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The Significance of High-Boreal to Subarctic Maerl Deposits in Northern Norway to Reconstruct Holocene Climatic Changes and Sea Level Oscillations

Die Bedeutung hochborealer bis subarktischer Maerlablagerungen Nordnorwegens für die Rekonstruktion holozäner Klimaschwankungen und Meeresspiegelfluktuationen

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KEYWORDS: CORALLINE ALGAE - MAERL - FACIES SUCCESSION - FACIES DISTRIBUTION - ISOSTATIC UPLIFT - CLIMATE - RADIOCARBON - REGRESSION - AGE ESTIMATION – NORWAY - HOLOCENE

CONTENT

SUMMARY

This paper describes (i) the Recent distribution pattern of various types of carbonate sediments in Troms county (northern Norway), and (ii) the onset of carbonate sedimentation after the final deglaciation of the Fennoscandian ice-shield. The distribution of major facies belts is strongly dependent on hydrographic and topographic constraints. The main bulk of carbonate deposits is derived from maerl-producing coralline algal biotopes that are restricted to the photic zone of wave-protected areas and influenced by tidal currents. Furthermore, extended mollusc and echinoderm-rich arenites are present in the area investigated. In deeper subtidal areas, terrigenous sediments of Late Weichselian to Early Holocene age are preserved. However, these are strongly influenced by later winnowing processes, generating a coquina lag deposit that serves as a secondary hardground for a diverse fouling community. The Holocene facies successions can be seen in several raised outcrops, containing the transition from glacigenic to Recent non-glacigenic depositional conditions. Autochthonous radiocarbon dated rhodolith banks, which mark the onset of carbonate sedimentation, yielded surprisingly young ages of 5,500 YBP. Around 5,500 YBP, present-day oceanographic and climatic conditions had already been firmly established. This time-lag can be explained with the behaviour of postglacial sea level fluctuations in the area. From 10,000

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YBP to 6,000 YBP rapid sea level oscillations occurred as a response to compensative movements of the former ice-laden Fennoscandian craton. Since 6,000 YBP, when this dramatic ice-isostatic compensation was finished, more or less uniform elevation rates with minor syngressions at around 5,500 YBP, 4,500 YBP, and younger occurred. We conclude from the known datings that the coralline algae were able to keep pace by forming extensive maerl banks only during periods of retarded sea level displacements, when a syngression compensates crustal uplifting.

ZUSAMMENFASSUNG

In dieser Publikation werden i) rezente Verbreitungsmuster unterschiedlicher Karbonatablagerungen aus dem Bezirk Troms, Nordnorwegen, und ii) der Beginn der Karbonatsedimentation nach dem Abschmelzen des fennoskandischen Eisschildes, beschrieben. Die Verteilung der dominanten Faziesgürtel unterliegen starken hydrographischen und topographischen Steuerungsmechanismen. Der Hauptanteil der Karbonatsedimente wird in Kalkalgenbiotopen gebildet, die auf die photische Zone im wellengeschützten aber gezeitendurchströmten Bereich beschränkt sind. Zudem sind ausgedehnte mollusken- und echinodermenreiche Arenite im Untersuchungsgebiet vorhanden. In größeren Wassertiefen des Subtidals wird der Meeresboden von spätpleistozänen bis jungholozänen terrigenen Sedimenten bedeckt. Diese unterliegen Auswaschungsprozessen, die zur Bildung von Coquina Restsedimentdecken führen. Die sekundär angereicherten Muschelschalen dienen als Hartgründe für diverse Fouling-Gemeinschaften.

Die holozäne litho- und biofazielle Entwicklung läßt sich mit Hilfe einiger über den Meerespiegel gehobener Aufschlüsse erschließen, in welchen der Übergang von glazigenen zu rezenten Ablagerungsbedingungen sichtbar wird. Autochthone Radiokarbon-datierte Rhodolithbänke, die den Beginn der Karbonatsedimentation markieren, erbrachten überraschend junge Alter um 5.500 Jvh. Den heutigen Verhältnissen vergleichbare ozeanographische und klimatologische Bedingungen haben sich um etwa 7.800 Jvh eingestellt. Diese zeitliche Differenz kann mit dem Verhalten nacheiszeitlicher Meeresspiegelfluktuationen im untersuchten Gebiet erklärt werden. Von 10.000 Jvh bis etwa 6.000 Jvh traten rapide Meeresspiegelschwankungen auf, die mit Kompensationsbewegungen des ehedem eisbeladenen Fennoskandischen Schildes verknüpft sind. Seit 6.000 Jvh, als diese dramatischen Ausgleichsbewegungen weitgehend ausklangen, sind betont gleichförmige Hebungsraten zu verzeichnen. Kleinere Syngressionsepisoden um 5.500 Jvh, 4.500 Jvh und jünger kompensierten die Hebungsraten der Kruste, so daß in diesen Perioden Kalkalgen günstige Umweltbedingungen vorfanden und ausgedehnte Maerl Bänke bilden konnten.

1 INTRODUCTION

Since Chave (1967) clearly pointed out that carbonate sedimentation is not restricted to shallow warm-water shelves, several authors have described a number of examples of non-tropical carbonates. A compilation of some comprehensive articles on Recent and fossil non-tropical carbonates is given by Nelson (1988). However, carbonate build-ups and their related deposits from locations above the Polar Circle still seemed to be unusual. Actually, carbonate sediments accumulated as skeletal fragments of various types of biota exist in different settings along the northeastern margin of the Norwegian-Greenland Sea from northern Norway to Svalbard. These carbonate secreting producers are benthonic foraminifers, azooxanthellate corals, serpulid and spirorbid polychaetes, barnacles, bivalves, echinoids, ophiuroids, bryozoans, brachiopods and coralline algae. Locally abundant are sabellarid polychaetes, ostracods, and gastropods, including planktonic forms. All these taxonomic groups are constitutive elements of the 'foramol' lithofacies and are characteristic of non-tropical carbonates (Lees & Buller 1972).

1.1 Purpose of study

The oceanographic conditions, e.g. intrusion of warm Atlantic waters into the high north with the Norwegian Current, and lack of terrigenous sediment supply, facilitates the extensive growth of carbonate secreting organisms. This setting offers a unique opportunity to observe the response of these biota to extreme seasonality in solar radiation and temperature north of the Polar Circle. In addition, the northern shelves also offer the possibility for studying the evolution and ecological succession of communities since the Early Holocene in response to ice sheet retreat from the area investigated at about 10 KY BP (Thomsen & Vorren 1986). The subsequent Holocene climatic evolution from arctic to high-boreal conditions combined with rapid sea level fluctuations is represented by marked sedimentary facies successions, indicating a shift from restricted glaciomarine surface water environments to open marine warm Atlantic water realms. As a result of ice-isostatic uplift of the area during Holocene time, the early carbonate deposits, especially those comprised of coralline algae, were exposed in various terraces. These terraces are still situated close to the modern biotopes and can be easily accessed. In this study we concentrate on the principle distribution and lithofacies patterns of Recent and Holocene maerl and associated carbonate sediments in Troms, northern Norway (Fig. 1). Supported by radiocarbon dated material, a preliminary model of the fate of this type of high-latitude maerl is introduced.

1.2 Previous work

Deposits derived from coralline algae are distributed from arctic to tropical environments (Adey & Macintyre 1973, Bosence 1983b). The Breton term 'maerl' refers to unattached branched or nodular coralline algae and algal gravels, including their deposits. Recent studies have shown that the occurrence of coralline algae on the genus and species level is constrained to narrow ecological conditions, and their occurrence can be used as a tool for reconstructing past environments (Johnson 1962, Adey 1976, Adey & Macintyre 1973, Bosence 1983a,b, Wray 1979, Woel-

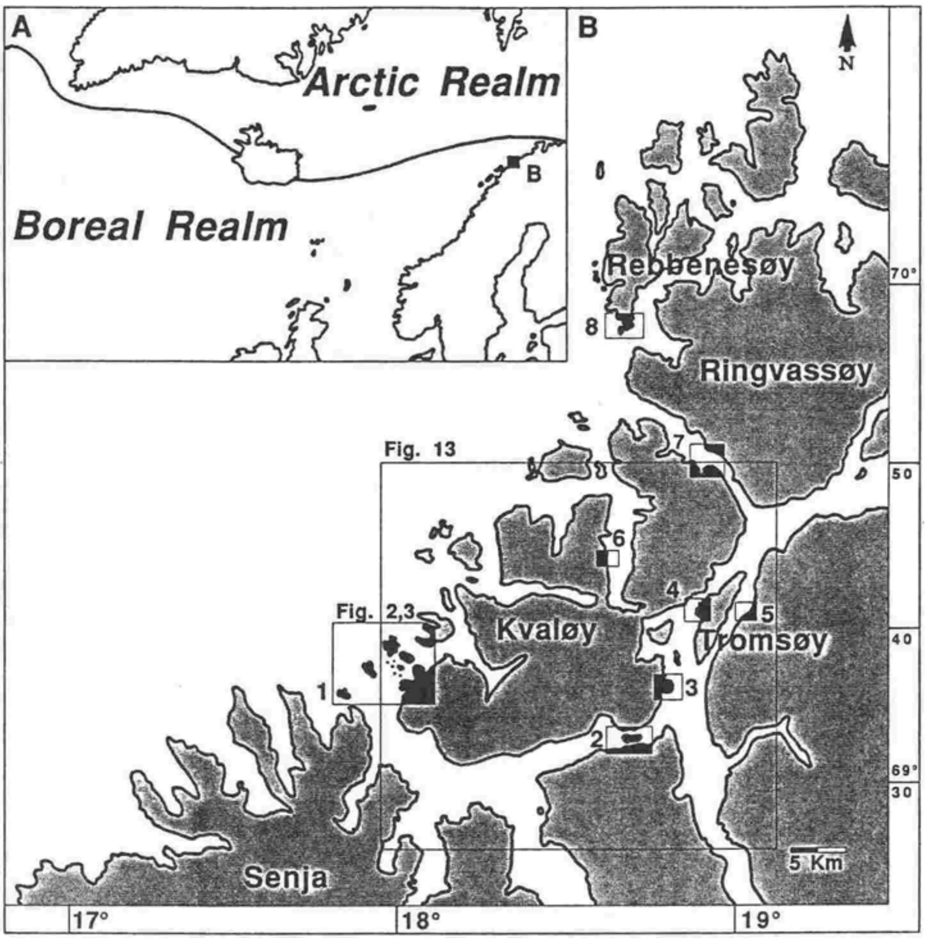

Fig. 1. Location maps. A: The zoogeographical subdivision of the oceanic surface water according to Feyling-Hanssen (1955). The black square marks the area shown in B. B: Western part of Troms county, including the areas investigated:
1) skerry area of Hillesøy, Sommarøy and Edøy;
2) Rya (Rystraumen);
3) Tisnes;
4) Langenes (Sandnessundet);
5) Thomasjordneset (Tromsøysundet);
6) Kaldfjorden;
7) Klubba (Kvalsundet);
8) Måsvik.

