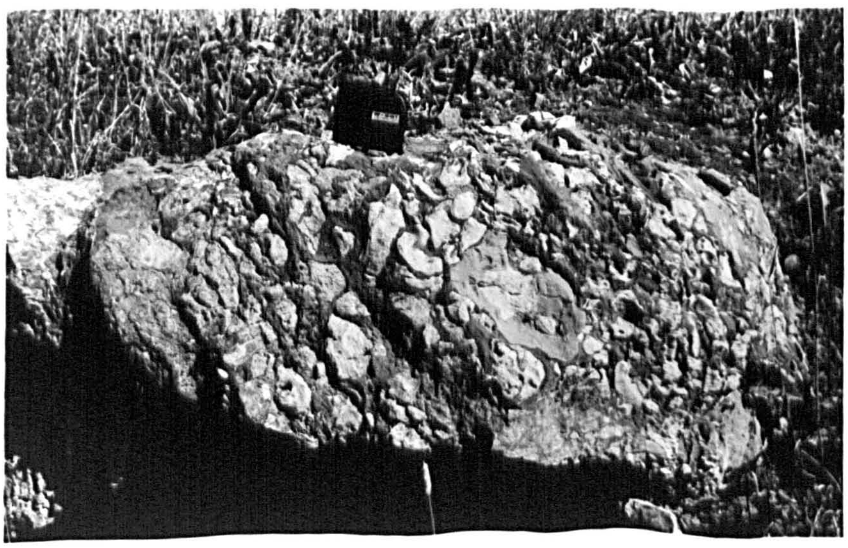
In the Toten district the Solenopora do not form such easily distinguished bioherms but appear as an amalgamation of small localised linear growth horizons. The general bioherm characteristic of closely packed, convex-upward, conical, trumpet, cabbage head or (more rarely) hemispherical shaped thalli, most of which are bored, still prevails; however, a fundamental size difference is apparent, the algae rarely exceeding 15cm max. diameter, (Figs. 5. 10a,b). Sediment content appears even higher than at Snippsand, and because of smaller thallus size, it is spread more evenly throughout the biomass (Fig . 5.10b). An additional biotic element is present in large colonies of Eoflecheria and, occasionally, Liopora; a branching alga (?Parachetes) is found at Børsvollen (Fig. 5.10c), but Solenopora remains the most abundant (80-90%) organic constituent. Well developed biomasses can be seen at Børsvollen, Eina, Løken, Aannerud, Engøydegaard, and Kallerud (Eoflecheria dominated). Sediments with these organic masses are dominated either by terrigenous clastic facies or bio-clastic grainstones; no well developed flank beds similar to those at Snippsand or Bergevika were observed, the algae pass laterally into the adjacent sediment, which is usually of the same composition as that within

Fig.5.10: Solenopora from the biomass at Bórsvollen. Tape case is 7cm long. Succession youngs to the right.

a) general view showing large thallus size and high sediment content.

b) growth unit with large thallus size and high sediment content overlies a bioclastic unit with small rounded thalli.

c) *in situ* branching form (?*Parachetes*)



the biomass. From this information it appears that biomass development in the Toten district was more restricted than at Snippsand and that an even lower relief prevailed.

III. THE NON-BIOHERMAL SOLENOPORA.

Within the Sivesindhagen Member (Toten district) and Furnesfjord Member (at Furuberget) there is an abundance of horizons which are conspicuous by their inclusion of small Solenopora. Often these are so numerous that the rock unit gives the impression of a grey (or black) micrite pebble conglomerate. In many cases, it appears that the Solenopora have behaved as sedimentary particles rather than an in situ biomass, although there are complex interrelationships between drifted and apparently non-drifted specimens. A description combined with a discussion of the palaeoecological and palaeogeographical implications of these distinctive strata is presented below.

Solenopora are commonly concentrated at the base of bioclastic grainstone beds. Typically, they are 1-7cm in size, although rare specimens up to 20cm have been recorded. Most are smooth edged, eliptical to circular in cross section, (occasionally irregular or conical) simple forms with no preferred orientation. Such concentrations, often immediately above a sharply defined (erosive) base, and large size of the algae relative to other bioclasts, suggests transportation by, and deposition from, a current of initially high, but rapidly waning, energy. The cellular structure of the algae, however, would result in a lower density compared to most enclosing bioclasts; the latter then assume a more important role as an energy indicator. Despite this fact, the Solenopora still appear to represent the heaviest particles and many beds show a vertical grading of specimens, both in terms of size (Fig. 5.11a), abundance (Fig. 5.11b) or both, away from the base. Because these beds are not regularly dispersed through any succession, it is reasonable to assume that they represent high energy influxes of a sporadic nature e.g. storm conditions.

The association of drifted Solenopora with single influxes of

Fig.5.11: Non-biohermal Solenopora forming "graded" beds.

a) basal concentration of small rounded thalli. Furnesfjord Member. Locality, Furuberget South. Hammer is 33cm long.

b) basal concentration of medium thalli which appear to have undergone little transport; many growth forms are recognisable. Note a large colony of Eoflecheria in top right of picture. Sivesindhagen Member. Locality, Sivesindhagen. Scale in cm.

higher energy conditions becomes more apparent by a brief consideration of the erosion surfaces which mark the lower boundaries of both the Eina and Holetjerm Members. The latter feature feature is well defined throughout the Toten district being conspicuous by its erosion of the underlying algal mats and introduction of drifted marine biota, including abundant Solenopora, in the overlying Hemmstadmoen Bioclastic Beds. All the Solenopora are small to medium in size, rounded, smooth edged and simple in form, with no preferred orientation. Although the thickness of this distinctive unit varies from a thin veneer to 1m, Solenopora always appear as described above. Similar features can be seen in the erosion surfaces at the base of the Eina Member; small rounded Solenopora form a basal veneer to the overlying bioclastic grainstones.

The periodic nature of the depositional conditions described above, together with the combination of Solenopora which represent different durations of exposure and abrasion of the substrate, raises the problems of how to recognise deposits formed under the prevailing sedimentary regime. In many localities (e.g. Sivesindhagen), very small Solenopora are found as stringers, parallel to bedding (Fig. 5.12a). Their lateral continuity is extremely variable, from 30 or 40 cm to 3 or 4m, but thickness is limited to one or two specimens only, each being separated from overlying and underlying individuals by bioclastic (pelmatozoan) grainstone which is Solenopora free or contains only widely dispersed specimens. The episodic introduction of these algae by the high energy, rapid influx methods proposed above becomes totally unsuitable in this instance, and an alternative has to be found. Because all the Solenopora appear to have undergone prolonged transport and abrasion, but are often close to a possible source, transportation over long distances is discounted. Gentle movement, perhaps oscillatory, across the sea floor is envisaged for these algae removed from the growth

Fig.5.12: Varying degrees of Solenopora abundance in non-biohermal facies. Sivesindhagen Member. Locality, Sivesindhagen. Scale in cm. Younging to the left.

a) 'scattered' small Solenopora with some 'stringers' in a bioclastic grainstone.

b) a close packing of medium Solenopora in a bioclastic grainstone. Rare growth forms can be seen (e.g. trumpet shape. lower centre) and the bed contains large fragments of Eoflecheria (centre).

areas in normal conditions, or which escaped burial in the high energy incursions. The concentration into linear veneers may be a reflection of current strength increasing sufficiently to produce bedload traction of these particles, or of deposition due to the cessation of local ephemeral eddies or turbulence.

The 'occasional' specimens indicate a very low concentration of mobile Solenopora detritus, which is randomly deposited; increased abundance is indicated by greater numbers of Solenopora and deposits such as those illustrated in Fig. 5.12b may not represent high energy conditions but simply fairly rapid deposition from moderate or low energy current activity. The fundamental difference between these deposits and those with basal concentrations is one of current action: in the latter example it is rapid, possibly unidirectional and high energy, while the former represents a gentle oscillation with slight increases or decreases giving local concentration of Solenopora bioclasts. High concentrations of these algae in such a situation represent either proximity to source or local abundance of debris: analysis of morphological and sedimentological parameters should help determine which situation is represented.

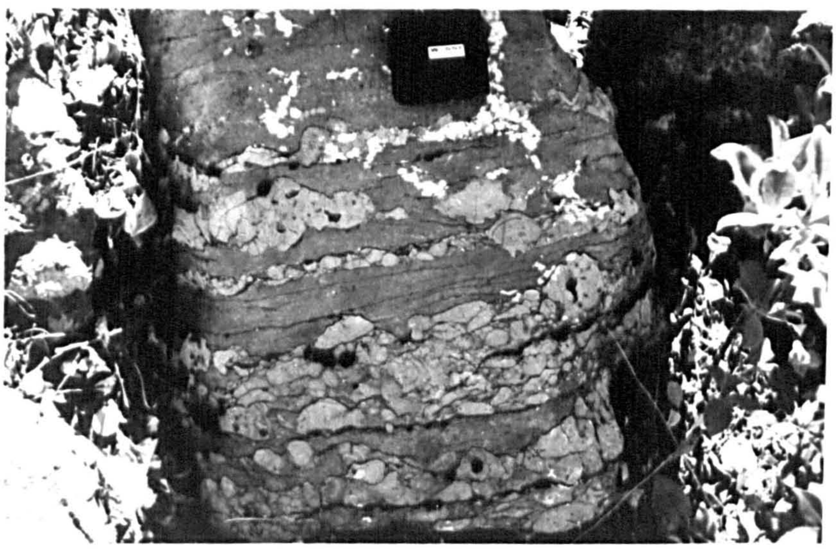
There are, naturally, examples where one is uncertain whether the algae are in situ or not. This is particularly true of single specimens which appear in a convex-upward orientation but do not possess all the characteristics necessary to facilitate an accurate determination, or possess characteristics which appear conflicting. In such situations there is little that can be done except to cite all possibilities. Where specimens are more numerous the situation is often clearer, although there may be a complex intermixing of shapes and sizes (Fig. 5.13a). In this instance the smaller rounded specimens are obviously drifted although some of the larger trumpets or cabbage heads may be in growth orientation. Three possibilities exist: i) all are drifted from the same source;

Fig.5.13: Mixtures of derived and in situ Solenopora in a non-biohermal facies. Sivesindhagen Member.

a) growth forms (large bored thallus in centre) predominate in an assemblage regarded as having moved a very small distance. Locality, Sivesindhagen. Tape case is 7cm long.

b) local colonisation of the substrate by sheets of small to medium Solenopora. Locality, Sivesindhagen. Tape case is 7cm long.

c) a mixture of growth and drifted forms. Locality, Løken, Scale in cm.



ii) there is a mixing of specimens from two sources, the small ones represent the *Solenopora* in constant movement and the larger specimens locally grown algae which have been dislodged and only moved a very small distance: iii) the large ones are all *in situ* and the smaller ones have become trapped by them. The example illustrated in Fig. 5. 13a is best explained by recourse to the second possibility cited above, as many of the larger *Solenopora* have 'growth' characteristics (i.e. shape, size and borings) but are disorientated.

The presence of *Solenopora* which appear to have grown in the immediate vicinity of their present position introduces another type of non-biohermal habit. Fig. 5.13b depicts thin bands in which *Solenopora* are densely concentrated. Despite the obvious effects of pressure solution a situation exists in which many of the specimens are in a growth orientation and show evidence of extensive boring, which implies that they may represent a local *in situ*, colonisation of the substrate.

All the previously discussed examples are enclosed in pelmatozoan dominated bioclastic calcarenites and even calcirudites. *Solenopora* are also found in quartz siltstones and by analogy with the bioherms discussed earlier in the chapter, the association of *Solenopora* and quartz siltstones should indicate the presence of a growing *in situ* biomass. Although this analogy generally holds true, there are many examples where a combination of drifted and non drifted specimens occur together (Fig. 5.13c). In such instances examination revealed that although there may be a numerical dominance of small rounded forms, there is a greater number of growth orientated, bored, trumpet or cabbage-head shaped *Solenopora* than were encountered in a similar situation in the bioclastic sediments. This evidence weighted the argument in favour of an indigenous population with local drifted additions.

IV. SUMMARY AND CONCLUSIONS.

Despite their abundance the *Solenopora* of the Mjøsa Limestone have only a limited importance in its environmental reconstruction.

Although these algae formed extensive sheet like bioherms of low relief, thrived despite rapid sedimentation and periodic storms, acted as a food source, domicile, shelter, sediment trap and a sediment source, the depth at which this considerable activity proceeded is uncertain. JOHNSON (1961, p. 251) states "one can say algal limestones are indicative of shallow water, usually very shallow water", while in an earlier paper he (ibid 1960, p.45) quotes a maximum depth of 200m for Solenoporaceae in tropical waters, but expected that "luxuriant growth" would have occurred at around 20m. RIDING (1975, p.177) notes that the Solenoporaceae have affinities to modern crustose corallines for which he states that the depth ranges are light controlled and best defined at species level, proffering a range of 0-75m based on work by ADEY (1966). From this evidence it is apparent that *Solenopora* is a poor depth indicator as it extends across a depth range which is too wide for the shallow deposits constituting the Mjøsa Limestone.

Comparisons between biohermal and non-biohermal *Solenopora* reveal differences in their external morphology which reflect different levels of stability relative to the substrate, as well as variations in periods of mobility. The apparently rigid calcareous thallus was particularly prone to attack by boring agents when growing, and as a result easily became fragmented during transport. Subsequent abrasion caused further breakage and particles rapidly attained smooth rounded outlines. This facilitates the distinction between both prolonged and short term drifted as well as non-drifted specimens of *Solenopora*.

Two methods of growth are evident; as large sheet-like bioherms or small scale local patches of substrate colonisation. Of the two the bioherms are regarded as developing in shallow offshore conditions where apart from the periodic catastrophic influxes, the substrate was generally more stable. The small encrusting sheets however represent very shallow water growth with constraints placed upon them either by mobility of substrate, depth of water, or both. The presence of oscillatory cross stratification in the enclosing sediments suggest that wave action, possibly tidal influences, were prevalent. Further evidence of extremely shallow water is provided by the overlying, and occasionally interbedded, red clastic facies; this facies represents prolonged emergence of a tidal flat environment.

Light intensity is discounted as a major influencing factor not only on the evidence of shallow water conditions but also because of an apparent lack of sufficient material in suspension to cause severe restriction to light penetration. Indeed, the bioherms at Snippsand and Børsvollen point to maximum organic development on a fine grained substrate in conditions of considerable water agitation; an ideal situation for turbidity to develop.

In terms of facies determination, the Solenopora bearing strata can best be divided into biohermal and non-biohermal lithofacies, which in terms of the numerical system adopted in Chapter 3 (p.63) would be designated Facies 11A and 11B respectively.

CHAPTER SIX

PALAEOGEOGRAPHY OF THE MJØSA LIMESTONE

PAGE MISSING IN ORIGINAL

I. INTRODUCTION

The erection of a viable chronostratigraphy between the three constituent districts of the Mjøsa region and the recognition of distinct facies types, diagnostic of certain depositional environments, within these divisions, allows palaeogeographical reconstructions to be effected for the Mjøsa Limestone.

Localities were relocated to their original positions relative to one another by the production of a palinspastic map which is presented here as an overlay to the main environmental reconstructions.

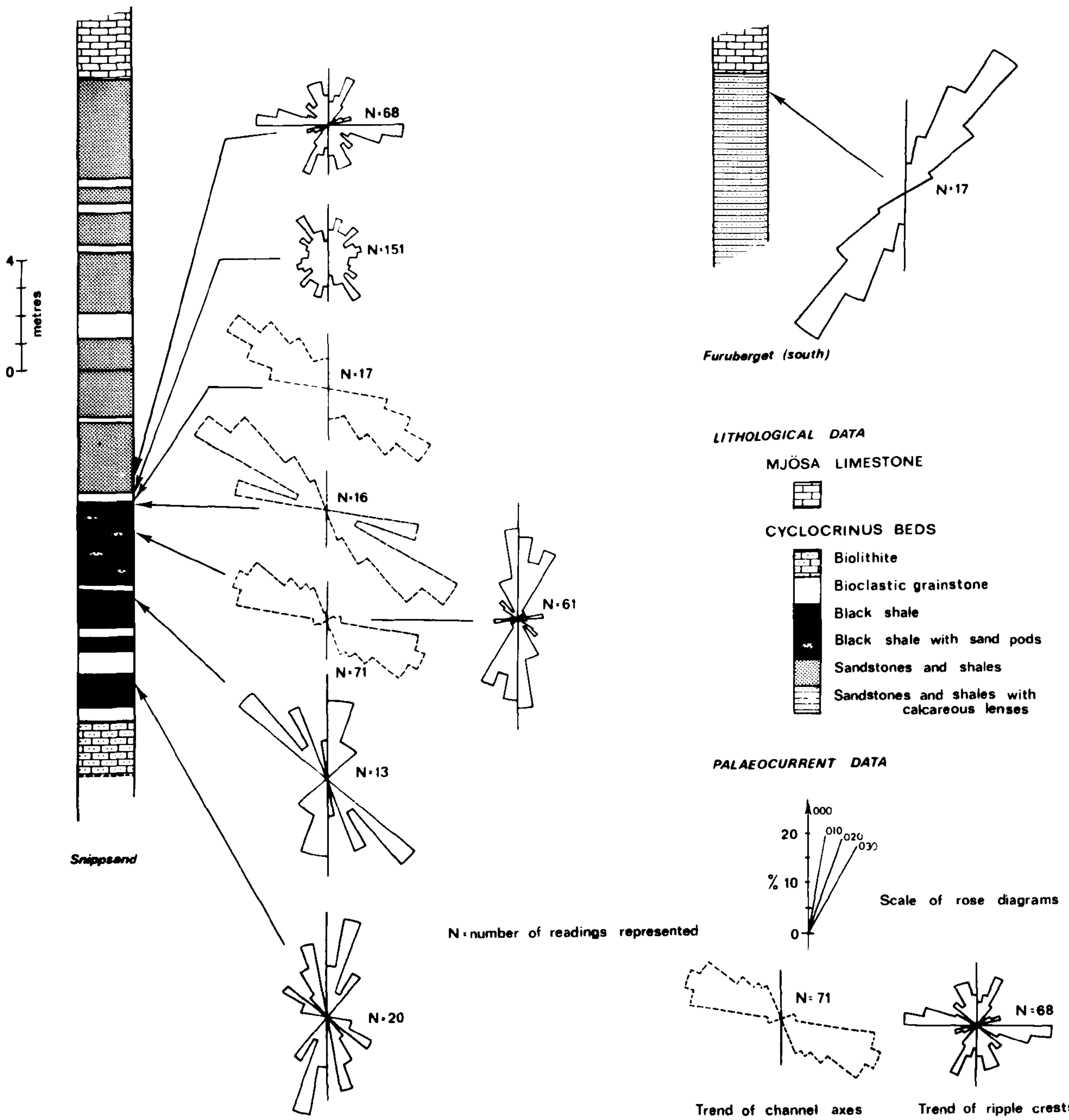
Consideration is given to each Member in turn, describing the changes in depth, energy and sediment supply which are thought to have occurred. By way of introduction, brief consideration is given to the Cyclocrinus Beds to emphasise the important environmental changes which took place at the beginning of the Mjøsa Limestone.

II. PALAEOGEOGRAPHICAL RECONSTRUCTION

The Cyclocrinus beds are in all respects identical to the Terrigenous Clastic Facies of the Mjøsa Limestone and can be regarded as deposits of a tidally influenced current system. Palaeocurrent data is given in Fig.6.1 and shows a polymodality of directions typical of such shallow water sediments. The strong northwest-southwest alignment of channels may give a suggestion of a southeasterly dipping palaeoslope and a more accurate reflection of current direction, particularly if they represent ebb flow structures.

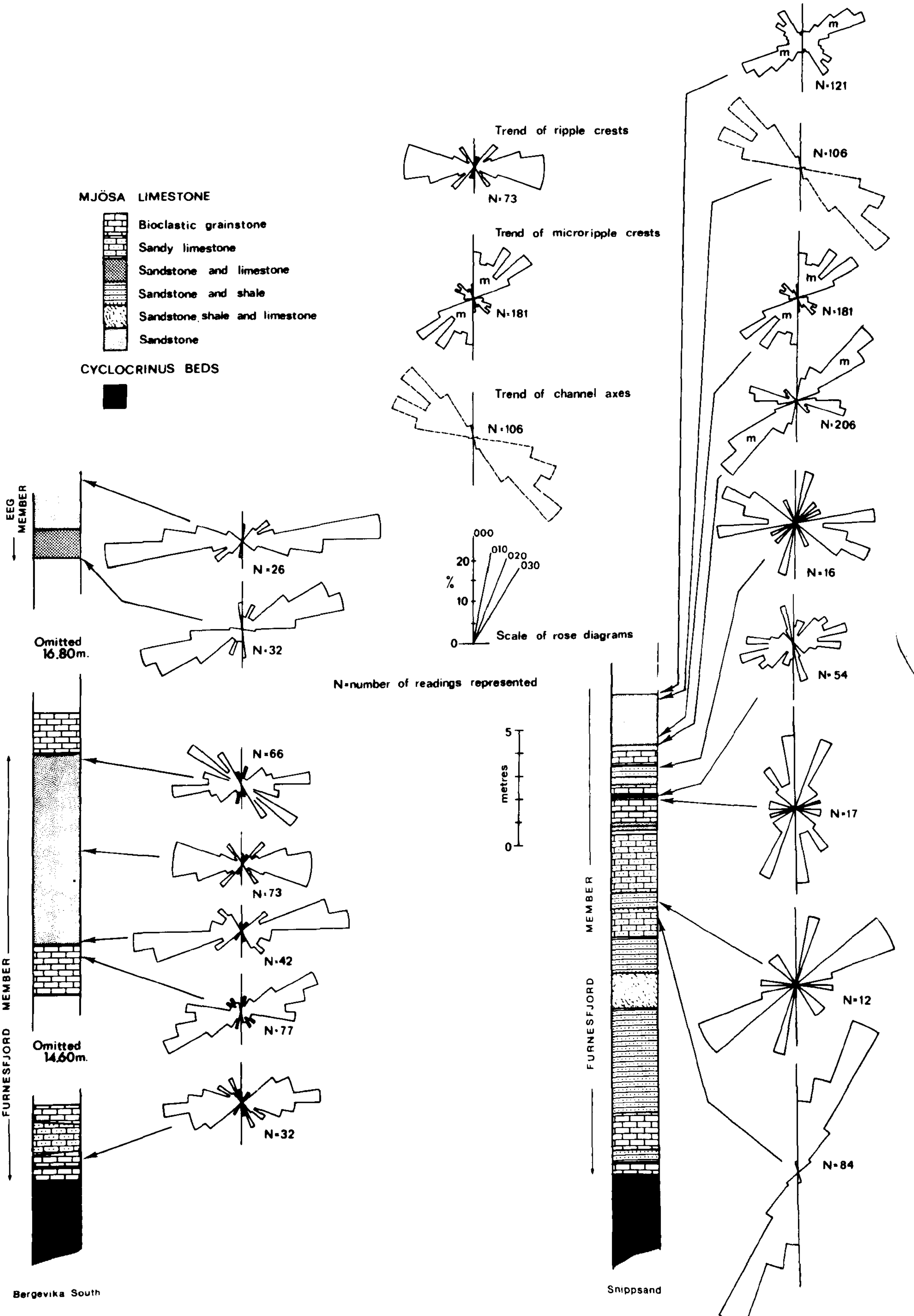
The transition to a limestone facies occurred with the progradation of carbonate sand shoals into the area. The basal horizons of the Mjøsa Limestone represent the prograding shoal margins. Palaeocurrent data is given in Fig.6.2 and supplemented in Fig.6.3. From this it can be seen that the lower limestone horizons have a dominantly north-south orientation, supplemented by a northeast-southwest component while the terrigenous clastic facies retains a polymodality but acquires a dominant northeast-southwest trend towards the upper part of the Furnesfjord Member. The palaeogeography is reconstructed in Fig.6.4a for this time. On parts of the substrate which became stable for sufficient periods, colonisation by Solenopora occurred. In the Toten district the bioclastic grainstones in which these algae are found contain structures which indicate deposition in a shallower (shoreface) environment than at Bergevika. It is apparent that the bioclasts were introduced from a southerly direction by the action of a strong longshore drift component which was refracted by the shoreface to give a more northwesterly-southeasterly palaeocurrent trend in the Toten district. The deepest, and most current scoured areas, appear to have been at Bergevika when the Solenopora bioherm developed adjacent to an area of high current activity which produced isolated megaripples of bioclastic

Fig.6.1: Palaeocurrent data. Cyclocrinus Beds.



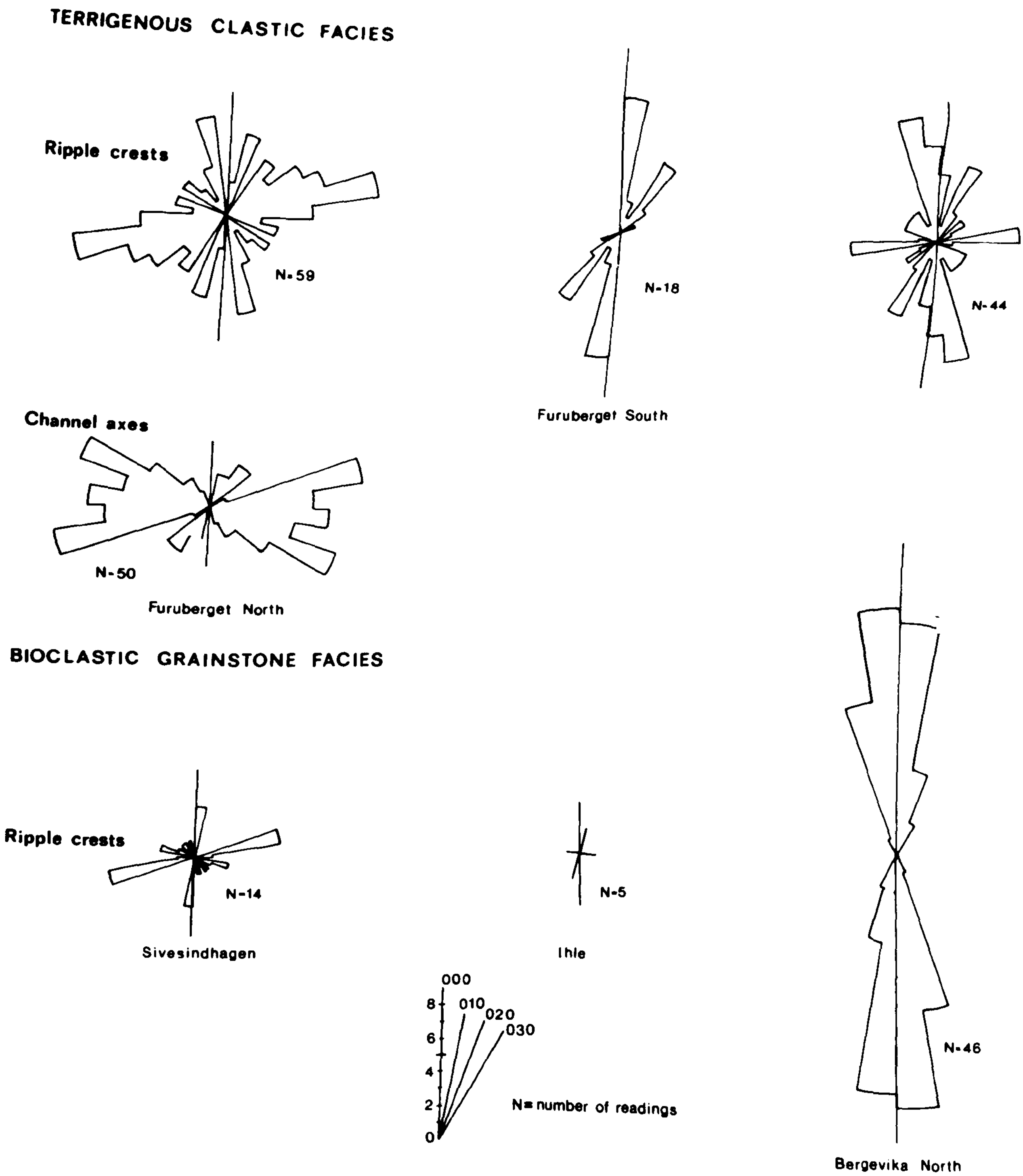
N·68
N·151
N·17
N·16
N·61
N·71
N·13
N·20
4
metres
0
Snippsand
N·17
Furuberget (south)
LITHOLOGICAL DATA
MJÖSA LIMESTONE
CYCLOCRINUS BEDS
Biolithite
Bioclastic grainstone
Black shale
Black shale with sand pods
Sandstones and shales
Sandstones and shales with calcareous lenses
PALAEOCURRENT DATA
000
010
020
030
20
% 10
0
Scale of rose diagrams
N·number of readings represented
N: 71
N: 68
Trend of channel axes
Trend of ripple crests

Fig.6.2: Palaeocurrent data. Mjøsa Limestone



MJÖSA LIMESTONE
Bioclastic grainstone
Sandy limestone
Sandstone and limestone
Sandstone and shale
Sandstone, shale and limestone
Sandstone
CYCLOCRINUS BEDS
Trend of ripple crests
N=73
Trend of microripple crests
N=181
Trend of channel axes
N=106
Scale of rose diagrams
000
010
020
030
%
N=number of readings represented
metres
EEG MEMBER
FURNESFJORD MEMBER
Omitted 16.80m.
Omitted 14.60m.
N=26
N=32
N=66
N=73
N=42
N=77
N=32
N=121
N=106
N=181
N=206
N=16
N=54
N=17
N=12
N=84
Bergevika South
Snippsand

Fig.6.3: Palaeocurrent data. Mjøsa Limestone.


TERRIGENOUS CLASTIC FACIES
Ripple crests
N-59
N-18
Furuberget South
N-44
Channel axes
N-50
Furuberget North
BIOCLASTIC GRAINSTONE FACIES
Ripple crests
N-14
Sivesindhagen
N-5
Ihle
000
010
020
030
8
6
4
2
0
N= number of readings
N-46
Bergevika North

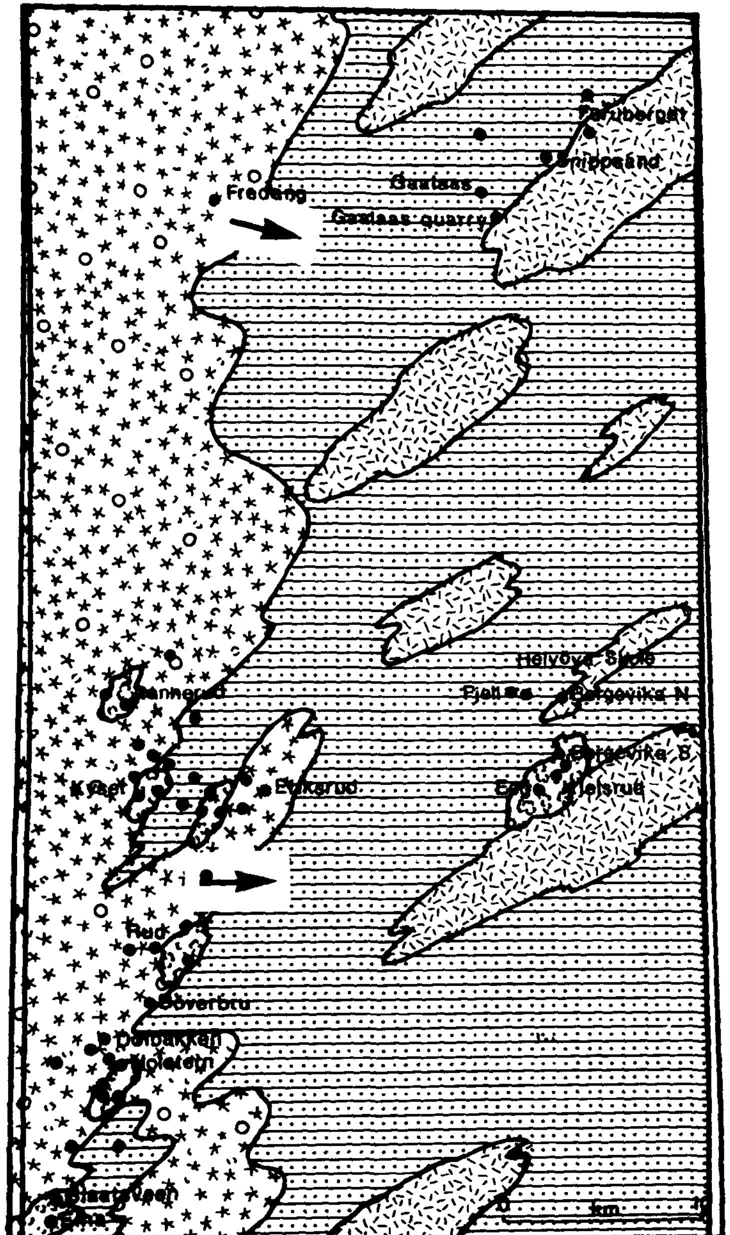
grainstone only (c.f. BROADHURST, 1968).

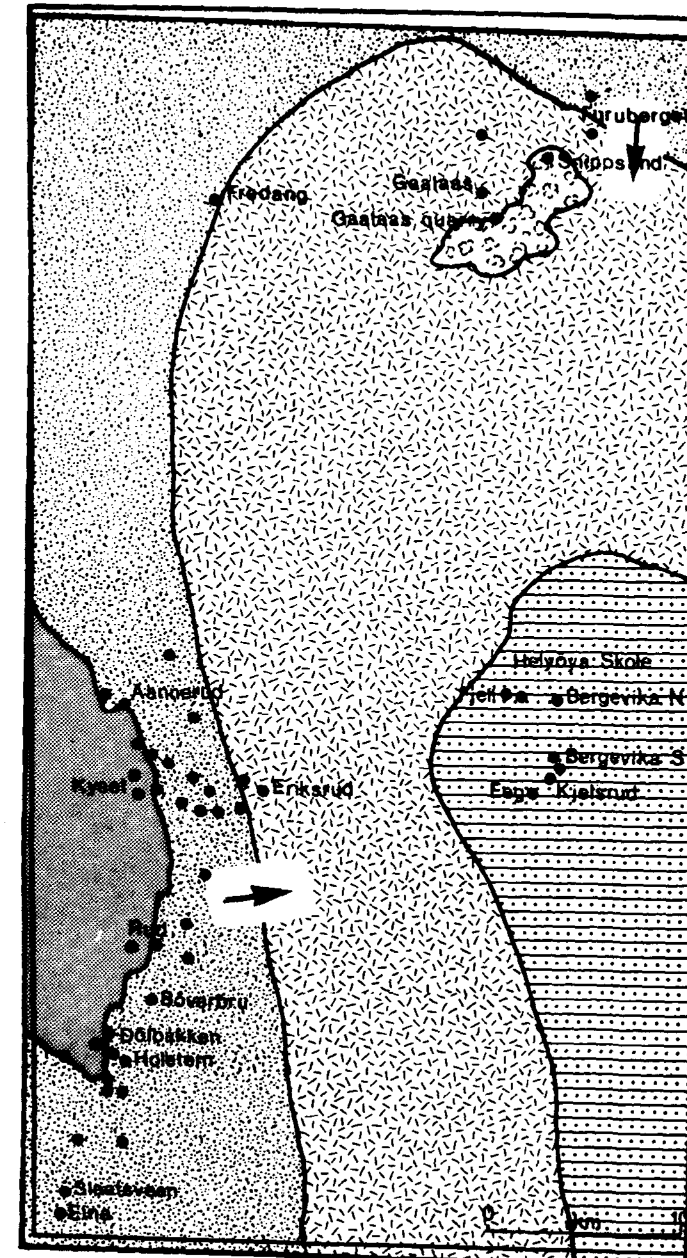
An apparent reduction in current energy towards the top of Sivesindhagen Member resulted in the stabilisation of the shoals, which had built up to or above the water level. Micritization of grains took place and early lithification gave a beach rock of peloidal grainstone. In the shelter of these, periodic flooding by waters containing a heavy suspension load of mud particles gave large areas of standing water where the finest grains settled out. Upon evaporation, these muds underwent dessication and attained a red colouration due to the subaerial alteration of iron minerals to haematite. Peloids also formed above bioclastic grainstones in the Furuberget localities, although no red beds exist here, and the well sorted nature of the sediments suggest that they either represent micritised ooliths or are the deposits of winnowed material. As with the lower parts of the basal members the Helgøya localities again appear the deepest showing a well developed thick terrigenous clastic sequence at an equivalent horizon. At Snippsand and in the Gaalaas area, a thriving Solenopora community existed. A reconstruction of the environment for the upper Sivesindhagen and Furnesfjord Member is presented in Fig.6.4b.