Kerling 1985, Moussavian 1989, Dullo et al. 1990). Major maerl-producing coralline algae in the north-western Atlantic are *Lithothamnium corallioides* Crouan and *Phymatolithon calcareum* (Pallas) Adey & McKibbin. Both form extensive banks of rhodoliths at the coast of northern Spain (Adey & McKinbbin 1970), Brittany (Berthois & Guilcher 1959, Cabioch 1966), and western Ireland (Lees et al. 1969, Bosence 1979, 1980). To the north these species are replaced by other rhodolith forming algae that are adapted to high-boreal and subarctic conditions (Adey & Adey 1973). *Lithothamnium glaciale* Kjellmann and *Phymatolithon polymorphum* Foslie are known to form maerl banks mainly in northern Norway (Foslie 1895, Kjellmann 1883). Apart from some localities near Christiansund (Sneli 1968), the occurrence of extensive maerl beds along the coast of southern Norway seems to be very restricted. *Lithothamnium glaciale* is partly replaced by *Lithothamnium tophiforme* Unger in arctic waters (Adey 1971, Adey & Adey 1973). Surprisingly, extensive localities covered with rhodoliths with diameters from 10 to 20 cm were recorded by Kjellmann (1883) from Mosselbukta, northern Svalbard (close to 80° N), and from Novaya Zemlya, Barents Sea.

Facies analysis of maerl deposits have been carried out in detail by Bosence (1977, 1979, 1980) and Gunatilaka (1977) from Mannin Bay, western Ireland. Based on field mapping, Bosence (1980) differentiated five facies belts that contain coralline algae and proposed a generalized facies model for these maerl-type deposits. Three of his facies-terms are adopted in this work. Generally, the diachronous evolution of these maerl deposits in Mannin Bay reflects a strong control by increase in topographic differentiation of a transgressive rocky coast which is void of terrigenous input. Additional case studies on maerl deposits in north-western Europe are known from the Malin Sea (Pendlebury & Dobson 1976) and on the northern and western Scotland shelf (Farrow et al. 1978, Scoffin 1988). In addition, extended deposits of the articulated *Corallina officinalis* are known from several localities along the western Swedish coast of Bohuslän (Hessland 1942, 1943). Maerl deposits in northern Norway have only been treated by geologists marginally. Maerl deposits that were misinterpreted as serpulid remains have been described from the vicinity of Harstadt, south of Tromsø (Gärtner 1958). Here the deposits originally fringed the sheltered flanks of skerries. They now are situated in an uplifted position of 12 m above mean tide level (a.m.t.l.) in terraces. Wrage (1937) described maerl sediments from tidal flats of the outer Ofotfjord near Narvik.

Investigation on carbonate production rates by coralline algae in boreal realms are relatively scarce. The mean annual marginal extension of the epilithic *Lithophyllum incrustans* Philippi is 2.875 mm (Edyvean & Ford 1987). Bank forming rhodoliths of the maerl species *Lithothamnium corallioides* and *Phymatolithon calcareum* accumulate up to 422 g $CaCO_3$ m^{-2} yr (Bosence 1980). Thus the accumulation rate can be as high as the accumulation rates in the *Thalassia-Penicillus* zone of tropical lagoonal environments (Bosence 1980). The

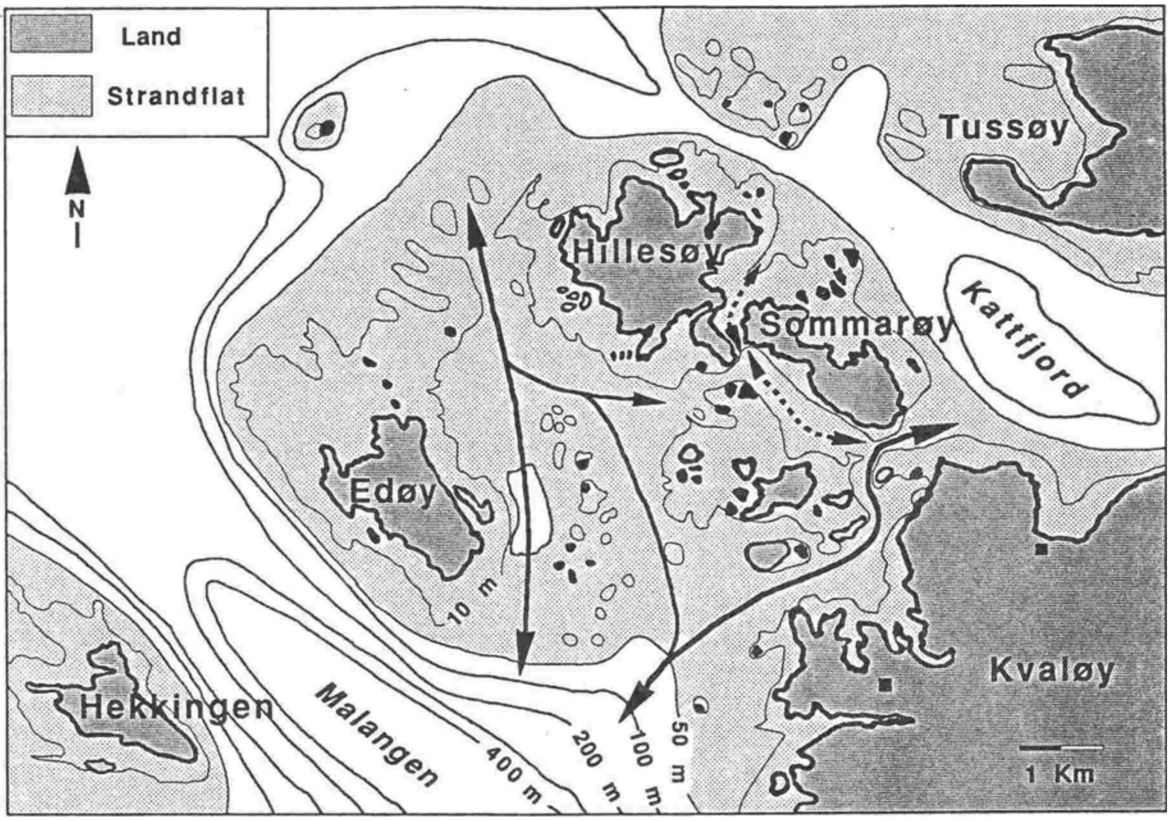

Fig. 2. Bathymetry and hydrography of the skerry area (= Location 1 in Fig. 1). The strandflat (0 to approx. 50 m water depth) is dissected by fjord troughs. The main tracklines of the shifting tidal currents are indicated by arrows. Black arrows mark strong current activity and weak current activity is given by dotted arrows. The evaluation of current force is deduced from the sedimentary facies (see Fig. 5).

yearly increase of growth layers of two coralline algae from Ria de Vigo, northern Spain, has been determined as 0.105 mm and 0.486 mm, for *L. corallioides* and *P. calcareum* respectively (Adey & McKibbin 1970). This is up to an order of magnitude lower compared to production rates of tropical coralline algae (Stearn et al. 1977). Field data for growth rates from high-boreal to subarctic coralline algae are known from *Clathromorphum circumscriptum* Foslie and *C. compactum* Rosenvinge from the Gulf of Maine, with marginal extension rates of 3 mm/yr and 0.23 - 0.33 mm/yr respectively (Adey 1970). The latter is not found in Norway. Highest daily growth rates of coralline algae from Troms have been measured in *Lithothamnium glaciale* and *Phymatolithon polymorphum* under laboratory conditions (Adey 1970). The maximum daily increment was 13 µm/day and 15 µm/day, for *L. glaciale* and *P. polymorphum* respectively. Both are the major rhodolith contributing coralline algae in the boreal-subarctic realm.

2 REGIONAL SETTING & METHODS

The area of maerl biotopes and deposits studied is situated well beyond the Polar Circle at 69°35'N to 70°11'N. Pronounced seasonality triggered by changes in solar radiation is observed. The intensity of solar radiation shifts from total winter darkness (late November to mid-January) to midnight sun conditions (late May to mid-July). Due to the influence of the northward-flowing and relatively warm Atlantic water masses, the climatic regime of Troms is humid-temperate with a mean annual temperature of 2.3°C. The warmest month is July with 12°C, and the coldest is February with -5°C.