Throughout the lower members of the Limestone, the Toten district emerges as the shallowest depositional area with a gradual deepening to the east (Helgøya) and a slight shallowing towards the northeast (Furuberget).

The lowest horizons of the Eina Member mark a small transgression across the intertidal - supratidal deposits of the Toten district, although the greater thickness of red beds in the north (Aannerud) suggest shallowing in this direction (Fig.6.5a). The Gaalaas, Snippsand and Furuberget localities possess similar lithologies, although here the red beds pass into green oncolite beds and ahermatypic stromatoporoid horizons. In all these northern areas, peloidal grainstones and fine grained carbonate account for the interbedded facies. In the south Toten localities bio-

Fig.6.4: Palaeogeographical reconstructions for the Sivesindhagen and Furnesfjord Members of the Mjøsa Limestone. The lower diagram represents the reconstruction for the early part and the upper diagram the later part of these members. This format is adhered to for Figs. 6.5, 6.6 and 6.7. A key is given with Fig.6.6. The overlay represents a palinspastic reconstruction; the scale is only approximate.


Fredang
Gaalaas
Gaalaas quarry
Helvöya Skole
Fjell
Bergevika N
Kjelsrud
Eriksrud
Rud
Böverbru
Dölbakken
Eina
0
km
10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Aanerud
Kvael
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Rud
Böverbru
Dölbakken
Holetern
Eina
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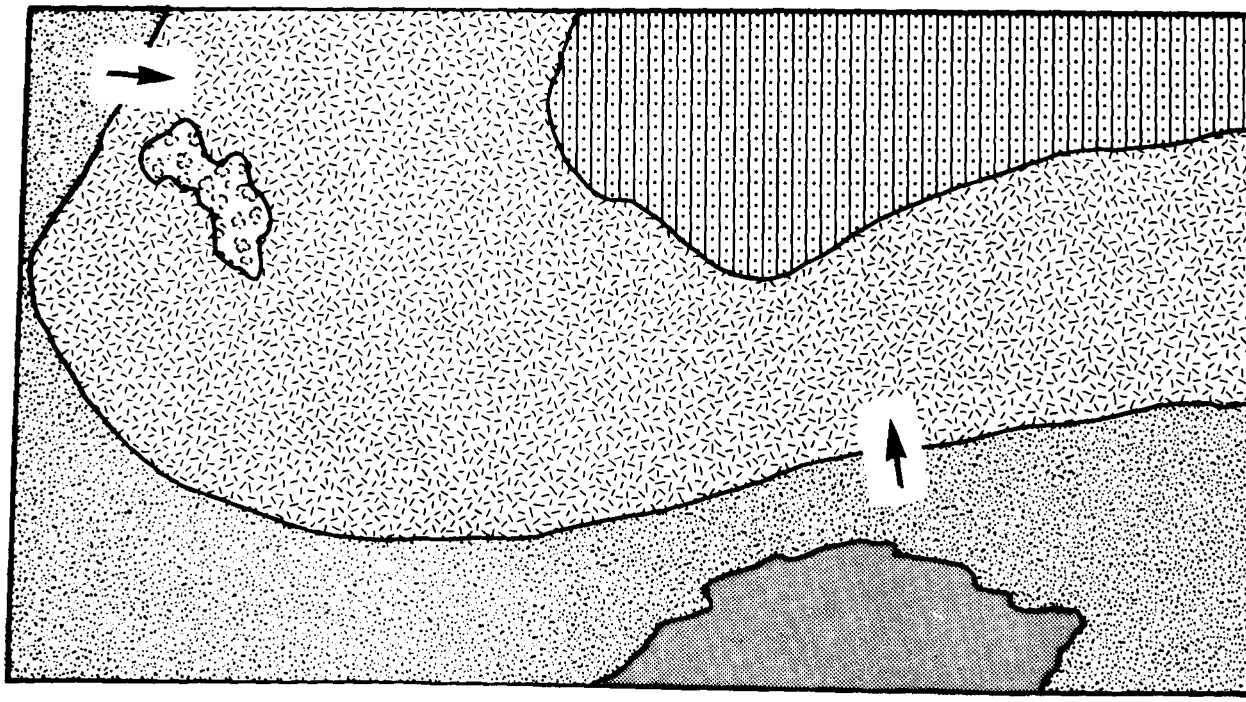

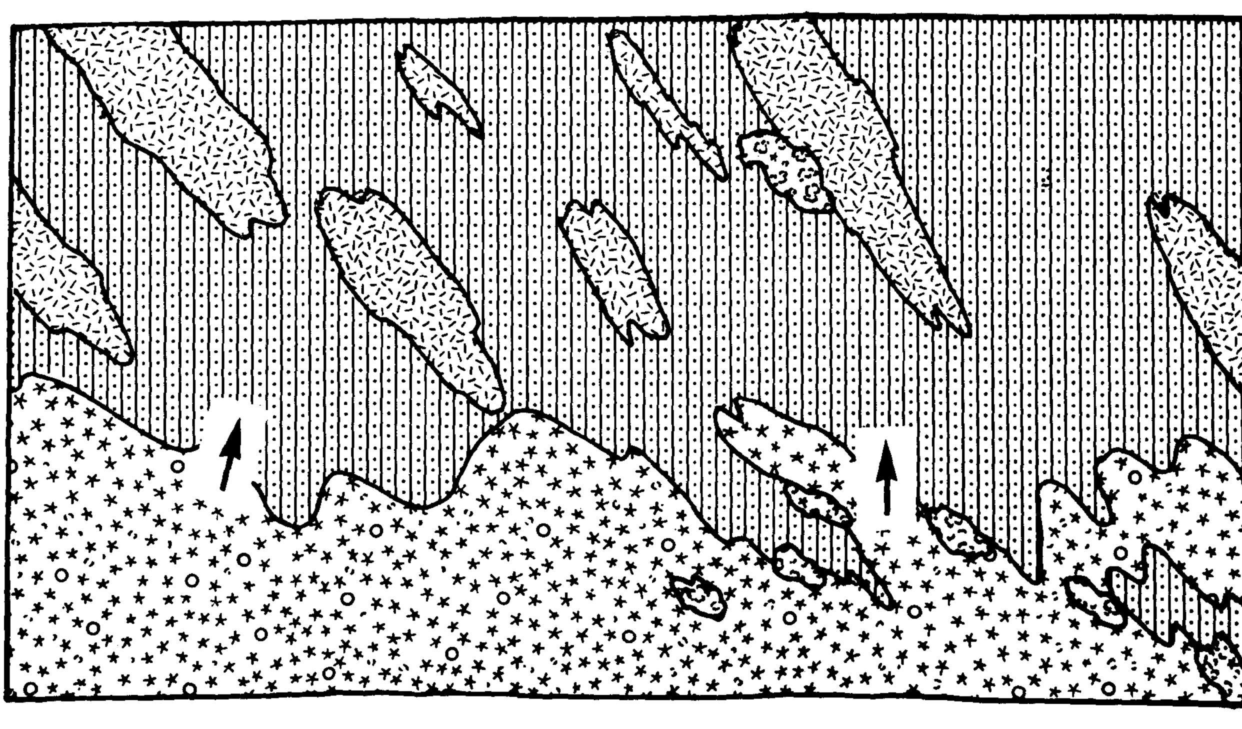

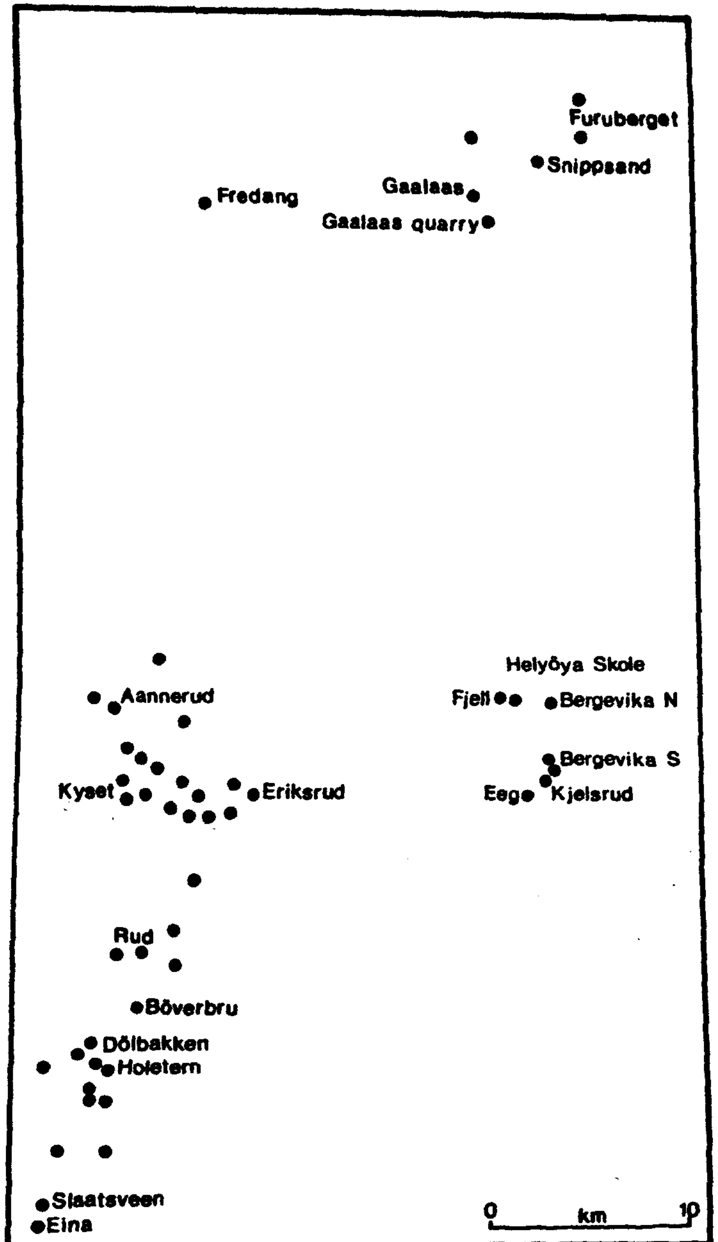
Furuberget
Snippsand
Fredang
Gaalaas
Gaalaas quarry
Helyöya Skole
Aannerud
Fjell
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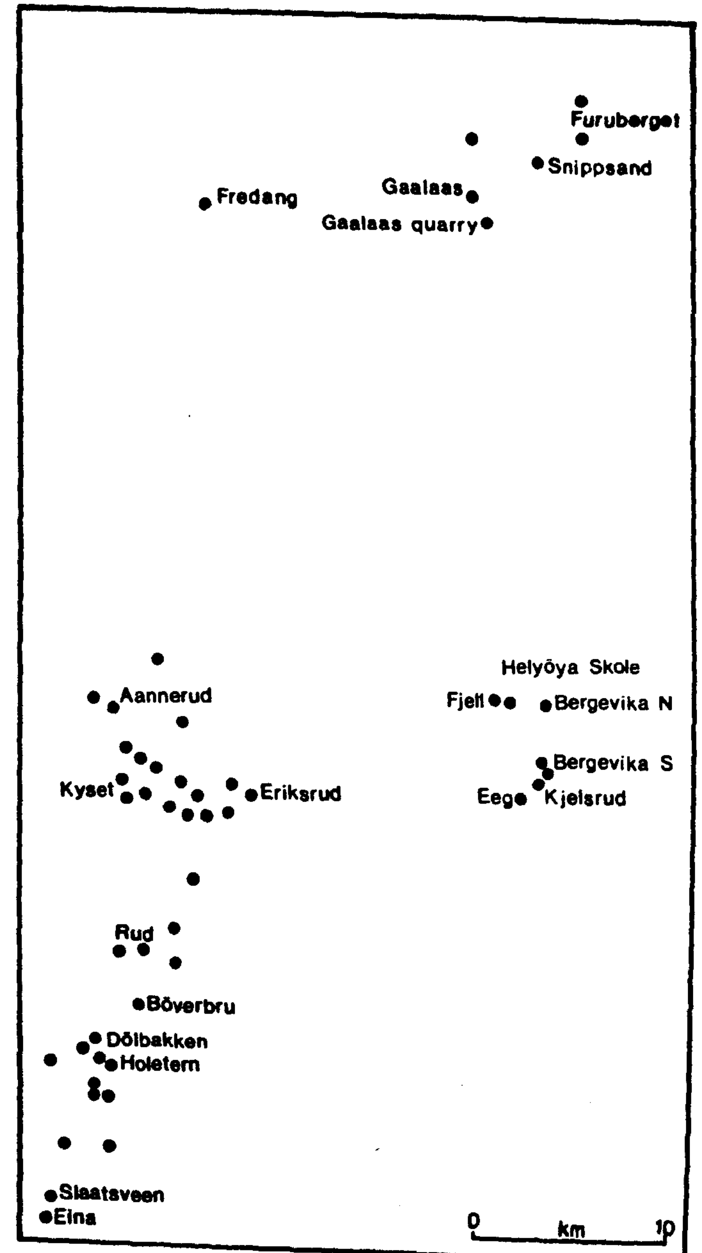
Furuberget
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Fredang
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Gaalaas quarry
Helyöya Skole
Aannerud
Fjell
Bergevika N
Bergevika S
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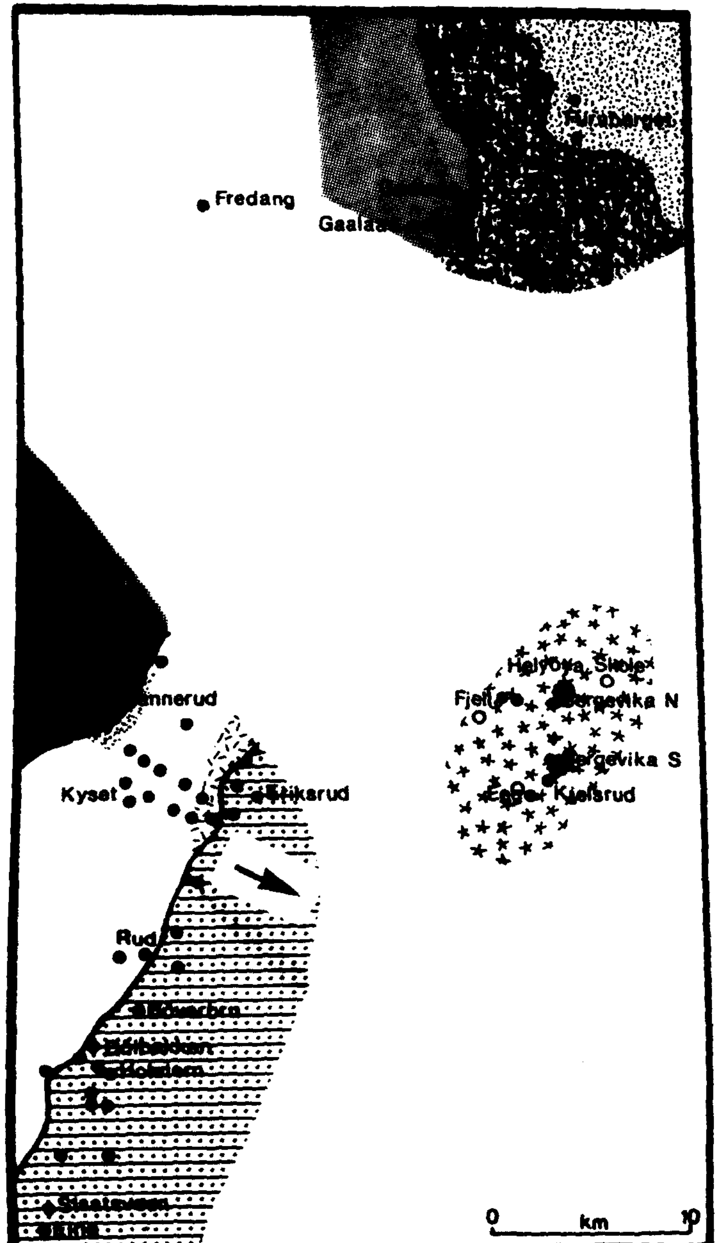
Eriksrud
Eege
Kjelsrud
Rud
Böverbru
Dölbakken
Holetern
Slaatsveen
Eina
0
km
10

turbated terrigenous clastic horizons are equivalent to massive pelmatozoan calcarenites in which a patch reef complex gradually establishes itself (Helgøya). As this reef complex grew it affected the circulation within the back reef area (Toten) and fine grained, often heavily bioturbated calcisiltites appear as lateral equivalents. The forereef deposits continued to be dominated by pelmatozoan calcirudites. At its maximum development the reef complex extended into the Toten district with small bioherms appearing at Eina and Bøverbru, and 'reefy facies' at Rud. Slaatsveen and Eriksrud (Fig. 6.5b).

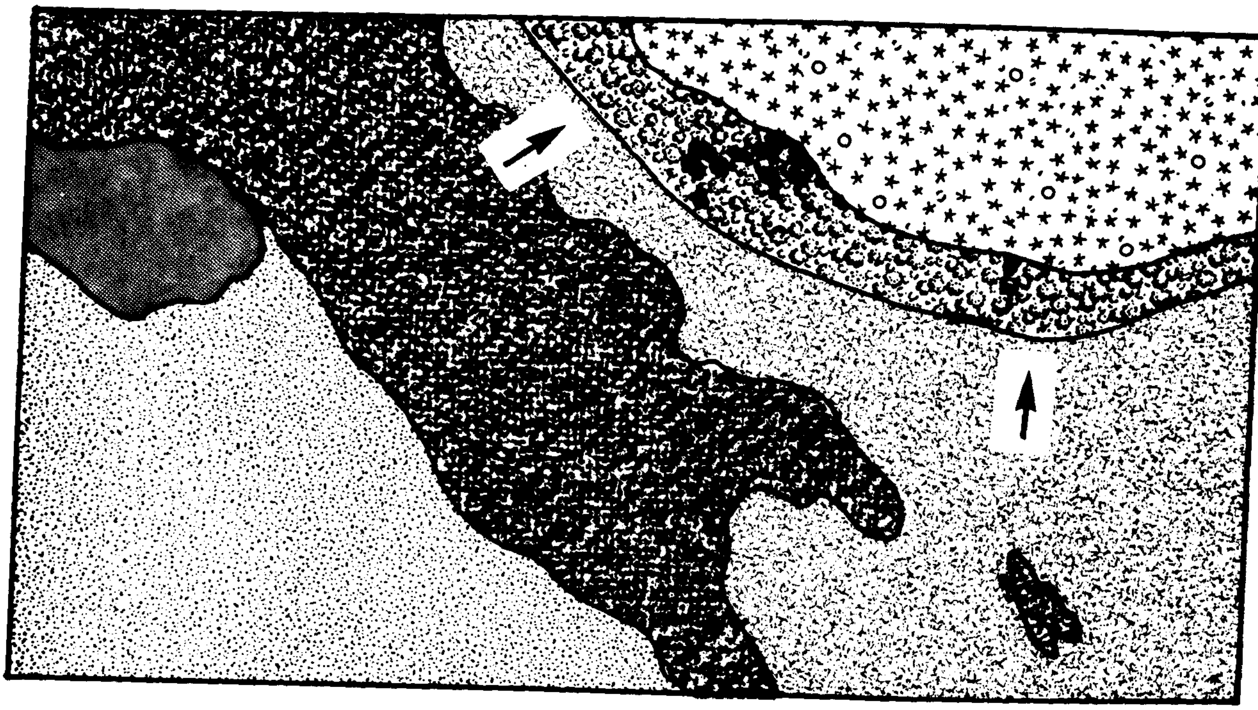
Following this marine phase of deposition the Toten district became shallower and the interbedded peloidal grainstones and algal mat successions represent the return of the intertidal conditions. Periods of exposure produced a variety of dessication features in the cryptalgal laminites, which contain no evidence of bulbous stromatolites. The equivalents on Helgøya are massive micrites, regarded as the material winnowed from the peloidal grainstones and deposited in a shallow offshore environment. Tidal activity appears to have been particularly curtailed at this time. The northern part of the area (Gaalaas; Furuberget) retains the stromatoporoid - peloidal grainstone successions previously described. A reconstruction is presented as Fig6.6 showing the interdigitation of these three main facies groups and a slight deepening to the north and east of Toten.

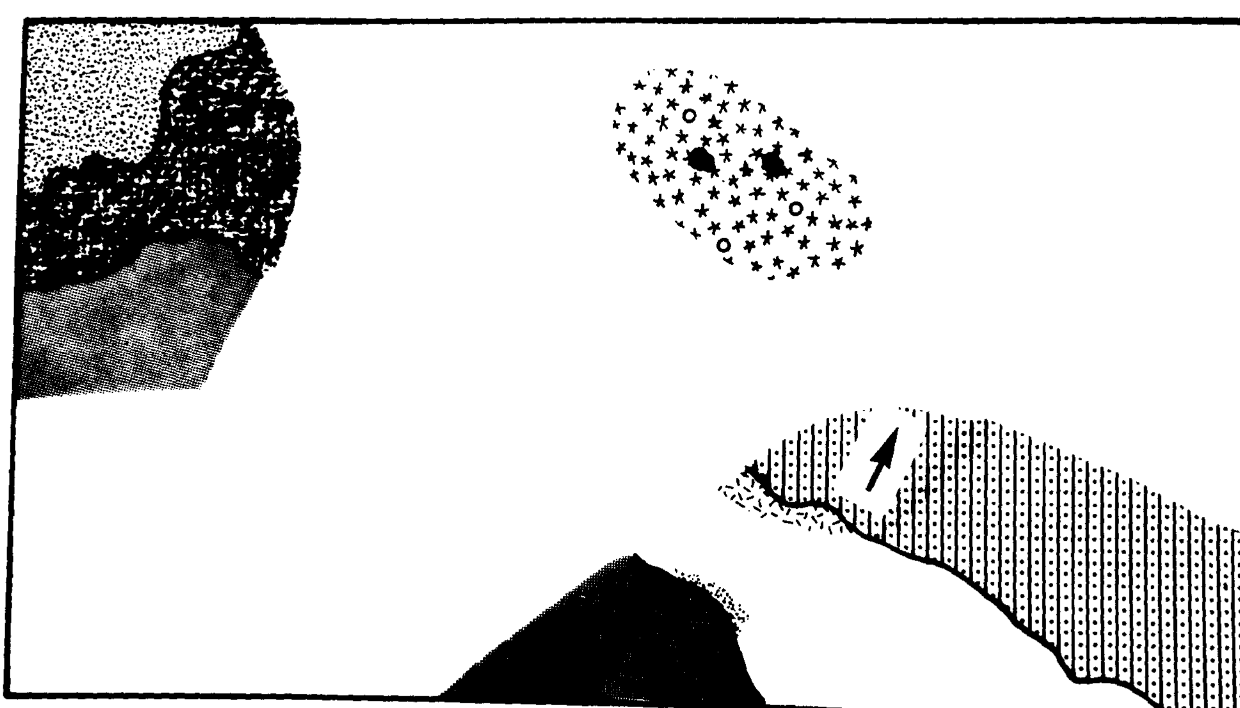
The base of the Holetjern, Eeg and Snippsand Members is marked by a definite return to more marine conditions throughout the area and at the base of the Holetjern Member a distinct erosion surface can be traced throughout the Toten district. Limited palaeocurrent data (Fig.6.2) from the extremely fossiliferous terrigenous clastic beds at the base of the Eeg Member indicate a dominant north - south current trend. Greatest variation is apparent within the Toten district where the Hemstadmoen Bioclastic Beds,

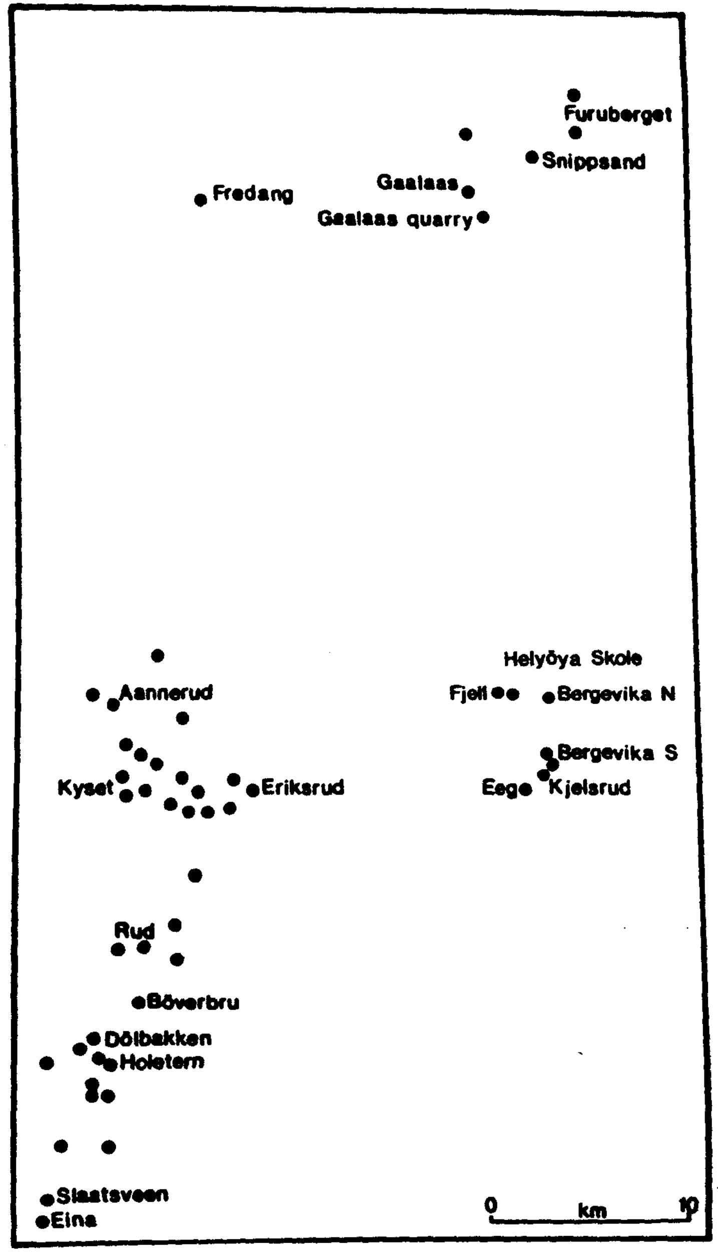
Fig.6.5: Palaeogeographical reconstructions for the lower and middle stages of the Eina, Bergevika and Gaalaas Members.


Fredang
Kyset
Rud
0 km 10


Fredang
Kyset
Rud






Furuberget
Snippsand
Gaalaas
Fredang
Gaalaas quarry
Helyöya Skole
Aannerud
Fjell
Bergevika N
Bergevika S
Kyset
Eriksrud
Eege
Kjelsrud
Rud
Böverbru
Dölbakken
Holetern
Slaatsveen
Eina
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km
10

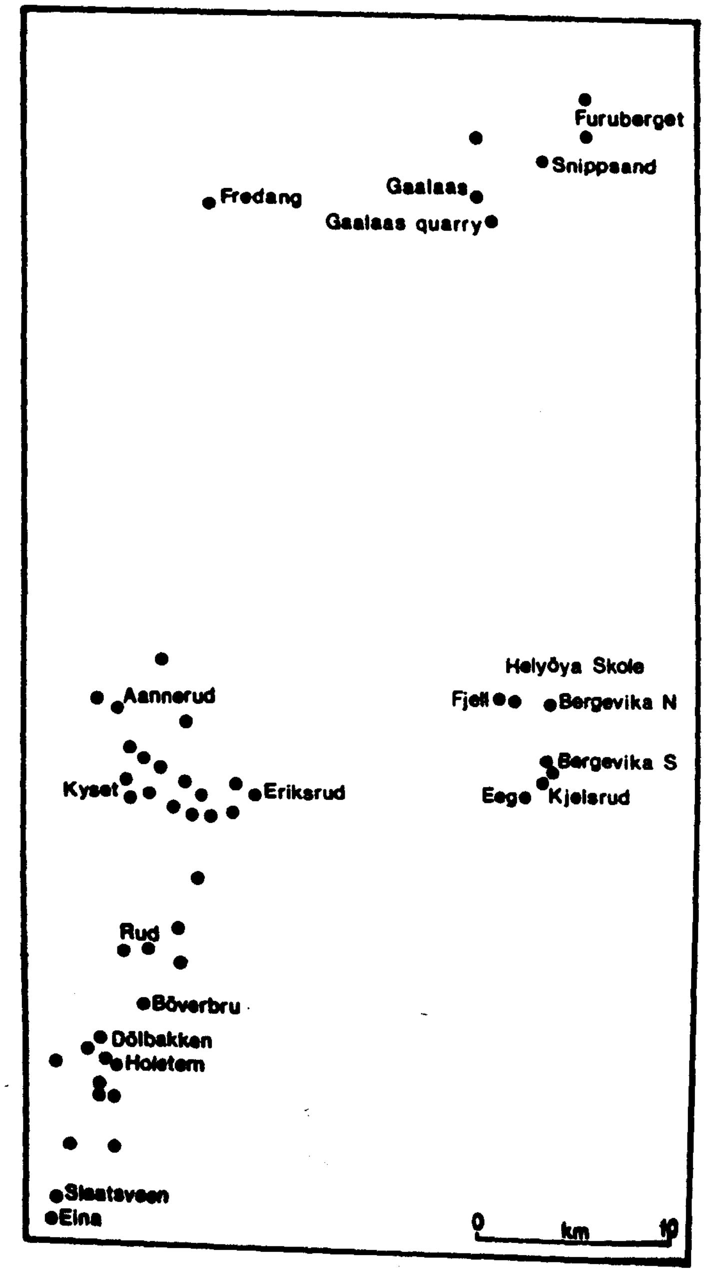
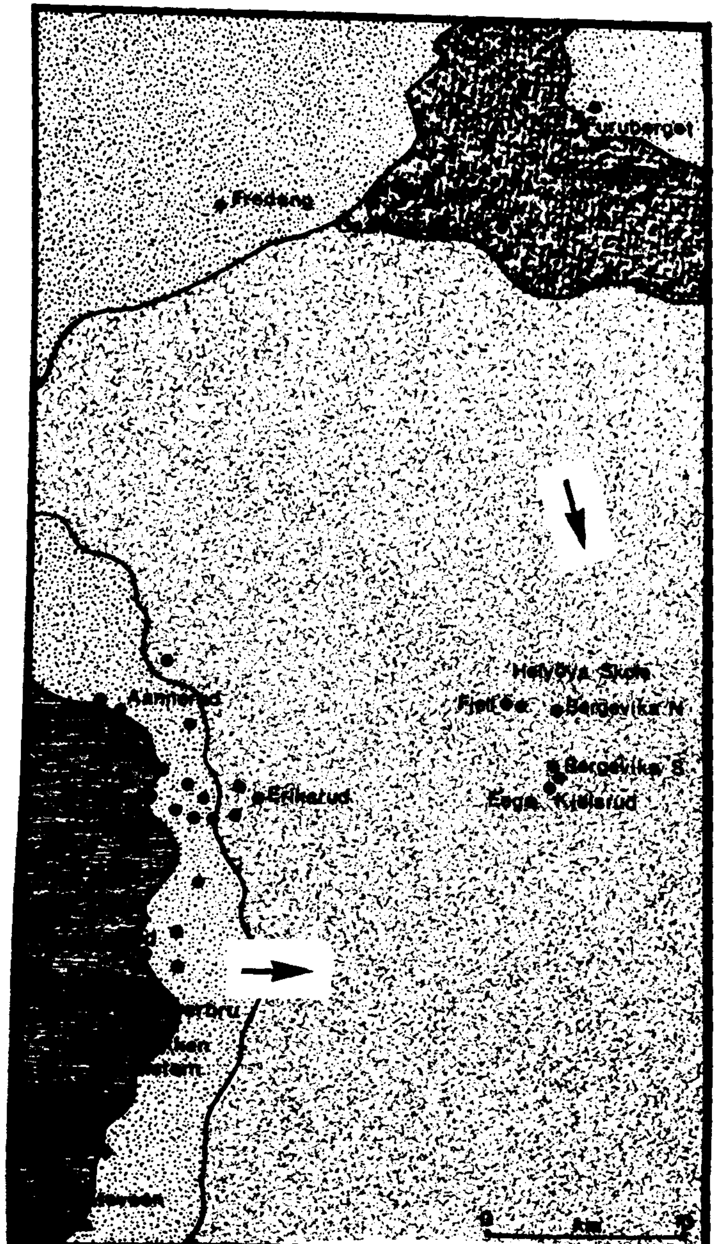
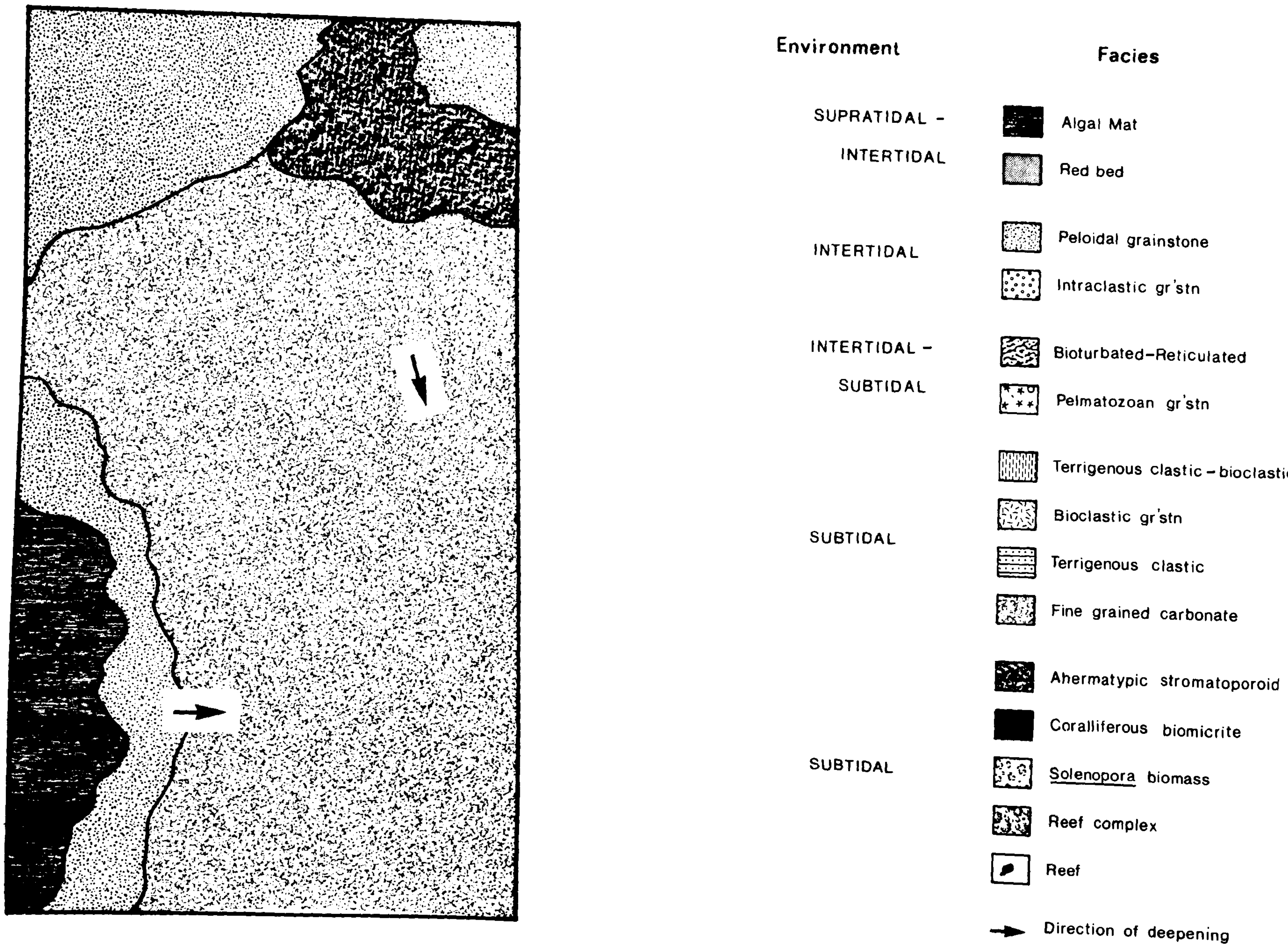
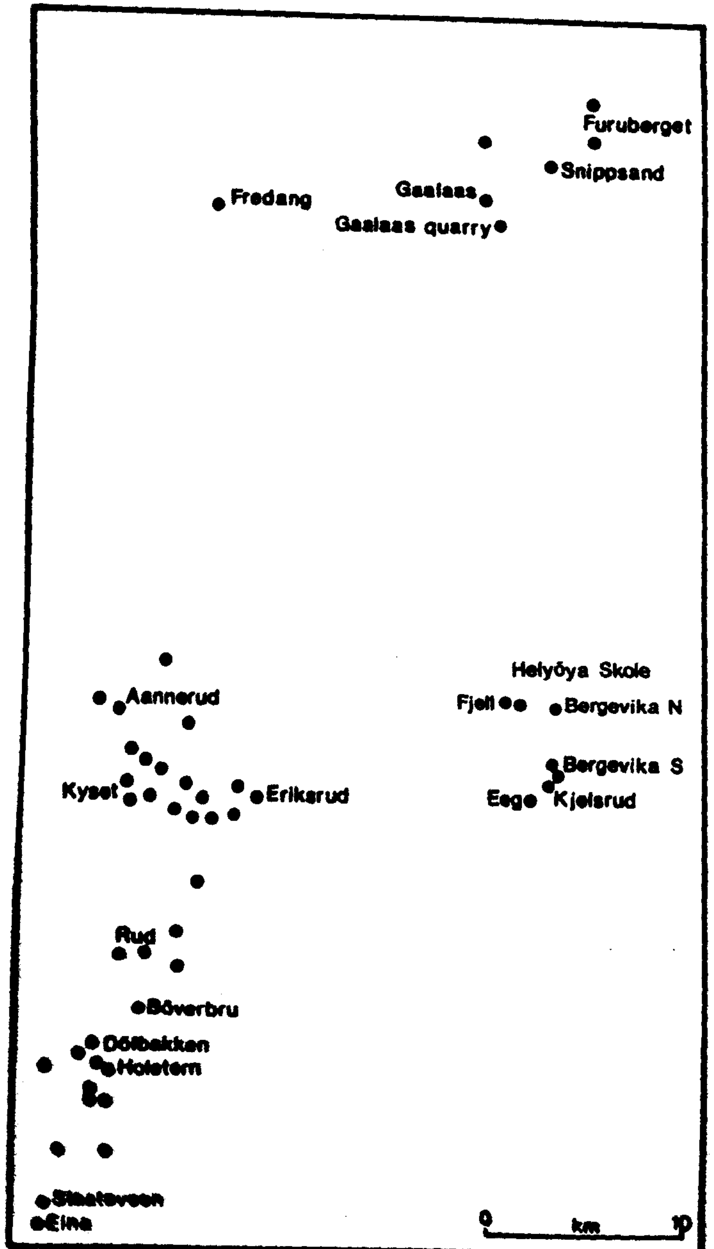

Furuberget
Snippsand
Gaalaas
Fredang
Gaalaas quarry
Helyöya Skole
Aannerud
Fjell
Bergevika N
Bergevika S
Kyset
Eriksrud
Eege
Kjelsrud
Rud
Böverbru
Dölbakken
Holetern
Slaatsveen
Eina
0
km
10

Fig.6.6: Palaeogeographical reconstruction for the upper stage of the Eina, Gaalaas and Bergevika Members.



Environment	Facies
SUPRATIDAL - INTERTIDAL	Algal Mat
	Red bed
INTERTIDAL	Peloidal grainstone
	Intraclastic gr'stn
INTERTIDAL - SUBTIDAL	Bioturbated-Reticulated
	Pelmatozoan gr'stn
SUBTIDAL	Terrigenous clastic - bioclastic
	Bioclastic gr'stn
	Terrigenous clastic
	Fine grained carbonate
SUBTIDAL	Ahermatypic stromatoporoid
	Coralliferous biomicrite
	<u>Solenopora</u> biomass
	Reef complex
	Reef
	Direction of deepening


Environment
Facies
SUPRATIDAL - INTERTIDAL
Algal Mat
Red bed
INTERTIDAL
Peloidal grainstone
Intraclastic gr'stn
INTERTIDAL - SUBTIDAL
Bioturbated-Reticulated
Pelmatozoan gr'stn
SUBTIDAL
Terrigenous clastic - bioclastic
Bioclastic gr'stn
Terrigenous clastic
Fine grained carbonate
SUBTIDAL
Ahermatypic stromatoporoid
Coralliferous biomicrite
Solenopora biomass
Reef complex
Reef
Direction of deepening

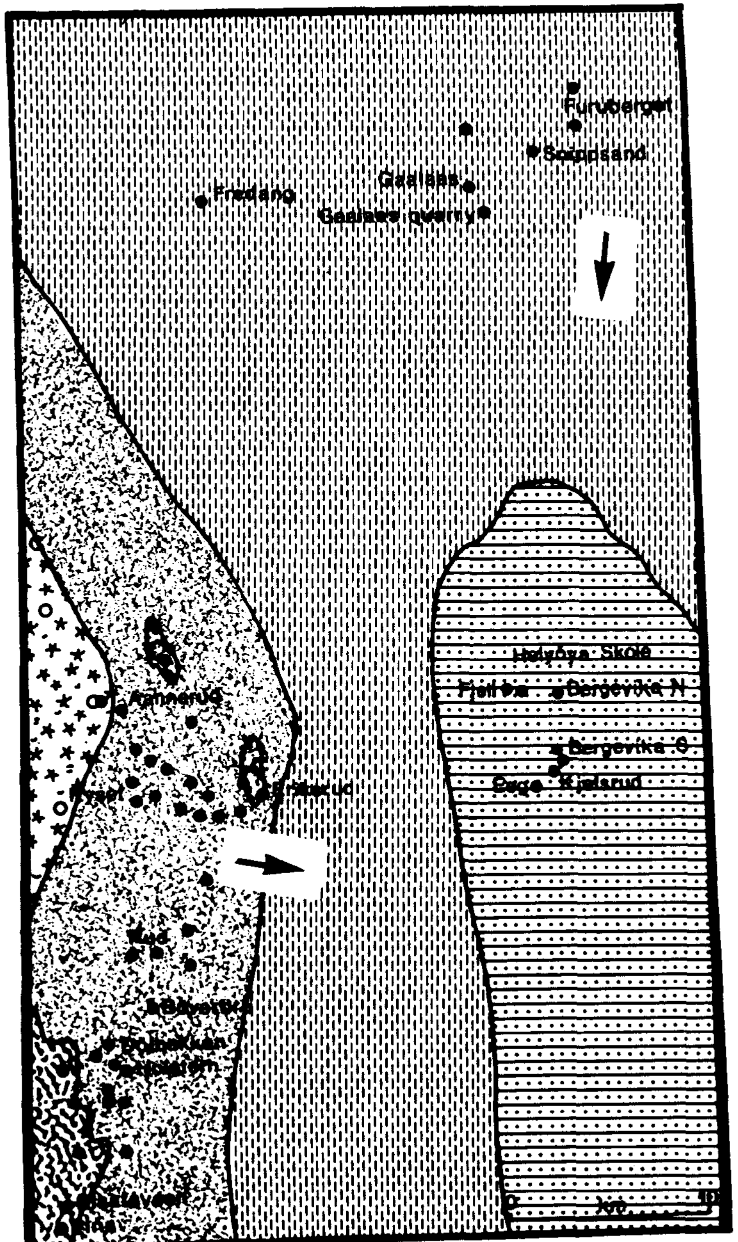


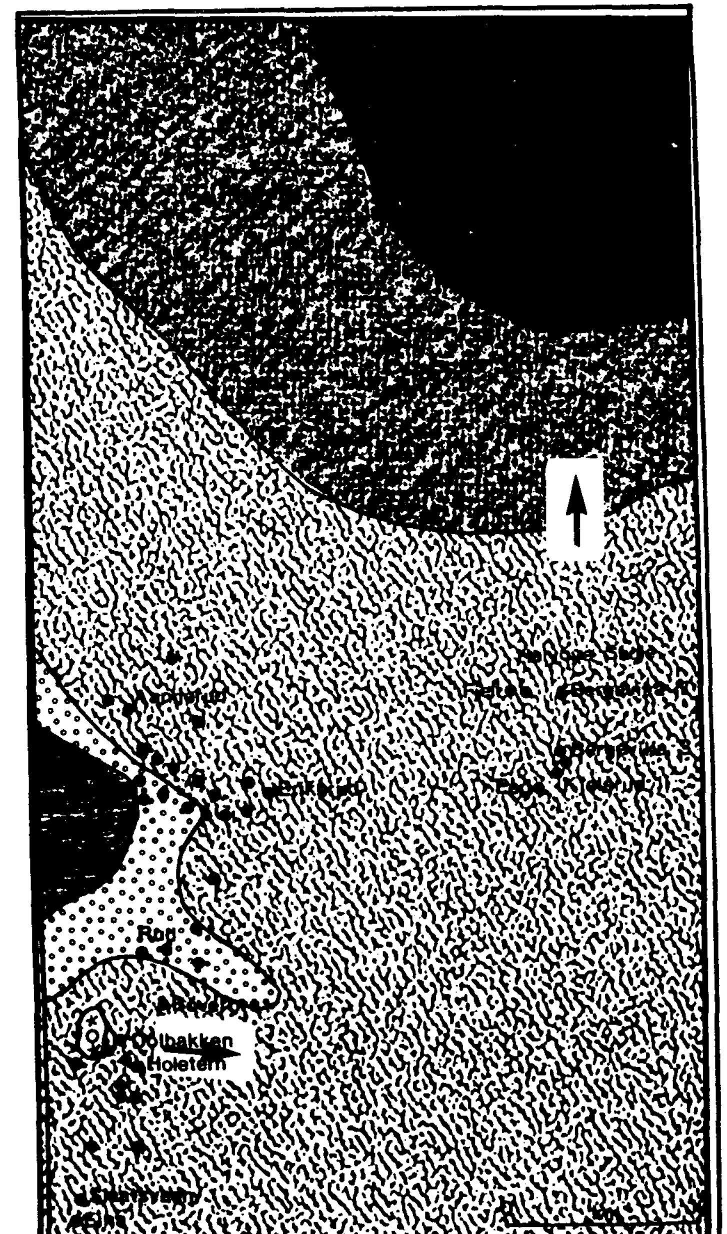
Furuberget
Snippsand
Fredang
Gaalaas
Gaalaas quarry
Helyöya Skole
Fjell
Bergevika N
Bergevika S
Kjelsrud
Aannerud
Kyset
Eriksrud
Rud
Böverbru
Dölbakken
Eina
0
km
10

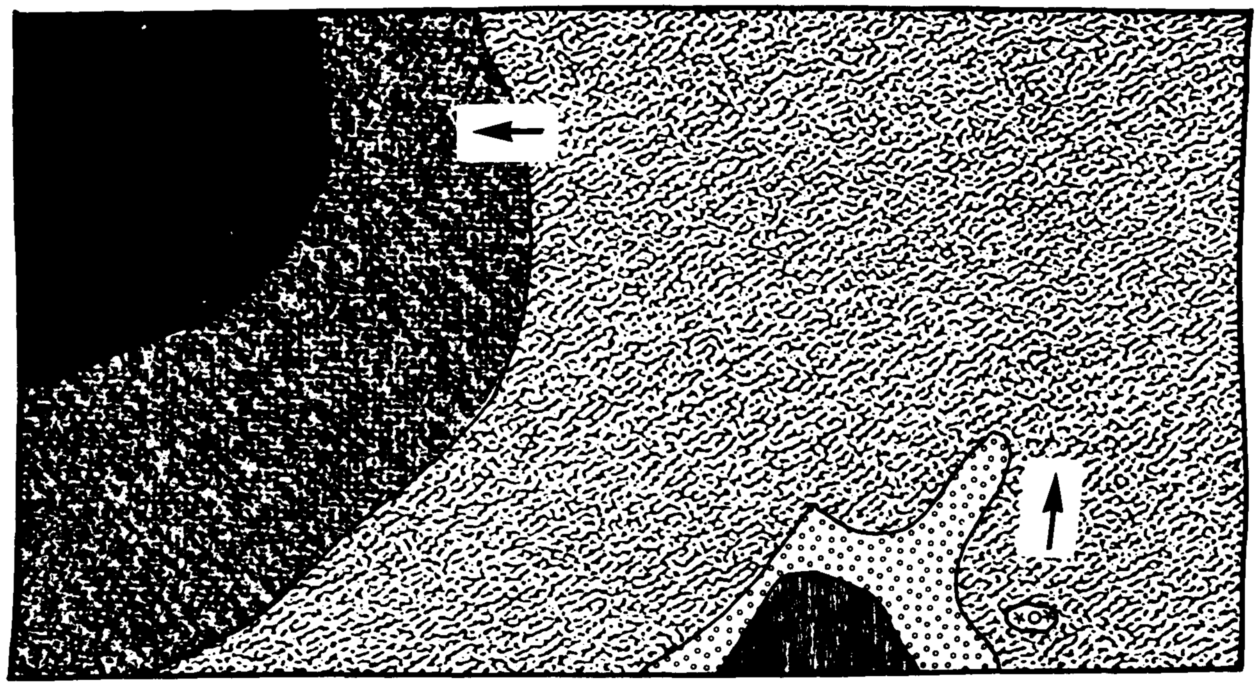
which wedge out northwards and add further credence to a southerly source, pass upwards into Vermiporella rich micrites and a reefy facies at Eriksrud. (Fig.6.7a). At Aannerud, herring-bone cross-stratification is commonly found in a massive pelmatozoan bioclastic grainstone and this is regarded as a beach deposit, indicative of shallower conditions still prevailing in this part of the Toten district.

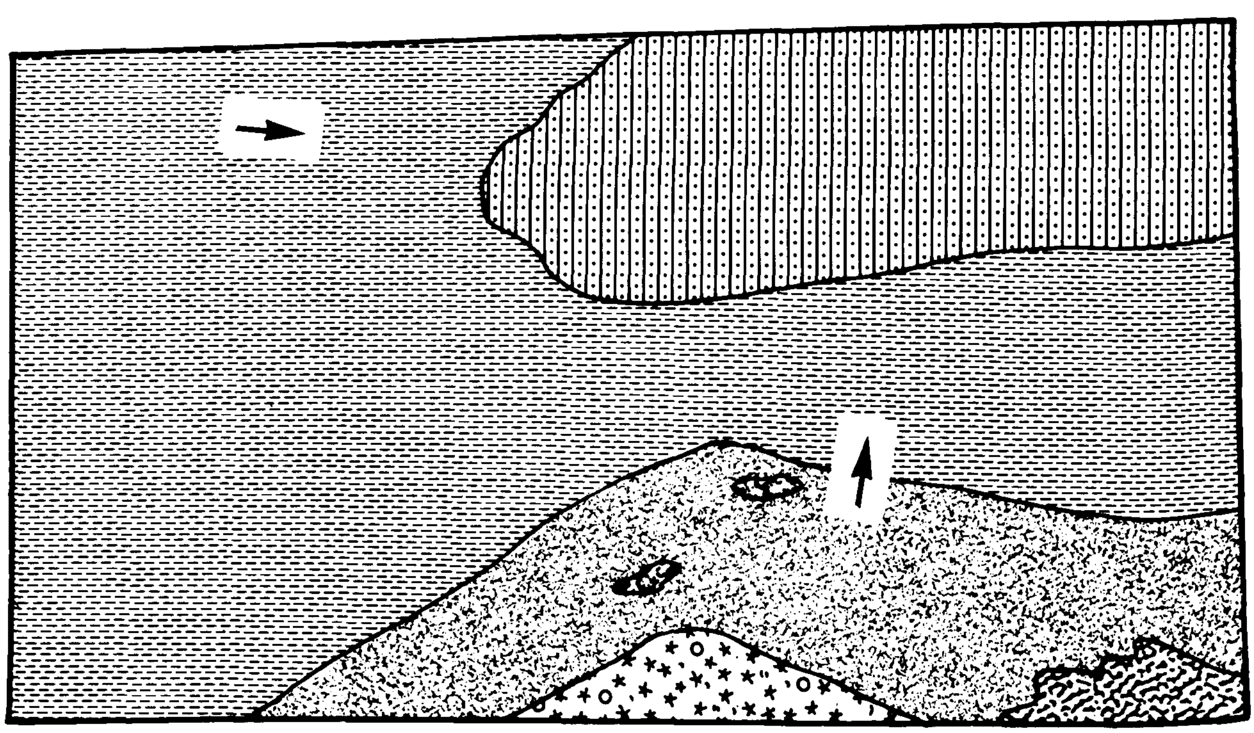
The main part of the Holetjern and Eeg Members is composed of inter-tidal (Toten) and shallow subtidal (Helgøya) bioturbated facies, equivalent to coral bearing biomicrites at Snippsand. Towards the upper boundary of the limestone peloidal grainstones with a high intraclastic content appear, either filling large channels cut in to the bioturbated facies (e.g. at Rud) or with sharply defined bases (Fjell). These are regarded as tidal channel fills, the sediment being derived from synsedimentary hardgrounds further to the west than the present exposures in Toten. In the Dølbakken localities, there is some lateral variation of this facies into pelmatozoan calcirudites and Solenopora rich sediments, probably indicative of a local crinoid-algal thicket in very shallow subtidal conditions. At Kyset, algal mat sequences are found overlying the bioturbated horizons and probably indicate a local development only. A reconstruction for the uppermost part of the limestone is given in Fig.6.7b.

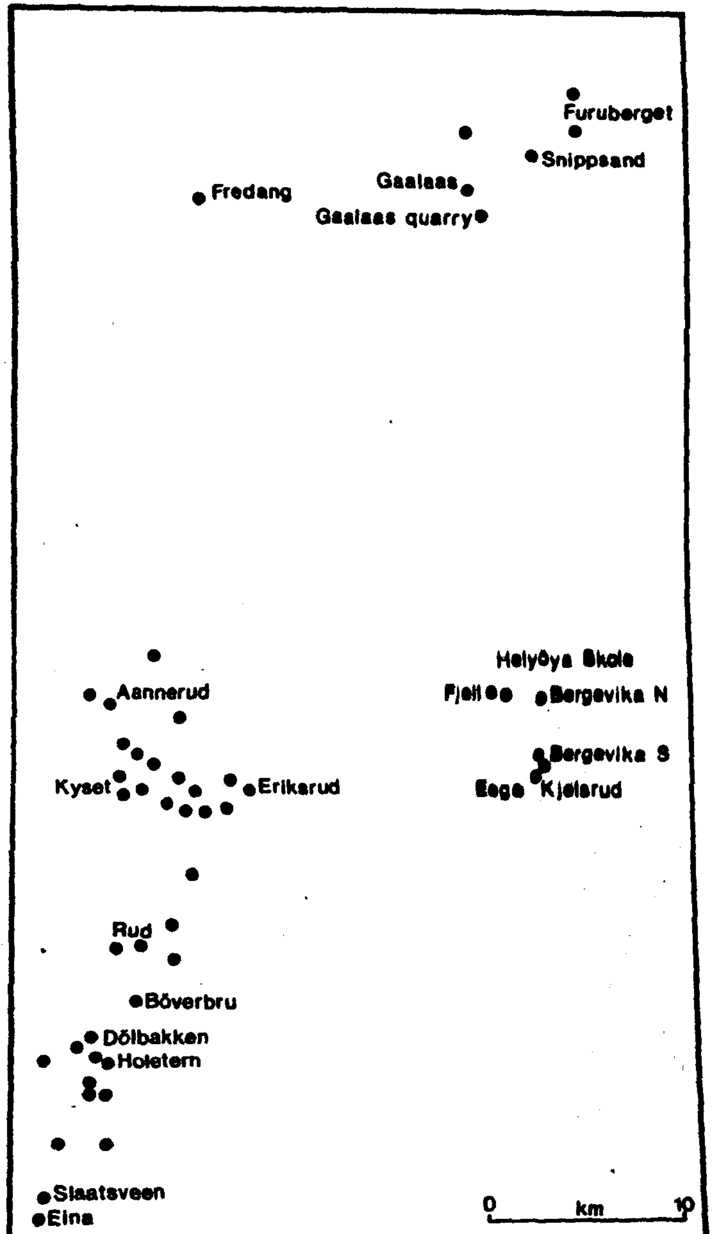
Fig.6.7: Palaeogeographical reconstructions for the Holetjern, Snippsand and Eeg Members.


Furuberget
Gaalaas
Fredang
Gaalaas quarry
Holøya Skole
Bergevika N
Bergevika Ø








Furuberget
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Bergevika N
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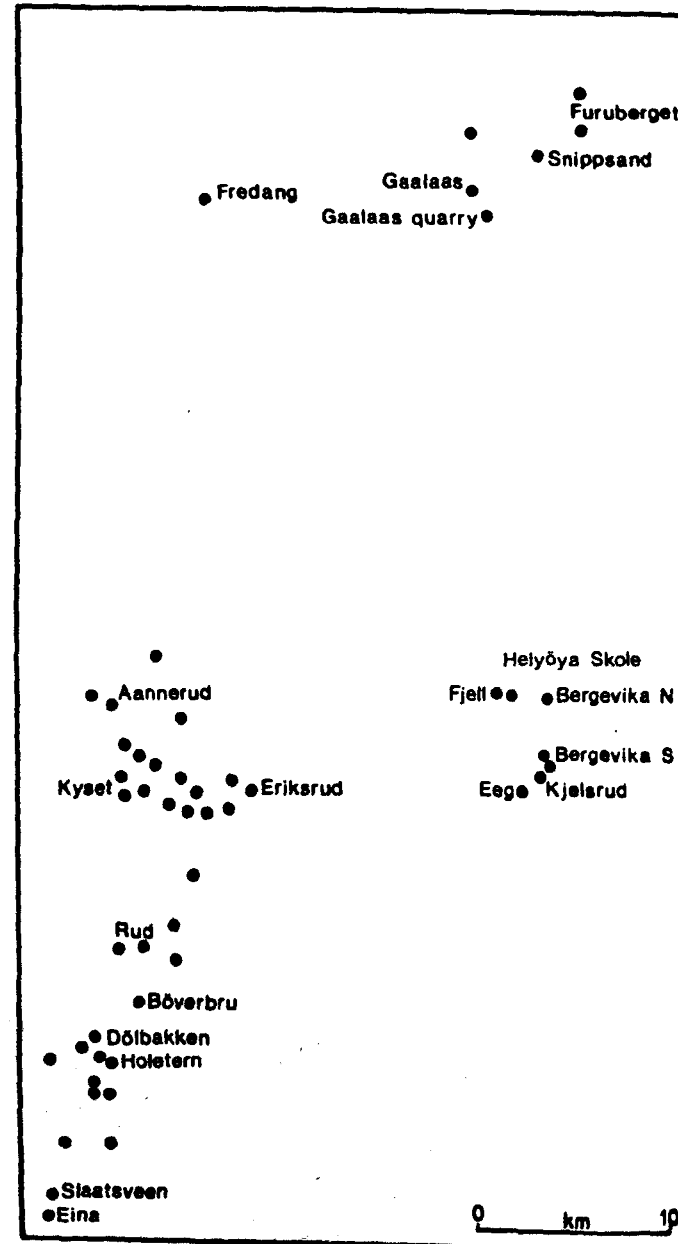
Dölbakken
Holetern
Slaatsveen
Eina
0
km
10


Furuberget
Snippsand
Gaalaas
Fredang
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Helyöya Skole
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Fjell
Bergevika N
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Eriksrud
Eege
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Rud
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Dölbakken
Holetern
Slaatsveen
Eina
0
km
10

III. CONCLUSIONS

The Mjøsa Limestone represents the deposits of a warm shallow sea which possessed a general palaeoslope to the east and local variations to both northeast and south of the shallowest areas. Tidally induced currents gave a dominant northwest-southeast palaeocurrent direction, although the main current directions responsible for the initial introduction of carbonate material as well as the periodic influxes of more "marine" sediments possessed a north - south trend. The general deepening to the south suggests that the source of this carbonate rich sediment also lay in that direction. The final regression was accompanied by exposure and solution weathering during the Ashgillian and lower Llandovery prior to a marked transgression (again from the south) in the Middle Llandovery.

CHAPTER SEVEN

SUMMARY AND CONCLUSIONS

Stratigraphically, the Mjøsa Limestone is a sufficiently distinct lithological unit to warrant formal classification as a Formation: the lower boundary being marked by the transition from a dominantly terrigenous to a dominantly carbonate rich succession, and the upper boundary by a well defined unconformity, often exhibiting palaeokarst solution features filled by the overlying Silurian. The recognition of three regressive phases within the limestone facilitated a sub-division into three Members in each of the districts comprising the main outcrop area. These were assigned a local nomenclature and could be further subdivided into formal and informal units. Chronostratigraphical correlation between the districts was effected using these regressive and transgressive events.

The age of the Mjøsa Limestone is regarded as uppermost Caradoc (zone of Dicranograptus clingani) and, in accordance with present Norwegian stratigraphical practice belongs to Stage 4bδ, being equivalent to the Upper Chasmops Limestone of the Oslo Region.

Nine distinct lithofacies and two biofacies can be distinguished within the Mjøsa Limestone. These are determined primarily on field characteristics, but can be subdivided into constituent microfacies by petrographical examination.

Three of the lithofacies are dominated by terrigenous clastic detritus and represent deposition in the subtidal (Terrigenous Clastic Facies), shallow subtidal - intertidal (Green Clastic Facies) and intertidal - supratidal (Red Clastic Facies) zones. Most current activity was tidally induced and water depths of less than 10m are envisaged. Epifaunal benthos were severely restricted by resuspension of the silt substrate, a condition promoted by a thriving infaunal community of soft bodied burrowers and, possibly, a high degree of fluidity at the sediment-water interface. The finest sediment remained in suspension due to the continuous tidal agitation, only being deposited in ponds, pools or lagoons behind beaches or bars, where evaporation caused exposure with subsequent dessication and the formation of haematite to give a characteristic red colouration. In the shallowest subtidal environments sufficient agitation existed to allow the formation of oncolites.

The carbonate dominated facies also reflect changes in energy levels within or across depositional zones. The bioclastic grainstones are regarded as the highest energy deposits as they represent prograding shoals and shoreface sediments; the implied environments are subtidal to intertidal. Once the shoals had stabilised, micritization of grains occurred and peloid rich sediments formed. Again there is evidence of subtidal, intertidal and even supratidal (i.e. above sea level) deposition in the Peloidal Grainstone Facies. The Fine Grained Carbonate Facies represents the lowest energy deposits and are almost certainly confined to the shallow subtidal zone. The Algal Mat Facies represents the shallowest carbonate facies (low supratidal to intertidal) containing evidence of periodic exposure and inundation by sheet floods. On the basis of burrow morphology and intensity of bioturbation the Bioturbated/Reticulated Limestones are regarded as being intertidal to subtidal deposits.

Diagenetic effects appear limited by early lithification. Dolomite selectively replaces micrite and two generations are clearly visible; the second commonly as a clear euhedral coating to dirty first generation subhedral to anhedral crystals. Authigenic quartz may be present as rinds to detrital quartz grains, but in certain micritic microfacies euhedral crystals can be observed. This appears to be the latest diagenetic event as in places the quartz is observed replacing second generation dolomite.

Some neomorphic sparry calcite is seen replacing the coenosteal tissue of stromatoporoids, but in general sparry calcite is confined to cement, which is both of the void filling and syntaxial rim (around echinodermal grains) varieties.

In situ epifaunal benthos are generally difficult to recognise, the exceptions being the stromatoporoid and *Solenopora* biofacies. Palaeoecological investigations showed that the major control on growth habits was depth of water especially related to the likelihood of exposure. The mobility of substrate appeared of secondary importance, although would obviously have had an effect on initial colonisation.

Stromatoporoids appear with corals and other biota as a series of patch reefs in a reef complex, which at its maximum development stretched westwards from the main site of development on the island of Helgøya into the Toten district. The northern equivalent in the Nes-Hamar district was sheets of stromatoporoids interbedded with peloidal grainstones. These ahermatypic occurrences never achieved a framework structure and were, usually, only one coenosteum thick, a feature attributed to extreme shallowness of water, due to their lateral equivalence with red beds.

Within the reef complex, a distinction could be made between the fore reef (crinoid rich) and back reef (calcisiltite and micrite) environments. The lack of sediment mixing and inferred change from high to low energy conditions implies that the reefs possessed topography, although the adjacent sediment lacks any evidence of having accumulated against a feature of significant relief; a gentle reef slope would also give such an effect and the dip of stromatoporoid coenostea at the reef front indicates this was probably the explanation.

Although the reefs themselves are dominated by stromatoporoids, a study of the biota in the reef pockets shows that a zonation into stabilization, pioneer, diversification and domination stages is achieved, although the domination stage is not always clearly defined. It is apparent from talus beds and erosional tops that the reefs grew into the surf zone and became eroded. Oncolite beds above the reefs indicate local high energy conditions. Niche competition was an extremely important influence on colony shape and faunal zonation, particularly with respect to stromatoporoids and the coral Eoflecheria. Where stromatoporoid growth was inhibited by soft substrate (reef bottom) or extreme shallowness (reef top) Eoflecheria thrived as massive colonies, but where stromatoporoids flourished, the coral assumed a reef pocket habitat. Although not such important controls, the effects of high sedimentation rates and current activity, as well as mobility of substrate, on the ultimate coenosteal shape can also be seen.

A distinctive fossil within the Mjøsa Limestone is the red alga, Solenopora, which forms an easily recognisable biofacies. Sedimentary evidence suggests that Solenopora flourished in areas of high sedimentation and strong current activity, where a delicate equilibrium existed between sedimentation and growth rates. It is this harshness of environment that is the most likely cause of the monotypical nature of the Solenopora biomasses. Vertical and lateral growth was in a series of irregular patches or sheets, which were probably only one or two thalli in thickness. Periodic, but catastrophic, inundation of sediment added to the build-up, but killed most of the biomass. The algae appear to have been particularly resilient and in periods of relative calm began lateral growth again. Within the biomass, Solenopora acted as food source, domicile, sediment source, sediment trapper and substrate for epifaunal encrustation. Most thalli show a high degree of preferential boring which considerably modifies the original growth shape, particularly as the algae appear to have had considerable regenerative powers enabling them to 'heal' after organic destruction or sediment inundation and incorporate sediment into the growing tissues.

A study of size, shape and peripheral condition of Solenopora not only allowed distinction of drifted and non-drifted forms, but also a recognition of shallower water growth features. As with the stromatoporoids an association with red beds and beach sediments brought a change in biomass development. In these environments a high percentage of small rounded (drifted) forms appear and growth appears as thin encrustations on the substrate; thallus size is also greatly reduced as is the number of specimens in a convex-upward orientation. Among the drifted forms, deposits from single surges of high energy (storms or strong tides) can be distinguished from those of local, more gentle, current activity.

Palaeogeographical reconstructions reveal that during deposition of the Mjøsa Limestone the shallowest conditions existed in the Toten district, particularly in the western outcrops, with a gradual deepening to the east and north east. This pattern continues through each of the three regressive phases which constitute the stratigraphical framework of the Formation, culminating in the exposure and solution weathering prior to deposition of the Silurian Helgøya Quartzite.

In all respects the sedimentary facies of the Mjøsa Limestone closely resemble the modern, warm, shallow water deposits of the Great Bahama Bank, and to some extent, although true evaporitic facies are absent, the Holocene carbonates of the Persian Gulf. The presence of peloids, grapestone, algal mats, algal and stromatoporoid-coral reefs are all indicative of a shallow marine environment with waters of normal salinity (BATHURST, 1967b). Deposition of the Mjøsa Limestone took place at the margin of the Middle Ordovician Baltoscandian epicontinental sea (JAANUSSON 1973; BJØRLYKKE 1974a) where the main direction of sediment transport was from deeper to shallower water due mostly to tidal influences.

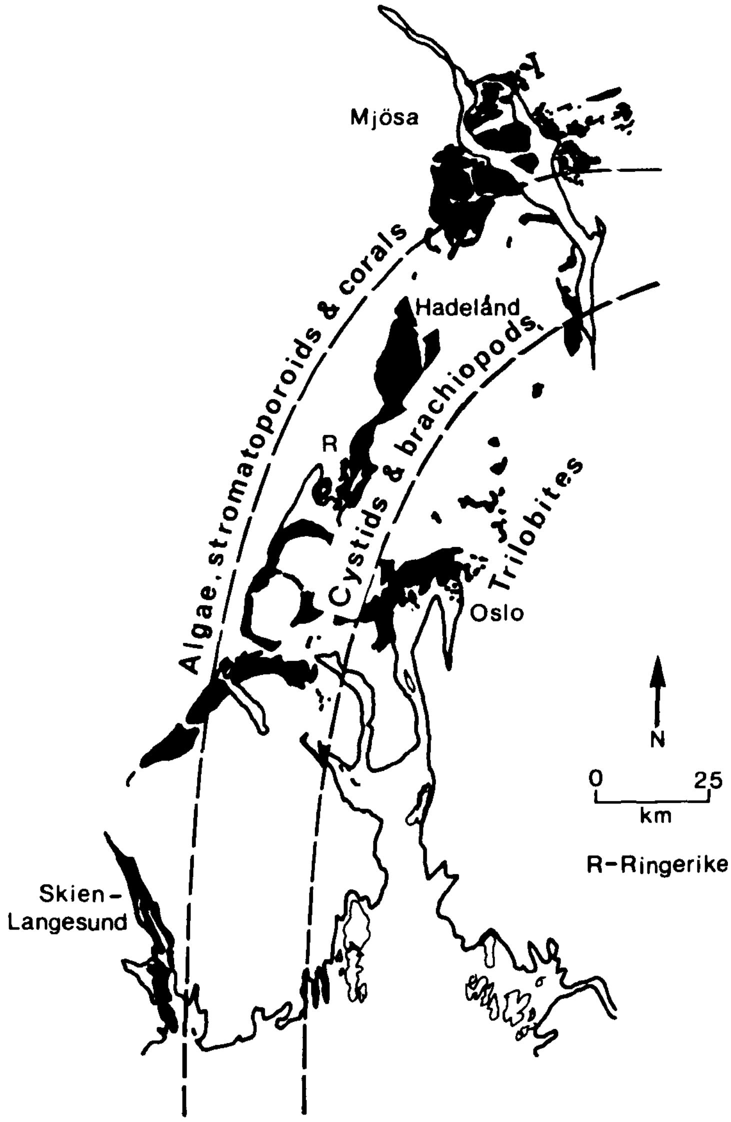
STØRMER (1953) has correlated the Mjøsa Limestone with the other calcareous facies which terminate the Middle Ordovician and suggested (1953; 1967) the existence of three concentric belts, singularly distinct by their facies and biota (Fig.7.1a). The western arc, exposed in the Mjøsa and Langesund - Skien districts only contains relatively pure limestones with abundant algae, stromatoporoids and corals, a condition Størmer regarded as due to deposition in well ventilated coastal waters. An examination of the Encrinite Limestone is being completed by T.Harland, who has found many similarities in the fauna and flora of both the Encrinite and Mjøsa Limestones. It appears that peloidal and micritic facies are generally lacking in the south, where terrigenous clastic and bioclastic (particularly pelmatozoan material) is dominant. Størmer's median belt is characterised by cystids, brachiopods and bryozoans, and represented by the Sphaeronid Limestone of Hadeland, a shaley nodular limestone unit which has as a direct equivalent to the Mjøsa Limestone a dark shale with limestone bands contain a trilobite - brachiopod fauna. The Upper Chasmops Limestone of Ringerike and Oslo-Asker districts appears as interbedded dark shales and continuous thin limestone horizons, with the dominant faunal element being trilobites. Størmer concludes that this distribution represents a southeastward transition from well ventilated to poorly ventilated conditions further from shore. Similar conclusions were reached by MÄNNIL (1965) and JAANUSSON (1973) who presented palaeogeographical reconstructions for the Baltic Region during the Ordovician. From these reconstructions and STØRMER'S (1953) correlation of the Norwegian and Swedish Caradocian sequences shows an identical pattern to that in the Oslo Region, with equivalents of the Mjøsa and Upper Chasmops Limestones appearing in the Kullsberg (reef bearing) and Macrourus Limestones respectively. Further correlation is possible with the deposits of Estonia (Fig.7.1b), which are almost identical in facies type (Vasalemma Stage), but are not satisfactorily correlated as yet (c.f. MÄNNIL (1968) and JAANUSSON (1976).).