2.1 Morphologic and geologic setting

The western part of Troms and the inner shelf off Troms is underlain by metamorphosed Cambro-Silurian rocks that were folded during Caledonian orogeny and uplifted in Tertiary times as part of rifting processes that led to the opening of the Norwegian-Greenland Sea. Cyclic fluctuations in orbital parameters caused drastic climatic shifts that correspond to glacial-interglacial sedimentary cycles during the past 2.56 Ma in the Norwegian-Greenland Sea, bearing evidence for a repetitive waxing and waning of large ice sheets on the Fennoscandian Shield (Henrich 1989, 1990, Vorren et al. 1989). Due to the abrasive activities of the glaciers, Troms county is dissected into fjords and sounds, as well as into mountainous peninsulas and islands (Fig. 1). The summits of the mountain ranges can reach up to 1.500 m, some are still covered by small glaciers today. In sharp morphological contrast, the western flanks of some mountainous islands are fringed by small islets and numerous skerries and shoals (Pl. 80/1), where most of the maerl deposits are located. The submarine morphology of the skerry area is also relatively flat and shallow, with smooth surface contours that are dissected by shallow channels and

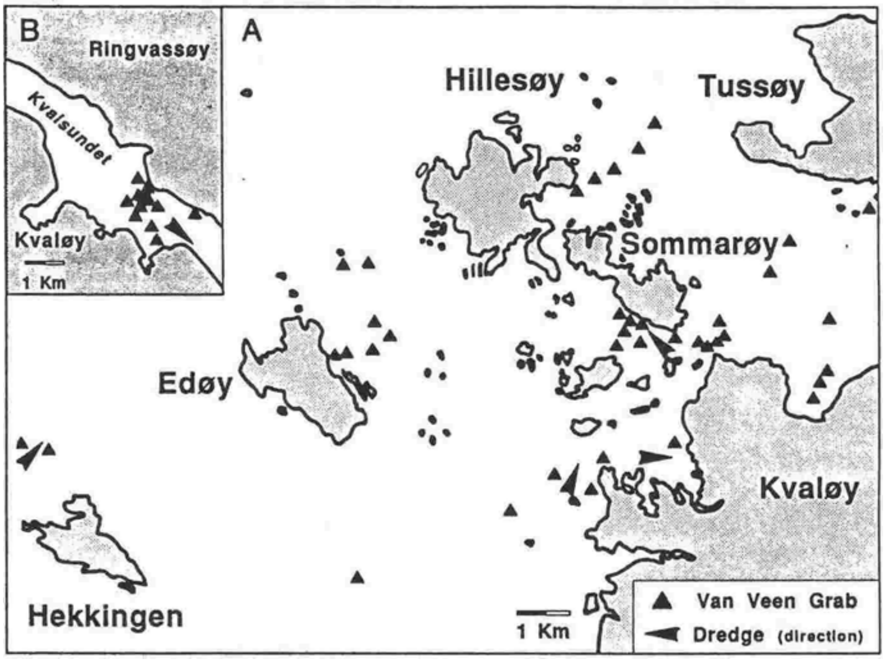

Fig. 3. Shipboard sampling stations in the skerry area (A; location 1 in Fig. 1) and in Kvalsundet (B; location 7 in Fig. 1).

small troughs with water depths not exceeding 60 m. The platform that fringes the islet and skerry area in front of the mountainous islands is known as strandflat (Evers 1962, Holtedahl 1962) (Fig. 2). The typical glacially sculptured morphological features continue onto the outer shelf (Andersen 1968, Rokoengen et al. 1977, Dekko & Rokoengen 1980, Vorren et al. 1983).

2.2 Hydrographic and oceanographic setting

The oceanographic conditions on the shelf off Troms are determined by two northward flowing current regimes, the Norwegian Current (NC), with salinities >35 ppt and the Norwegian Coastal Current (NCC), with salinities ranging from 27 to 34 ppt (Soot-Ryen 1934). In a westward thinning wedge, the NCC overlies the more saline Atlantic water masses of the NC (Sætre & Ljøen 1972). More information on the surface water current regime is given by Eide (1978) and Sundby (1983). The hydrographic conditions in the skerry and islet area studied are determined by the NCC mixing with fresh water run-off from the melt-water discharge during the summer period. This can reduce the salinity to 25 ppt in surface water layers (Soot-Ryen 1934, Sælen 1950). The mean tidal range measured close to Tromsøy is 1.78 m, the maximum range is 2.93 m (Sætre 1972). Due to this range violent currents with several knots of velocity can occur between the skerries and islets having a strong imprint on maerl facies distribution. These tidal currents can change their direction at different times (Soot-Ryen 1934). As evidenced by the distribution of current affected types of sediments, the main pathways of stronger and weaker tidal currents can be deduced in the skerry area studied (Fig. 2). The hydrographic conditions of the sounds and of the fjords, differ markedly from that of the open seas. Thresholds at the narrowest parts of Rystraumen near Rya and east and west of Tromsøy with minimum water depths of 55 m, 8 m, and 9 m, respectively, restrict water exchange. However, tidal currents are very strong in the areas mentioned above. In the Tromsøysundet current velocities of up to 168 cm/s were measured (Sætre 1972). The net transport of water in the Rystraumen - Tromsøy area is directed northward. Main bulk of water transport passes Tromsøy through Sandnessundet (Eilertsen et al. 1981) with water temperatures ranging from 1°C to 12°C in February and August respectively. Within the same period salinity varies from 33 ppt in February to 29 ppt in August.

2.3 Methods

Several transects selected from specific bathymetric features seen in the nautical maps of the area, beginning in the shallow subtidal and ending in fjord troughs, give evidence of the bathymetric setting. The distribution of different sedimentary facies was evaluated from 65 grab sampling stations (Van Veen Grab) and 6 dredge stations (Triangle dredge) (Fig. 3). The sediments were photographed, described and stored in plastic bags. Living floral and faunal elements were preserved with ethanol and/or with formaline after determination. Field mapping of selected areas of tidal flats was carried out on Avløysbukta (Hillesøy), Sandvik (Kvaløy), Klubba (Kvalsundet) and Måsvik (Rebbenesøy). Based on these data, a facies map was drawn which provides information on the spatial distribution and the sampling points of different intertidal facies. The samples were either collected from the surface or as short core sections. Raised Holocene terraces and beach ridges were levelled and the different niveaus were mapped in the region of Hillesøy, Sommarøy and Brensholmen. Roadcuts and coastal exposures at Thomasjordneset, Tisnes and Langenes on Tromsøy were measured, described and sampled at selected levels.

All samples were stored at 4°C. Floral and faunal elements were studied under the binocular microscope and the scanning electron microscope (SEM). The taxonomical study on crustose corallinaceans is still in progress. The sediment was washed, weighed and wet-sieved to gain an overview on the general grain-size distribution. The carbonate content of some selected homogenized samples was measured with a LECO CNS 125 carbonate analyser.

Radiocarbon datings were performed on a number of carbonate samples that were considered to be of Holocene origin (Tab. 1). The radiocarbon dated material is derived from bivalves and coralline algae found in life position. They were dated at the Radiocarbon Laboratory of the Kiel University. The calculated ages given in years BP (BP = before present = before AD 1950) are based on the conventional radiocarbon age (half-life 5,568 years and recent

Tab. 1. C^{14}-dated autochthonous rhodolithes and bivalves. The C^{14} age is corrected for $\delta^{13}C$ = -25 ppt. 400 years are subtracted as 'milieu-effect'.

Sample No.	Object	Locality	$\delta^{13}C$	C^{14}-age	Position (in m above mean tide level)
KI-3246.04	*Astarte borealis*	Tromsøy Profile II	+1.48	4.230±65	+5.19 m
KI-3246.05	Rhodolith	Tromsøy Profile II	- 3.55	5.520±80	+4.15 m
KI-3247.02	*Mya truncata*	Avløysbukta (Hillesøy)	+1.56	4.340±80	- 0.20 m
KI-3248	*Mya truncata*	Tisnes	+0.91	9.100±90	+0.45 m
KI-3249.01	*M. modiolus*	Måsvik (Rebbenesøy)	+0.04	4.450±70	0.00 m
KI-3249.02	Rhodolith	Måsvik (Rebbenesøy)	- 3.39	4.530±75	- 0.15 m
KI-3250 (Rec.)	Rhodolith	E' of Sommarøy	- 0.45	(103.93±0.44)%	10-11 m water depth (!)
KI-3251	Rhodolith	Avløysbukta (Hillesøy)	- 3.76	5.450±60	- 0.50 m
KI-3252 (Rec.)	*M. modiolus*	Rystraumen	+0.56	(96.6±0.5)%	18-26 m water depth (!)

activity at all times equal to the standard recent value). The ages are normalized to $\delta^{13}C$ = -25 ppt according to $T_{corr} = T + 16(\delta^{13}C + 25)$. A 'milieu-effect' of 400 years is subtracted assuming the recent activity in the surface layer of the sea to be 5% less than in wood or terrestrial plants (see also MANGERUD & GULLIKSEN 1975, WILLKOMM 1976). Only for samples with atomic bomb effect this correction was not made.

3 RESULTS

Fragments of coralline algae are the most prominent contributors to the budget of Recent carbonate deposits in the coastal areas of Troms. Subtidal maerl deposits, ranging from 2 m to 52 m water depth are located in wave-protected environments in the strandflat area of the skerries. Maerl is also found in sounds of the island belt of Troms, e.g. in Kvalsundet and Rystraumen. Additional important macrocarbonate skeletons are bivalves and, to a lesser degree, gastropods, scaphopods, barnacles, serpulids, and brachiopods. Sand and silt fraction carbonate constituents include fragments of above mentioned biogenics. In addition, abundant benthonic foraminifers, common echinoderm fragments, and rare ostracods and pieces of disarticulated cyclostome bryozoans are present. Maerl type deposits in the area studied were piled up locally during the Holocene to a thickness of 6 m to 9 m.

3.1 Impact of hydrodynamic and topographic conditions on major facies belts

Eight distinct sedimentary facies belts have been mapped in Troms. The texture, composition, and distribution of the sediments indicate that local hydrographic and topographic conditions are the major constraints during growth, destruction, and redeposition of maerl type carbonates. The submarine topography of the skerry landscape in the surroundings of Hillesøy, Sommarøy, and Edøy reflects all the typical features of a strandflat plain that fringes the coastlines in several bathymetric niveaus from 10 m down to approximately 50 m water depth (Fig. 2). The strandflat system is surrounded by main fjord troughs which slope down to water depths of 100 m to 412 m and also by the transversal troughs on the inner shelf. Small-scaled glacially eroded and now drowned channel systems are major internal features of the strandflats. This submarine setting is influenced by two major hydrographic forces, the open ocean waves and the tidal current regime. The waves are most effective on the exposed western flanks of the skerry zone and also on specific relatively unprotected sectors of the inner skerry zone, e.g. the subtidal flank of Edøy. The sheltered areas of the inner skerry zone are predominantly influenced by the tidal current regime. A similar configuration is found in the sound areas, e.g. Kvalsundet and Rystaumen. The principle

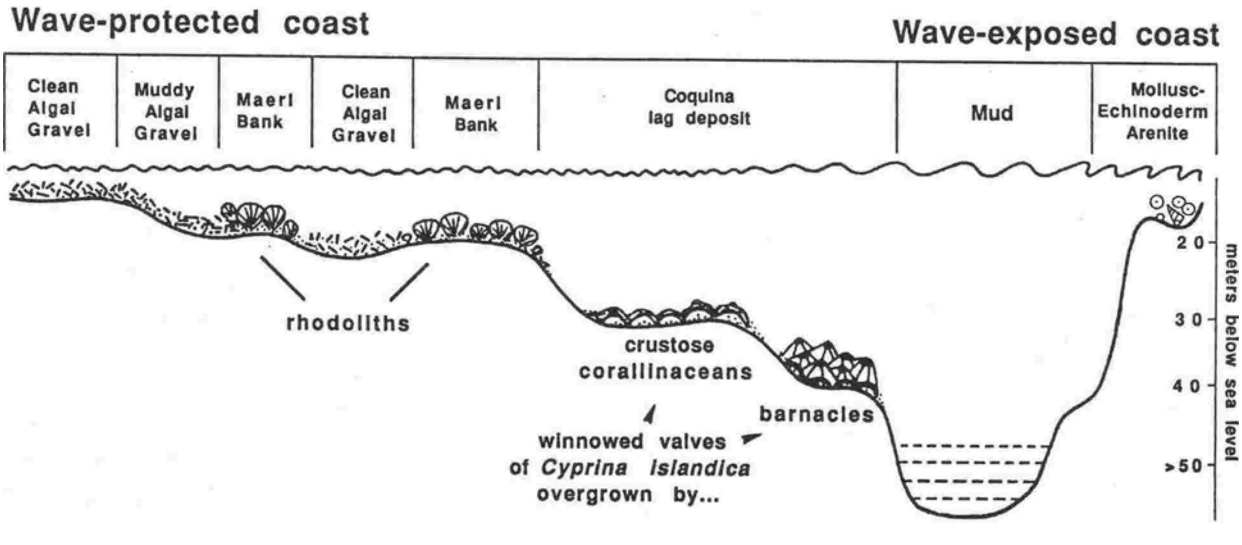

Fig. 4. Idealized profile of a glacially sculptured strandflat and fjord topography with major sedimentary facies belts. The overgrowth of the winnowed valves of the coquina lag deposit facies depends on position relative to the lower boundary of the photic zone (during summer).

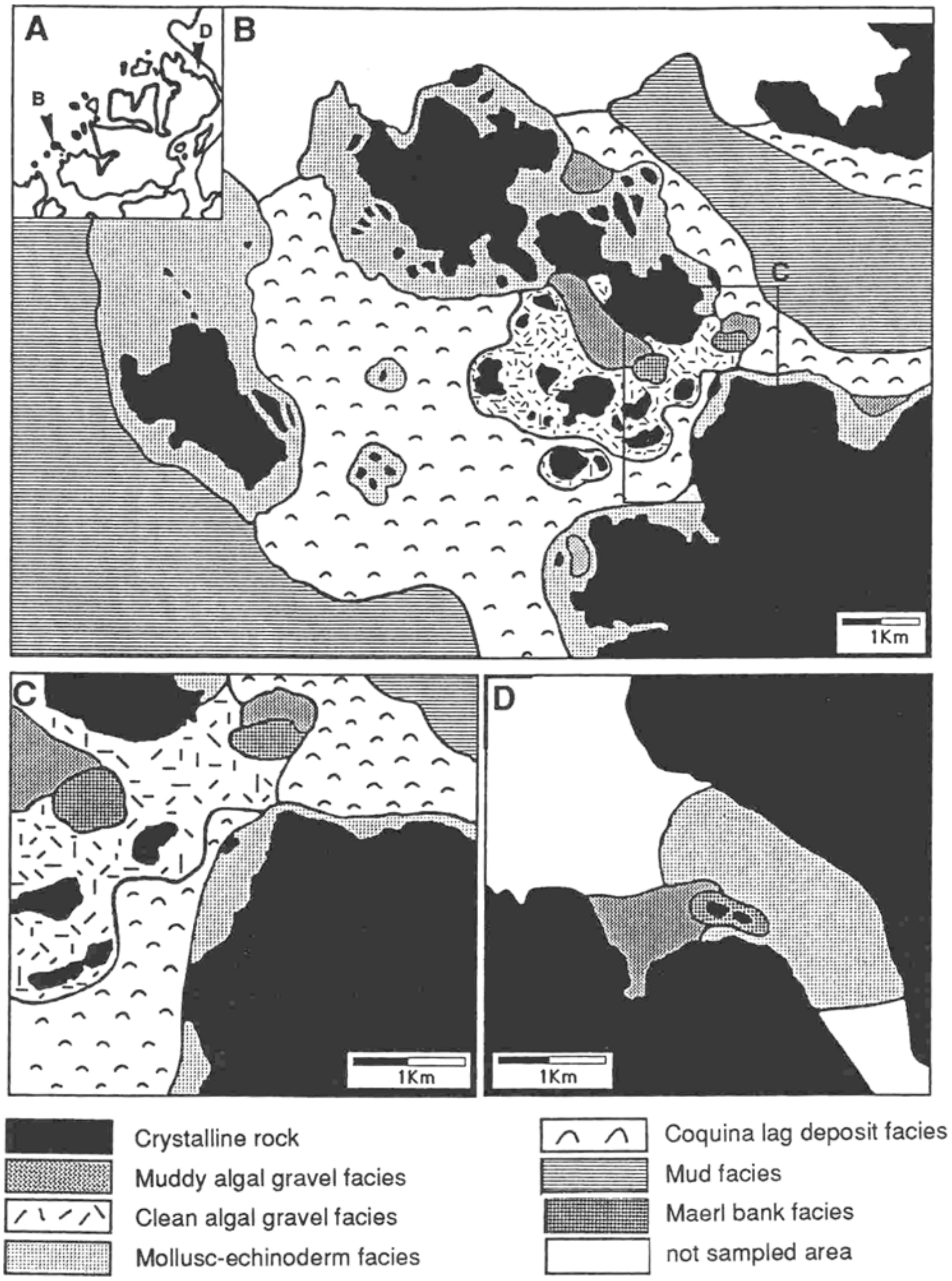

Fig. 5. Distribution of different sedimentary facies in the skerry and Kvalsundet areas. A) Sketch map of the selected areas studied. B) Facies belts in the skerry area. C) Enlargement of the sound channel between Sommarøy and Brensholmen, where all major facies belts are present. D) Facies belts in Kvalsundet. The intertidal sand and gravel facies as well as the *Corallina*-gastropod rudite facies are not indicated, because of their small-dimensioned occurrences.

vertical facies succession and the spatial distribution in the subtidal zone is shown in figures 4 and 5a-d respectively. The recognized different sedimentary facies are listed below:

The maerl bank facies developed on flanks and shoals that are not affected by vigorous tidal currents, but which still reveal moderately agitated current regimes (Fig. 5b-d, Pl. 80/2). On shoals and tidal flats in the surroundings of the maerl bank facies, wide extended areas are covered by parautochthonous to allochthonous clean algal gravel facies (Pl. 80/5). The muddy algal gravel facies is developed in sounds and embayments that are weakly influenced by tidal currents (Pl. 80/4). The descriptive terms of the maerl dominated sediment types are introduced by BOSENCE (1980). The mollusc-echinoderm arenite facies is established in wave-affected areas, e.g. east of Edøy, as well as in almost completely wave-protected areas, e.g. the Sandvik bay, and the outer shallow subtidal zone east of Avløysbukta on Hillesøy (Fig. 5b, Pl. 83/9). Temporary beach deposits lying as a thin veneer on the semi wave-exposed rocks comprise the *Corallina*-gastropod rudite facies, e.g. at Jevik on Hillesøy (Pl. 80/6 and 84/10). Depositional features of the intertidal sand and gravel facies of the protected inlets are controlled by small-scaled tidal currents. Different sediment components are supplied from the surrounding facies belts and are uncovered by tidal scour from terraces flanking the tidal flats. The coquina lag deposit facies predominantly occurs in channels of the inner skerry zone that are affected by strong tidal bottom currents (Pl. 81/6). Another important feature of this facies is that it is only found at water depths below the zone of luxuriant growth of coralline algae (Fig. 5b, c). A pure mud facies is deposited in the deeper fjord troughs, e.g. the Kattfjord Trough and the Malangen Trough (Fig. 5b, c).

The spatial facies distribution of the Kvalsundet fjord shoulders resembles that of the skerry zone. However, a clean algal gravel facies and a coquina lag deposit facies are lacking there. The bathymetric setting differs from sound to sound and, the facies belts may also differ. As an example, a specific *Sabellaria* facies was found on the deep flank of Rya in the Rystraumen. In the semi-protected shallow and deeper subtidal zones of outer fjords and sounds, different hardrock biota encrusted outcropping crystalline rocks as well as cobbles and boulders. Dense populations of the pectinid *Chlamys islandica* forming extended shell beds are known from several locations in Troms.