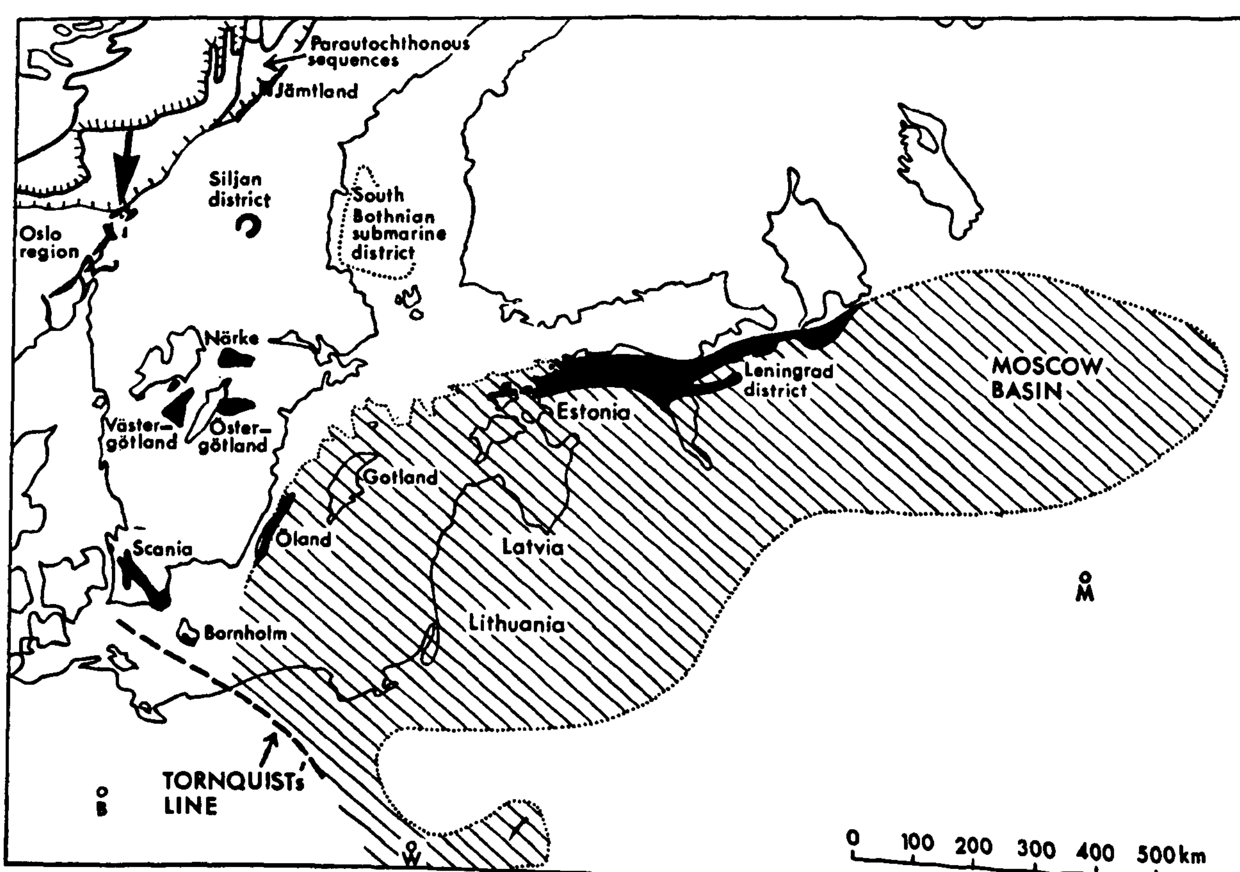
Despite these discrepancies of correlation it appears that the Mjøsa Limestone forms part of a belt of shoreline carbonate deposits which circumscribed the Middle Ordovician Balto-scandian epicontinental sea and are characterised by the accumulation of algal or reefoidal biomasses together with associated 'Bahamian' facies types.

In an early attempt at palaeogeographical reconstruction during the

Fig.7.1a: Biofacies zones in the upper Caradocian of the Oslo Region (after STØRMER 1967).

Fig.7.1b: The distribution of the Middle Ordovician in Baltoscandia (after JAANUSSON 1976). The shaded area represents the extent of the subsurface and submarine Ordovician on the Russian Platform. The Mjøsa district is arrowed; B - Berlin, W - Warsaw, M - Moscow.


Mjösa
Hadeland
Algae, stromatoporoids & corals
Cystids & brachiopods
Trilobites
R
Oslo
N
0 25
km
R-Ringerike
Skien-
Langesund


Parautochthonous sequences
Jämtland
Siljan district
South Bothnian submarine district
Oslo region
Närke
Väster-götland
Öster-götland
Gotland
Estonia
Leningrad district
MOSCOW BASIN
Latvia
Öland
Scania
Lithuania
Bornholm
M
TORNQUISTs LINE
B
W
0 100 200 300 400 500km

uppermost Caradoc (4bδ), STØRMER (1953, p.128) attributed the similarity of Baltic fauna in the Oslo Region and the Baltic area sensu stricto, envisaging their connection through a "common sea" or "common coastal waters". He also thought that the reefs would have grown around the "shores and festoons of low islands" which restricted circulation and gave rise to the "less well aeriated waters behind them" where trilobites flourished. This is presumably a reference to the Upper Chasmops Limestone of Oslo. The islands are apparently all that remain of the great land mass "Telemark Land" (SKJESETH, 1952) which contributed so much clastic material to the lower Middle Ordovician sediments. STØRMER (1953) envisaged the uplift of the Mjøsa district at the end of the Caradoc to give a barrier to circulation which had the dual effect of causing deposition of the Tretaspis shale over southeast Norway and Sweden as well as preventing its deposition in the Mjøsa district. By correlation of tectonic disturbances and influxes of clastic material into the Oslo Region, STØRMER (1967) showed the Caradoc-Ashgill boundary to be equivalent to the Ekne disturbance, which was probably a precursor to the main Taconic earth movements. The emergence of the Mjøsa district and subsequent slight tilting of the craton have been used to explain the presence of small disconformities, increases in clastic material or appearances of conglomerates and phosphate nodules at this chronostratigraphical boundary throughout the Oslo Region.

Geochemical analyses of the Oslo Region Middle Ordovician sediments by BJØRLYKKE (1974a,b) revealed a high concentration of detrital chromite (1200ppm) similar in composition to that from the Feragen serpentinite in the southeast of the Trondheim Region. The increase in chlorite content associated with clastic influxes and corresponding tectonic activity (STØRMER, 1967) led BJØRLYKKE (1974a,b) to conclude that the emergence of an island are system in the eugeosynclinal zone of Caledonian geosyncline was responsible for much of the sedimentary features in the Oslo Region.

The lack of a suitable chromite source elsewhere in Norway led Bjørlykke to conclude that, by analogy with the movement in suspension of heavy mineral grains in the Indian Ocean today, the chromite had indeed been transported from the deeper oceanic (i.e. geosynclinal) side of the Oslo Region by tidal and storm influence, rather than from the low energy, relatively shallow epicontinental (cratonic) side. Bjørlykke's hypothesis implies that open circulation existed between the geosynclinal and epicontinental seas, and that in all probability the Mjøsa district was sited on or very near the edge of the craton. This location and open circulation would account for the mixing of Scoto-Appalachian, Anglo-Scandic and Baltic type faunas as illustrated by SPJELDNAES (1961, Fig.3).

Both Bjørlykke and Størmer have used VOGT'S (1945) chronology and nomenclature for the phases of tectonic activity. During the summer of 1977 this author was priviledged to carry out joint work in the Meldal area of the Trondheim Region with Drs. P. Ryan and M. Williams, who, together with D. Skevington are in the process of radically revising the existing stratigraphy of the area.. The general consensus was that both Vogt's and CHALOUPSKY'S (1970) stratigraphy was unreliable, and that sedimentation took place in local basins with rapid facies variations from deep to shallow or subaerial environments. Indeed, it also transpired that much of the tectonic activity was also localised and not so neatly concentrated at precise stratigraphical horizons, or even the same horizons, as previously thought.

In view of this chronostratigraphical dubiety and the consistency of the Caradoc - Ashgill break throughout the Oslo Region, the hypothesis of eustatic control was investigated. SPJELDNAES (1961; 1976) has given a description of the climatic zones prevalent throughout the Ordovician, indicating that a general warming occurred throughout the Llandeilo and Caradoc, reaching a maximum at the top of the Caradoc, which was abruptly followed by a minimum in the lower Ashgill. This transition is marked by a return of 'colder' faunas and widespread regressions in Europe. Both SPJELDNAES (1961) and JAANUSSON (1973) have described the Mjøsa Limestone as having been deposited in warm waters, citing the coral-stromatoporoid reefs and 'Bahamite' facies as evidence. Jaanusson (ibid, p.14) even quotes a minimum temperature level of 25-27°C. The analogies between the Mjøsa Limestone and Recent sub-tropical carbonate sediments have been continuously stressed and, in this author's opinion, such conclusions are perfectly valid. SPJELDNAES' (1961) interpretation of the climatic belts is based on a 'cooling' of faunas to the south and 'warming' to the north, with the resultant placing of the Ordovician south pole in southern Africa and an equatorial belt circling northern Scandinavia. FAIRBRIDGE (1971) and HARLAND (1972) have both modified Spjeldnaes' original polar position to lie further north in Africa, probably in western Africa.

The topic of an Ordovician Ice Age has been reviewed by FAIRBRIDGE (1971) and HARLAND (1972; 1975). Evidence from the Sahara shows that fossiliferous Caradocian strata underlie glacial sediments, suggesting an Ashgillian age for these (FAIRBRIDGE, 1971; HARLAND, 1975; ALLEN, 1975). A glacial advance of this nature would account for the rapid cooling noticed by SPJELDNAES (1961). WILLIAMS (1975, p.863) gives a precise date of 445 $\pm$ 5 m.y. for the mean age of this glaciation, and, although FITCH et al (1976) have outlined the problems of relative dating in the Ordovician, this would certainly be within the Ashgillian. The Saharan tillites can be extended into Morocco where they are undoubtedly Ashgillian age (HARLAND, 1972, p.453).

Whilst glacial advance can provide the mechanism for emergence and non-deposition of the Tretaspis shale in the Mjøsa area together with a marked regression and break in sedimentation at the Caradoc - Ashgill boundary throughout southeast Norway, the minor regressive phases witnessed within the Mjøsa Limestone are best explained by epeiric block movements of the

Baltic Shield in this area.

From the evidence presented it appears that the Mjøsa Limestone represents the shallow deposits of the northwestern margin of the Baltoscandian epicontinental sea during the uppermost Middle Ordovician. There appears to have been open circulation with the geosyncline to the north with no evidence of a separating landmass at this time. The major sedimentological controls appear to have been applied firstly by epeirogenic movements and finally by advances of the polar ice caps. These ice advances may correspond with phases of tectonic disturbance, volcanic activity and, according to WILSON (1975), the passage of the Sun through galactic regions least distorted by the action of the Magellenic Clouds. This causes a change in the interstellar medium or energy output of the Sun which has important periodic climatic consequences for the Earth.

APPENDIX I.

STRATOTYPE DESCRIPTIONS.

INTRODUCTION

In naming and describing stratotypes an identical procedure is adopted in all cases. The locality name is derived from the nearest geographical feature, or failing that, named house of farm represented on the 1:5,000 maps. In giving the location, latitude and longitude are taken from the 1:50,000 maps preceded by the appropriate sheet number (and name). The reference number in parenthesis refers to the relevant 1:5,000 map.

The descriptions contain divisions into the formal and informal divisions proposed in Chapter 2, as well as the appropriate facies allocation and thickness of individual beds, or units. To avoid duplication reference is made to relevant passages in the text where certain phenomena may have been described in detail (e.g. the Bergevika Reef Complex).

In addition to the locations given in Fig. 1.1, locality maps of the Toten and Nes-Hamar districts are provided as a visual guide to the distribution of the main localities. Geographical reference to these localities is provided as a supplement.

KALLERUD

Location: Blad 1816 II (Eina), 60°40'50"N, 10°42'45"E. Approx. 350 m northeast of Kallerud farm and 350 m north of Holte cross roads, on the Bøverbru-Gjøvik road (CN 63/4).

General: exposure in the road cutting and bank providing a boundary stratotype for the Mjøsa Limestone in the Toten district. Total exposure is 16 m. Dip 60/334.

Description:	Facies	Thickness (m)
CYCLOCRINUS BEDS		
Interbedded quartz siltstones and shales.	1	2.00
Impure bioclastic grainstone lens.	2	0.30
Interbedded quartz siltstones and shales with thin (less than 3 cm thick) lenses, sheets or stringers of bioclastic material in the upper 1 m.	1	7.30
Medium grained pelmatozoan bioclastic grainstone lens.	2	0.15
Interbedded quartz siltstones and thin bioclastic grainstone pods; some contain siltstone laminations which enhance low angle planar cross-stratification; a 10 cm. bioclastic horizon develops at the top of the unit.	1	0.80
Interbedded siltstones, shales and calcareous siltstone horizons, with an influx of bioclastic detritus occurring in the upper 60 cm.	1	5.90

MJØSA LIMESTONE

SIVESINDHAGEN MEMBER :

Terrigenous clastic and bioclastic beds.

Medium grained calcarenitic bioclastic grainstone dominated by pelmatozoan debris and containing occasional small rounded *Solenopora*, which increase in size (2 to 8 cm diameter) in the upper 50 cm.	2	1.20
Large *Eoflecheria*, apparently in growth orientation, with small *Solenopora*, (1 to 2 cm) between them. The surrounding sediment is siltstone dominated often showing evidence of it being washed in and swamping the corals. Bioclastics and dolomite are also present but in minor quantities only (less than 20%).	11	0.40-0.60
Coarse calcarenitic - calciruditic pelmatozoan bioclastic grainstone with *Solenopora*, and *Solenopora* with *Eoflecheria* in the upper 20 cm.	2/11	0.80
Interdigitating quartz siltstones and *Eoflecheria*-*Solenopora* boundstones; the *Eoflecheria* show a range of colony size from a maximum of 40 x 60 cm to small 'nodules' in the siltstone beds of 2 x 1 cm dimensions. Sediment occurring within the corals is mostly siltstone or dolomite, but some pelmatozoan bioclastics are frequently seen to surround them. Towards the top of the unit an increase in *Solenopora* abundance is noticeable. The majority (70%) of the *Eoflecheria* are in a growth orientation and there is a suggestion of fine sediment being trapped on one side of the colonies, indicating that these are growth phenomena. *Solenopora* are however regarded as drifted due to their small size, smooth edges and general lack of convex sided forms.	1/11	2.20

Mudstone/siltstone dominated unit containing abundant (and large) Solenopora with a rapidly decreasing Eoflecheria population.	1/11	1.40
Scrappy exposures of a siltstone unit which contains large Eoflecheria in growth orientation.	1/11	2.70
More scrappy exposure of a similar facies but Eoflecheria has been replaced by Solenopora, bryozoa and occasional Liopora, while at the top of the bed encrusting stromatoporoids are very much in evidence.	1/11	1.00
Massive unit of calcarenitic pelmatozoan bioclastic grainstone containing abundant calciruditic Solenopora fragments. Apart from the abundance of this alga, the bed also shows a fine development of oncolitic coats to almost all grains as well as an abundance of encrusting organisms in general e.g. Grapthodictyon, stromatoporoids and Girvanella.	2	1.10
Siltstone dominated unit containing abundant Liopora and Eoflecheria colonies, most of which display 'drapes' of siltstone indicating they are in growth position.	1	0.60
Medium to fine bioclastic calcarenite.	2	0.30
Parallel laminated thinly bedded quartz siltstones, containing Solenopora (7 to 8cm diameter), which show evidence of boring and varied orientations, together with large (3-4cm) oncolites.		0.50
Interbedded quartz siltstones and shales with Chondrites, Solenopora rich horizons occur between 80 and 120cm from the base, while the uppermost 17cm show an increase in fine bioclastic content.	1	1.80

Above an irregular (erosional?) base 20cm of Solenopora rich bioclastics grade into siltstone rich beds. The Solenopora show evidence of boring and are generally less than 2cm diameter (maximum 4-5cm). 2/1 0.50

Interbedded fine calcarenitic bioclastics and siltstones, the latter containing abundant Chondrites. Poorly developed nodules appear to be present, giving the beds a "lumpy" appearance. 0.90

HELSET

Location: Blad 1816 II, 60°42'17"N, 10°42'15"E; at the junction of the Bøverbru-Gjøvik road with the road to Eriksrud. (CN 063/2).

General: a small roadside cutting which is a boundary stratotype for the base of the Mjøsa Limestone. Grubbings and small outcrops are situated in the overgrown bank and woodland for approximately 80m southeast of the main exposure. The total thickness of Mjøsa Limestone represented here is approximately 23.83 m. Dip 78/77.

Description:	Facies	Thickness (m)
CYCLOCRINUS BEDS		
Interbedded quartz siltstones, shales and occasional thin (< 10 cm) sheets, pods or lenses of bioclastic calcarenites. The beds become richer in carbonate content towards their upper boundary.	1	11.00
MJØSA LIMESTONE		
SIVESINDHAGEN MEMBER		
Quartz siltstone bed with pelmatozoan bioclastic material in stringers at the base but increasing in abundance upwards, with whole ossicles standing out on the surface and occasionally displaying cross-bedding.	1	0.22
Calciruditic pelmatozoan bioclastic grainstone with small *Solenopora* fragments.	2	0.30
Calciruditic pelmatozoan bioclastic grainstone with broken *Chasmops*; stick bryozoa, orthids, and crinoid ossicles.	2	0.80

As above but with an average grain size of 4 mm and large scale channel cross-bedding.	2	1.20
A similar unit to the underlying one, but with a complete dominance of pelmatozoan (crinoidal) bioclasts, slightly smaller grain size (still a calcirudite), well developed large scale planar cross-bedding (Table I.1.i) and an apparent high bitumen content.	2	0.65
Highly bituminous coarse calcarenitic grainstone, composed almost exclusively of pelmatozoan material and with large scale planar cross-bedding. (Table I. 1.ii).	2	0.25
Shale parting.		
Medium grained calcarenitic bioclastic grainstone with a small asymmetrical channel cut into its top surface.	2	0.17-0.14
Ripple drift bedded quartz siltstones acting as channel fills (Table I.1.iii) and forming a bed of variable thickness.	1	0.10-0.17
Calciruditic bioclastic grainstone, mostly composed of pelmatozoan material. The upper surface is eroded by small channels.	2	0.25-0.30
Thinly bedded siltstone unit.	1	0.05-0.15
Medium to fine calcarenitic bioclastic pelmatozoan/grainstone with an increased siltstone content, low angle oscillatory cross-bedding and containing Solenopora fragments with Diplotrypa.	2	0.26
Interbedded calcarenitic bioclastics and quartz siltstone.	2/1	0.10
Massive bioclastic grainstone with an erosional base, and high angle planar cross-stratification passing into low angled planar cross-stratification (Table I.1.iv).	2	0.60
Weathered siltstones and shales.	1	0.30

Bioclastic grainstone with a fining up tendency to the grain size.	2	0.26
Siltstone parting.		
Bioclastic calcarenite.	2	0.10
A siltstone filled channel (Table I.1.v) on the upper surface of the calcarenite developing into a thin bed.	1	0.05
Interbedded medium to fine bioclastic calcarenites and quartz siltstones.	2/1	0.40
Weathered unit of interbedded quartz siltstones and shales, with thin pods or stringers of bioclastic material throughout, occasionally in channels.	1	4.48
N.E.		0.50
Calciruditic pelmatozoan bioclastics in grubbings.	2	0.20
N.E.		0.30
Calciruditic pelmatozoan bioclastics in grubbings.		0.15
N.E.		0.80
Bioclastics in grubbings.		0.12
N.E.		

TABLE I.1: Palaeocurrent data: Helset

i) 13.52m above base of the limestone

Large scale planar cross-bedding: foreset azimuth

008 008 008 028 017 025 012 012 005

ii) 14.17m above base of the limestone.

Large scale planar cross-bedding: foreset azimuth

188 176

iii) 14.59m above base of limestone.

Channels in siltstone

074 100 080

iv) 15.57m above base of limestone.

Channels at base of a limestone bed.

090 096

v) 16.83m above base of limestone.

Channels filled by bioclastic limestone

090 072 096

SIVESINDHAGEN

Location: Blad 1816 11 (Eina) 60°39'22"N, 10°39'E; approx. 500 m northwest of Sivesindhagen farm and 450 m southeast of Døl bakken farm. (CN 062/1).

General: a small disused quarry and pavement area exposing 52.20 m of Mjøsa Limestone and providing the stratotype for the Sivesindhagen Member. Dip 64/198.

	Facies	Thickness (m)
Description:		
MJØSA LIMESTONE		
SIVESINDHAGEN MEMBER		
Terrigenous clastic and bioclastic beds.		
Massive unit of pelmatozoan bioclastic calcarenite with well developed parallel stylolites and stringers of small rounded Solenopora in the upper 2.30 m, gradually increasing in size (up to 6 cm) and becoming dispersed through the bed. Large Eoflecheria are found in the bed, both as convex-downward and convex-upward individuals as well as thickets up to 3.40 m long and 50 cm high; these trap both quartz siltstones, small Solenopora as well as showing local concentrations of dolomite.	2	4.70
Massive pelmatozoan calcarenite with a gradual increase in size and concentration of Solenopora; up to 60 cm from the base, thalli are small, rounded, after that the algae become densely packed, and after 115 cm bored trumpet shapes (in convex sideways orientation) appear. Large Eoflecheria colonies also in growth orientation are found in this bed.	2/11	1.50

'Conglomerate" of Solenopora, generally less than 4 cm diameter with both rounded and trumpet shapes in evidence in a coarse calciruditic pelmatozoan grainstone. Small Eoflecheria colonies are also present in growth orientation.	2/11	0.60
Solenopora dominated calciruditic grainstone with the lower 110 cm showing closely packed ragged thalli with associated disorientated Liopora colonies and some oncolites, mostly bean shaped. The upper 130 cm are similar to the basal facies but show large scale cross-stratification and an increasing Solenopora size range (10 cm max.).	11	2.40
Well bedded bioclastic grainstone with a high percentage of closely packed, rounded Solenopora.	11	1.60
Bioclastic grainstone with a concentration of very small Solenopora in the basal 90 cm (size range 0.5 - 1 cm), but only scattered individuals in the upper 50 cm (size range 0.5 - 5 cm).	2	1.40
Bioclastic grainstone with small Solenopora at the base and an increasing silt content towards the top.	2	0.90
Quartz siltstone with stringers of small Solenopora.	1	0.35
Thinly bedded quartz siltstones.	1	1.20
Solenopora and quartz siltstones.	11	0.40
As above	11	0.50
Interbedded calcirudites (with Solenopora) and siltstones.	2/1	0.40
Thinly bedded siltstones with ripple drift, small scours and scattered Solenopora, Sowerbyella, bryozoan and Chondrites.		

Transitional beds from siltstones (basal 30 cm) to cross-stratified (siltstone laminated foresets) and finally bioturbated, bioclastic grainstone.	1/2	1.00
Solenopora rich bioclastic beds.	11	1.40
Siltstone with ripple drift and planar cross - stratification.	1	0.90
Interbedded bioclastic grainstones and silt-stones. Cross-stratification dips westward.	2/1	0.70
Unit of bioclastic calcarenites with a basal concentration of Solenopora and general fining upwards to a medium calcarenite. Small scale oscillatory planar cross-stratification is common towards the top of the unit.	2	2.80
Green siltstones with stringers of bioclastic debris. Upper 70 cm become purple coloured and may have a higher bioclastic content.	8	1.70
Massive bed of pink pelmatozoan bioclastic calcarenite.	2	4.20
Red quartz siltstones.	7	0.90
N.E.		1.60
Medium calcarenite of pelmatozoan material. Parallel stylolites mimic low angle planar cross-stratification.	2	1.00
As above.	2	0.60
As above, but contains an increasing number of large Solenopora which appear to encrust the substrate, as well as oscillatory cross-stratification.	2/11	1.00
N.E.		1.40
Pelmatozoan bioclastic calcarenite (grainstone) with trains of large Solenopora and oscillatory low angle planar cross-stratification.	2	1.40

Above a channelled base (144^{o} trend) have a veneer of Solenopora bioclastics and siltstones before a 10 cm horizon of rippled (Table I.2.i) Solenopora bioclastics. Remainder of beds is interbedded thin Solenopora bioclastics and siltstones.	2/11	0.80
Massive Solenopora-rich bioclastic grainstone (calcarenite). Solenopora vary in abundance but show a concentration in trains and along the foresets of high angle planar cross-stratification, where a crude grading exists. The upper 1 m contains less Solenopora, more siltstone and attains a purple colouration.	2/11	2.20

Ihle Peloidal Beds

Grey-green fine siltstone.	7/1	0.30
Peloidal grainstone.	3	0.20
Bioclastic calcarenite with basal veneer of small Solenopora. The top of the bed shows cross-bedding and small scale scour structures (Table I.2.ii).	2	0.30
Medium bioclastic calcarenite coarsening upwards. Pelmatozoan material dominant but unit also contains scattered Solenopora, and high angle cross-stratification (Table I.2.iii).	2	0.90
Medium calcarenite of pelmatozoan material, with scattered Solenopora and sub-parallel stylolites.	2	0.60
Fine bioclastic calcarenite.	2	0.20
Basal 20 cm of peloidal grainstone grading through a fine bioclastic calcarenite into a cross-bedded medium calcarenite with poorly developed grading of Solenopora on the foresets. Unit then becomes finer and in upper 80 cm get small scale planar cross-stratification and parallel stylolites.	3/2	1.90

Bioturbated peloidal grainstone.	3	0.70
Fine bioclastic grainstone with parallel stylolites.	2	1.10
Peloidal grainstone with parallel stylolites, some oncolites and occasional <u>Solenopora</u>. Upper 40 cm have a fine dolomite net.	3	0.80
Peloidal grainstone with dolomite net.	8	0.40
As above.	3	0.20
Bioturbated peloidal grainstone. Base yields oncolites and <u>Ancistrorhyncha</u>, upper part looses oncolites but gains flat gastropods and orthocones.	3	0.80
Mixed fine bioclastic/peloidal grainstone.	2/3	0.50
Peloidal grainstone.	3	0.50
Mixed fine bioclastic/peloidal grainstone.	2/3	0.50
Siltstone rich fine bioclastic grainstone, passing into peloidal grainstone with dolomite net. Unit is eroded by overlying beds.	2	0.26-0.40

EINA MEMBER

Pelmatozoan calcarenitic grainstone.	2	0.26
Siltstone.	1	0.15
Pelmatozoan calcarenitic grainstone.	2	0.20
Laminated siltstone.	1	0.15
Calcareous siltstone with ripple drift.	1	0.10
<u>Solenopora</u> rich pelmatozoan bioclastic calcarenite.	2	0.90

Table I.2 : Palaeocurrent data, Sivesindhagen

i) 37 m above base of section.

Ripple crests:

076	080	074	076	074	078	116	108	102
132	188	180	186	162				

ii) 40.75 m above base of section.

Small scours:

034	036	032	042

iii) 41.65 m above base of section.

Cross-stratification azimuth:

030	038	028	020	034	036	042	036	036
038	016	034	034	030	042	040		

IHLE

Location: Blad 1816 11 (Eina), 60° 41' 10"N 10° 42' 40"E Approx. 400m north of Ihle and 850m south east of Helset cross roads on the Bøverbru-Gjøvik road (CN 062/2).

General: new roadside cutting exposing 36.98m of the basal Mjøsa Limestone, which displays a higher quartz silt content throughout the succession than is normally encountered. Exposure is insufficient to permit a definite determination of the formation base. Dip 88/246.

Description:	Facies	Thickness (m)
MJØSA LIMESTONE		
SIVESINDHAGEN MEMBER		
Terrigenous clastic and bioclastic beds.		
Weathered quartz silts with *Grapthodictyon* stick bryozoa, orthids, strophomenids and *Chasmops* fragments.	1	3.10
Calciruditic pelmatozoan bioclastics with abundant *Solenopora*, often exhibiting packite textures.	11	0.90
Interbedded fine bioclastic calcarenites with bioturbated siltstones and shales.	1/2	0.70
Fine bioclastic calcarenite with siltstone partings throughout; some show a red colouration and/or ripple drift laminations. The top surface of the bed is a bioturbated siltstone.	2	0.90
Grubbings of a deeply weathered calcareous fine sandstone containing scattered pink pelmatozoan bioclasts.	1	0.50

Grubbings of fine bioclastics, and siltstones with pelmatozoan fragments.	2/1	0.80
Calcarenitic pelmatozoan bioclastics with thin quartz siltstone laminations accentuating planar cross stratification passing into a parallel laminated siltstone with some Chondrites.	2/1	0.45
Calcareous siltstones which are deeply weathered.	1	0.28
Pelmatozoan bioclastic calcarenite with abundant Solenopora.	2	0.10
Weathered quartz siltstone.	1	0.10
Veneer of Solenopora and pelmatozoan bioclastic material.	2	0.10
Weathered fossiliferous parallel laminated calcareous quartz siltstone.	1	0.25
Interbedded quartz siltstones and shales with abundant Chondrites, ripple drift stratification, gutter casts, and planar small scale cross-stratification. Bioclastic veneers often line or fill small channels.	1	2.99
Massive unit of calcarenitic pelmatozoan bioclastic grainstone with quartz siltstone beds at irregular intervals; these contain parallel laminations and small scale low angle planar cross-stratification.	2	1.85
Pelmatozoan bioclastic calcarenite which shows a gradual fining up of grain size and accompanying increase in quartz siltstone content in the uppermost 47cm; the final 7cm are a fine bioclastic calcarenite with siltstone accentuated low angle cross-stratification.	2	1.37
Quartz siltstones.	1	0.20

Fine bioclastic calcarenite.	2	0.40
Bioclastic calcarenite with a high quartz siltstone content, manifested in large scale planar cross stratification (Table I.3).	2	1.00
Bioclastic calcarenite with erosional (channeled) base.	2	0.25
Interbedded quartz siltstones and bioclastic calcarenites, with low angle planar cross-stratification.	1	0.53
Fine bioclastic calcarenite with a quartz siltstone upper 4cm.	2	0.44
Fine bioclastic calcarenite with oscillatory quartz siltstone accentuated planar cross-stratification.	2	0.12
Bioclastic calcarenite with occasional small _Solenopora_ and quartz siltstone laminations.	2	0.80
Quartz siltstone dominated unit with some calcarenites.	1	0.90
Bioclastic calcarenite with occasional _Solenopora_ and quartz siltstone laminations.	2	0.30
Weathered quartz siltstones with bioclasts	1	0.12
Fine bioclastic calcarenite with abundant quartz siltstone partings and occasional small rounded _Solenopora_.	2	0.90
Very finecalcarenite with quartz siltstone confined to inclusions along the sub-parallel stylolites.	2/1	0.60
As above but with an increased quartz content in the lower 20cm and bioturbation in the upper 20cm.	2/1	0.60

The Ihle Peloid Beds.

Fine rather indistinct, peloidal grainstone with	3	0.36

subparallel stylolites.		
Fine bioclastic calcarenite.	2	0.80
Indistinct peloids in a massive unit with parallel stylolites and a weathered dolomite rich upper surface.	3	0.45
Fine peloidal grainstone with amalgamation of grains in patches to give a mudstone texture. Parallel stylolites are abundant throughout this thinly bedded unit. The uppermost 12cm is a rotten horizon of dolomite, quartz siltstones and pelmatozoan bioclasts.	3	1.00
Irregularly bedded peloidal grainstone unit with an oncolite, stromatoporoid (?) bearing lower 35cm. A fine dolomite net in the lower beds is replaced by parallel stylolites in the middle, while the upper 20cm appears bioturbated and contains molluscan bioclasts and small gastropods. There appears to be a coarsening of peloidal size throughout the whole unit, while individual beds are often seen to have a veneer of bioclasts at their bases.	3	0.80
A thinly bedded composite unit consisting of fine black bioclastics with bioturbated quartz siltstone horizons which gradually pass into a fine peloid rich upper 40cm with a deeply weathered, bioturbated top. The bioclastics include abundant fragments of stick bryozoa, molluscan debris and *Ancistrorhyncha*.	2/3	1.30
Fine black bioclastic calcarenite with recogniseable peloids well developed in parallel stylolites approx. 2cm apart and an 8cm bioturbated dolomite/quartz siltstone top.	2	0.40
As above but containing a higher percentage of peloids.	2/3	0.45
Peloidal grainstone containing pelmatozoan bioclasts, and *Phytopsis* which is concentrated in a 5cm band directly below the upper 6cm of *Ancistrorhyncha*	3	0.24

bearing quartz siltstone/dolomite.