3.1.1 The autochthonous maerl bank facies

The autochthonous maerl bank facies consists of predominantly living unattached coralline algae which form a semi-rigid carpet of rhodoliths (Pl. 80/2). Two rather narrow depth intervals are occupied by the dense maerl bank communities (9 to 12 m and 17 to 20 m water depth). The hydrodynamic environments of the maerl bank facies reflects a permanent influence of tidal currents of intermediate strength. These conditions prevail on the higher flanks near the entrance of sound channels and as a belt fringing the flanks of shoaling mamillated rock grounds (Fig. 5c, d). Both principal environmental settings can be developed in the inner wave-protected skerry zone as well as in sounds in the island belt of northern Norway.

The banks lie parallel to the main current direction and can reach a length of several tens of meters and a width of three to six meters. In the skerry zone the maerl bank facies laterally grades into the muddy algal gravel facies or the clean algal gravel facies. In the Kvalsundet fjord environment, the maerl bank facies is completely rimmed by the muddy algal gravel facies. The shapes of the thalli vary from ellipsoidal to spheroidal. The apices of the spheroidal rhodoliths are often abraded and thus give evidence of rolling movements on the ground during nodule growth. Discoidal shapes have only been rarely observed. Another rhodolith type is irregularly shaped, forming internal caves or cryptic habitats (Pl. 80/3). The rhodoliths are open branched or densely branched.

Bivalves are the most prominent biogenic admixtures that have been incorporated in maerl deposits, e.g. single valves of *Mya truncata, Astarte sp., Modiolus modiolus* and *Cyprina islandica*. Most of them are overgrown by encrusting coralline algae (Pl. 83/4). Almost all rhodoliths exceeding a size of 5 cm reveal one or more borings by *Hiatella arctica.*

Comparing all sites of autochthonous maerl bank facies, the differences in the faunal and floral assemblages can be attributed to bathymetry (as a function of light penetration into water column). A much broader spectrum of growth forms and species seems to be present in the Kvalsundet fjord environment. Rhodoliths in the skerry zone comprise mainly open-branched growth forms developed by only a single, not yet taxionomically determined, species (Pl. 83/3). In contrast, densely branched (Pl. 83/2) and nodular forms appear (Pl. 83/1) at Kvalsundet in water depths more than 15 m. At both localities, the associated flora and fauna reveal a much higher diversity in water depths greater than 15 m. This holds true for hydrozoans, bryozoans, brachiopods, bivalves and encrusting coralline algae together with filamentous red algae. *Corallina officinalis* only appears in maerl bank facies shallower than 10 m.

3.1.2 The autochthonous muddy algal gravel facies

The muddy algal gravel facies is composed of abraded algal gravel in a matrix of muddy sand (Pl. 80/4). It occurs in sheltered positions from 6 m in the shallow subtidal down to 52 m. The main distribution area is located in a shallow sound between Sommarøy and the skerries around the island of Lille Sommarøy (Fig. 5b). This sound is not strongly affected by shifting tidal currents (Fig. 2), since the main water transport by tidal currents is forced along the coastline of Kvaløy. Beside this rather extended muddy algal gravel facies outcrop, isolated patches of muddy algal gravel facies occur in the lower part of the deeper strandflat. The algal debris and the bivalve shells (e.g. most abundant *Mya truncata*) of these localities are iron-stained and show a pitted surface, indicating a relatively long period of exposure at the sea floor. We assume this algal gravel was derived from the higher positioned maerl bank facies in the region. In Kvalsundet the muddy algal gravel facies is concentrated in areas affected by medium current activity (Fig. 5d).

The coarse carbonate fraction (>2 mm) of the muddy algal gravel facies consists of coralline algae (>80%) and mollusc debris (<18%). The algal material consists either of abraded branches of dead rhodoliths or of intact living small open branched rhodoliths. The boundary between the autochthonous muddy algal gravel and the maerl bank facies is not distinct. Epifauna within the muddy algal gravel facies grows only on the maerl fragments and rhodoliths. The floral and faunal elements are equal as in the maerl bank facies, but are rarer.

3.1.3 The parautochthonous clean algal gravel facies

The clean algal gravel facies is distributed along the flanks and the bottoms of shallow sound channels in the skerry zone affected by strong tidal currents. Additionally, the sediments of this facies fringe the intertidal to shallow subtidal flanks of the inner skerries, forming elongated gravel bars and tombolas. The sediment of the clean algal gravel facies consists predominantly of abraded branches of rhodoliths (Pl. 80/5 and Pl. 83/11). Megaripples with wave lengths of 2 to 3 m and heights of approximately 0.5 m created by strong tidal currents are commonly found in the sound channels. In the skerry zone, the clean algal gravel facies covers areas close to the maerl bank facies or to the muddy algal gravel facies (Fig. 5b, c).

At Leirstrand on Rebbenesøy, beach ridge systems with a maximum heigth of 1.50 m and a 15 m long luv zone have accumulated. The beach ridge is built up by alternating

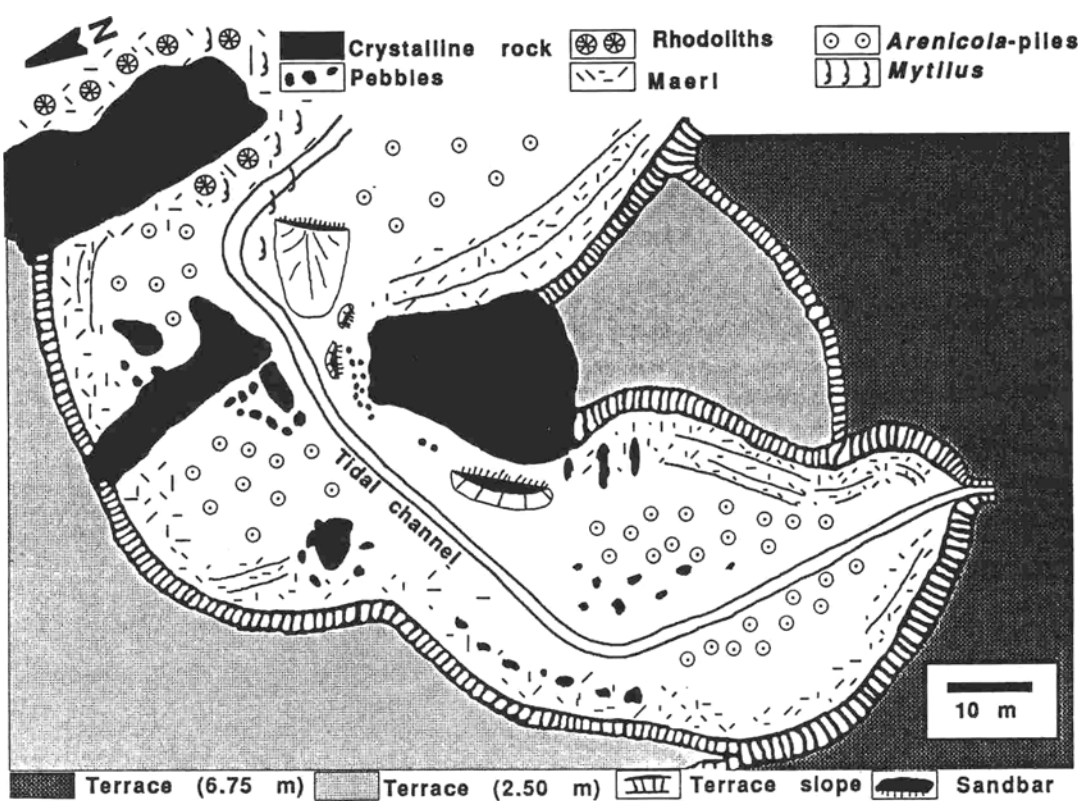

Fig. 6. The tidal inlet of Avløysbukta on Hillesøy, showing intertidal sand and gravel facies with characteristic sedimentary structures. This area reveals a specific mode of redeposition of winnowed Holocene rhodoliths by kelp-rafting (cf. Fig. 12). (m.a.m.t.l. = meters above mean tide level)

layers of maerl (Pl. 83/11) and bivalve-rich horizons with occasional intercalations of terrigenous sediments.

3.1.4 The mollusc-echinoderm arenite facies

The mollusc-echinoderm arenite facies is found at the exposed habitats of the shallow subtidal zone along the eastern coastline of Edøy, ranging from 7 m to 11 m water depth. This facies definitely has a much larger distribution around the shallowest areas of the strandflats that fringe the skerries (Fig. 5b). Additionally, the mollusc-echinoderm arenite facies cover wide areas at semi-sheltered locations, where living conditions for coralline algae are not favorable because of insufficient water motion (algal borers and grazers prefer quiet water conditions (Akpan & Farrow (1985)) and too increased light penetration, e.g. on the outer intertidal flat east of Hillesøy. In Kvalsundet this facies has been found in areas affected by strong tidal currents (Fig. 5d). The carbonate content derives mainly from bivalve fragments and disarticulated echinoderm skeletons (Pl. 83/9). Maerl is only rarely admixed into this facies. Since the supply of terrigenous components is shut off in the Recent environments, the biogenic components gain greater importance in sediment composition. The mollusc-echinoderm arenite facies grades laterally into several other facies: the muddy algal gravel facies, the coquina lag deposit facies and the intertidal sand and gravel facies.