A thinly bedded mixed unit of fine bioclasts and peloidal horizons, containing abundant Ancistrorhyncha, Strophomena, Solenopora and gastropods in a thin (5cm) band 9cm above the base; the unit displays a gradation from bioclasts to peloids with a bioturbated upper dolomite rich horizon.	2/3	0.90
Peloidal grainstone showing development of a heavy dolomite net.	3	0.20
Bioclastic calcarenites with parallel stylolites.	2	0.20
Quartz siltstones with parallel laminations, ripple drift cross-stratification and Chondrites.	1	0.16
Coarse calcarenitic pelmatozoan bioclastic grainstone with very rare small Solenopora.	2	0.25
Quartz siltstone with parallel laminations.	1	0.07
Bioclastic calcarenite with quartz siltstone filled channels grading into a 10cm quartz silt horizon.	2	0.35
Bioclastic calciruditic grainstone dominated by pelmatozoan material, much of which shows a pink colouration, and containing small Solenopora.	2	1.00
Bioturbated quartz siltstone with Chondrites.	1	0.06
Fine bioclastic calcarenite with a high percentage of peloids in the basal 17cm.	3/2	0.27
A unit of fine bioclastic calcarenite and peloidal grainstones with parallel stylolites. The whole bed is finely brecciated by thin viens of black calcite.	2/3	0.46
Bioturbated deeply weathered quartz siltstone.	1	0.14
Massive peloidal-fine bioclastic unit, again with black calcite viens and brecciation.	2/3	0.90
N.E.		0.40

Dominantly a peloidal grainstone showing good development of a dolomite net and brecciation.	3	0.25
Peloidal grainstone with subordinate fine bioclastic calcarenite. The main feature is the development of a heavy dolomite net. Small Solenopora are scattered throughout the upper 14cm, which also contain a greatly increased percentage of pelmatozoan bioclasts.	3/2	1.04

EINA MEMBER

Bioturbated calcilutites, quartz siltstones and bioclastic beds.

Pelmatozoan dominated bioclastic calcarenite with a gradual coarsening upwards of bioclasts and an increase in numbers of scattered small Solenopora.	2	0.30
Densley packed Solenopora "conglomerate" in a coarse pelmatozoan dominated calcarenite.	11	0.50
Bioclastic calcarenite with quartz siltstone horizons.	2	0.20
Coarse calcarenitic grainstone of pelmatozoan bioclasts with occassional scattered small Solenopora.	2	0.35
Parallel bedded quartz siltstone with a slight development of ripple drift cross-stratification. The main feature is the development of straight vertical burrows, 4mm wide which penetrate the whole unit. The upper 6cm contain an increased number of bioclasts, particularly small Solenopora.	1	0.18
Interbedded fine bioclastic calcarenites and quartz siltstones.	2/1	0.20
Fine bioclastic calcarenite containing abundant red pelmatozoan bioclasts.	2	0.50

Fine bioclastic calcarenite containing small rounded, but scattered, Solenopora.	2	0.60
Quartz siltstone.	1	0.08
Coarse calcarenitic grainstone of dominantly red pelmatozoan bioclasts and abundant small rounded Solenopora.	2	0.40
Quartz siltstone with Solenopora.	1	0.20
Large Solenopora in a calciruditic grainstone of red pelmatozoan (crinoidal) bioclasts.	2	0.50

Table I.3. Palaeocurrent data. Ihle

c 6.50 m above base of exposure.

Ripple crests

170	178	064	024	096

EINA

Location: Blad 1816 11 (Eina), 60°38'22"N, 10°35'10"E, approx. 850m north-northeast of Eina station and 100m east of the main road (Reinsvoll-Eina). (CN 062/3).

General: disused quarry and cleared pavement combine to give a continuous section through 89.75m of Mjøsa Limestone and provide the type locality for the Eina Member. Dip vertical, strike 087.

Description:

MJØSA LIMESTONE

SIVESINDHAGEN MEMBER

Description	Facies	Thickness (m)
Terrigenous clastic and bioclastic beds		
Siltstones with bioclastic interbeds.	1	0.80
Fine to medium pelmatozoan bioclastic grainstone with an upward increase in siltstone content scattered *Solenopora* and low angle, planar, oscillatory cross-stratification.	2	2.10
Massive unit with *Solenopora* and *Eoflecheria* in the lower 1.20m. Siltstone content increases upwards.	2/11	3.00
Interbedded quartz siltstones and bioclastic grainstones containing ragged oncolites in the basal beds, and occasional clumps of *in situ* *Solenopora* throughout.	1/2	3.30
Bioturbated interbedded siltstones and bioclastic grainstones.	1/2	1.60

Massive pelmatozoan bioclastic calcarenite with parallel stylolites and scattered small Solenopora.	2	4.00
Pink pelmatozoan calcirudite.	2	0.80
Interbedded siltstones and bioclastic grainstones with abundant Solenopora. Algae are a mixture of in situ and small drifted thalli.	11	2.60
Pelmatozoan calcirudite.	2	0.50
Massive unit of Solenopora, most appear in growth position, although they are small forms. Lateral sediments include drifted Solenopora in a bioclastic grainstone/siltstone sequence.	11	4.80
Massive unit with much detail obscured due to the quarry face coinciding with a fault plane at this point. Unit begins as a bioclastic calcirudite with abundant small rounded Solenopora, passed into finer bioclastic calcarenites with a high Solenopora content, gastropods, stromatoporoids and ends as a fine black bioclastic calcarenite.	2	5.80
Fault fractured bed of fine black bioclastic calcarenite with small scattered Solenopora.	2	0.70
Fault fractured, slightly purplish medium to fine bioclastic calcarenite.	2	1.50
Ihle Peloidal Beds		
Mixed peloidal and bioclastic grainstones, containing bryozoa, gastropods and Ancistrorhyncha.	2/3	0.30
Fine, black, bioclastic calcarenite	2	0.30
Mixed bioclastic and peloidal grainstone; upper horizons are a coarse calcarenite of peloidal grainstone.	3/2	1.20

Peloidal grainstone with parallel stylolites.	3	0.30
Peloidal grainstone with a bioturbated upper surface. Main feature is the irregular erosion surface which cuts into the bioturbated part of the unit.	3	0.60

EINA MEMBER

Bioturbated calcilutites, quartz siltstones and bioclastic beds.

Basal channel fill is of Solenopora rich fine pelmatozoan calcarenite which grades rapidly into a fine black bioclastic limestone, with parallel stylolites mimicking low-angle planar cross-stratification.	2	0.60-1.10
Coarsening upward pelmatozoan calcarenite with an increasing Solenopora content. Parallel stylolites and low-angle cross-stratification are common.	2	0.85
Fault.		
Arenaceous bioclastic calcarenite.	2	0.40
Shale.	1	0.01
Black bioclastic calcarenite.	2	0.20
Shale.	1	0.03
Fine bioclastic calcarenite	2	0.14
Shale.	1	0.02
Fine siltstones with abundant Chondrites.	1	0.20
Bioclastic grainstone containing pelmatozoan fragments, small Solenopora and branching bryozoa.	2	0.15
Fine siltstones with abundant Chondrites. Bioclastic beds appear disturbed by bioturbation.	1	0.34
Interlaminated siltstones and bioclastic pods or veneers. The siltstones are full of Chondrites and occasionally show small Diplotrypa in a convex upward	1	5.60

orientation. The bioclastic beds contain abundant fragments of stick bryozoa, small orthids, occasional strophomenids, dalmanellids and rhynchonellids and rare trilobite fragments. Comminution increases towards the top of this unit.

As above but the degree of disturbance between the clastic and bioclastic fractions increases.	1	2.10
Black calcisiltite with virtual absence of fossils (bryozoa fragments).	4	2.36
Small fault wedge contains a nodular micrite, which is identical to the overlying beds. Nodules appear to have formed around small <u>Phytopsis</u>-like areas of sparry calcite. Pyrite is abundant in this unit.	4	3.70
Black calcisiltite	4	2.40
Arenaceous calcisiltite with a gradation into quartz siltstones containing <u>Chondrites</u>.	4/1	1.50
Calcisiltite and calcilutite	4	0.40
Quartz siltstone with <u>Chondrites</u>	1	0.35
Calcisiltite with an increasing bioclastic content and nodular development in the upper 60cm.	4	1.10
Nodular biomicritic wackestone/mudstone. Some evidence of bioturbation.	4	0.60
Calcisiltite (siltstone) with interlaminated bioclastic horizons, which are generally thin (1-5 cm) discontinuous and dominated by bryozoa. The calcareous siltstone horizons contain a <u>Chondrites</u>-like ichnofauna.	1/4	4.20
As above, in a wedge between two faults.	1/4	0.60
As above, again between two faults. Bioclastic horizons become more disturbed towards the top.	1/4	2.20-4.00

Wedge of well bioturbated bioclastic grainstone/ siltstone/calcisiltite bed. Fossils include Solenopora, trilobites, bryozoa and a few orthid valves.	1/2/4	1.60
As above, burrows appear mostly vertical, although swirled structures are also present. Most burrows are dolomite filled.	1/2/4	1.10
Bioturbated fine bioclastic calcarenite.	2	0.60
Medium-fine bioclastic calcarenite with intense bioturbation. Unit contains a small Eoflecheria-Solenopora-stromatoporoid biomass with a fringing apron of oncolitic grainstone.	2	0.80
Fault.		

Rud Peloidal Beds

Peloidal and bioclastic grainstone with low angle oscillatory cross-stratification.	3/2	1.70
Peloidal grainstone with an upward increase in dolomite net development.	3	0.20
Peloidal grainstone (coarse calcarenite) with a well developed dolomite net at the top.	3	0.50
Micrite with dolomite developing a laminar aspect.	4	0.30
Algal mat with well laminated dolomite.	6	0.25
Peloidal grainstone with amalgamation of peloids to give a mudstone texture. Bioturbation is evident near the top of the unit.	3/4	1.00
Algal mat. Mostly parallel laminated but some crinkly mat and poorly developed hemispheres can be seen.	6	1.35
Algal mat. Laminations gradually die out.	6	0.90

Coarse calcarenitic-calciruditic peloidal grainstones with parallel stylolites.	3	1.40
Dolomite.	5	1.10
N.E.		0.70
Calciruditic peloidal grainstone.	3	0.20
Algal mat.	6	0.10
Bioturbated micritic mudstone with the upper surface showing an irregular, erosional contact with the overlying beds.	4	0.50

HOLETJERN MEMBER

Hemstadmoen Bioclastic Beds.

Coarse pelmatozoan calcarenite with *Solenopora*, orthocones, *Streptelasma*, bryozoa, *Liopora* and ragged oncolites.	2	0.60
N.E.		1.40

Bioturbated bioclastic limestones and dolomites.

Pronounced vertical, dolomite filled, burrows in a fine bioclastic calcarenite or micritic mudstone.	9	9.50

RUD

Location: Blad 1816 11 (Eina), 60°40'37"N, 10°41'E, approx. 1 Km. east of Rud farm and 750m southeast of Krekerud on the Raufoss-Boverbru road. (CN 063/4).

General: A disused quarry section which exposes 41 m of Mjøsa Limestone and provides the unit stratotype for the Rud Peloidal Beds. Dip

	Facies	Thickness (m)
Description:		
MJØSA LIMESTONE		
EINA MEMBER		
Bioturbated calcilutites, quartz siltstones and bioclastic beds.		
Massive unit of calcisiltites with concentrations of orthocones at 90 cm, Phytopsis and nodular horizons at 1.50 m above the base. General fauna is broken stick bryozoa and Parallelodus - Modiolopsis type bivalves, with scattered trilobite fragments and a solitary Lingula. The upper 60 cm are interbedded fine bioclastic calcarenites and siltstones with Chondrites.	4	4.10
Fine black bioclastic calcarenite.	2	0.30
Fine black bioclastic calcarenite with an irregular (scoured ?) base and Chondrites in the finer upper 20 cm. Bioclastic material includes pelmatozoan and Dimorphosiphon fragments.	2	0.60
Massive unit of calcisiltite with bioclastic horizons. The lower 50 cm are heavily bioturbated while nodules are developed at 160 m above the base.	4	5.00

Fine black bioclastic calcarenite.	2	0.50
Rud Peloidal Beds		
Fine black bioclastic calcarenite grading into a mixed peloidal-bioclastic grainstone. Upper 40 cm are a peloidal calcarenite-calcirudite.	2/3	2.00
Bioturbated bioclastic-peloidal grainstone containing planulate gastropods.	2/3	0.50
Micritic mudstone (amalgamated peloids) with vertical dolomite filled burrows on the upper surface.	4/3	0.60
Micritic mudstone.	4	0.15
Fault zone.		1.90
Bioturbated fine peloidal grainstone.	3	0.56
Peloidal grainstone which coarsens to a calcirudite in the middle of the bed but reverts to a fine calcarenite at the top. Poorly developed _Phytopsis_ appear scattered throughout.	3	1.50
Mixed bioclastic-peloidal grainstone passing into pure peloidal calcarenite. Bed contains parallel stylolites.	2/3	0.75
Peloidal calcarenite coarsening upwards to a calcirudite. Parallel stylolites throughout.	3	0.77
Massive unit of peloidal grainstone and amalgamated peloids. The lower 1 m contains bryozoa and _Ancistrorhyncha_, although fauna is generally absent. A fine dolomite net appears throughout, although the upper 50 cm are dolomite free and show _Phytopsis_ like features.	3	2.90
Peloidal calcarenite/calcirudite with the uppermost horizons showing amalgamation and vertical dolomite filled burrows.	3	1.10

Bioturbated fine black peloidal grainstone.	3	0.40
Peloidal calcirudite/intraclastic grainstone, with parallel stylolites and Phytopsis in the upper horizons.	3	0.50
Peloidal calcarenite with Phytopsis.	3	0.17
Fine peloidal calcarenite with upper 10 cm. dolomitised.	3	0.30
Peloidal calcarenite/calcirudite.	3	0.14
Peloidal calcarenite passing through amalgamated peloids to a fine peloidal calcarenite with a vertically burrowed, micritic top.	3	0.87
Massive unit of peloidal grainstone with parallel stylolites and Phytopsis. After 80 cm a vertically burrowed horizon is immediately succeeded by a coquina of broken gastropod shells before passing into a fine peloidal calcarenite.	3	1.25
Peloidal grainstone with dolomite net passing into finely laminated algal mat.	3/6	0.60
Dolomite.	5	0.20
Algal mat with vertical spar filled shrinkage cracks.	6	0.60
Algal mat.	6	0.30
Fault.		
Mixed peloidal-micritic and bioturbated bed with a dolomite net throughout and Phytopsis in the more peloidal fractions.	3/4	1.00
As above but with poorly developed dolomite laminations. Upper boundary is irregular due to erosional contact with the overlying bed.	3/4/6	0.40

HOLETJERN MEMBER

<u>Hemstadmoen Bioclastic Beds</u>

Bioclastic calcarenite dominated by *Solenopora* and pelmatozoan material but also contains *Streptelasma*, bryozoa and broken orthocones.

Deeply weathered fine black bioclastic calcarenite.	2	0.20

Bioturbated bioclastic limestones and dolomites

Deeply weathered exposure in quarry side, mostly covered in loose earth which appears to be fine bioclastic limestones and dolomites.	9	10.20

Better exposures of the uppermost beds of Holetjern Member of the Mjøsa Limestone can be found in the two quarries 1 km to the west of this locality directly north of Rud farm (60°40'35"N, 10°40'20"E):-

	Facies	Thickness (m)

<u>Description</u>:

<u>MJØSA LIMESTONE</u>

HOLETJERN MEMBER

Bioturbated bioclastic limestones and dolomites.

Massive dolomite with ragged, convex sideways stromatoporoids concentrated in bands at the top and bottom of the bed.	5	2.90
Interbedded pelmatozoan calcarenites and dolomites (10 cm - 5 - 7 cm thick units) which contain abundant vertical dolomite filled burrows• in the upper 1.75 m.	9	4.90

As above but with well developed vertical dolomite filled burrows: the calcarenite bands contain small scale oscillatory and herring-bone cross-stratifaction.	9	5.00
Massive peloidal (intraclastic grainstone) This bed has been quarried out but can be traced laterally into the westernmost quarry and pavement where it appears as a large channel (6.45 m max. thickness) cutting the underlying bioturbated facies.	3	5.65

HELGØYA QUARTZITE

In the westernmost quarry the Mjøsa Limestone continues above this peloidal grainstone :-

Dolomite.	5	0.75
Peloidal/intraclastic grainstone	3	1.00
Dolomite	5	1.60

HELGØYA QUARTZITE

(In places this penetrates down into the major peloidal grainstone unit, c 6 m from the uppermost contact).

HOLETJERN 2

Location : Blad 1816 11 (Eina) 60°39'35" N, 10°39'40" E; along the southern shore of Holetjern, approx. 1 km southwest of Bøverbru in a series of quarries. The three major exposures are taken from west to east and called Holetjern 1, 2 and 3 respectively. (CN 062/1, CN 062/2).

General : a series of small disused quarries and limestone pavements which have been extended and amalgamated by recent blasting operations. Exposures are in the Rud Peloidal Beds and overlying Holetjern Member, for which these localities form the unit stratotype. Thickness of exposed strata varies from 35-41 m.

Description :

MJØSA LIMESTONE

EINA MEMBER

Rud Peloidal Beds

	Facies	Thickness (m)
Massive peloidal calcarenitic grainstone with parallel stylolites and a bioturbated upper 10 cm overlying a poorly developed dolomite net.	3	0.60
Algal mat unit with a basal 30 cm of dolomite passing into parallel laminated dolomite units. The surface of the upper bed has acted as a plane of slippage as witnessed by abundant slickensides and buckling of the overlying bed.	6	0.80
Algal mat with the basal 30 cm deformed by slippage and the upper 20 cm containing parallel laminations of dolomite..	6	0.50

Massive peloidal grainstone with parallel stylolites throughout, except in the upper 12 cm which contains thin parallel dolomite laminations.	3	1.00
Algal mat unit of thin parallel dolomite laminations, except for the lower 14 cm which are bioturbated.	6	0.70
Peloidal calciruditic/coarse calcarenitic grainstone with parallel stylolites. Bioclasts are present and usually appear to be fragments of mollusca.	3	2.85
Algal mat unit of thin parallel laminated dolomite.	6	0.45
Bioturbated algal mat unit. This bed is often completely removed by the erosion surface and overlying unit.	6	0.20

HOLETJERN MEMBER

Hemstadmoen Bioclastic Beds.

Pelmatozoan dominated bioclastic calcarenite with a high dolomite/siltstone content. Solenopora are common throughout.	2	0.30
Bioclastic calcarenite with Solenopora and and dolomite/siltstone showing a general interbedded nature at the base before the bioclastics become concentrated into lenses.	2	0.90

Bioturbated bioclastic limestones and dolomites.

A complete irregular admixture of dolomite/calcisiltite and lenses or pods of fine bioclastic calcarenite. The boundaries between the two lithologies are usually heavily stylolitised.	5/4/2	0.90
Massive unit of dolomite/calcisiltite with irregular highly weathered patches of sparry calcite that in places show a Vermiporella like tubular structure. The upper 1.10 m have rare stromatoporoids which appear to become more dominant towards the top of the unit.	5/4	5.60

Dolomite/calcisiltite unit with patches of very irregular sparry calcite (stromatoporoids ?) becoming more common together with Solenopora, Nyctopora and Vermiporella. The sediment between the organisms appears bioturbated in many places, especially the upper 50 cm where they are associated with sheets of sparry calcite (laminar stromatoporoids ?).	5/4	0.50
Dolomite (calcisiltite with abundant evidence of bioturbation and common irregular stromatoporoids, and occasional stick bryozoa.	9	1.00
Dolomite/calcisiltite with bioturbation and sparry patches which are assumed to be stromatoporoids. The top of the unit contains Streptelasma, Vermiporella, Solenopora and pelmatozoan bioclasts, before being truncated by a fault.	9	1.30
Massive beds of bioturbated fine bioclastic calcarenites. Burrows are both vertical and horizontal in orientation and are dolomite filled. The uppermost 2.40 m may contain stromatoporoids.	9	15.40

HOLETJERN 3

Description:	Facies	Thickness (m)
MJØSA LIMESTONE		
EINA MEMBER		
Rud Peloidal Beds		
Fissile, dolomite rich top of the underlying unit contains abundant gastropods.		
Bioturbated black micritic mudstone.	4	0.40
Micrite and peloidal packstone with bioturbation in the upper 15 cm.		0.40
Peloidal calcarenitic grainstone with pronounced horizontal stylolites.	3	2.46
Fine calcarenitic peloidal grainstone with closely spaced (1-2 cm) parallel stylolites.	3	2.50
Algal mat unit of predominantly parallel fine dolomite laminations, although the basal and upper 30 cm are mostly dolomite, the latter having developed from a bioturbated horizon.	6	2.48
Peloidal grainstone with parallel stylolites; the upper 30 cm are bioturbated and contain well developed dolorite filled vertical tubes.	3	2.60
Area of algal mat units and peloidal grainstones smashed or contorted by faulting.	6/3	1.00
Peloidal grainstone with parallel stylolites, some *Phytopsis* and a bioturbated top.	3	1.05
Algal mat unit.	6	0.75

Massive peloidal grainstone.	3	3.60
Bioturbated unit.		0.60
Algal mat unit with the upper 15 cm sometimes removed by the erosion surface and overlying facies.	6	0.70

HOLETJERN MEMBER

Hemstadmoen Bioclastic Beds

Pelmatozoan bioclastic calcarenite with a high dolomite/silt content, containing medium sized rounded Solenopora, Streptelasma and the occasional branching bryozoa.	2	0.50

Bioturbated bioclastic limestones and dolomites.

Bioclastic grainstone pods and lenses in a dolomite/calcisiltite unit. The pods of fine bioclastic material are irregularly spaced and have heavily stylolitised boundaries.	5/4	2.30
Dolomite/calcisiltite, with small pods of fine bioclastic calcarenite and irregular sparry areas that have a Vermiporella like tubular structure.	5/4	1.50
Dolomite/calcisiltite with some bioturbation, together with Solenopora, Vermiporella, and stromatoporoids; the upper 3.20 m contain specimens of Liopora as well as the previously mentioned biotic constituents.	5/4	5.20
Dolomite/calcisiltite with an increasing amount of bioturbation and the appearance of stromatoporoids; these vary in size from 30 x 80 cm to 5 x 2 cm, but all appear domical rather than laminar in shape.	5/4	1.80
Bioturbated fine bioclastic calcarenites with dolomite filled burrows which appear to lie mostly in a vertical rather than horizontal plane.	9	11.00

HEMSTADMOEN

Location: Blad 1816 11 (Eina) 60^{o} 39' 10" N, 10^{o} 39' 10" E.
The locality is situated approximately 300m west of the Børsvollen road junction on the Bruflat road, and 100m south-south-east of Hemstadmoen. (CN 062/1).

General: A small disused quarry exposing 11.56m of Mjøsa Limestone providing the stratotype for the Hemstadmoen Bioclastic Beds. Dip 50/344. Due to continued use of the quarry for burning material in, much detail in the lower half has been obscured.

Description:	Facies	Thickness (m)
MJØSA LIMESTONE		
EINA MEMBER		
Rud Peloidal Beds.		
Peloidal grainstone with the upper 30cm showing weathered dolomite laminae and an intraclastic breccia.	3	1.00
A dolomite bed with occassional micritic laminations; the upper 10cm show a finely laminated dolomite with dessication cracks.	5	0.40
Peloidal grainstone.	3	0.60
Algal mat unit showing a gradation from crinkled to parallel dolomite laminations.	6	0.30
Peloidal grainstone with the upper 20cm showing evidence of bioturbation.	3	0.90
N.E.		1.60
Algal mat unit of dominantly parallel laminated dolomite and micrite.	6	0.32

Peloidal grainstone.	3	0.12
Algal mat.	6	0.17
Thinly bedded peloidal grainstone.	3	0.60
Massive peloidal grainstone with well developed parallel stylolites and <u>Phytopsis</u> rich horizons.	3	0.70
Peloidal grainstone, extremely rich in <u>Phytopsis</u> but contains no stylolites.	3	0.15
Bioturbated peloidal bed.	3	0.10
Peloidal grainstones with an increasing dolomite content which attains a laminar orientation near the top of the unit.	3	0.20
Algal mat unit of laminated, brecciated and dolomitised material, with a well developed 50cm dolomite horizon 10cm below the upper surface.	6	1.00
Massive peloidal calciruditic grainstone with abundant <u>Phytopsis</u>, parallel stylolites and a bioturbated horizon occupying the uppermost 20cm.	3	0.50
Massive calcarenitic peloidal grainstone with well developed parallel stylolites which mimic low angle oscillatory cross-stratification; the uppermost 10cm display a slight parallel laminated aspect and overlie 10cm of bioturbated material.	3	1.40
Parallel laminated and brecciated algal mat; up to 20cm are cut out by the overlying erosion surface.	6	0.70

HOLETJERN MEMBER

<u>Hemstadmoen Bioclastic Beds.</u>

A pelmatozoan bioclastic bed containing a high quartz silt (dolomite) content and bioclasts of very variable	2	0.30

grain size, these are mainly rounded Solenopora, Streptelasma, Rhynchotrema (and other coarse ribbed brachiopods), together with branching bryozoa; most show evidence of transportation. The high silt/dolomite content imparts a brown colouration to the unit and together with the coarse bioclastic nature of the grains causes rubbly weathering; both features are in complete contrast to the underlying light coloured massive peloidal and algal mat succession.

Although identical in lithology, this bed contains a 2 0.50
greater variety of bioclasts than the underlying unit; Grapthodictyon is abundant together with the small coral Nyctopora; also much in evidence are Streptelasma, rounded Solenopora, a coral resembling Palaeophyllum, bushy branching bryozoa, planulate gastropods, orthocones, crinoid stems and large ragged oncolites.

FURUBERGET NORTH

Location: Blad 1916 IV (Hamar) 60°49'02"N 11°30'E. Exposure is sited along the eastern shore of the Furnesfjord and in railway cuttings immediately north of Kalkbrenneri.

General: lakeside and railway cuttings expose c 53 m of the lower Mjøsa Limestone and a thick sequence of Cyclocrinus and Coclosphaeridium Beds on the northern limb of the Furuberget syncline. Dip 32/161.

Description:

Description	Facies	Thickness (m)
FURUBERGET FORMATION		
Thick sequence of contorted shales, interbedded quartz siltstones, fine sandstones, calcareous horizons, grainstone pods or sheets, and shales that form the succession below the Mjøsa Limestone.	1	
MJØSA LIMESTONE		
FURNESFJORD MEMBER		
Grey bioclastic calcarenite containing abundant calciruditic fragments of *Chasmops* and *Encrinurus*, scattered, fragmented ?*Kjaerina* valves and stick bryozoa. After 25 cm the quartz siltstone content increases and the top of the bed becomes a fine quartz sandstone/siltstone which grades into the overlying unit.	2	0.75
Laminated quartz siltstone fining upwards into shales.	1	0.38
Fine quartz sandstone/siltstone with irregular channelled base, and planar small scale cross bedding	1	0.44

which gradually wedges out into the shales.

Shale unit with variable thickness due to irregular nature of adjacent beds.	1	0.06-0.14
Fine quartz sandstone with asymmetric channels on a sharply defined irregular base and displaying ripple drift within the unit.	1	0.13
Interbedded thick shales and fine quartz sandstones/siltstones, with much wedging out and interdigitating of units.	1	0.17
Fine quartz sandstone/siltstone with an irregular base which has a veneer of small brachiopods and bioclastic debris.	1	0.42
Thinly interbedded unit of fine sandstones/siltstones and shales with abundant gutter casts and channels.	1	0.42
Fine quartz sandstone/siltstone with sharp irregular channelled base, planar small scale cross-bedding and ripple drift. Immediately above the base is some bioclastic material containing *Ctenodonta*, *Chasmops* fragments, gastropods and a few bryozoa fragments.	1	0-39
Thinly interbedded fine sandstone, siltstones and shales.	1	0.51
Fine quartz sandstone/siltstone with sharply defined channelled base and veneer of bioclastic material. Sedimentary structures include in phase ripple and parallel laminations at the top.	1	0.23
Finely laminated quartz siltstone.	1	0.29
Massive quartz rich bioclastic calcarenite. The lower 40 cm contain abundant *Strophomena*, with some coarse ribbed rhynchonellids, *Zygospira*, *Paraharpes*	2	1.90

(brims only) *Chasmops* (fragments and pygidia), branching bryozoa and pelmatozoan debris. Above this the coarse ribbed form ?*Apatorthis* becomes dominant along with a smaller coarse ribbed orthid and *Chasmops* becomes scarce, but the remainder of the association remains much the same.		
Unit begins with a dolomite rich horizon containing *Solenopora*, *Streptelasma*, and branching bryozoa, together with *Paraharpes* brims, coarse ribbed rhynchonellids and crinoid dominated pelmatozoan material. This has the appearance of a debris bed and appears to lie in a channel. There is gradation from this into a bioclastic pelmatozoan dominated grainstone, with large scale planar cross-bedding, and contains abundant ?*Apatorhis*. Quartz content increases towards the top of the unit which is gradational into the next bed.	2	3.18
Interbedded quartz siltstone/fine sandstone and fissile siltstones/shales. Ripple drift and gutter casts are common sedimentary structures (Table I.4.i).	1	0.92
Bioclastic calcarenitic grainstone with calciruditic fraction of rounded *Solenopora* and large coarse ribbed rhynchonellids directly above the irregular base. Broken bryozoa and pelmatozoan debris are contained within the upper parts which are quartz rich.	2	0.32
Shale.	1	0.10
Identical to the underlying grainstone, but the base is more irregular and the unit contains less quartz contamination.	2	0.26-0.32
Unit of interbedded quartz siltstones (fine sandstones and shales). Small asymmetric channels and gutter casts are the commonest structures observed, although ripple drift, ripples (interference?), small scale planar	1	1.42

cross-stratification and parallel laminations are present. <u>Chondrites</u> is occasionally found in the finer siltstone horizons. Body fossils are uncommon, being confined to broken branching bryozoa, and some scattered coarse ribbed rhynchonellids and <u>Solenopora</u>. Bedding surfaces are sharply defined with the bases of the sand bodies, often appearing erosional. There is also much lateral variation of thickness.

Bioclastic calcarenitic grainstone with a considerable quartz content, rich in coarse ribbed rhynchonellids stick bryozoa and with occasional small rounded <u>Solenopora</u> associated with the quartz rich units. The base of the unit is highly irregular.	2	0.12-0.15
Shale parting.	1	0.02
Similar to the above limestone.	2	0.13
Fissile calcarenite lense.	1	0.05
Calcareous quartz siltstone/fine sandstone with small scale planar cross-bedding, and a concentration of brachiopods with pelmatozoan debris immediately above a sharply defined base.	1	0.11
Interbedded quartz siltstones/fine sandstones and shales/fissile fine siltstones have well defined bases, some with a veneer of shell debris directly above, most with small asymmetric channels and gutter casts beneath. Ripple drift and ripples are common, as are oscillatory low angle small scale planes cross-bedding and parallel laminations towards the upper parts of the units. The finer beds contain <u>Chondrites</u>. Fauna are scarce: some coarse ribbed brachiopods and bryozoa in the bioclastic fractions together with the occasional <u>Solenopora</u>.	1	0.20

Calcareous quartz siltstone/fine sandstone with bioclastic rich areas, and an extremely uneven channelled, erosive base. The thickness of the unit is irregular, in places it wedges out completely only to reappear further along the strike. Fauna are confined to a few *Strophomena* and *Sowerbyella*, some stick bryozoa and *Solenopora*, Sedimentary structures consist of asymmetric channels, gutter casts, ripples, large scale planar and trough cross-bedding.	1	0.12
Shales/fissile siltstones in a discontinuous bed.	1	0.02
Calcareous quartz siltstones/fine sandstones with a relatively high bioclastic content. The irregular channeled, erosive base shows a veneer of bioclastic grainstone lenses containing *Strophomena* and *Solenopora*. Trough cross-bedding is well developed throughout the unit.	1	0.52
Shales/fissile siltstone.	1	0.04
Calcareous fine quartz sandstone/siltstone unit with an increasing bioclastic content, becoming an impure sandy limestone. The base is irregular, sharply defined and erosive on the underlying shales, with concentrations of bioclastic debris (including large *Solenopora*) in lenses or sheets. *Strophomena* and *Sowerbyella* are found here, among other comminuted material. Trough and planar cross-bedding is emphasised by weathering of the calcareous debris.	1	0.30-0.34
Massive unit of quartz rich bioclastic calcarenitic grainstone, composed dominantly of pelmatozoan and comminuted brachiopod material. The base is irregular and appears erosive on the underlying unit. Channels (Table I.4.iii) are filled by pockets of *Solenopora* rich bioclastic debris, a few of the algae being larger than 10 cm diameter. Small scale scours and ripples	2	1.70

are developed within the unit as well as oscillatory low angle planar cross-bedding, often containing laminations of quartz siltstone.		
As above, but with a decreasing quartz content, scattered *Solenopora*, abundant comminuted *Strophomena* common articulated coarse ribbed rhynchonellids and pelmatozoan debris.	2	2.40
Shale.	1	0.03
Quartz siltstone.	1	0.07
Grey bioclastic calcarenitic grainstone, with scattered small *Solenopora*, less comminuted brachiopods but more articulated individuals than the previous limestone unit. Broken stick bryozoa, occasional trilobite remains and pelmatozoan material account for the remaining bioclasts.		
Grey bioclastic calcarenite with abundant *Strophomena* and containing a dolomite (?) pebble conglomerate at the base.	2	1.25
Bioclastic grainstone with a relatively high quartz content with *Solenopora* which appear as possible growth forms protruding into the overlying bed.	2	0.18
Thinly interbedded fine quartz sandstones, siltstone shales, calcareous siltstones and bioclastic rich horizons. Many of the coarser units display erosive bases with small gutter casts and asymmetric channels rippled tops, planar and ripple drift cross-bedding as well as parallel laminations. Fauna are mainly fragmental brachiopods and trilobites, although a single colony of *Eoflecheria* in growth orientation was also found. The upper 40-50 cm are rich in bioclastic components, with *Solenopora*, ?*Apatorthis*, *Platystrophia*,	1	3.92

Rhynchonella, Rhynchotrema, Strophomena, Chasmops fragments and Tallinella all common in the pelmatozoan grainstone horizons. Chondrites, Planolites (?) and a bifurcating form which appears to follow the foreset beds only occasionally cutting them, represent the ichofaunal components.