The Mollusc-Echinoderm facies of the rocky coastlines crosses the kelp-belt. Huge rounded pebbles and adult *Modiolus modiolus* serve as settling ground for the strong laminarian holdfasts. *Laminaria hyperborea* is a habitat for several organisms. The holdfast region of this brown algae is often overgrown by *Corallina officinalis*. The long leaves of kelps are overgrown by the bryozoan *Membranipora membranacea*. The prosobranch *Helcion pellucidus* was commonly found on the kelps. According to Vahl (1983), *Helcion* is adapted to a life on kelp by the ability of mucus drifting between the leaves of *Laminaria* when the limpet is dislodged. Apart from the bivalve *Venus gallina*, other infauna was rarely observed in this turbulent environment. The outer intertidal flats are inhabited by brown algae (*Fucus vesiculosus*, *Fucus serratus* and *Ascophyllum nodosum*) attached to single pebbles, bivalve shells or redeposited rhodoliths. In the shallow subtidal zone, down to approximately 20 m, living epifauna is sparse. Single uncovered valves serve as holdfasts for the long brown algae *Chorda filum*. The undersides of the valves form a cryptic habitat inhabited by grazing gastropods (*Acmaea* sp., *Patella* sp.) and chitonids.

3.1.5 The *Corallina*-gastropod rudite facies

This facies is restricted to wave-exposed localities of the outer island flanks. A thin veneer of this rudite covers the abraded crystalline rocks, e.g. at Jevik on Hillesøy (Pl. 80/6). The sediments are piled up to a maximum thickness of 35 cm in strandwalls parallel to the coast line. This facies is accumulated mainly by storm waves or, totally eroded in the next storm event. The sediment consists almost exclusively of gastropod and *Corallina* remains. Of minor importance are conches of *Patella vulgaris*, *Gibbula cineraria*, *Nucella*

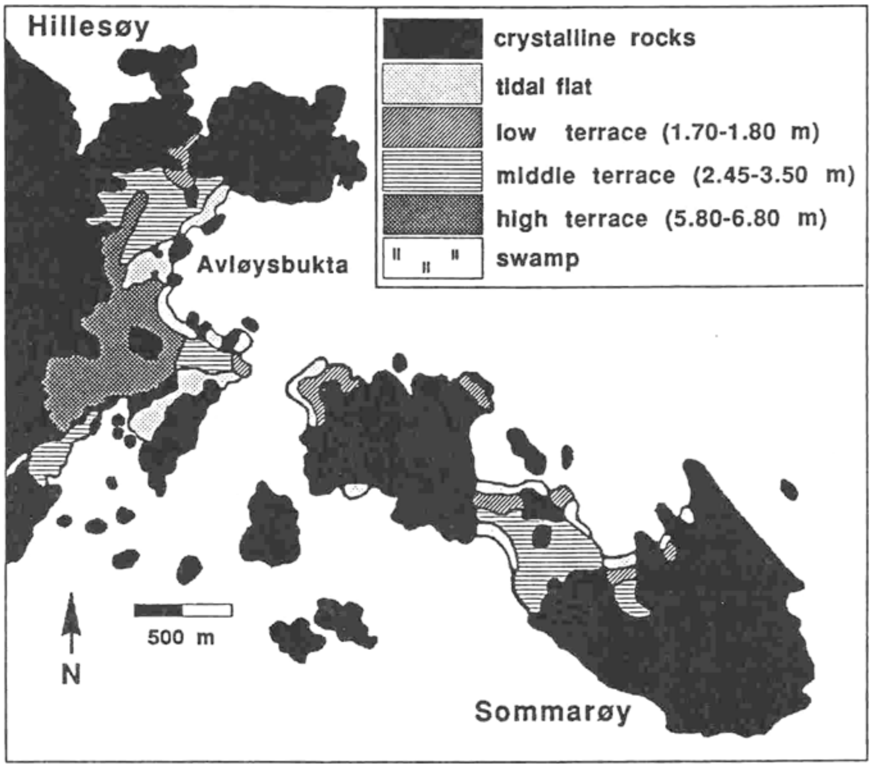

Fig. 7. Elevated Holocene carbonate deposits at the eastern coastline of Hillesøy and on Sommarøy reflect different erosional stages, dependent on the grade of exposure to fetch, tidal currents, alongshore drift, and waves. (meters = meters above mean tide level)

lapillus, *Helcion pellucidus*, *Lunatia sp.* and *Margarites sp.*, as well as plates of barnacles (Pl. 83/10). Depending on the frequency and intensity of reworking processes, the gastropod tests show different stages of destruction. Quartz gravels and crystalline rock fragments occur at certain levels. The strandwalls reveal classical examples of sorting with gastropod enrichment in the high turbulent zone and enrichment of the delicate *Corallina* segments in the swell zone. The carbonate material derives from a well-developed broad *Fucus*-belt that fringes the crystalline rocks between the high-tide mark and the shallow subtidal (Pl. 80/7). This belt serves as a habitat for rich populations of *Littorina*. *Corallina* lives in tidal-pools that exist in depressions of the crystalline rocks (Pl. 80/8).

3.1.6 The intertidal sand and gravel facies

This facies is restricted to the protected inner intertidal flats, e.g. Avløysbukta on Hillesøy (Pl. 81/1), Måsvik on Rebbenesøy, and Sandvik on Kvaløy (Fig. 6). It is also present in small sheltered pockets at Klubba in Kvalsundet.

The intertidal sand and gravel facies consists either of biogenic carbonate-dominated sediments or terrigenous particle-dominated sediments as well as of mixtures of both. Grain sizes range from fine sand to gravel. The spectrum comprises more or less well-sorted maerl debris, well-sorted quartz sands enriched with mollusc and echinoderm particles, and a mixture of both. These sediments show different stages of sorting maturity which are controlled by tidal activities and by small wave swell entering the inlet during high-tides. The latter creates temporarily pronounced zonated trash lines (Pl. 81/2-4). The supratidal sediments reveal aeolian transport, as indicated by small aeolian oscillating ripples. The intertidal flats reveal a variety of typical sedimentologic features, e.g. tidal channels of 2 to 3 m width and 0.4 m depth surrounded by tidal bars and sand flats, as well as a characteristic coastal zone with various strand walls and beach deposits.

The well-sorted quartz sand patches are strongly bioturbated by *Arenicola marina*. The coarse maerl gravel patches near the low water line are inhabited by *Mytilus edulis* attached by byssus to several gravel components, thus enhancing the stability of the sediment (Pl. 81/5). In places 'gravel-clumps' several centimeters high are held tightly together by byssus fixation of *Mytilus*. Dense bank-forming settlements of *Mytilus* are not developed in the maerl gravel patches but rather on the well-sorted sand flats and overwashed sand bars of the Sandvik intertidal flat. The outer well-sorted sand bars are inhabited by *Mya arenaria* and to a smaller degree by *Cerastoderma edule*. The maerl type constituents in the intertidal flats are derived from two prominent sources. One is the subfossil maerl carbonate, either rafted into the tidal flat by fucoid brown algae (see chapter 3.3.2) or eroded and redeposited from terraces. Almost all of the maerl sediments from Avløysbukta are subfossil, according to ^{14}C data of rhodoliths. Many sand-sized carbonate components reveal borings of endolithic algae, fungi and bacteria (Pl. 83/15-16).

3.1.7 The coquina lag deposit facies

The coquina lag deposit facies covers the deeper channels of the inner skerry strandflat, where the bulk of water transport is due to pumping tidal currents (Fig. 2 and 5b, c). Two major channels are situated along the coastline of Kvaløy, passing Brensholmen, and between Hillesøy and Edøy. Both join together south of Edøy, sloping down into the Malangen Trough. Here sandy surface sediments enriched

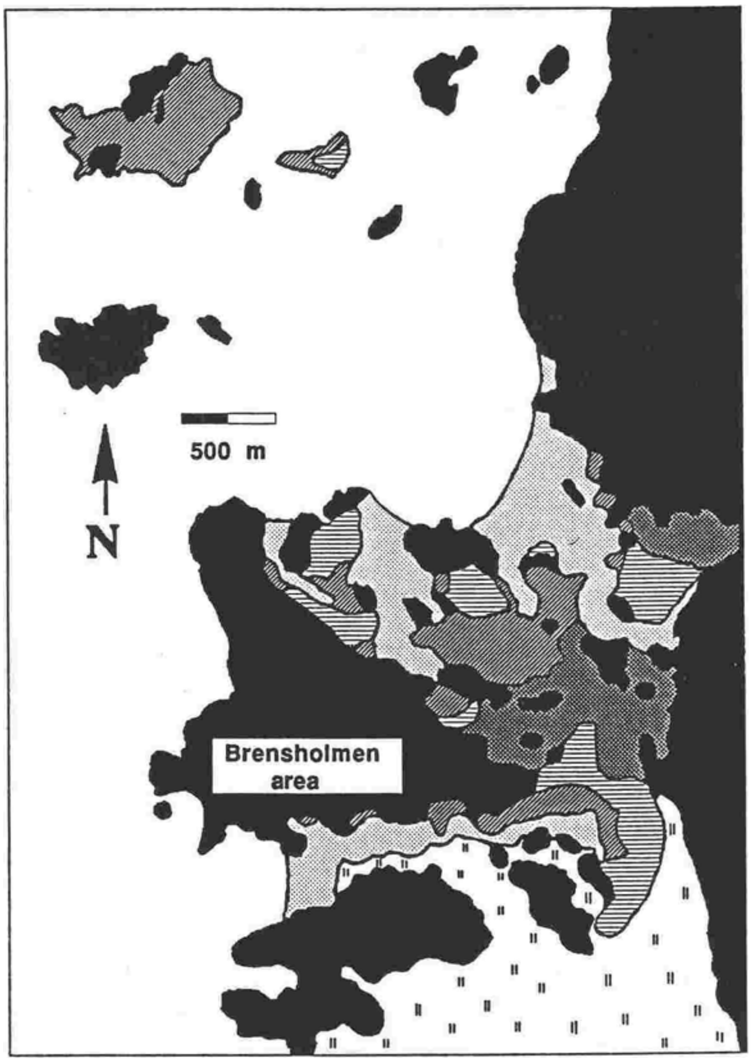

Fig. 8. Elevated Holocene carbonate deposits at Brensholmen area, southeast of Hillesøy and Sommarøy. Almost all higher terraces are protected against erosional forces by crystalline rocks. The legend is given in Fig. 7.

with infaunal shells indicate bottom current activities down to water depths of at least 89 m.