Pelmatozoan (coarse calcarenite) grainstone. Many of the fragments are red. The unit contains abundant stylolites and appears rippled at the base, with burrows following the ripple casts. The upper part of the bed becomes fine grained and peloidal with Phytopsis and a faint dolomite net in the upper 20.00 cm below a 8.00 cm fissile siltstone band.	2/3	1.77
Massive fine bioclastic calcarenite. Much of the dominant pelmatozoan debris in the lower part is pink coloured, stylolites are a common feature, representing a larger scale feature than in the preceding unit, and Solenopora are present as small ragged widely dispersed specimens. The upper portion of the bed is distinctly micritic probably peloidal and contains a Phytopsis layer as well as a well developed fine dolomite net.	2/3	1.77
Shale.	1	0.08
Well weathered soft muddy limestone containing Ancystrorhyncha and irregular patches of wavy calcite spar which may represent stromatoporoids. Immediately above this an horizon of grey micritic blobs which may be Solenopora but are more likely to be oncolites. This muddy unit passes into an upper 43 cm of very fine bioturbated bioclastic calcarenite containing occasional patches of calcite spar.	2/4	0.65
Shale.	1	0.05
Black micrite (mudstone) which may be bioturbated.	4	0.40

Massive dark grey fine peloidal grainstone with abundant Phytopsis and a well developed dolomite net. Grain size tends to coarsen towards the top of the unit.	3	2.10
Shale/fissile quartz siltstone.	1	0.08
Bioturbated fine peloidal grainstone/micrite (mudstone) with a concentration of very large Solenopora at the top of the bed. The base is stylolitised and extremely irregular.	3/4	0.92
Solenopora rich unit. Algae are rounded, small ragged and smooth, and densely packed in the basal portion, giving an impression of grading. Associated sediments are domite and quartz siltstone in a mainly bioclastic calcarenite.	1	0.97
Interbedded calcareous mudstones, fine quartz siltstones and shales. Rippled upper surfaces (Table I.4.v.) are a common feature of the siltstone units while the whole unit is bioturbated, which together with the weathering give it a nodular appearance. Fossils are not abundant. Ancystrorhyncha appears throughout with occasional Solenopora, Chasmops and other trilobite fragments, Rhynchonella and some strophomenids. Small stringers of bioclastic material show an abundance of pink pelmatozoan fragments. The uppermost bedding planes contain large Strophomena and Sowerbyella.	1	1.16
Dark grey bioclastic grainstone with a concentration of brachiopods in the lower 33 cm before a concentration of Solenopora above a thin shale parting. The algae are densely packed, small and rounded, but become less abundant, larger and more conical towards the top of the bed.	2	0.80

Interbedded calcareous mudstones, quartz siltstones and shales, with a concentration of coarser (fine quartz sandstone) material in the lower 38 cm. Above this the thinly interbedded units display rippled tops, occasional channelled bases (Table I.4.vi.) and <u>Chondrites</u>. Fauna appear to be limited to a few brachiopods.	1	1.40
GAALAAS MEMBER		
Massive unit of fine bioclastic calcarenite, coarsening upwards into a pelmatozoan coarse calcarenite/calcirudite. <u>Solenopora</u> are scattered throughout the unit, occasionally concentrated in stringers or pockets but increase in abundance towards the top of the unit, complementing the increasing grain size and appearance of pink pelmatozoan material. The main feature, however, is the stylolite enhanced large scale planar cross-bedding which strikes generally at 050 and dip south eastwards.	2	2.12
Calcareous siltstone horizon with a streaked appearance of limestone giving a nodular look not dissimilar from stromatoporoid horizons in the lower 20 cm, the remainder being <u>Solenopora</u> rich at the base.	1	0.47
Black fine bioclastic calcarenite with scattered <u>Solenopora</u>, which sometimes are concentrated into stringers.	2	0.53
Shale partings above and below a fine black calcarenite.		0.07
Fine black calcarenite with a base rich in <u>Solenopora</u> and the upper part rich in fine peloids and <u>Phytopsis</u> burrows.	2/3	0.69
Stromatoporoid horizon. Irregular coenostea in a highly argillaceous sediment which has an irregular base.		0.22
Fine peloidal grainstone with parallel stylolites and a concentration of small <u>Solenopora</u> near the base.	3	1.61

Poorly developed stromatoporoid horizon in interbedded muddy limestones and silts. Ancystrorhyncha is present in the lower part of the bed.		0.32
Black micrite containing laminations of fine peloids, a fine dolomite net and a dolomite concentration near the base.	4	1.24
Fissile muddy calcareous siltstone with stromatoporoids (?).	10B	0.10
Bioturbated fine peloidal packestone/grainstone, containing pelmatozoan debris and scattered very small Solenopora.	3	1.10
Fissile calcareous silty bed which may contain stromatoporoid or two.		0.10
Massive unit of biomicrite (wackestone/mudstone) with a fine dolomite net at the base passing into a bioturbated peloidal grainstone at the top. Small Solenopora are widely scattered throughout and articulated Ancystrorhyncha are present at the top.	4/3	2.40
Shale parting.		0.03
Peloidal grainstone with fine dolomite net.	3	1.00
Shale parting.		0.01
Bioturbated peloidal grainstone with a noticeable bioclastic content.	3	1.60
Calcareous silt unit with stromatoporoid (?) and small oncolites.	10B	0.10
Grey fine peloidal grainstone changing by an increasing amalgamation of grains to a mudstone texture.	3/4	0.61
Shale parting.		0.06

Mixed fine peloids and micrite to give a variety of textures. Unit contains small stromatoporoids with irregular coenostea.	3/4	0.60
Micrite (mudstone) near base with a mixture of textures as peloids gradually increase upwards. Fine dolomite net develops especially well in these horizons although it is present throughout the upper half of the unit. The lower half is occupied by stromatoporoids. At the top of the bed, sparry calcite filled cavities are observed.	3/4	1.77
Shale parting.		0.05
Peloidal grainstone with molluscan debris and dolomite net.	3	0.72
Shale parting .		0.04
Peloids and micrite in a variety of textures with small domical stromatoporoids near the base.	3/4	0.57
Shale.		0.02
Calcareous mudstone.	4	0.02
Shale.		0.03
Suggary, recrystalised looking micritic (peloidal)? unit, with occasional Ancythrorhyncha and developing parallel lamination in the upper 50 cm.	3	1.96

TABLE I.4. Palaeocurrent data. Furuberget North

i) Ripple crests: 9.30 to 10.10 m above the base of the Mjøsa limestone.

026	044	024	091	168	050
106	006	158	128	116	110
110	072	074	078	086	098
092	024	058	080	086	026

ii) Ripple crests: 12.50 to 13.80 m above limestone base

080	084	126	060*	086
076	092	086*	049	
060	066	096*	057	

* oscillatory

Channels:

138	093	070	104	101	122	083
084	111	129	110	107	084	085
090	111	131	121	101	122	093
046	085	109	134	123	117	118
130	149	104	156*	134*	142*	163*
154*	120					

* gutter casts

iii) 13.80 m above limestone base.

Channels

096	106	084	096	086	120	096

iv) 20 to 24 m above limestone base.

Ripple crests:

169	167	155	156	167	163	167	070	078
044	062	046	068					

Channels :

126

v) 32.80 - 33 m above limestone base.

Ripple crests :

082 108 080 128 134 019 134 000
144

vi) 33.80 - 35.20 m above limestone base.

Channels.

042 036 024 084* 058* 052*

* gutter casts

SNIPPSAND

Location: Blad 1916 IV (Hamar). 60°48'2"N, 11°0'40"E, approx. 1.8 km north-northeast of Grefsheim farm on the southern side of the small peninsula in to the Furnesfjord, known locally as Grefsheimlandet. (H 16/4).

General: a cliff and lakeshore exposure giving 29.80 m of the Furuberget Formation and c 85 m of Mjøsa Limestone. This locality is the stratotype for both the Gaalas and Snippsand Members. Dip 36/315.

Description:	Facies	Thickness (m)
FURUBERGET FORMATION		
This section begins above a massive limestone with trilobite rich bioclastic limestones, followed by black shales and black shales with pods of channelled and ripples sandstone. A thick (15m) sequence of sandstones, siltstones and shales with interbedded bioclastic grainstones forms the upper unit of these beds. (A detailed section log with palaeocurrent data is presented as Fig. 6.1; p. 244).		29.80
MJØSA LIMESTONE		
FURNESFJORD MEMBER		
Bioclastic grainstone with scattered orthocones, trilobite, molluscan, ostracod, bryozoan and pelmatozoan fragments. The bed contains small irregular pockets of cross-stratified sandstone.	2	0.47
Interbedded coarse and fine quartz siltstones.	1	0.50

Massive unit of bioclastic grainstone containing abundant orthocones, Chasmops, Encrinurus, orthids, rhynchonellids, branching bryozoa and abundant pelmatozoan detritus. Large scale, siltstone accentuated, planar and trough cross-stratification is present and forms a diagnostic feature.	2	1.62
Fissile fine siltstone.	1	0.37
Bioclastic grainstone with siltstone accentuated planar cross-stratification.	2	0.34
Fine siltstone/shale.	1	0.06
Bioclastic grainstone with a high siltstone content.	2	0.40
Fissile siltstone.	1	0.12
Bioturbated, cross-stratified fine sandstone.	1	0.28
Interbedded siltstones, fine sandstones and pods of bioclastic grainstones.	1	1.00
Fine sandstone with a basal veneer of bioclastic grainstone, unit shows well developed festoon bedding. Fossils include orthocones, Paraharpes, bryozoa and broken orthid valves.	1	0.18
Impure bioclastic limestone. Fauna similar to underlying bed.	2/1	0.46
Fissile siltstone.	1	0.07
Impure bioclastic limestone. Fauna dominated by Paraharpes.	2/1	0.23
Fissile siltstone.	1	0.52
Impure bioclastic limestone.	2/1	0.29
Bioclastic limestone with siltstone accentuated planar cross-stratification containing small Solenopora	2	0.38

rhynchonellids, orthids, Zygospira, branching bryozoa orthocones and Chasmops fragments.

Fissile siltstones with channels of fine sandstone containing fragments of fine sandstone and bryozoans.	1	0.50
Interbedded fine siltstones, fine sandstones and bioclastic pods, stringers, veneers and thin beds.	1	1.04
Fine sandstone with shale bands and abundant cross-stratification.	1	1.62
Bioclastic grainstone with a high siltstone content. Base of unit is channelled (relief 4-12 cm) while upper surface shows microripples (Table I.5.i) in a siltstone rich horizon.	2	1.18
Interbedded fine and coarse siltstones, the latter appear as thin beds which amalgamate to give a thicker unit. Ripple crest trends are given in Table I.5.ii. The unit also displays climbing ripples, slumps and larger scale ripples.	1	0.72
Bioclastic calcarenite with a high quartz content. Subparallel stylolites 5-8 cm apart give a thinly bedded appearance to the unit. Apart from pelmatozoan fragments the bed contains little other recognisable fossil material and appears extremely well sorted. At the top small channel like features, the walls are distorted due to pressure solution with the adjacent sediment, are irregularly dispersed.	2	2.53
Coarse calcarenite/calcirudite of pelmatozoan material with abundant articulated orthids and rhynchonellids.	2	0.20
Coarse siltstone, which is gradational from the underlying bioclastic unit and fines upwards into a fissile siltstone layer.	1	0.30

Coarse calcarenite with rhynchonellids and and orthis as well as small clasts of siltstone. The upper 27 cm contain an increasing siltstone content and the upper siltstone horizons are rippled (Table I. 5. iii).	2	0.57
As above with the upper 25 cm containing a high siltstone content.	2	0.49
Well laminated coarse siltstone with interfer-ference ripples (Table I. 5. iv).	1	0.11
Bioclastic calcarenite with abundant orthids and rhynchonellids. The upper 20 cm form a gradation into the overlying bed.	2	0.45
Cross-bedded coarse siltstone.	1	0.25
Interbedded siltstones and fine sandstones, with ripple marls (Table I. 5. v.) in the coarser beds. Lenses of extremely comminuted bioclastic material are also present.	1	0.45
Coarse bioclastic calcarenite with coarse ribbed orthids and rhynchonellids in a Solenopora, bryozoan pelmatozoan groundmass. Pebbles of siltstone are seen at the base of the bed.	2	0.63
Fine sandstone.	1	0.30
Interbedded fine and coarse siltstones with inter-ference ripples and microripples (Table I. 5. vi). This unit is equivalent to the basal parts of the Solenopora bioherm (see Chapter 5 for a detailed discussion of the relationship of sediment to biomass).	1	2.16
Massive bioclastic calcarenite with a channelled (Table I. 5. vii) siltstone rich base.	2	
The above calcarenite is a lateral equivalent of the Solenopora bioherm and its associated sediments.	11	15.00

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Fine bioclastic calcarenite with parallel stylolites which often mimic low angle, small scale cross-stratification. Pelmatozoan debris and small <u>Solenopora</u> are the only visible bioclasts.	2	2.00-2.50
Arenanceous micritic mudstone containing small stromatoporoids.	10	0.45
Micritic mudstone and amalgamated peloidal grainstone with occasional bioclastic rich horizons.	3/4	1.40
Dolomite with small, generally elongate stromatoporoids.	5/10	0.30
Fissile dolomite/siltstone.	5/1	0.24
Massive peloidal grainstone, with some amalgamation to give a micritic texture. The upper 24 cm are heavily bioturbated and appear to have a mudstone texture.		
Silty, micritic stromatoporoid bed.	10	0.88
Massive bioturbated micritic mudstone, amalgamated peloidal grainstone and peloidal grainstone.	4/3	2.70
Stromatoporoid horizon. Matrix has a high clay content and oncolites above the stromatoporoids.	10	0.40
Peloidal grainstone with parallel stylolites.	3	0.98
Silty micrite with articulated <u>Ancistrorhyncha</u> and small stromatoporoids.	10	0.15
Bioturbated biomicrite.	4	0.36
Stromatoporoids in silty micrite: coenostea display good lateral spreading.	10	0.58
Massive peloidal and amalgamated peloidal grainstone with bioturbated micritic mudstones.	3/4	2.77
Stromatoporoids in silty (fissile) micrite.	10	0.30

Bioturbated micritic mudstone.	4	0.83
Argillaceous micrite with articulated Ancistrorhyncha and small stromatoporoids.	10	0.30
Peloidal grainstone with parallel stylolites, and bioturbated upper surface.	3	0.91
Fissile siltstone with small stromatoporoids which grow into the overlying bed.	10	0.08
Peloidal grainstone with parallel stylolites.	3	0.79
Bioturbated micritic mudstone/peloidal grainstone.	4/3	1.50
As above.	4/3	2.30
Silty micrite with a developing fissility, small ragged stromatoporoids and ragged oncolites.	10	0.22
Peloidal grainstone with oncolites.	3	0.29
Fissile siltstone.	1	0.04
Peloidal grainstone with large ragged oncolites and stromatoporoids at the base and Phytopsis at the top.	3	0.43
Silty micrite with nests of articulated Ancistrorhyncha and stromatoporoids.	10	0.25
Amalgamated peloid and peloidal grainstone.	3	1.00
Silty micrite with oncolites.	1	0.05
Ancistrorhyncha rich micritic mudstone with some bioturbation.	4	0.51
Silty micrite with branching trace fossils on the upper surface.	10/1	0.17
Amalgamated and very fine peloidal grainstone passing into a micritic mudstone with parallel laminated and fenestral spar filled pores at the top.	3/4	1.94

Dolomite	5	0.15
Stromatoporoids in a silty, somewhat laminated horizon. Small oncolites appear at the top.	10	0.50
Micritic mudstone and amalgamated peloids with laminar stromatoporoids	4/3	0.20
Pelmatozoan bioclastics with oncolites at the base passing into peloidal grainstones.	2/3	0.90
Fine peloidal and bioclastic grainstone.	2/3	1.63
Fissile siltstone/dolomite horizon.	1/5	0.22
Massive unit of fine peloids with parallel stylolites at the base (60 cm) passing into 90 cm of heavily bioturbated biomicrite.	3/4	1.50
Dolomite/siltstone.	5/1	0.20
Massive unit of bioturbated biomicrite (25 cm) passing into an amalgamated peloidal grainstone with dolomite net and finally into a peloidal grainstone (40 cm).	4/3	0.80
Bioturbated peloidal grainstone.	3	0.30
Biomicritic mudstone-wackestone.	4	0.50
Peloidal grainstone.	3	0.20
Heavily bioturbated amalgamated peloidal grainstone.	3	0.70
Amalgamated peloidal grainstone.	3	0.60
Biomicritic wackestone and amalgamated peloidal grainstone.	4/3	1.00
Coarse calcarenite/calcirudite of peloidal (intraclastic) grainstone.	3	0.80
Very dark biomicrite with possible stromatoporoids.	4	0.30

Black micritic mudstone.	4	0.30
As above.	4	0.20
Stromatoporoids, bryozoa, orthocones and Hedstroemia in a very black micritic mudstone.	4/10	0.20
N.E.		c 1.20

SNIPPSAND MEMBER

Terrigenous clastic and bioclastic beds.

Interbedded quartz siltstones and bioclastic grainstone lenses and pods in a scrappy lakeshore exposure. Limestone contain abundant orthids and other brachiopods in a pelmatozoan groundmass. Terrigenous beds contain Chondrites, ripple drift, low angle planar cross-stratification.	1	1.92

Coral bearing biomicrites.

Massive limestone unit which has a high silt content at the base and appears bioturbated. This passes into a biomicrite containing stromatoporoids, Favositid and Halysitid corals.	4	2.73
N.E.		0.75
As above but at least two species of Halysitid coral and a bizarre form of stromatoporoid appear, together with large flat gastropods.	4	0.76
N.E.		5.60
As above.	4	1.00

TABLE I.5 : Palaeocurrent data, Snippsand.

1) 11.63 m above the base of the Mjøsa Limestone.

Channels:

126	090	063

Microripple crests

022	024	028	026	040	026	020	020	175	006
006	009	071	012	011	016	016	016	018	015
075	176	176	011	002	004	004	018	018	020
028	035	012	002	000	002	006	006	006	007
018	018	016	015	015	031	016	022	022	000
177	004	011	162	174	160	177	002	022	022
016	018	022	020	026	028	020	020	076	018
020	024	211	004	006	037	031	031	026	022
020	020	022	024						

2) 12.35m above Mjøsa Limestone base.

Ripple crests:

084	066	064	009	056	140	012	127	054

3) 15.95m above Mjøsa Limestone base.

Ripple crests:

140	130	047	099	038	074	024	138	020	082
020	166	160	090	150	171	166			

4) 16.55m above Mjøsa Limestone base.

Ripple crests:

150	062	061	034	044	092	096	052	046
118	114	066	080	132	160	086	040	008

116	008	052	082	066	014	159	072	054
093	063	002	068	054	164	024	062	036
036	082	164	068	086	086	020	100	024
086	070	000	106	097	162	146	126	194
144	170							

5) 17.70m above Mjøsa Limestone base.

Ripple crests:

104	118	007	110	092	084	006	106	148	104
040	084	082	056	110	116				

6) 20.79 m above Mjøsa Limestone base.

Ripple crests:

095	120	002	058	114	126	158	124	143
152	122	136	124	138	136	024	086	040
006	046	024	055	130	058	052	012	100
132	042	149	142	048	144	062	047	041
041	092	004	140	108	052	030	050	110
130	052	099	169	044	126	045	144	060
066	164	040	052	116	140	058	004	040
060	054	069	168	092	084	040	042	054
020	150	072	070	046	122	026	120	132
037	048	056	109	112	048	080	122	098
101	047	061	063	040	062	056	062	102
128	060	048	060	066	030	076	060	170
032	064	034	066	110	034	067	142	062
082	136	128	106	050				

Microripple crests:

037	041	039	035	039	039	039	045	039
057	030	043	025	031	034	041	045	055
043	057	051	039	053	053	051	043	041
025	009	011	017	061	067	059	059	039
039	051	031	033	022	023	011	031	026

030	061	053	053	055	052	058	058	061
030	026	025	011	017	023	051	056	062
053	067	081	053	064	066	062	049	051
031	030	034	014	022	021	024	028	033
061	052	054	055	058	056	061	053	044
043	045	037	031	058	067	063	061	065
127	131	133	111	087	089	129	105	111
110	091	097	103	087	131	147	133	124
137	139	111	113	105	101	114	116	119
121	125	123	133	131	091	092	165	171
173	005	009	011	159	137	173	007	009
001	178	006	003	003	177	173	158	006
017	009	015	011	159	001	003	007	018
023	026	019	007	011	003	005	167	007
009	152	141	147	009	015	121	020	008

Channels:

114	087	108	092	135	121	117	119	117
125	119	134	109	145	160	105	119	107
139	137	117	144	154	155	132	155	112
165	132	137	103	161	116	134	136	135
105	150	115	115	141	143	141	127	120
125	115	131	121	119	145	105	141	133
125	121	139	123	115	135	117	129	123
131	120	109	107	127	141	120	131	141
127	145	117	131	131	135	111	122	131
145	105	117	127	120	107	138	130	124
121	101	119	130	105	115	141	133	109
103	131	132	111	135	130	134		

7) 21.00 m above Mjøsa Limestone base.

Channels:

125	144	128	115	143	131	145	143	141
105	117	131	125	144	147	141	125	

BERGEVIKA SOUTH

Location : Blad 1916 111 (Ostre Toten). $60^{\circ}44'45''$ N, $11^{\circ}01'10''$ E. Cliff and shoreline exposures around the southern promontory of Bergevika bay, Helyøya.(H.18).

General : Exposure of Cyclocrinus beds and c 77 m of the Mjøsa Limestone ending in reticulate micrites along the edge of the lake. By comparison with Bergevika North the lower part of the succession is more calcareous. Dip 31/334.

	Facies	Thickness (m)
Description :		
FURUBERGET FORMATION		
Massive unit at base of cliff section - thinly, irregularly bedded fine quartz sandstones, siltstones and shales with thin discontinuous sheets, lenses or pods of bioclastic grainstones. Chondrites, interference ripples, small scour and fill, gutter casts, parallel laminations, ripple drift and general low angle small scale cross-bedding are typical sedimentary structures. Some of the larger calcareous sandstone units with irregular bases often have a basal veneer of bioclastic grainstone. Sharp bases and sharp tops are features of bedding in this unit as is general irregularity (wedging, lensing or erosion). Fauna are dominated by drifted Sowerbyella, bryozoa, Chasmops and Asaphid trilobite debris in the grainstones, while drifted branching bryozoa, bivalves (?) and Chondrites are typical of the terrigenous sediments.	1	22.00

MJØSA LIMESTONE

FURNESFJORD MEMBER

Terrigenous clastic and bioclastic beds.

Grey bioclastic grainstone with thin (1-2 cm) laminae of brown quartz siltstone accentuating low angle planar cross-bedding. Dominant bioclasts are Chasmops, Asaphus and ? Tallinella fragments although stick bryozoa, molluscan debris, gastropods and brachiopods (Platystrophia, Orthambonites, Kjaerina) are also present, together with a general 'groundmass" of pelmatozoan material. This is separated from the upper portion of the bed by an irregular siltstone unit, scoured out by the channel base to the upper limestone unit. This shows large symmetrical ripples accentuated by siltstone laminations which increase in abundance towards the top and become thinly bedded units. The fauna remains similar, but appears more comminuted:- Chasmops, Eucrinurus, Kjaerina, molluscan debris, branching bryozoa, rhynchonellids, pelmatozoans and Osmospira. 2 1.00

A small thrust feature folds this part of the sequence back upon itself, exposing the upper part as being rippled by small straight crested ripples with some interfering trends (Table 1.6.i.). Another feature is vertical burrowings, now dolomite filled (Tigillites) and small 1 x 0.4 cm ovoid areas scattered around on the bedding plane. Faunal changes occur here, trilobites becoming less common, while Platystrophia, rhynchonellids and strophomenids increase in abundance. Towards the upper surface there is a dramatic increase in ostracod (? Tallinella) abundance until they become, with Kjaerina the dominant faunal element. 2 0.80

Interbedded fine quartz sandstones, siltstones, shales and bioclastic grainstones. Much detail is hidden by faulting and tectonic deformation, but ripple drift cross-lamination, straight crested ripples (Table I. 6.ii.) and Chondrites seem abundant in the terrigenous component while limestone units display sharp bases, silt rich, rippled (?) tops and contain abundant ?Tallinella, Sowerbyella, Platystrophia and Rhynchotrema, with small orthids, branching bryozoa, trilobite fragments and a dalmanellid.	1	1.14-1.47
Coarse (calcirudite) bioclastic grainstone. Grain size is variable from one or two mm to 10 or 15 cms. Faunal content is diverse, but most skeletons are broken or comminuted. Exceptions to this are the large encrusting bryozoa Grapthodictyon and an encrusting stromatoporoid or coral, as well as Streptelasma, Nyctopora (often encrusting large grains) and an encrusting bryozoa. Solenopora, pelmatozoans (mostly crinoid ossicles with occasional stems up to 5 cm long), and some brachiopods. Platystrophia, Rhynchotrema a dalmanellid and some Hedstroemina are present in varying degrees of breakage. The coarser shells tending to remain whole. Another feature is the abundance of coated grains, either by large encrusting organisms, e.g. Nyctopora, or by algae (?) giving a rind of 1 or 2 mm thickness to smooth bean like oncolites.	2	0.70
Solenopora bioherm with lateral equivalent bioclastic (calcirudite and calcarenite) grainstones.	11	6.00
Massive unit of coarse (calcarenite with some calcirudite) bioclastic grainstone. In the basal 70 cm lenses of mud up to 30 cm thick and 1.50 m long are found. Lithologically and faunally this bed is identical to that underlying the mound; the only slight	2	1.80

variation being an increase in abundance of Streptelasma. Solenopora is not abundant. Concentrations of small forms exist in the lower part and larger individuals towards the top.

Lithology as above, but the proportion of crinoidal material, Streptelasma and Solenopora increases in the lower 1.8m and then decreases.	2	2.10
Bioclastic grainstone unit as above, but in the basal portion only. Above this grain size decreases, Streptelasma becomes common, Solenopora becomes concentrated in pockets and the percentage of quartz increases. Although essentially a massive unit the increased quartz material tends to segregate, giving a thinly bedded appearance.	2/1	2.80
Unit of increasing quartz concentration in an essentially calcarenitic bioclastic grainstone. Solenopora is confined to stringers and pockets of quite large specimens. The unit remains pelmatozoan (crinoid) rich with common Streptelasma, Sowerbyella, Strophomena, Dalmanella and Rhynchotrema.	2/1	1.24
Transitional unit containing an increasing quartz content which changes from thinly bedded bioclastic grainstones and quartz siltstones (fine sandstones with increasing bioturbation, to a Chondrites bearing siltstone horizon at the top. The fauna changes from a Hedstroemina dominated to Sowerbyella dominated; the associated genera being a Dalmanellid, Rhynchotrema and a small coarse ribbed orthid with occasional branching bryozoa, Chasmops fragments and Streptelasma. Gastropods also increase with the Sowerbyella. With the quartz increase, small scale interference and straight ripple become evident (Table I.6.iii); ripple drift too becomes a noticeable feature and a variety of ichno fauna appear.	2/1	2.16

Massive unit of thinly bedded fine quartz sandstones, siltstones and shales with a Chondrites dominated ichnofauna and the typical small scale straight and interference ripples associated with this facies. (Table I.6.iv.). Apart from occasional sheets, bioclastic grainstones are confined to small lenses or pods. These have a Sowerbyella, Mjøsina, Hedstroemina brachiopod fauna. Single specimens of Diplotrypa appear in the sandy units, but these are rare, only obtaining any concentration (9 or 10 specimens in a bed) near the top of the unit. Lenses of impure bioclastic grainstone appear 1.85 m below the top of the unit and gradually increase in concentration. These contain dominantly branching bryozoa as well as a mixed Sowerbyella - Platystrophia brachiopod fauna, have well oscillatory developed ripples and become dominant at the top of the unit.	1	8.30

BERGEVIKA MEMBER

Bergevika Reef Complex

Bioclastic (calcarenite) grainstone. Basal 54 cm are quite sandy but the unit is dominated by pelmatozoan debris with branching bryozoa fragments, Streptelasma, Dalmanellids, Vellamo ? Zygospira, Leptaena and an orthid. Grapthodictyon is also abundant and some Chasmops fragments are present.	2	1.80
Dolomite with patches of coarse bioclastic grainstone.	5	0.20
Coarse bioclastic grainstones. Dominated by calciruditic pelmatozoan debris, with small biohermal growths of stromatoporoids, Solenopora, Liopora and Eoflecheria.	2	2.96

Dolomite with Eoflecheria. Unit is irregular, often due to the pronounced stylolitic upper and lower contacts. Stylolites are very well developed with the bed too.	5	0.30
Coarse (calcarenite/calcirudite) bioclastic grainstone which contain fragments of corals, stromatoporoids, coarse ribbed brachiopods, bryozoa - but are dominated by pelmatozoan debris. Quartz siltstone is also present as laminae and pods.	2	1.27
Quartz siltstone horizon with pods of bioclastic material.	1	0.60
Interbedded bioclastic grainstones (calcarenites), quartz sandstones and mudstones.	1/2	0.40
Thinly bedded bioclastic (calcarenite) grainstones.	2	0.40
Laminar stromatoporoid horizon. Dome shapes are present, but usually convex down, with a matrix of impure bioclastic grainstone.	10	0.90
Laminar stromatoporoids in a quartz siltstone dominated sediment.	10	0.90
Main unit of stromatoporoid - coral reefs with associated biomicrites, bioclastics and overlying oncolite rich grainstone horizons.	10	10.00
Biomicrite and bioclastic beds.		
Bioclastic grainstone. Grain size variable, calcilutite to calcrudite. Fossils are in all stages of breakup and represent the widest range of fauna. Coiled and high spired gastropods, stick bryozoa, Liopora fragments, trilobite debris, Platystrophia, Kjaerina, Strophomenids, Sowerbyella orthocones and abundant	2	1.70

pelmatozoa (crinoid stems and ossicles). Solenopora, Dimorphosiphon and bean oncolites are the algae present. These bioclastic units occur in a series of small lenses which are cross-bedded (low angle, small scale, planar type) and may represent small channel fills as they are erosive upon adjacent units, but form recognisable beds 10-15 cm thick. With a decrease in biotic content the upper 1 m becomes micritic (mudstone) but still retains its thinly bedded nature.

Thinly bedded black biomicrites. Bioclasts occur irregularly throughout the unit giving a variety of textures. Bioturbation is evident towards the base with large Thalassinoides like burrows apparent on the underside of beds, and Chondrites in the finer silty partings between beds. After 4 m the unit assumes an almost reticulate look with dolomite becoming abundant within a stylolite bounded three dimensional network. Brachiopods (strophomenids) are abundant here. The unit is faulted and in the upper 3 m above this the reticulation disappears and thinly bedded biomicrites are encountered. These contain a Mjøsina mjøsensis - and spar filled shells which are probably bivalves, together with occasional Platystrophia, a Rhynchonellid and Encrinurid trilobite fragments. In the upper 20 cm bioclastic pods appear together with a gastropod crinoid band which show low angle cross-bedding dipping mainly southwards. The top of the unit appears to be broken up and the spaces between the clasts filled by quartz, sandstone/siltstone identical to the overlying bed. This top surface is extremely irregular, apparently cut by small channels, usually between 6 and 10 cm. deep. 4 7.70

EEG MEMBER

Terrigenous siltstone beds.

The basal part of this unit contains small lenses of bioclastic grainstone, rich in Rhynchotrema and orthids, broken branching bryozoa which fill the hollows in the underlying bedding surface. Above this are thin bioclastic sheets and quartz siltstones. The limestones contain a Sowerbyella, Dalmanellid, Mjøsina, Rafinesquina, Vellamo, Hedstroemina, Strophomena, Platystrophia, Cyclospira dominated fauna, while the siltstones are rich in bivalves and Chondrites. Ripples and cross bedding are abundant in the silty horizons too (Table I.6.v). As the upper part of this unit is reached the Sowerbyella become replaced by Mjøsina.	1	1.15
The basal 2 m of this unit contains more massive calcareous quartz siltstones, with bioclastic beds up to 25 cm thick. Above this more muddy sediments interbedded with calcareous sandstones and siltstones are common and contain a bivalve and stick bryozoa dominated fauna respectively. Sowerbyella, Mjøsina, dalmanellids and orthids are found toward the base. Sedimentary structures are limited to interference ripples (Table I.6.vi.) in the siltstones which also contain Chondrites. Solitary Diplotrypa are also found in this unit.	1	5.65
Dominantly a quartz siltstone unit with bryozoa, A mixture of brachiopod faunas, trilobites and some gastropods are found in thin discontinuous bioclastic lenses and sheets. Bioturbation both by vertical burrows and Chondrites increases upwards. Sedimentary structures appear as occasional evidence of ripple drift, although a calcareous quartz silt unit at the top of the unit contains some planar cross-bedding.	1	2.50

Quartz siltstones with thin bioclastic veneers containing Sowerbyella in abundance. 1 2.50

Extremely bioturbated quartz siltstone rich unit in which all bedding except for occasional stringers of coarser grainstone has been destroyed by organic activity. This unit appears to represent a transition into the overlying beds. 1 2.00

Reticulate limestone beds.

Massive bioturbated biomicrites (wackestones). Near the base there is a high quartz silt content and some grainstone textured bioclastic units, but dolomite and micrite contents both rapidly increase to give the familiar reticulated texture of a three dimensional dolomite network. Trilobite debris appear the most abundant bioclasts, but large planulate gastropods, orthocones, Sowerbyella, Mjøsina, Dalmanellids, Platystrophia, and branching bryozoa are all represented, usually occurring as separate concentrations. 9 6.00

TABLE I.6: Palaeocurrent data, Bergevika South.

(i) 1-1.80 m above limestone base.

Ripple crests

105	133	059	051	065	075	083	066	076
070	173	153	085	127	156	079	065	067
037	058	083	081					

(ii) 1.80-3.10 m above limestone base.

Ripple crests

125	101	115	093	101	081	093	099	093
089								

(iii) 19-20 m above limestone base.

Ripple crests

069	052	062	059	051	059	063	071	067
066	076	063	077	077	033	091	083	079
075	071	067	055	071	057	097	081	091
099	103	047	063	093	127	067	083	011
099	073	061	097	081	103	079	159	127
095	065	169	061	113	049	051	111	135
065	037	143	043	121	141	073	067	023
158	013	043	039	091	099	079	163	019
083	013	065	083	081				

(iv) 20-28 m above limestone base.

Ripple crests

087	075	055	051	085	061	105	081	095
083	081	056	034	135	089	067	105	079
091	109	111	135	079	097	088	145	143
167	115	071	129	073	125	133	055	081
075	079	085	089	075	077	101	077	094
089	099	077	085	069	107	085	095	104

(iv) (continued)

096	107	103	114	087	097	079	105	091
109	007	085	113	027	049	001	074	069
091	079	099	023	167	081	103	089	099
091	149	079	049	045	097	084	103	165
091	105	087	105	115	147	069	109	151
143	077	048	083	131	147	043	083	082
127	079	113	137	165	053	059	077	091
093	141	089	087	111	147	051	053	096
089	065	149	125	067	093	123	082	135
121	107	149	111	075	081	165	133	123
081	125	101	109	053	121	075	051	083
089	127	049	061	077	083	105	071	127
069	142	017	087	125	141	131	101	161
015	129	017	087	109	097	037	179	025
009								

(v) 53-54 m above base of limestone.

Ripple crests

069	071	071	065	067	067	069	079	073
075	031	049	053	029	085	066	077	077
091	081	064	087	076	081	059	054	083
174	014	027	173	001				

(vi) 54-50 m above base of limestone.

Ripple crests

084	103	109	083	089	091	097	091	105
114	053	126	091	091	079	089	007	083
073	065	055	045	085	081	085	087	

EEG.

Location: Blad 1916 II (Østre Toten) 60°44'35"N, 11°0'5"E, appox 200-250 metres north northeast of Eeg farm on the small track leading from the farm to Helgøya Skole over the eastern flank of Eskberget. (H18.5)

General: three separate exposures along the bank, in a small disused pit and in the track itself, combine to give a a 38.00 m type section for the Eeg Member and contact with the Helgøya quartzite. Dip 080/174.

Description:	Facies	Thickness (m)
MJØSA LIMESTONE		
BERGEVIKA MEMBER		
Biomicrites and bioclastic beds		
Grubbings of fine bioclastic grainstone/wackestone, containing abundant stick bryozoa, gastropods and other molluscan debris.	4	c 1.00
EEG MEMBER		
Terrigenous siltstone beds		
Small disused quarry, with quartz siltstones. *Chondrites*, convex up *Diplotrypa*, stick bryozoa, gastropods, *Mjøsina*, *Sowerbyella* and comminuted pelmatozoan material are the main bioclastic elements. Parallel lamination and ripple drift are the main sedimentary structures present. Bioclastic pods are composed predominantly of pelmatozoan and bryozoan debris.	1	c 2.00
Exposure in track:		

BERGEVIKA MEMBER

Biomicrites and bioclastic beds.		
Thinly bedded black wackestones.	4	1.20

EEG MEMBER

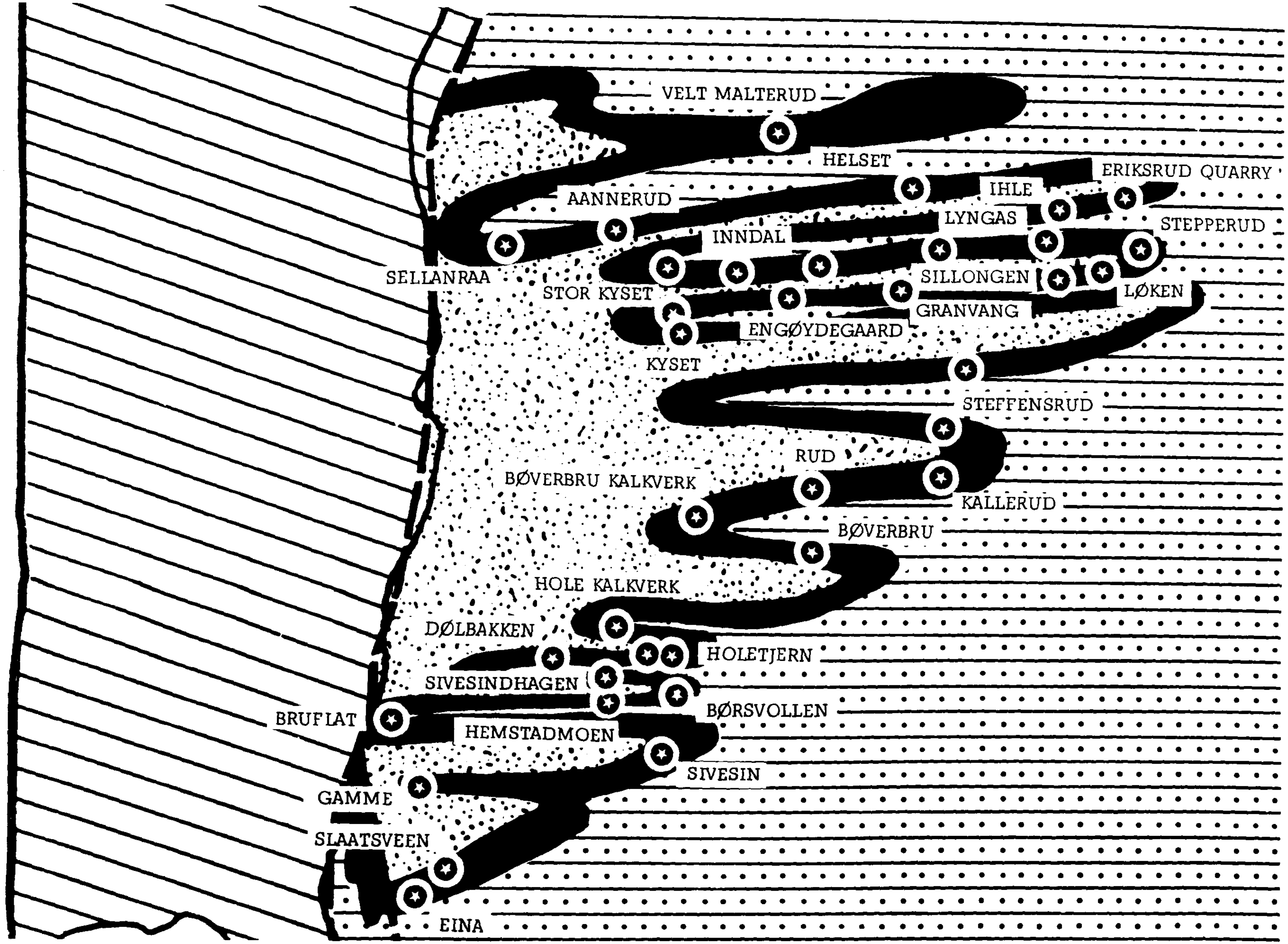
Terrigenous siltstone beds		
Quartz siltstones with *Chondrites* and *Diplotrypa* showing progressive thickening of limestone units towards top of unit.	1	7.40
Calcareous quartz silstone.		1.10
Calcareous quartz siltstone developing a bioturbated texture.		3.60
N.E.		3.30
Silty, impure limestone with *Diplotrypa* and and pelmatozoan debris.		1.60
N.E.		4.40
Reticulate limestone beds		
Bioturbated dark grey biomicrite (wackestone). Burrows are dolomite filled.	9	4.10
N.E.		5.00
Dolomitised (?) unit. Micritic pods in a dolomite (fine quartz sandstone net).	9	2.20
N.E.		0.80

HELGØYA QUARTZITE

Brown quartzite (grubbing?)		0.30
N.E.		3.00

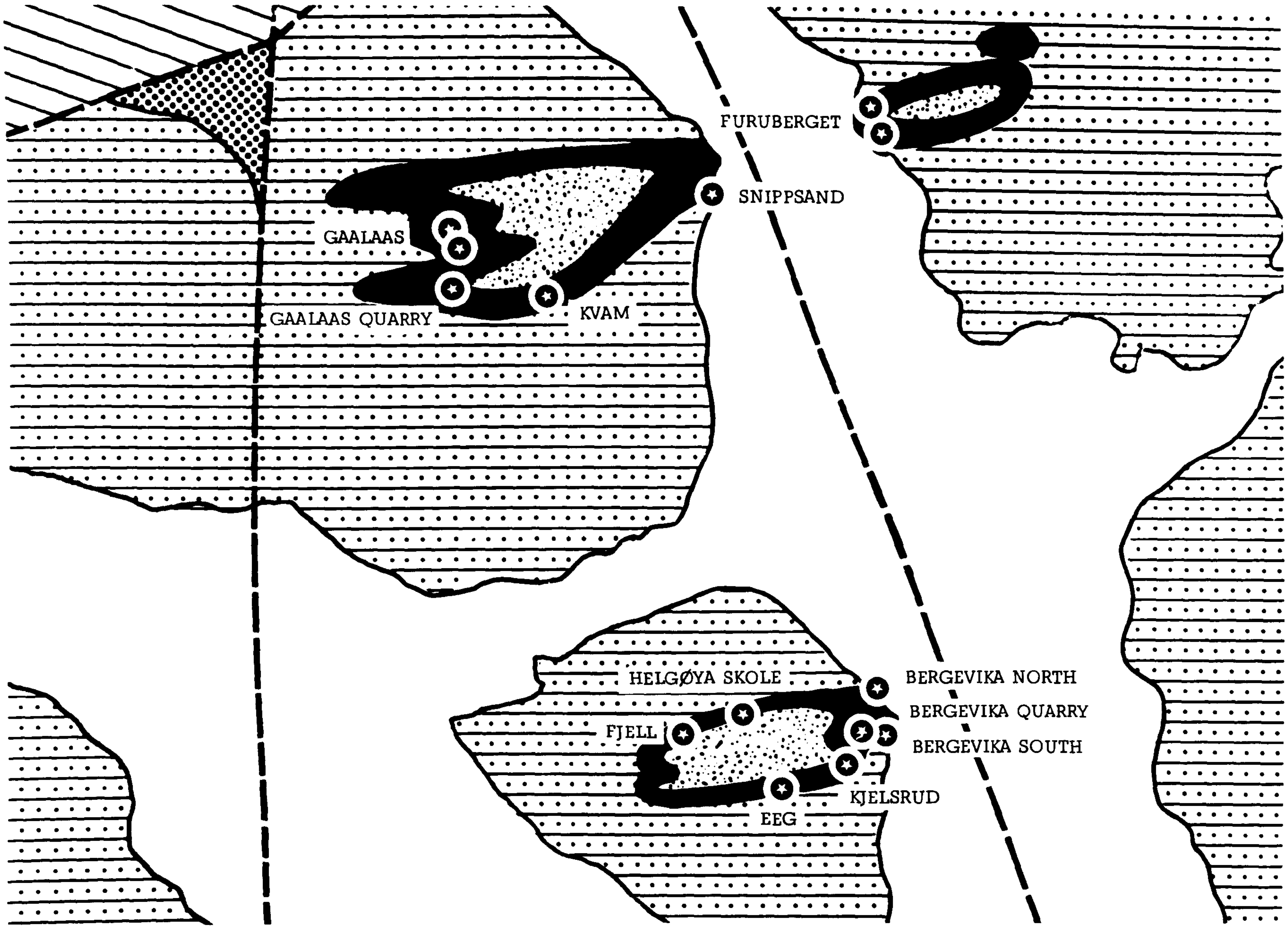
Definite *in situ* quartzite. A very steep slope dips away northwards from this horizon.

Fig. I.1 : Locality map for the Toten district



VELT MALTERUD
HELSET
ERIKSRUD QUARRY
IHLE
AANNERUD
LYNGAS
STEPPERUD
INNDAL
SELLANRAA
SILLONGEN
LØKEN
STOR KYSET
GRANVANG
ENGØYDEGAARD
KYSET
STEFFENSRUD
RUD
BØVERBRU KALKVERK
KALLERUD
BØVERBRU
HOLE KALKVERK
DØLBAKKEN
HOLETJERN
SIVESINDHAGEN
BØRSVOLLEN
BRUFLAT
HEMSTADMOEN
SIVESIN
GAMME
SLAATSVEEN
EINA

Fig. I.2 : Locality map for the Nes-Hamar district.


FURUBERGET
SNIPPSAND
GAALAAS
GAALAAS QUARRY
KVAM
HELGØYA SKOLE
BERGEVIKA NORTH
BERGEVIKA QUARRY
FJELL
BERGEVIKA SOUTH
KJELSRUD
EEG

TOTEN DISTRICT

Aannerud	Blad 1816 II (Eina)	60°42'05"N, 10°38'55"E
Bruflat	" "	60°39'20"N, 10°36'20"E
Børsvollen	" "	60°39'20"N, 10°39'40"E
Bøverbru	" "	60°40'05"N, 10°41'10"E
Bøverbru Kalkverk	" "	60°40'05"N, 10°39'50"E
Dølbakken 1	" "	60°39'32"N, 10°38'50"E
Dølbakken 2	" "	60°39'32"N, 10°38'55"E
Dølbakken 3	" "	60°39'32"N, 10°39'05"E
Engøydegaard 1	" "	60°41'45"N, 10°40'52"E
Engøydegaard 2	" "	60°41'47"N, 10°40'55"E
Engøydegaard 3	" "	60°41'52"N, 10°41'E
Eriksrud quarry	Blad 1916 II (Østre Toten)	60°42'17"N, 10°43'30"E
Finnstad	Blad 1816 II (Eina)	60°41'30"N, 10°41'38"E
Fredang	Blad 1816 I (Gjøvik)	NN 379922
Gamme	Blad 1816 II (Eina)	60°39'55"N, 10°37'20"E
Granvang	" "	60°41'45"N, 10°37'E
Hole Kalkverk	" "	60°39'47"N, 10°39'E
Inndal	Blad 1816 II (Eina)	60°41'26"N, 10°40'07"E
Kyset	" "	60°41'17"N, 10°39'10"E
Lyngas	" "	60°41'55"N, 10°42'30"E
Løken	Blad 1916 III (Østre Toten)	60°41'55"N, 10°44'35"E
Sellanraa	Blad 1816 II (Eina)	60°41'55"N, 10°38'10"E
Sillongen 1	Blad 1916 III (Østre Toten)	60°41'55"N, 10°44'10"E
Sillongen 2	" "	60°41'55"N, 10°42'E
Sillongen 3	" "	60°41'N, 10°44'E
Sivesin	Blad 1816 II (Eina)	60°39'55"N, 10°39'10"E
Slaatsveen	" "	60°39'25"N, 10°37'42"E
Steffensrud 1	" "	60°41'05"N, 10°42'30"E
Steffensrud 2	" "	60°41'10"N, 10°42'40"E
Steffensrud 3	" "	60°40'56"N, 10°42'30"E
Steffensrud 4	" "	60°40'50"N, 10°42'42"E
Steffensrudtjern	" "	60°40'50"N, 10°42'15"E

Stepperud 1	Blad 1916 III (Østre Toten)	60°42'05"N, 10°44'50"E
Stepperud 2	" "	60°42'05"N, 10°44'52"E
Stor-Kyset	Blad 1816 II (Eina)	60°41'27"N, 10°39'37"E
Velt Malterud	" "	60°42'58"N, 10°41'20"E

NES-HAMAR DISTRICT

Bergevika cross roads	Blad 1916 III (Østre Toten)	60°44'35"N, 11°00'05"E
Bergevika North	" "	60°45'N, 11°04'10"E
Bergevika Quarry	" "	60°44'45"N, 11°01'E
Fjell	" "	60°44'45"N, 11°01'E
Furuberget South	Blad 1916 IV (Hamar)	60°48'52"N, 11°00'40"E
Gaalaas	" "	60°47'52"N, 10°55'35"E
Gaalas quarry	" "	60°47'42"N, 10°55'50"E
Helgøya Skole	Blad 1916 II (Østre Toten)	60°44'32"N, 10°58'50"E
Kjelsrud	" "	60°44'25"N, 11°00'55"E
Knatterud	Blad 1916 IV (Hamar)	60°48'15"N, 10°55'40"E
Kvam	" "	60°47'35"N, 10°56'25"E

RINGSAKER DISTRICT

Brattberg	Brad 1916 IV (Hamar)	60°50'15"N, 10°48'50"E
Brattberg Lille	" "	60°50'10"N, 10°48'35"E
Torsaeter	" "	60°57'05"N, 10°58'50"E
Torsaeter bru	" "	60°56'45"N, 10°59'20"E

APPENDIX II.

PETROGRAPHICAL TERMINOLOGY

INTRODUCTION

As a supplement to Chapter 3 (Facies Analysis) it was considered necessary to present a brief definition of the terminology adopted in both field and microscope studies of the Mjøsa Limestone. Although primarily concerned with carbonates the discussion also includes the clastic facies and sedimentary structures, as well as a consideration of grain size analysis.

SEDIMENTARY STRUCTURES

REINECK and SINGH (1975) present a detailed analysis of primary sedimentary structures and textures for modern clastic sediments. These definitions are adhered to as far as possible in this study and reference to additional descriptive material is indicated in the text.

GRAIN SIZE ANALYSIS

The size scale employed to classify grains is given below :

	GRAIN SIZE		CRYSTAL SIZE	
	Gravel	Calcirudite		
2 mm	(C)	(C)		
0.6 mm	(M) Sand	(M) Calcarenite	Sparite	
0.2 mm	(F)	(F)		
0.06 mm	(C)			60μ
0.02 mm	Silt (F)	Calcisiltite		20μ
0.004 mm				4μ
	Clay	Micrite mud	Micrite	

Letters in parentheses indicate coarse (C), medium (M) or fine (F) grained members.

The scale represents an amalgamation of clastic and carbonate terminology. Allochems (FOLK, 1959) are defined as carbonate grains greater than 60 μ diameter; silt sized carbonate grains are regarded as matrix, although silt sized quartz grains are not.

The main areas of discrepancy arise in the lower sizes represented, due mainly to the limitations imposed by the petrographical microscope in distinguishing (and measuring) fine silt and mud grades in carbonates. BATHURST (1971, p. 89) presents a discussion of the "coarser calcilutites" and quotes the range of crystal sizes adopted by various workers, as being between 1 and 35μ. Calcisiltites in the Mjøsa Limestone have a size range of 2-50μ, with modes of 10-25μ and 40μ. Both these are above the ranges given by Bathurst for silty calcilutites, but can be accommodated within a calcisiltite range of 4-60μ given above. The finer (less than 4μ) crystal sizes can be regarded as 'micrite mud' (Bathurst's calcilutite). The calcisiltites are optically distinct from the micrite muds which have a crystal size range of less than 2.5μ to a maximum of 25μ, but generally lie within a range 2-6μ. In view of this, FOLK'S (1959) original maximum crystal size of 4μ, rather than DUNHAM'S (1962) 20μ, for microcrystalline calcite is applied to both micrite muds and micrite cement (e.g. in micrite envelopes the maximum observed crystal size was 5-6μ).

LEIGHTON and PENDEXTER (1962, p. 37) introduced the terms 'microclastic' and 'microcrystalline' for classification of micrites. The former were defined as having a dull lustre, being muddy in appearance and contained silt-sized quartz and some fossil debris, while the microcrystalline micrites have a high lustre and a mosaic of tightly interlocking calcite crystals. Application of this scheme to the fine grained carbonates of the Mjøsa Limestone revealed that the calcisiltites could be readily described as microclastic, while, in general, the micrite muds were microcrystalline.

GRAIN DETERMINATION

This is confined to the allochemical component of the rocks. FOLK (1959) described an allochem as any grain that formed within the basin of deposition. This definition is adhered to, and 7 sub-types may be recognised.

1. Bioclasts

This is a convenient term to define a fragmental particle derived from the breakdown of any sort of calcareous shell, test or skeleton, regardless of whether the breakdown was mechanical or caused by organic agents (WILSON, 1975, p. 9). The term was restricted by some workers to the latter process only, but this is considered too interpretative. The term biogenic is used (along with biota) to include all biological particles, both faunal and floral, Identification of bioclasts has been greatly aided by the excellent comprehensive works of MAJEWSKE (1969), BATHURST (1971) and HOROWITZ and POTTER (1971). More specifically, the various algae were identified from descriptions given by PIA (1927), HØEG (1927; 1932; 1961), JOHNSON (1960, 1961) and JOHNSON and HØEG (1961).

2. Peloids

McKEE and GUTSCHICK (1969) proposed the useful term 'peloid' to embrace all grains constructed of an aggregate of cryptocrystalline carbonate, irrespective of origin. Such an umbrella term is extremely useful, indeed necessary, because the origin of these aggregates is often in doubt. They can, however, be referred to without genetic implication by use of the term 'peloid'. By definition, peloids will include faecal pellets, intraclasts and grapestone, but sufficient detail exists to allow recognition and separate classification of these allochems.

In discussing the origin of Recent micrite envelopes and peloids, BATHURST (1966, 1971) describes how modern, non-calcareous boring chlorophyte and cyanophyte algae can cause widespread destruction of all types of grain. The grains become riddled with holes and are particularly liable to abrasion, giving the most densely bored grains the highest degree of roundness. The borers have a further effect than mechanical destruction. The emptied bores are apt to become filled with micritic carbonate, and by repeated boring, post mortem vacation followed by micrite filling, the whole grain is gradually and centripetally replaced by micrite; this process has been termed micritization (BATHURST, 1966), and is fully described by BATHURST (1971, p. 381-392).

An examination of Recent peloids from Bimini Lagoon, and comparison with the descriptions given by BEALES (1955) and WOLF (1965 a, b) of similar micritic grains, leads this author to conclude that the irregular, or circular, shaped grains of micrite which cannot be classified as pellets, intraclasts or grapestone, are analgous to the modern peloids described above.

3. Faecal pellets

Most sedimentary petrographers agree that in both Recent and ancient carbonate sediments, elongate peloids, elipsoids of revolution, are faecal pellets. According to FOLK (1962), they show a dark brownish colour in reflected light due to the presence of organic matter, a feature helpful in distinguishing them from a microcrystalline calcite matrix. Pellets are undoubtedly polygenetic in origin, e.g. WOLF (1965 a, b) suggests an algal origin and SCOFFIN (1972) shows that micrite filling of bryozoan zoanthellae can produce pellets. Size ranges quoted for faecal pellets are considerable, from 20μ to several millimetres. Although FOLK (1962) suggested an upper size limit of 150μ (anything larger was intraclastic), the size of faecal pellets depends on the diameter of the ailmentary canal of the producing animal, a factor which leads to a constancy of size within a particular sample. BEALES (1958; 1965) has noted how some pellets are destroyed to give "merged calcarenites", while others lack compaction features, a situation which GEORGE (1972) attributes to bonding by point contact accretion of carbonate, either immediately after excretion or within the anal tract. R. WILSON (1967) considers the use of the term 'pellet' to be too general, and suggests it should be confined to cover elongate particles that are well rounded and sorted, and abundant in a particular sample.

For the purposes of this study, pellets which are considered to be faecal in origin, possess a uniformity of shape (ellipsoids of revolution) and size, smooth outlines, are micritic in texture with no internal structures, and are found together in abundance.

4. Intraclasts

FOLK'S (1959) original definition of "particles that have at some stage been incorporated in the floor of the area of deposition, and have subsequently been reworked" is perfectly adequate, if applied broadly (i.e. the intraclasts contain extrabasinal quartz grains). WOLF'S (1965b) terminology of limeclasts and extraclasts is regarded as confusing. The definition of intraclasts employed for this study corresponds to R. WILSON'S (1967) class of "eroded lumps", and depends for recognition upon the truncation of constituent allochems (or cement) by the particle surface. No size range is envisaged, and composition is variable, but usually micritic or pelleted. By their intrabasinal origin intraclasts imply syn-sedimentary lithification by interference of penecontemporaneous erosion and deposition. Clasts which are externally derived are regarded as lithoclasts.

5. Grapestone

ILLING (1954) proposed the term 'grapestone' to describe the amalgamation of carbonate sand grains of various kinds into larger irregularly shaped grains, "occasionally reminiscent of lithified bunches of microscopic grapes", in Recent carbonate sands in the

Bahamas. The grains are generally peloidal in nature and cemented by micritic aragonite. BATHURST (1971, p. 316-319) briefly reviews the origin of these grains, concluding that they are formed by prolonged immobilization in a tough subtidal mat, where pore waters are depleted of CO_2 by the metabolism of numerous boring algae. The grains are welded together in bundles or sheets by the precipitation of micritic aragonite. MONTY (1967) has described similar grains from the back reef lagoon of Andros Island, where the grains were heavily micritized and bound together by Schizothrix-type algal filaments. Similar grains with accretionary textures can be recognised within the Mjøsa Limestone and are distinguished from intraclasts by the grain determined boundaries which show no evidence of truncation. Peloids are the most common constituent grain, but bioclasts and quartz grains (silt-size) are also incorporated.

6. Ooids

Ooids are generally scarce within the Mjøsa Limestone but can be recognised by a strongly radial coating of clear calcite (c.f. oncolites) around a central nucleus. BATHURST (1971, p. 295-319) presents a detailed account of the formation of ooids. It may be that the paucity of these allochems is due to a lack of water supersaturated with $CaCO_3$; there appears to have been sufficient agitation to form oncolites. Many of the ooids are small (60-100μ) and possess coats less than 50μ in thickness; these are termed superficial ooids by BATHURST (1967a), after ILLING'S (1954) original term for a thin coating around a large nucleus.

7. Oncolites and Algal coats

Oncolites are distinguished from ooids by their larger size (max. diameter 3.5 cm) and dark micritic coating composed of algae. Like ooids a degree of movement is required to turn the grains and allow growth on all sides of the nucleus. LOGAN et al. (1964) have allocated oncolites an SS (spheroidal structure) nomenclature in their classification of algal stromatolites, attributing formation to the growth of a series of stacked hemispheres around the nucleus. Two main types of oncolite were observed in the Mjøsa Limestone; a smooth outlined, Girvanella dominated algal association, and a ragged (often large), Hedstroemia dominated type. In both cases the algal coat appeared as a complex of various algae, spongiostrome textures were common in both types and structures akin to Wetheredella and Sphaerocodium were also observed. The inclusion of silt-sized quartz grains and occasional bioclasts indicates that in common with the algal mats, these algal communities had the ability to trap sedimentary particles.

WOLF (1965 a, b) has proposed a series of terms to describe algal encrustations, but these were regarded as too cumbersome for the purposes of this study. Apart from oncolites, grains which showed a constructive type of micritic coating, attributed to algal activity, were described as having an "algal coat". This is distinguished from an oncolite by its general lack of structures (occasional Girvanella tubes or a spongiostrome texture were observed), and poorer development, both in terms of thickness (max. thickness was 300µ) and irregularity of coating. These grains were regarded as representing conditions where either the cessation of growth or lack of mibility prevented development of oncolites.

Micrite envelopes

These structures have been described in great detail by BATHURST (1966, 1971), who attributes their origin to attack by boring algae and the subsequent process of micritization. FRIEDMAN et al. (1971) have shown that such destructive processes are not confined to the actions of photosynthetic algae, fungi, bacteria and hetertrophic algae can also produce similar results, while PURSER and LOREAU have described Recent chemically precipitated aragonitic coats to grains in the supratidal environment of the Trucial Coast.

The distinguishing factor of the micrite envelopes is that unlike algal coats they represent destructive algal activity and are therefore a replacement of the grain. The outer surface is generally smooth, while the inner surface abutting against the grain (or cement casts i.e. molluscan bioclast) is irregular and commonly shows blebs or tubes of micrite (BATHURST 1971, p. 90). The envelopes are composed of micrite and are completely structureless.

Although not a true allochem, the description is included at this juncture because of the intimate association of this feature with bioclasts, and represents a penecontemporaneous modification of grains.

POROSITY

In a comprehensive review of porosity types, CHOQUETTE and PRAY (1970) have suggested a scheme of nomenclature for the basic pore systems encountered in carbonate rocks. They make the important distinction between fabric selective and non-fabric selective (usually post lithification) types. The classification proposed by these authors has been adhered to, as has the abbreviated nomenclature, throughout this text.

CALCITE CEMENT

This is equivalent to BATHURST'S (1958; 1959) granular cement, rim cement and drusy mosaic, as well as FOLK'S (1959) sparry calcite cement. An informal definition of cement was adopted by the Bermuda Seminar on Carbonate Cementation, September 1969- "a non-skeletal void filling, precipitated on an intergranular or intra-sedimentary free surface". Crystal size is usually greater than 10μ, and is distinguished from micrite primarily by its clarity, although these feature is chiefly a function of grain size. BATHURST (1971; pp. 415-457) presents a detailed discussion of cementation and the recognition of cements in thin section. In this study, two types of cement are commonly recognised, optically continuous, syntaxial rim cements to echinodermal grains, and blocky, void-filling cement. The latter has precipitated from solution and grown from cavity walls to give clear calcite crystals which characteristically have plane interfaces, increase in size but decrease in abundance away from the cavity wall and lack relict structures. This distinguishes it from "neomorphic spar" (FOLK, 1965) in which the equigranular crystals have curved to wavey intercrystalline boundaries (BATHURST, 1971, pp. 484-485). In the Mjøsa Limestone neomorphic spar is confined to replacing stromatoporoid coenostea with an ensuing obliteration of microarchitecture; it never appears as an interparticular fill.

CLASSIFICATION OF CARBONATE ROCKS

Of the many classifications proposed for carbonate rocks, those of FOLK (1959; 1962) and DUNHAM (1962) are the most widely used. Although Folk's terminology could be adequately used for most carbonate rock types observed in the Mjosa Limestone, the rigidity involved in applying the particle type prefixes and the compounding of nomenclature make it a less favoured option than Dunham's terminology. The packing concept inherent in Dunham's classification together with its implications for original depositional fabrics and interpretation of energy conditions, make it more useful for the purpose of this study. The original classification together with its subsequent modification by EMBRY and KLOVAN (1971) is illustrated in Fig. II.1. Rocks are therefore classified by prefixing the main allochemical component to the appropriate textural class, e.g. bioclastic grainstone.

PETROGRAPHICAL TECHNIQUES

Standard petrographical techniques were employed including the production of acetate peels, stained peels and stained thin sections. A variety of staining methods were experimented with, the most successful being a cold acidic solution of Alizarin Red S and Potassium

Fig. II.1 : Classification of limestones. DUNHAM'S (1962) classification appears above a modified version given by EMBRY and KLOVAN (1971).

<table>
<tr><td colspan="5">Depositional Texture recognizable</td><td rowspan="6">Depositional texture not recognizable

Crystalline carbonate

(Subdivide according to classifications designed to bear on physical texture or diagenesis.)</td></tr>
<tr><td colspan="4">Original components not bound together during depositions</td><td rowspan="4">Original components were bound together during deposition... as shown by intergrown skeletal matter, lamination contrary to gravity, or sediment-floored cavities that are roofed over by organic or questionably organic matter and are too large to be interstices.</td></tr>
<tr><td colspan="3">Contains mud (particles of clay and fine silt size)</td><td rowspan="3">Lacks mud and is grain-supported</td></tr>
<tr><td colspan="2">Mud-supported</td><td rowspan="2">Grain-supported</td></tr>
<tr><td>Less than 10% grains</td><td>More than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Boundstone</td></tr>
</table>

<table>
<tr><td colspan="6">Allochthonous limestones original components not organically bound during deposition</td><td colspan="3">Autochthonous limestones original components organically bound during deposition</td></tr>
<tr><td colspan="4">Less than 10% > 2 mm components</td><td colspan="2">Greater than 10% > 2 mm components</td><td rowspan="4">By organisms which act as baffles</td><td rowspan="4">By organisms which encrust and bind</td><td rowspan="4">By organisms which build a rigid framework</td></tr>
<tr><td colspan="3">Contains lime mud (< .03 mm)</td><td>No lime mud</td><td rowspan="3">Matrix supported</td><td rowspan="3">> 2 mm component supported</td></tr>
<tr><td colspan="2">Mud supported</td><td colspan="2" rowspan="2">Grain supported</td></tr>
<tr><td>Less than 10% grains (> .03 mm < 2 mm)</td><td>Greater than 10% grains</td></tr>
<tr><td>Mudstone</td><td>Wackestone</td><td>Packstone</td><td>Grainstone</td><td>Floatstone</td><td>Rudstone</td><td>Bafflestone</td><td>Bindstone</td><td>Framestone</td></tr>
</table>

Ferricyanide; the method was slightly modified from DICKSON'S (1965; 1966) original for the differentiation of ferroan and non-ferroan calcite. Staining for dolomite by immersion in boiling 30% sodium hydroxide solution with a variety of dyes (FRIEDMAN 1959; WARNE 1962) was generally unsuccessful due to the faint colouration. Dolomite was best identified by negative staining i.e. a blanket stain of Alizarin Red S was applied and all calcite stained red, a procedure which also heightened the relief of the dolomite crystals.

As the ultimate goal of the petrographical analysis was the reconstruction of depositional environments, primary depositional fabrics and textures were examined in more detail than diagenetic aspects. Microfacies were determined qualitatively rather than quantitatively, although point count analysis was employed to indicate the percentage ranges of each constituent component. Frequency of occurrence was estimated visually and the relative abundance recorded in the following manner, after BATHURST (1966, p.92):

(i) Common - more than half the total constituents,
(ii) Present - less than half the total constituents,
(iii) Rare - detectable with difficulty,
(iv) Absent

Data was tabulated and the results presented in Chapter 3.

Crystal shape (mostly dolomite) was described as :-

Anhedral - crystal faces absent,
Subhedral - crystal faces partially developed,
Euhedral - crystal faces present.

Subhedral or euhedral quartz was regarded as authigenic.

APPENDIX III.

PALAEOECOLOGICAL PARAMETERS FOR STROMATOPOROIDS AND SOLENOPORA.

INTRODUCTION

In spite of their obvious phylogenetical differences both the stromatoporoids and Solenopora encountered in the Mjøsa Limestone present similar palaeoecological problems, due principally to a lack of visible macrostructures in combination with the two dimensional nature of the exposure.

Many authors, especially those studying both the Devonian reefs of Canada (e.g. KLOVAN 1964; FISCHBUCH 1968) and the U.S.A. (e.g. PERKINS 1963; LAPORTE 1967; WILSON 1967; KAPP 1974) as well as the European Lower Palaeozoic (e.g. LECOMPTE 1956, 1959; BROADHURST 1966; MANTEN 1971), have proposed a variety of terms for stromatoporoid coenosteal shape and ensuing palaeoecological implications, which are contradictory and confusing. This situation is largely a result of each worker drawing conclusions from his own area of study and presenting it as a general hypothesis. In an attempt to standardise shape nomenclature ABBOT (1973) presented a brief review of relevant literature and proposed the adoption of a classification which standardised coenosteal shape into ten major divisions. Although representing a rational approach to the problem, this author considers that the subject of stromatoporoid shape requires an even simpler approach and the erection of a basic classification in which a minimum number of growth forms are clearly recognisable.

In stark contrast, the paucity of existing palaeoecological studies involving Solenopora necessitated the erection of a series of parameters by which drifted and non-drifted thalli could be recognised within a limestone unit containing a unique abundance of this alga. As with a stromatoporoid classification it was felt desirable to keep terminology as simple as possible.

Accordingly a series of simple morphological parameters flexible enough to encompass both stromatoporoids and Solenopora and which could be rapidly obtained at any two dimensional outcrop was desirable. A scheme which could yield the necessary amount of useful data to allow determination of the ecological preferences and mode of growth of the organisms in question was devised and presented below:-

1. Shape and Size (Stromatoporoids and Solenopora)
2. Orientation (Stromatoporoids and Solenopora)
3. Form (Solenopora)
4. Peripheral condition (Stromatoporoids and Solenopora)

Each parameter is discussed separately for stromatoporoids and Solenopora; the use of parentheses in the above page table is intended as a guide to indicate for which organism the established parameter is most useful. The decision to discuss each organism in turn was based on their separate modes of occurrence within the limestone rather than any morphological or phylogenetical differences.

SHAPE AND SIZE

Assuming the exposure faces to be random, stromatoporoid coenostea together with Solenopora thalli were measured for their length and height, or maximum and minimum axes.

Stromatoporoids

Difficulties were only experienced where, within the reefs, it was almost impossible to distinguish individual colonies due to intergrowth with one another which were often accompanied by a change of cocnosteal shape in any one stromatoporoid. An original attempt to erect a series of parameters based on a height-length-width ratio was abandoned due to the overwhelming lack of three dimensional exposure. Although a study carried out on a two dimensional exposure will have limitations, these are not regarded as imposing severe restrictions on the usefulness of the empirical scheme adopted.

On the basis of simple two dimensional observations, coenosteal shapes of Mjøsa Limestone stromatoporoids were divided into four broad categories:-

(i) Domes - domical: hemispherical or subhemispherical coenostea with a flat base (representing the maximum width of the colony) and convex upper surface.

(ii) Sheets - laminar: thin coenostea, often, although not always possessing a flat base and displaying greater development laterally than vertically.

(iii) Tubes, cylinders of cones - tubular, cylindrical or conical: coenostea without a flat base where the maximum growth is in a vertical rather than horizontal plane.

(iv) Spheres, elipses - spherical or eliptical but more commonly grouped and referred to as "rounded"; coenostea which have no clearly defined base and are most likely to represent cross sections through any of the above forms.

Within this simple framework a more detailed classification can be attempted and many of Abbot's shapes can be regarded as variations of one of the above basic shapes e.g. hemispherical, bulbous and domal would be part of the dome class, and sheets would include lamellar and tubular.

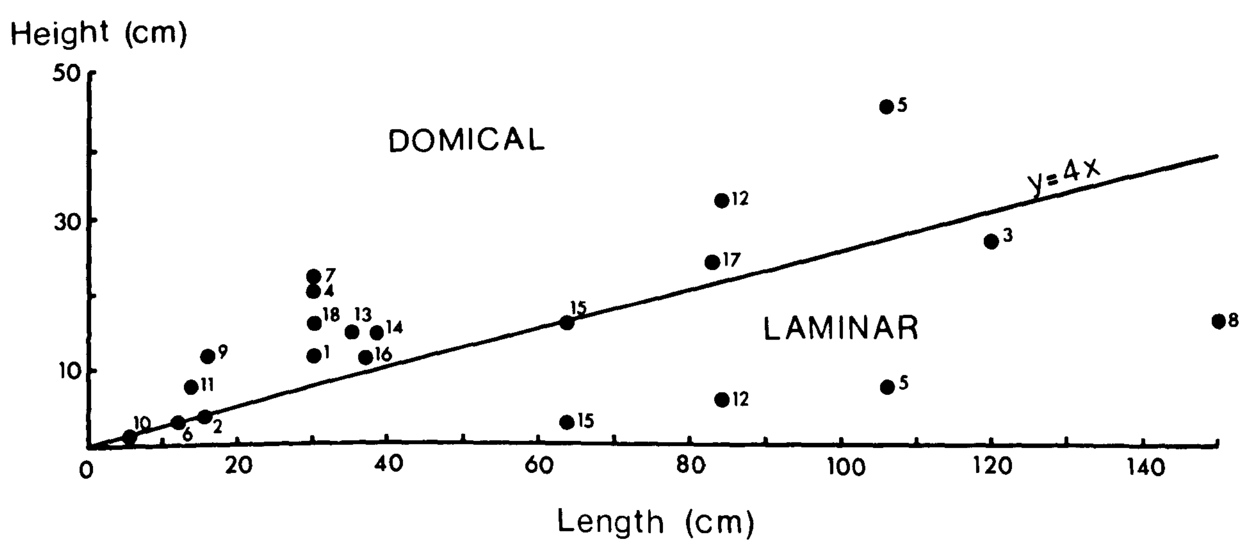
To refine the general coenosteal shape a semi-quantitative approach can be adopted as illustrated by the small study recounted below. Eighteen coenostea were measured from the Bergevika (southern) reef and the results reproduced in Fig. III.1 alongside the simple qualitative shape determinations arrived at in the field. From the graph a length height ratio of less than 4 distinguishes the domical from the laminar coenostea (which have a length height ratio of more than 4). Such an agreement between totally qualitative and semi-qualitative approaches was found in all cases and encouraged the adoption of this simple, rapid approach whereby the two most obvious physical parameters were measured at the outcrop and yielded a meaningful shape classification.