Biogenic debris consists of bivalves, gastropods, barnacles, serpulids, brachiopods and scaphopods. Coralline algal gravel occurs subordinately, but frequently crusts of red algae are found on exposed shells in water depths down to 35 m (Pl. 83/5). These current excavated, formerly infaunal bivalves are densely overgrown by barnacles (*Balanus balanus*), encrusting sponges, serpulids, hydrozoans and filamentous red algae (Pl. 81/6 and Pl. 83/6). In addition, bivalves (*Chlamys islandica, Modiolus modiolus*) and brachiopods (*Hemithyris psittacea, Macandrevia cranium, Terebratulina retusa*) settle on these secondary hardgrounds. The empty tests of barnacles serve as microenvironment for *Hiatella arctica*, which burrow into the fine grained sand trapped within the barnacles. The thick shells of *Cyprina islandica* are heavily infested with boring sponges (*Cliona* sp.), phoronids (*Phoronis ovalis*), and sipunculids, thus indicating a long period of exposure on the sea bottom (Pl. 83/13-14).

3.1.8 The mud facies

This facies covers almost all bottom areas of the fjord troughs sampled (e.g. outer Kattfjord Trough: 153 m water depth; and Malangen Trough: 412 m water depth; Fig. 5b, c). The sediment of the mud facies consists of silt and clay (>88%) with an admixture of fine sand (<11%). Taxodont bivalves are the most important biogenic carbonate constituents. Additionally, thin-valved pectinids and valves of *Thyasira sp.* occur. Scaphopods and otoliths are of minor importance.

3.1.9 The facies of the subtidal fjord cobble and hardrock biota

These biota live on cobbles exposed on the flanks of fjords and sounds as well as on steep slopes in areas that are affected by strong tidal currents. Two different types have been sampled. The cobbles of the shallowest subtidal zone are encrusted with epilithic crustose coralline algae (outer Kaldfjorden). Numerous cobbles are fringed by 'microtrottoirs' of crustose algae (Pl. 81/8). Dense populations of *Strongylocentrotus droebachiensis*, chitonids, acmaeid and patellid gastropods graze on these crustose algae (Pl. 81/7). This facies reaches down to the *Laminaria*-belt (Hagen 1983).

Near Rya in the Rystraumen, another hardground biota was sampled in water depth of more than 40 m. Here, sabellarid polychaetes, forming dense calcareous tube-colonies together with poriferans, ascidians, caprellid crustaceans and bryozoans occur, indicating a strong current regime. The sabellarid colonies are intensively bored by *Hiatella arctica* (Pl. 83/7-8). Additionally, the clam *Chlamys islandica* forms extended shell beds, particularly in northern Norwegian fjords that are provided with a shallow

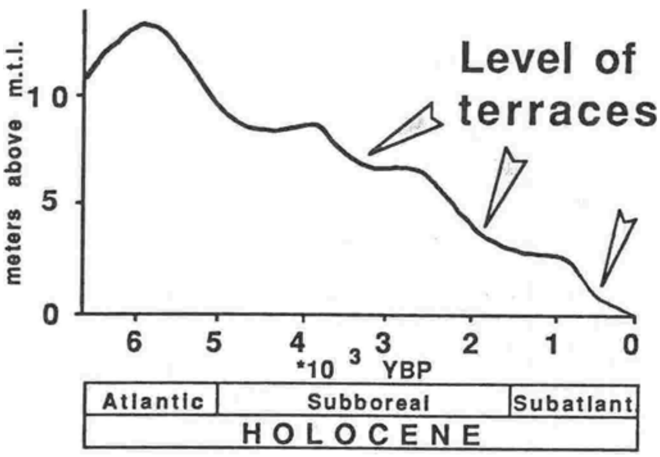

Fig. 9. Shoreline displacement curve from Sommarøy based on Møller (pers. comm.). The terraces in Fig. 7 and 8, were formed in the Subboreal and Subatlantic stages of the Holocene (arrows).

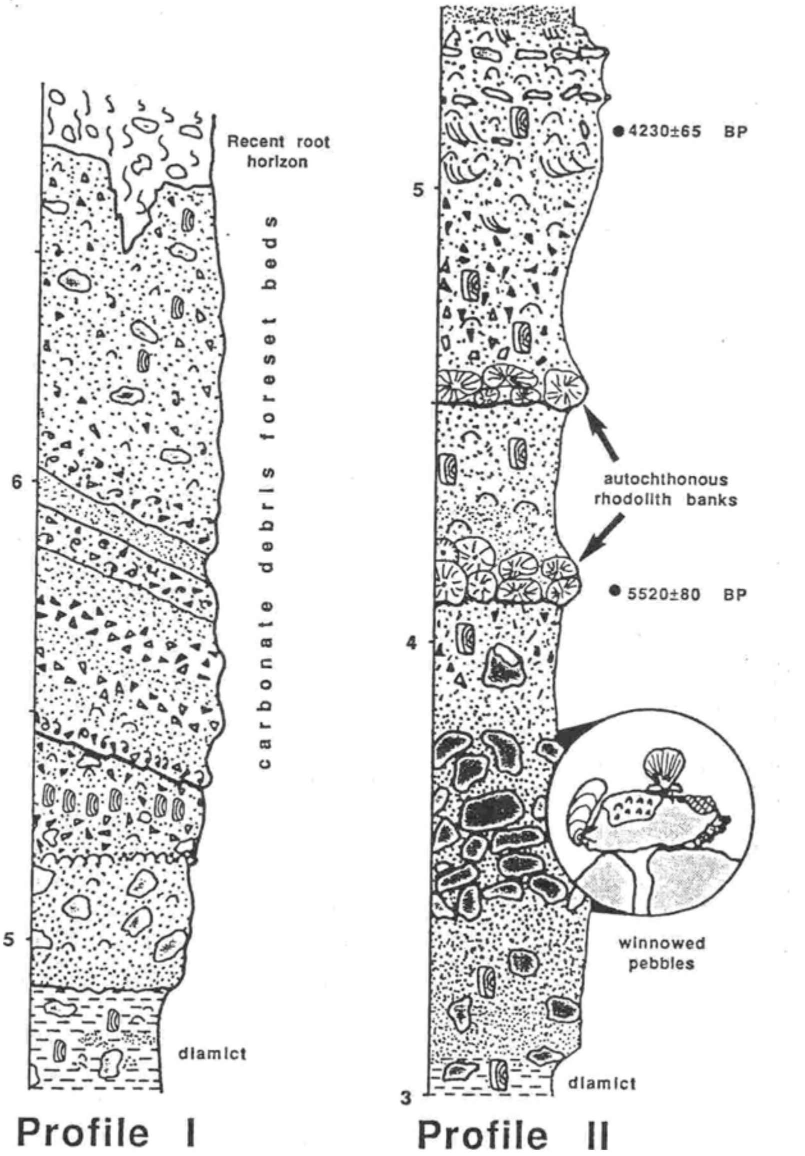

Fig. 10. Different types of carbonate deposits from two profiles at Langenes on Tromsøy. Profile I: The sedimentary sequences above the unconformity consist predominantly of carbonate debris, whereas terrigenous sediments dominate the sequences below the unconformity. Profile II: The circuit enlargement points to details of an autochthonous hardground community found in the pebble horizon: *Modiolus modiolus*, *Chlamys islandica*, *Balanus balanus*, encrusting bryozoans and crustose corallinaceans. (Legend see Fig. 11)

threshold near the entrance (Wiborg 1963, Sundet 1988). The clams serve as a habitat for a diverse fouling community (Schäfer & Freiwald 1990).

3.2 Morphology and regional distribution patterns of Holocene carbonate terraces and beach ridges

Raised carbonate sediments have been mapped on Hillesøy, Sommarøy (Fig. 7) and Brensholmen area (Fig. 8). Here, raised Holocene terraces and beach ridges (Pl. 82/1) with at least three distinct erosional levels are present in locations that are sheltered by crystalline elevations. Nearly the entire eastern part of Hillesøy, as well as the central part of Sommarøy, are covered by Holocene carbonate deposits and are sheltered between prominent crystalline elevations. In the vicinity of Brensholmen, wide plane areas are underlain by raised carbonate deposits. Holocene shorelines are indicated by at least three distinct levels. The lowest level lies between 1.70 m and 1.80 m above the present mean tide level (using the *B. balanoides*-belt as base line slightly above mean tide level), the second level ranges from 2.45 m to 3.50 m, the third level ranges from 5.80 m to 6.80 m. According to the relative shore level displacement curve of Sommarøy the raised terraces have been formed during syngressions in the Subboreal and Subatlantic stages (Møller 1986, 1989, pers. comm.; Fig. 9). The wide ranges of the second and third level can be explained by differently intense tides, storms and surface erosion. This results in an overall smoothing of the elevation range. All three levels are present on Hillesøy and in Brensholmen area. On Sommarøy, only two clearly raised levels were detected. Some sediments situated on higher, unterraced positions are known. Other raised Holocene carbonates are present at several localities near Tromsøy and in Kvalsundet, e.g. along the coastline from Tisnes to Klubben, at Kvaløysletta, at Thomasjordneset, and Langenes on Tromsøy (Fig. 1).

3.3 Facies successions and stratigraphic evolution of exposed terraces and roadcut profiles

Raised Holocene carbonate deposits can be observed at several coastal and roadcut exposures, yielding information on:

- the underlying Early Holocene glaciomarine sediments and fossils,
- their transition to the onset of carbonate sedimentation,
- the development of distinct Late Holocene autochthonous carbonate facies leading to the present day situation.