Further refinements could be added to broaded the scope of the classification if this was felt to be beneficial e.g. tubular forms would have a length/height ratio of less than one. Also the laminar forms could be expanded, if necessary, to include Abbot's divisions i.e. Lamellar - length/height ratio of more than 10; Tubular - length/height ratio of less than 10

Specimens which plot out near the origin of the graph are likely to provide some discrepant results as they could represent a section through

Fig. III.1 The relationship between length and height of stromatoporoid coenostea from the Bergevika (southern) reef.

Plot No.	Length (cm)	Height (cm)	Field determination of coenosteum shape
1	30	12	Laminar – Domical
2	16	4	Laminar – Domical
3	120	26	Laminar
4	30	20	Domical
5	106	8-44	Laminar – Domical
6	12	3	Laminar
7	30	22	Domical
8	150	16	Laminar
9	16	12	Domical
10	6	2	Laminar
11	14	8	Domical
12	84	32-6	Laminar – Domical
13	35	15	Domical
14	39	15	Domical
15	64	16-3	Laminar
16	37	12	Domical
17	83	24	Domical
18	30	16	Domical



the peripheral area of a larger dome or sheet. In this case the procedure adopted was to view the remainder of the plots on the graph. If a general spread of points similar to that illustrated by Fig. III.1 was present then the small individuals could either be genuine small forms or oblique sections through larger individuals, but if the population was confined to these low value intercepts then they were regarded as genuine small forms.

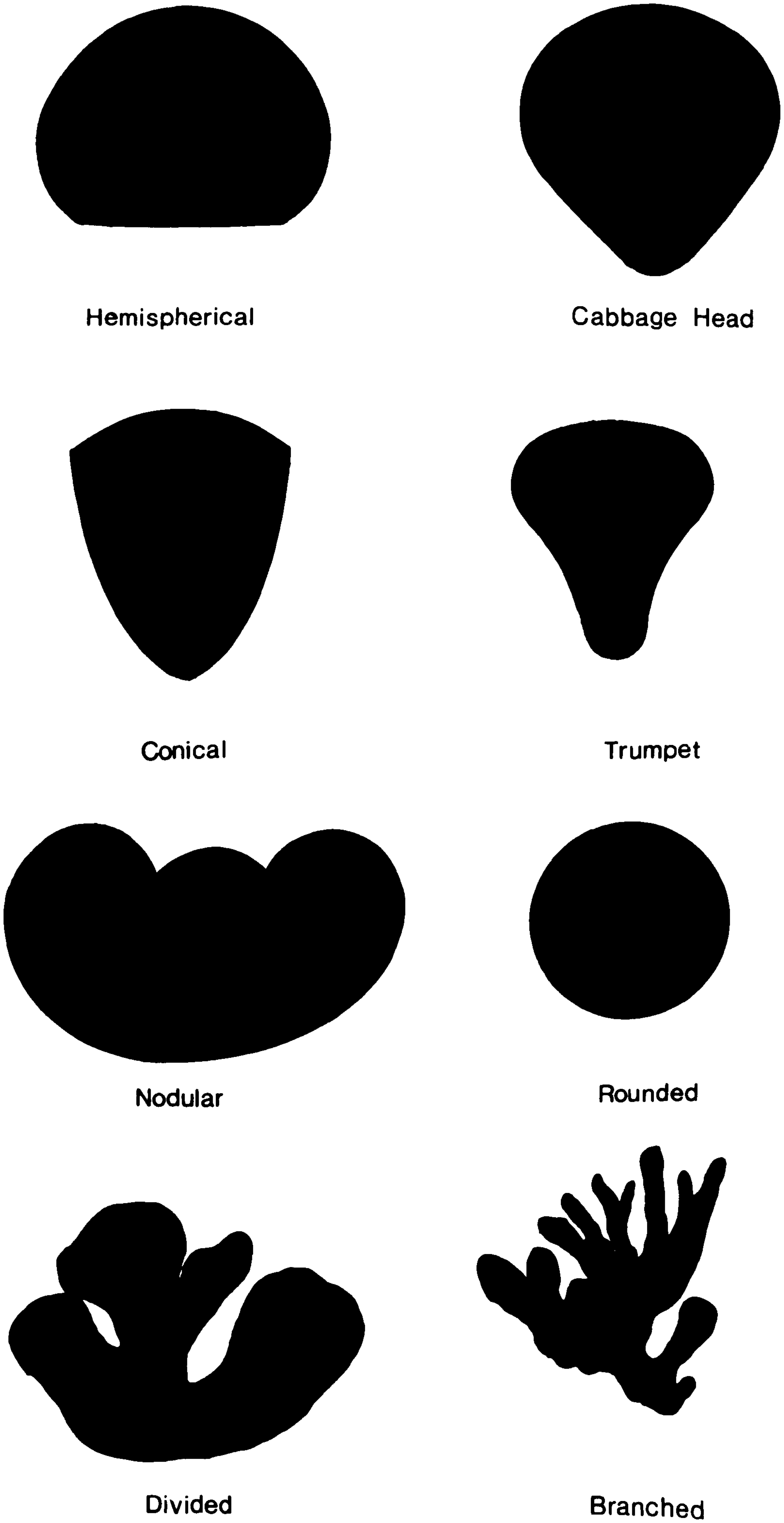
Examples of more than one growth form exhibited by a single coenosteum are not unusual within the reef habitat. They can be most effectively treated by assignation of compound terminology with reference to field observations and plotting each constituent shape separately on the graph (see Fig. III.1).

In view of the complexities involved in determination of coenosteal shape, quantification of size was not attempted. Unlike the Solenopora thalli, stromatoporoid coenostea did not fall into convenient size groups (see below) but were represented by a wide range of heights and lengths. To make divisions into small or large was also regarded as unnecessary and the representation of stromatoporoid size is given in terms of the actual measurements obtained.

Solenopora

A wider variety of shape classes exist within the Solenopora than the stromatoporoids. The typical domical and laminar forms defined above are generally rare, although the corresponding shapes, termed Hemispherical and Laminar can be found. More common are the Cabbage Head, (Inverted) Bell and Trumpet shapes, which are distinguished by the nature of the perimeter opposite the convex surface common to all three (as well as the Hemispherical type). As with stromatoporoids, Spherical and Eliptical shapes are commonly assigned to the term Rounded, but in contrast Divided, and rarely, Branching forms are found. Complication to the basic shape form is achieved by destruction or distortion of the thallus during growth and thus gives rise to Divided or Irregular shape categories. Some of these shapes are illustrated in Fig. III.2. In view of the purely descriptive nature of these shape categories, their variety and complications together with the lack of internal structures reducing the palaeoecological

Fig. III.2 *Solenopora* shape chart


Hemispherical
Cabbage Head
Conical
Trumpet
Nodular
Rounded
Divided
Branched

significance of shape classification, it was decided that any attempt to introduce width/length ratios would only constitute a mathematical exercise yielding no significant results.

However size measurements of Solenopora thalli showed that a very wide range was present from fragments of 0.5 cm. and less to a maximum of 38 or 40 cm. Also it is common, within a given occurrence, for the individuals present to fall into one or two of the size ranges (maximum axis) cited below. In view of this, they became convenient classes to adopt and a descriptive terminology was allotted to them:-

i)	less than 1 cm.	very small (fragments)
ii)	1 to 5 cm	small
iii)	5 to 10 cm	medium
iv)	10 to 20 cm	large
v)	greater than 20 cm	very large.

Another disuading factor from any attempt at quantification of data was the problem of determination of thallus outline in the biohermal occurrences of Solenopora where they are often divided and separated by thin layers of dolomite and/or sediment. This poses the problem of whether one is dealing with a single, divided large thallus, or separate, small individuals, and is well illustrated in Fig. 5.3b as a gradual transition from recogniseable to unrecognisable thallus outline. Despite the reticulation with dolomite, a primary hemispherical Solenopora can be distinguished; this gives rise to a nodular extension which exhibits signs of break up until it apparently becomes a series of scattered smaller thalli. In many respects the situation is analagous to that encountered when attempting to determine packing textures during sedimentological investigations. Correspondingly, an approach regarding the small dolomite or sediment separated Solenopora as being in three dimensional contact (packites) or isolated and matrix supported (wackites) was considered; packite textures would represent a single divided thallus while wackites a series of separate individuals. The limitations of this scheme are obvious, but as an initial guide to thallus determination it was found to have some merit. Similar complex shapes can be seen in Fig.5.3c, where thin bands of apparently included sediment, cause a break up of the thallus into closely spaced, separately defined, smaller units or branched individuals. Field determination of individual Solenopora in both illustrated examples is physically impossible and could only be accomplished by detailed serial sectioning. The scale of such an operation makes it impractical, and only enhances the necessity for a simple, observational classification.

ORIENTATION

Both groups of organism possess a similar pattern of growth (viz. upward and outward from the initial point of colonisation), although recognition of this poses problems in the field. Consequentially a single classification, which is purely descriptive in terms of growth surfaces, is proposed for both stromatoporoids and Solenopora in the Mjøsa Limestone.

Stromatoporoids

In all growth forms the laminae and latilaminae usually grow concentrically away from the base of the coenosteum, giving the impression of a series of hemispheres increasing in radius away from the original point of growth. To facilitate specimen orientation in the sediment, a simple classificatory nomenclature was adopted and is illustrated in Fig. III.3. The proposed terminology allows coenosteal attitude to be described independently of shape or growth direction and overcomes the use of phrases such as "growth position", which as PHILCOX (1971) points out are ambiguous. This is achieved by describing the orientation of the convex (i.e. growth) surface, as convex upward, convex downward or convex sideways.

To illustrate the use of this classification and its possible implications for stromatoporoid palaeoecology, a small pilot study was conducted in the lower stromatoporoid bearing horizon at Eriksrud. Here the stromatoporoids are unique to the non-reef habitat of the Mjøsa Limestone in that they are found in a grainstone rather than micritic mudstone and appear to consist of a series of individual coenstea forming discrete "clumps" of organisms. It is assumed that such a distribution is indicative of an original growth unit on the sea bed.

Many authors e.g. LECOMPTE (1956) and KLOVAN (1964) associate massive stromatoporoids with clean sparry limestones. KLOVAN (ibid) lists six criteria which he considers diagnostic of massive stromatoporoid units. However, only three of these are present in the unit under consideration viz.

i) fragmental remains of other organisms are common in the surrounding sediment.

ii) medium to coarse skeletal grains predominate in stromatoporoid rich rocks.

iii) sparry calcite is often abundant in associated sediments.

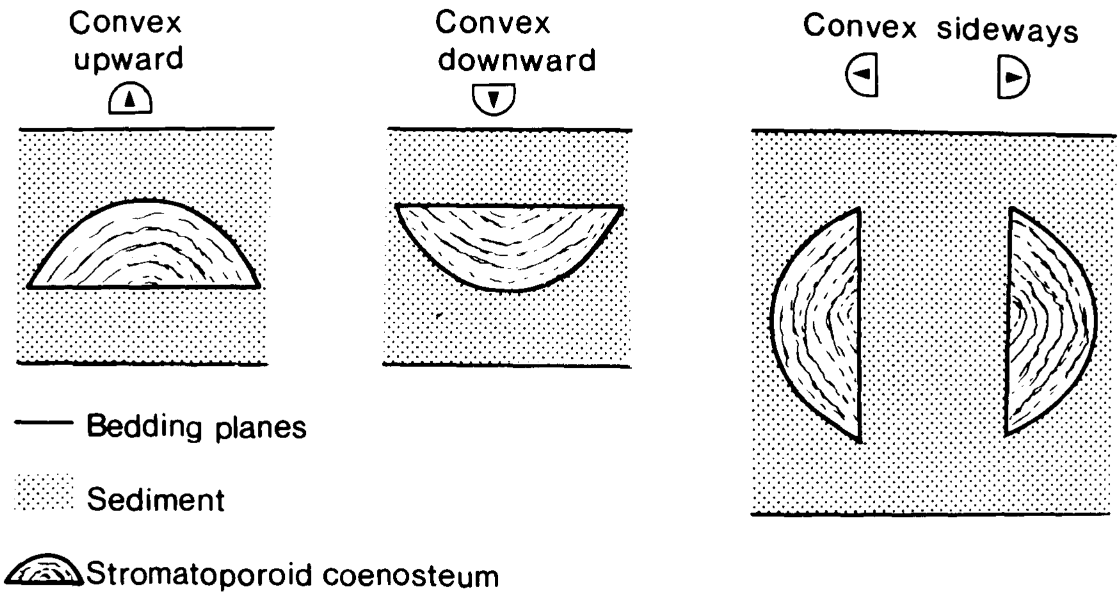
A fourth criteria viz "oncolites are sometimes associated with massive stromatoporoids", may be applicable in a limited sense because the beds underlying the stromatoporoids are rich in oncolites.

The sediment associated with the stromatoporoids is an algal-molluscan peloidal grainstone with particle size ranging from 7 mm to less than 1 mm and composed of Dimorphosiphon Hedstroemia , uncertain molluscan material or phylloid algae with echinoderm,brachiopod and trilobite debris. Grapestone and intraclasts are present, while many peloids and grains in advanced stages of micritisation are present. The lack of micrite indicates a high energy environment (FOLK 1959), although the presence of unbroken long and delicate bioclasts would suggest little transport or reworking of material. However, it is the type of sedimentary environment that most authors would consider as typical and ideal for stromatoporoid growth, and as such is regarded as a useful horizon at which to begin a study of orientation and growth forms.

The results are presented as Fig. III.4. From this it can be seen that domical (and laminar) coenostal forms are confined to convex upward or convex downward attitudes, while the tabular forms are mainly convex sideways. The simplest interpretation of this is that all colonies other than those exhibiting a convex upward attitude had obtained their position either by transportation, or by breakage and subsequent settling in the sediment. However, if the morphology of the coenosteum is considered

Fig. III.3 A simple classification of stromatoporoid orientation

Fig. III.4 Stromatoporoid orientation and shape data; Eriksrud grainstone horizon near base of quarry section.



Convexity \ Sample Site	1	2	3	4	5
Upward	-	5d	1d;1t	2d	2d;1l
Downward	1d	3d	2d	4d	3d
Sideways (right)	-	1t	2t	-	-
Sideways (left)	1t	3t	2t	-	1t

Coenosteum shape; d - domical, t - tubular, l - laminar it is possible to advance other explanations.

If clumps of stromatoporoids, consisting of four or five coenostea are growing together on the sea bed, it is reasonable to assume that some will be in a more favoured position and therefore able to grow faster, better and possibly larger than the others. Such a process would cause the remaining, less favoured stromatoporoids to adapt to a restricted niche, with a morphological reflection of this constraint apparent in the coenosteum. Many specimens within the Bergevika reefs possess shapes which can be attributed to niche restriction by more successful neighbours.

Niche restriction can also be attributed to sedimentation rates, but as demonstrated by PHILCOX (1971) and KAPP (1974) this is mainly effective against single rather than small groups of organisms. The effects of current direction and sediment inclusion within the coenostea has been shown by BROADHURST (1966) to have a marked effect upon the ultimate shape of the stromatoporoid.

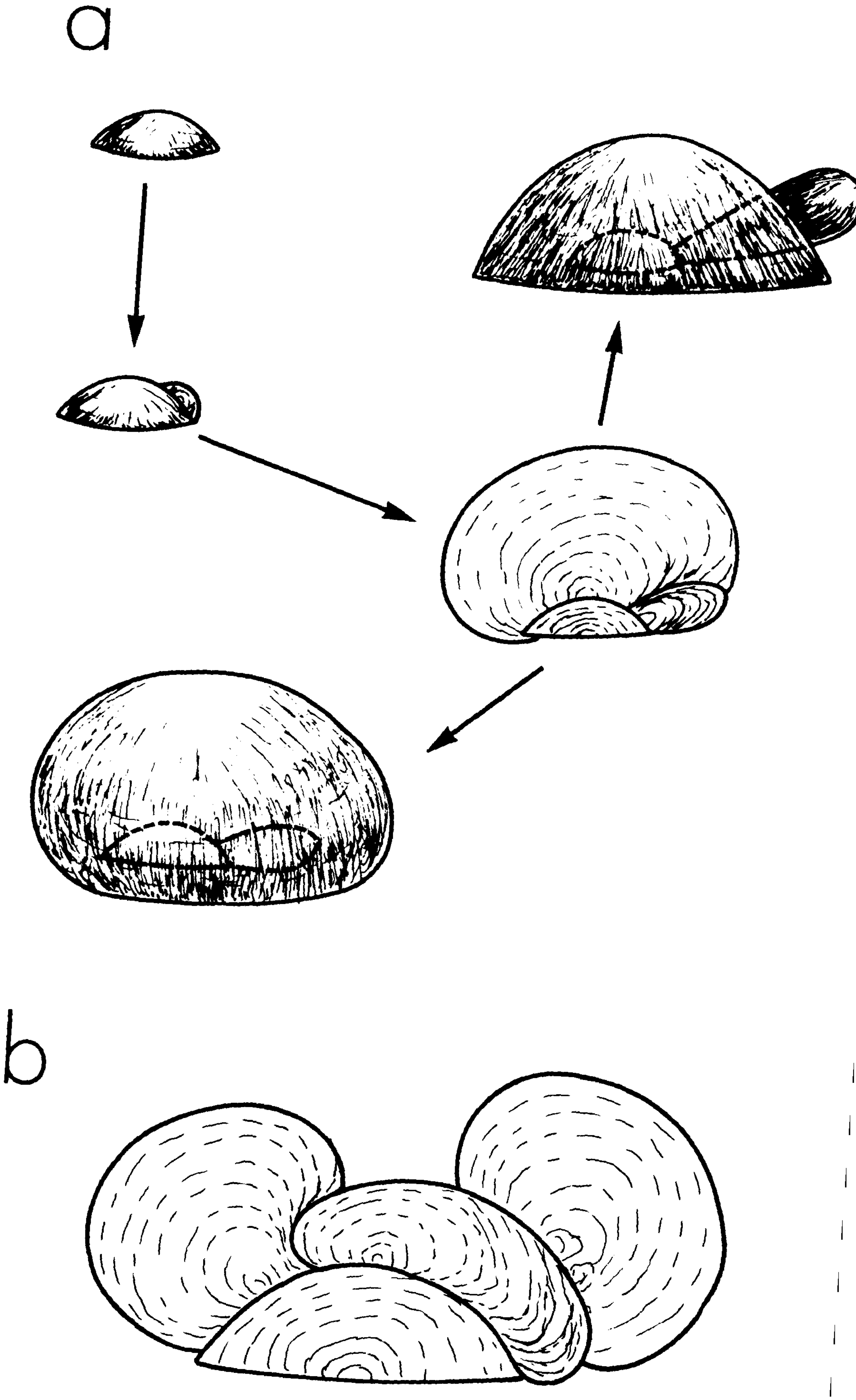
It is apparent from the above discussion that niche restriction by competition with more successful neighbours is more likely to affect the ultimate orientation of a stromatoporoid rather than sedimentological restriction which principally affects the shape. In view of this a series of hypothetical reconstructions which could account for the examples recorded from the Eriksrud horizon are presented in Fig. III.5.

A further possibility is that owing to the two dimensional nature of the exposure, a convex downward coenosteum may be part of an individual in an elevated growth position relative to the substrate. The downward orientation is due to overlapping of this local irregularity in much the same way as the asymmetric stromatoporoids of the Bergevika reefs appear to have grown on the reef front and draped themselves over the slope. In cross section none of the above mentioned draping coenostea would possess an inverted hemispherical cross section, and herein lies a method of distinguishing drifted and non drifted stromatoporoids. Indeed this is found to be the case in the Eriksrud bed, and it is reasonable to assume that the apparently anomalous forms encountered owe their divergence to

Fig. III.5 : Hypothetical stromatoporoid growth patterns. These are based on shape and orientation data collected from Eriksrud Quarry.

(a) stromatoporoid begins life as a single coenosteum, until its virtual demise. Regeneration initially proceeds from one point on the coenosteum. Growth begins from another part and is more successful. This leads to restriction of the less favoured coenosteum which is either forced to adopt a tubular shape or is completely smothered.

(b) three points of regeneration are envisaged with the two outer locations becoming more successful. This forces the inner coenosteum to grow downwards over the original and gives a convex downward orientation for an in situ stromatoporoid.


a
b

niche restrictions by competition rather than drifting.

The purpose of the pilot study was not to propose situations of stromatoporoid growth and orientation but to advocate the use of a simple classification for coenosteal attitude which is independent of implied growth position and simply describes specimen orientation. To obtain meaningful palaeoecological conclusions, the expression of the growth surface orientation as convex upward, downward or sideways, needs to be coupled with a simple morphological classification as well as the attitude of this shape and relationship to neighbouring organisms. Thus the convex downward orientation of isolated, inverted domical forms is more likely to indicate transport from the site of growth than a similar orientation within a closely packed group of coenostea.

Solenopora

The lack of visible internal structures within the Solenopora thallus precludes the employment of such a classificatory scheme as outlined above. Occasionally, however, specimens are encountered which display an incorporation of fine sediment (micrite) into the thallus. Examination with a microscope shows this sediment to run parallel to the growth surfaces, and to represent a 'ghost' growth surface, formed by original settling onto the periphery of a growing Solenopora. From such evidence it is apparent that most Solenopora grew with an arcurate convex upper surface away from the basal perithallus, and that an orientation nomenclature identical with that proposed for stromatoporoids can be employed. In practice it was found that the usefulness of orientation as a palaeoecological parameter, even when employed in conjunction with the other criteria, was limited to those thalli falling into the large or very large size ranges.

FORM

As indicated previously (p. 365) this parameter is applicable to Solenopora only.

Solenopora

Preliminary observations revealed that many of the larger Solenopora appeared to be composed of numerous smaller individuals. This resulted in the adoption of the terms 'solitary' and 'colonial'. Subsequent studies of morphology and internal structure under the microscope revealed that many 'colonial' forms were a complex interrelationship of sediment and organism, produced either by division of a single thallus or by the growth in close proximity of numerous thalli. Even under microscopic analysis distinctions between the two were often impossible to achieve and in view of this, a more general division into 'simple' and 'complex' forms were favoured. 'Simple' forms comprised those Solenopora with sharply defined boundaries clearly indicating one was dealing with a single thallus only. 'Complex' then became a blanket term to encompass all forms whose outlines were less clear and boundaries indistinct.

PERIPHERAL CONDITION

The peripheral morphology of an organism will reflect its dynamic relationship with the surrounding sediment, and in the case of sedentary organisms such as stromatoporoids and Solenopora, hold significance as an additional palaeoecological parameter.

Non drifted stromatoporoids and Solenopora will reflect the delicate balance between sedimentation and growth rates, by the incursion of sediment into the organism or growth of the latter out over the sediment. In this respect, peripheral morphology represents an extension of the general shape determination as presented by BROADHURST (1966), and such instances of periodic sediment incursion indicate a relatively high sedimentation rate. The periods of lower sedimentation rates which are not accompanied by a corresponding increase in growth rate may express themselves in other ways e.g. encrustation by epifauna. Sedentary organisms are open to attack by other organisms seeking food or shelter and a bored periphery has considerable significance.

Drifted organisms with a calcarcous skeleton would undergo abrasion in the normal way of all sedimentary particles, ultimately giving a rounded shape with a smooth periphery.

Four convenient peripheral conditions to consider in conjunction with other palaeoecological parameters are:-

i) Smooth
ii) Ragged
iii) Bored
iv) Encrusted

SUMMARY

The purpose of the preceeding discussion has been to present a set of simple parameters which can be rapidly obtained in the field from two dimensional exposure and be employed to further palaeoecological studies of the organisms in question. The basic parameters considered for both stromatoporoids and Solenopora are:- 'Shape and Size'; 'Orientation'; and'Peripheral Condition' , whilst 'Form' is a useful addition to Solenopora studies.

Nomenclature adopted for stromatoporoid classification is given below, whilst that for Solenopora is presented in Fig. III.6.

Stromatoporoid

i) Shape - Domical; Laminar; Tubular; Rounded.
Size - as measured
ii) Orientation - Convex upward; Convex downward; Convex sideways.
iii) Periphery - Smooth; Ragged; Bored; Encrusted.

Fig. III.6. A rapid field classification of Solenopora.

SIZE	SHAPE	FORM	PERIPHERY
f = very small	H = hemispherical	x = simple	α = smooth
s = small	C = cabbage	y = complex	Γ = ragged
m = medium	B = bell		β = bored
l = large	T = trumpet		δ = encrusted
h = very large	D = divided		
	N = nodular		
	I = irregular		
	S = spherical		
	E = ellipsoidal		
	R = rounded		
	L = laminar		
I	II	III	IV

Classification is achieved by the allocation of the appropriate symbols from columns I to IV. This order is always adhered to. Therefore, a specimen which possessed a 4cm. diameter trumpet shaped, simple formed thallus with a bored margin would be represented as: sT x β

APPENDIX IV.

ALGAE AS CONTRIBUTORS TO THE BUILDUP OF SEDIMENT.

The petrographical and palaeoecological studies undertaken as part of this thesis have revealed that algae, or the products of algal activity, are important constituents of the sediments comprising the bulk of the Mjøsa Limestone. As a prelude to further detailed study, a simple classification of the various contributory roles adopted by algae within the Mjøsa Limestone is presented as Fig.IV.1 and briefly discussed below.

The broad division into a constructive or destructive role is based upon ORME and BROWN'S (1963) concept of grain growth or grain diminution, and involves the production of a new fabric or the destruction of an original grain and its fabric.

In a constructive role algae can contribute to sediment accumulation by building growth structures themselves (e.g. Solenopora bioherms, Hedstroemia biolithites) or by assisting other organisms to do so (e.g. corals; by analogy with the symbiotic relationship in Recent corals). Here the algae are performing in two different ways, firstly as a direct contributor themselves, and secondly by an indirect, although essential, contribution. Similarly, by their sediment trapping properties, stromatolitic algae directly contribute to sediment accumulation in the algal mat facies, and, when eroded, indirectly contribute as intraclasts. Other examples of direct constructive algal contribution are given in Fig. IV.1.

Post-mortem disintegration is considered an indirect constructive role because, although the algae are not actively growing, they are contributing to the sediment by forming an allochemical constituent. Evidence of possible fodinichnia within the Solenopora and analogy with BATHURST'S (1967c) gelatinous algal mat, indicate that algae form an important element to the lower part of the food chain. The fauna which feed upon them make a direct contribution to the sediment and the algae are therefore regarded as acting in an indirect constructive way.

The boring action of endolithic algae leads to the destruction of grains and the initial formation of micrite envelopes (BATHURST, 1966; 1971), prior to complete micritisation to give peloids. Bathurst has also shown that micritisation of the outer walls leads to a general rounding of grain outline by abrasion of the aragorite needles, which themselves would contribute to the accumulating sediment. In a detailed analysis of some Australian (Devonian) algal limestones, WOLF (1965) describes a similar process and also includes corrosion of grains by secreted organic acids. The latter process is regarded as constituting an indirect destructive action in the classification proposed herein (Fig. IV.1).

Complex interactions are bound to strain such a classificatory system, e.g. grapestone formation which requires the presence of a gelatinous algal mat (indirect constructive) to allow boring and micritisation of the grains (direct and indirect destructive) prior to cementation and binding (direct constructive). Despite this, however, the recognition of these various stages and algal roles indicates the value of such a classificatory scheme.

Among the non-calcareous algae, preservation potential is exceedingly low, but even if the original organisms themselves cannot be recognised, their effects on the sediment have often remained. By interpretation of these, a broader picture of the palaeoecological importance of these algae can be made, and another facet added to the interpretation of the depositional environment.

Fig. IV.1 : Algal contribution to the sediments of the Mjøsa Limestone.

ROLE	ACTION	EXAMPLES	
CONSTRUCTIVE	DIRECT	1. Bioherm formation:	algae responsible for buildup e.g. Solenopora.
		2. Stromatolites:	algae act as sediment trappers e.g. algal mats, baffles
		3. Binders:	algae responsible for binding grains or organisms together, e.g. reef pocket dwellers or binders.
		4. Encrusting:	algae enlarge original grains by growth action, e.g. Girvanella oncolites, Hedstroemia.
	INDIRECT	1. Disintegration:	post-mortem breakage gives sedimentary grains of various sizes, e.g. Dimorphosiphon, Solenopora.
		2. Symbiosis:	Indirect contribution to sediment building by association with other organisms, e.g. corals.
		3. Food source:	contribution to the food chain allowing faunal elements to thrive and contribute to the sediment, e.g. algal mat. Solenpora.
DESTRUCTIVE	DIRECT	Boring :	destruction of original grain fabric, e.g. micrite envelopes to peloids.
	INDIRECT	Solution :	secretion of organic acids causes corrosion of grains, e.g. serrated edges of grains beneath algae.

APPENDIX V.

CLASSIFICATION OF ALGAL MAT MICROSTRUCTURES.

Detailed logging of the morphological changes in laminae and interlaminated sediments contained within the algal mat facies of the Mjøsa Limestone revealed that a sequence of mat development could be established (Chapter 3, p. 124). The data which allowed this is presented below.

CLASSIFICATION SCHEME

The algal mats are divided into four main lithological and morphological units together with those of the main lithofacies described in Chapter 3 (i.e. Micritic, Bioclastic and Peloidal facies). For brevity these are assigned a convenient letter and any subdivisions indicated by a suffixed number. Further division is represented by an additional suffixed letter.

1. Dolomite units.

D_1 - dolomite with discrete micrite patches.
D_2 - structureless dolomite.
D_3 - dolomite with faint laminations.

2. Laminated units.

C_1 - thin dolomite laminae (max. 3 mm).
C_{1a} - planar, poorly developed.
C_{1b} - planar, well developed.
C_{1c} - planar, inclined.
C_{1d} - domical.
C_{1e} - planar with vertical spary calcite filled shrinkage cracks.
C_{1f} - planar with 'T' shaped shrinkage cracks.
C_{1g} - wavey laminations.
C_2 - thick dolomite laminae (0.3-1 cm).
C_{2a} - poorly developed, irregular.
C_{2b} - well laminated.
C_3 - discrete laminae (thin) of micrite in dolomite.

3. Broken units.

B_1 - broken thin laminae.

B_2 - broken thick laminae.

B_3 - intraclasts of broken thinly laminated units.

4. Dolomite net units.

A_1 - reticulate/bioturbated structures.

A_2 - fine dolomite net.

A_3 - heavy dolomite net.

A_4 - fine dolomite net attaining a laminar aspect.

5. Micritic units.

M_1 - micrite with dispersed dolomite.

M_2 - dismicrite with dolomite.

M_{2a} - dolomite is laminar in aspect.

M_{2b} - dolomite is scattered.

M_3 - micrite with no dolomite.

6. Other units.

B = Bioclastic grainstone.

P = Peloidal grainstone.

ALGAL MAT CLASSIFICATION

The mats at seven localities were measured in detail and the results presented in the abbreviated style outlined above.

The figures in parentheses refer to the thickness (in cm) of each unit.

Horizontal solid lines indicate the beginning of a mat sequence.

Vertical solid lines indicate that two or more units are incorporated but have gradational boundaries.

Sequences are arranged in chronological order, youngest at the base.

Holetjern 2

- C_{1b} (4)
- C_{1c} (8)
- A_4 (44)
- M_2 (14)

- C_{2b} (5)
- C_{1b} (7)
- D_2 (3)
- C_{1b} (6)
- C_{1b} (3)
- C_{1c} (20)
- A_2 (4)

- C_{2b} (3)
- A_2 (4)

- C_{1b} (13)
- C_{1b} (5)
- C_{1g} (4)
- C_{1b} (2)
- A_4 (3)

- C_{2b} (7)
- M_3 (4)
- A_4 (3)
- A_4 (4)

- D_1 (2)
- A_4 (25)
- A_4+B_3 (2)

- D_1 (33)

Holetjern 3

- C_{1b} (4)
- C_{1a}, A_2 (6)

- D_9, A_2 (4)

- C_{1b}, B_1 (3)
- B_1, C_{1b} (5)
- A_2 (4)

- C_{1b} (14)
- C_{2b} (3)
- C_{1b} (5)
- A_4 (9)
- A_4 (5)

- C_{1b}, A_4 (31)

Holetjern 3

- C_{1b}, C_{1e} (38)
- C_{1b} (5)
- M_2 (3)

- C_{1b} (4)
- M_{2b} (4)

- C_{1b} (6)
- C_{1b} (1)
- A_4 (5)
- L (4)

Holetjern 3

C_{1b}	(20)
C_{1a}	
C_{1b}	
C_{1a}	
C_{1b}	
M	(8)
D	(1)
M	(8)
D	(1)
M	(2)
A_2	(3)
M	(3)

C_{1a}	(8)
P	
A_4	(6)
L	(10)
A_2	

Holetjern 3

$C_{1b}+C_{1d}$	(59)
P	(24)
$P+B_3$	(17.5)

C_{1d}	(9)
A_4	(1.5)
A_2+B_3	(2)

$C_{1b}+C_{1d}$	(5)
C_{1b}	(5)
$P+B_3+A_4$	(24)

Rud

C_{1e}	(3)
C_{1b}	(7)
C_{1f}	(8)
C_{1b}	(9)
B_3	(8)
A_2	(55)

D_2	(22)
C_{1d}	(3)
C_{1b}	(29)
M_1	(24)

Gamme

A_4	(8)
A_2	(20)
———	———
D_1	(6)
D_2	(5)
B_2	(2)
C_{1b}	(19)
A_4+B_1 / A_2	(31)

Eina

A_2	(3)
———	———
C_{1b}	(7)
$C_{1a}+A_3$	(20)
N.E.	(110)
D_2	(70)
A_2 / ——— / B_3	(138)
C_{1b} / A_4	(100)
———	———
C_{1b}	(25)
C_{1a} / C_{2a}	(230)

(N.E. = No exposure)

Kyset 1

D_2	(45)
D_3	(6)
A_2	(3)
———	———
C_3	(3)
B_2	(2)
C_{2a}	(10)
C_{2b}	(2)
C_{1a}	(5)
B_2	(8)
A_4	(6)
———	———
C_{2b}	(3)
C_{2a}	(7)
C_3 / A_4 / A_1	(20)

Kyset 2

D_2	(140)
D_3	(19)
A_2	(34)
C_{2b}	(32)
A_4	(7)
C_{1b}	(7)
B_2	(4)
A_3	(6)
A_1	(40)
A_3	(20)

Kyset 2

D_2	(60)
C_{2b}	(28)
M_1	(5)
C_{1a}	(9)
A_3	(17)
M_1	(13)
A_3	

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