3.3.1 The glaciomarine sediments and the onset of carbonate sedimentation

Glaciomarine deposits overlain by carbonate sediments have been mapped near Tisnes, Avløysbukta on Hillesøy and Sandvik on Kvaløy. The most detailed information comes from two roadcuts at Langenes near the Tromsø international airport (Profile I and II in Fig. 10). At the base of Profile I, a bluegrey clay, partly laminated, with sand lenses was dug out (Pl. 82/3). Randomly dispersed well-rounded pebbles (up to 20 cm in diameter) are present in the clay. Extremely thick-valved *Mya truncata* and *Hiatella*

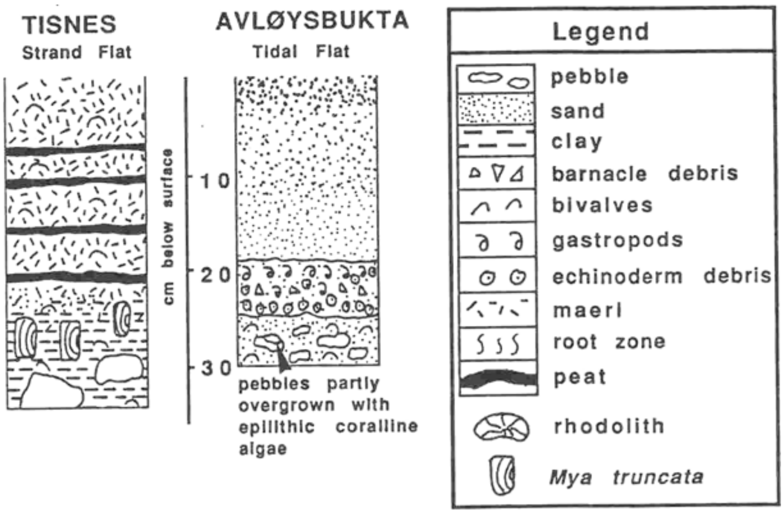

Fig. 11. Two short cores revealing the transition from terrigenous to carbonaceous depositional environments. The *Mya truncata* found in life position in the diamict of the Tisnes core yields an age of 9,100 YBP. The sediment of the core from the tidal flat of Avløysbukta (Hillesøy; see Fig. 6) is dominated by terrigenous components. The exception is a pronounced layer comprised of echinoderm- and barnacle fragments and *Littorina*-conches.

arctica have been found in life position. In addition, *Arctinula (Pecten) greenlandica, Heteranomia squamula,* plates of *Verruca stroemia* and fish vertebrae were found. The clay grades into a poorly sorted terrigenous sand enriched with fragmented plates of barnacles, bivalves and echinoderms in the uppermost part. In this section a *Modiolus modiolus* - horizon is intercalated. On top, numerous *Mya truncata* with 'normal' valve thickness are found in life position in a quartz sand rich layer (Pl. 82/4). A marked unconformity separates the sections described above from a series of coarse carbonate foreset lobes primarily composed of reworked plates of *Balanus balanus.* The foreset lobes with a mean dipping angle of 20° towards SE cover the eastern flank of a mamillated rock complex.

Near Tisnes (Loc. 3; Fig. 1), the transition between the glaciomarine clay sequence and the overlying carbonate sediments is exposed close to the beach (Fig. 11). Thick-valved *Mya truncata* found in life position (dated at 9,100 ± 90 YBP) are embedded in a bluegrey clay. This clay is enriched with pebbles and sand lenses approaching the transition zone. Many branches of coralline algae, valves of *H. arctica, H. squamula, Astarte borealis, Astarte elliptica, Cardium sp.,* and conches of *Acmaea sp., Punctuella noachina, Margarites sp.* indicate a more turbid environment than in the underlying clay section. Numerous spines and teeth of the echinoid *Strongylocentrotus droebachiensis* are present. The terrigenous sediments diminish gradually, finally resulting in a pure maerl deposit. Some peat horizons (1 to 2 cm thick) are intercalated just above the transition zone.

Another transition zone sediment has been dug out in the inner part of Avløysbukta (Fig. 11). The profile starts with a pebble layer admixed with single bivalves at the base. Outlined by a sharp boundary, a layer composed of spines and plates of the echinoid *Strongylocentrotus sp.* and plates of *B. balanus* follows on top (Pl. 83/12). This horizon was replaced by a layer rich in *Littorina*-conches. The covering unit is a terrigenous sand with a winnowed surface resulting in a coarse sand top layer deposited in the intertidal zone.

3.3.2 Holocene autochthonous carbonate deposits

Exposures comprising autochthonous Holocene carbonate structures have been mapped at Langenes on Tromsøy, Avløysbukta on Hillesøy, and Måsvik on Rebbenesøya.

At Langenes near the Tromsø international airport (Loc. 4; Fig. 1), Profile II gives information on the biofacial development of the coralline algae (Fig. 10; Pl. 82/5). Profile II is situated closer to the modern shore. The distance between Profiles I and II is approximately 90 m. At the base of this profile the gradual transition from bluegrey clay with dispersely distributed pebbles to a quartzose sand is exposed with some *Mya truncata* in life position. With a sharp contact to the section below, a pebble horizon overlies. Nearly all upper surfaces of the pebbles are encrusted by crustose coralline algae. Additionally, encrusting bryozoans and colonies of *Balanus balanus* grow on the overhangs of pebbles (Pl. 82/6). Complete bivalves of *Modiolus modiolus* and *Chlamys islandica,* which were attached by byssus to the pebbles, also lived in this turbid environment (Fig. 10). The upper boundary of the pebble horizon grades into a coralline algal gravel layer with *Mya truncata* in life position. This sediment is overlain by a marked rhodolith horizon (dated with C^{14} to 5,520 ± 80 YBP). The shape of the thalli is ellipsoidal to spheroidal. Most of them are intensely bored by *Hiatella arctica.* Cracked thalli contain up to six borings by *H. arctica.* In the overlain carbonate sand layer reworked parts of rhodoliths and valves of *M. modiolus* are inserted. The carbonate is derived from highly fragmented *B. balanus* and to a lesser degree from bivalves (*Crenella decussata*) and echinoderm spines (*Strongylocentrotus droebachiensis*). *Mya truncata* is present in life position. Above a sharp boundary a second rhodolith horizon of 5 to 15 cm in thickness is exposed. This horizon in turn, is overlain by barnacle debris with *Mya truncata* in life position and by a coarse carbonate sand layer with many reworked valves of *Chlamys islandica, M. modiolus, Astarte borealis, Cyprina islandica* and conches of *Littorina littorea.* Numerous polymict and imbricated pebbles are intercalated that are not overgrown by encrusters. *Mya truncata, Cyprina islandica* and *Macoma sp.* have been found in life position. A radiocarbon dated valve of *Astarte borealis* yields an age of 4,230 ± 65 YBP.

At the outer part of the tidal inlet of Avløysbukta a crystalline mamillated rock is fringed by a belt of rhodoliths (Fig. 12). Excavations around this rock have shown that the

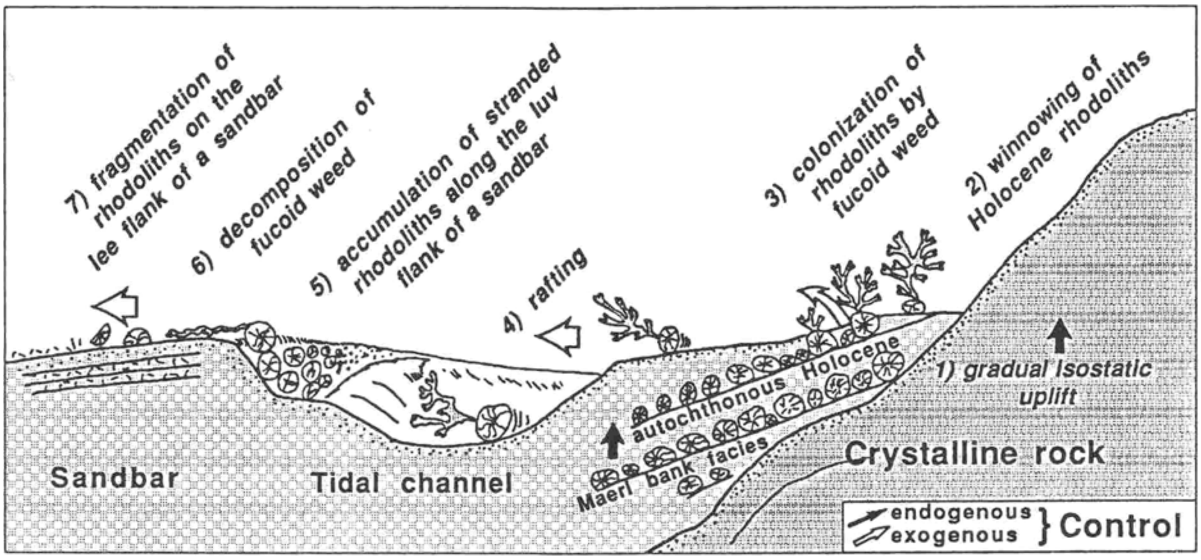

Fig. 12. Schematic model of the development of the rhodolith-gravel beds, pointing to the complexity of redeposition phenomena in the Avløysbukta tidal flat.

rhodoliths are only present close to the rock surface. The age of a rhodolith is 5,450 ± 60 YBP. This is nearly the same age as for the lower rhodolith horizon of the Langenes Profile II. After burial of the rhodolith belt, the substrate was inhabited by *Mya truncata*. A radiocarbon dated valve pair found in life position yielded an age of 4,340 ± 80 YBP. This rhodolith belt is autochthonous and, due to ice-isostatic uplift, this belt has reached now the modern low water tide mark of the intertidal flat. At the sediment surface the rhodoliths as well as the associated *M. modiolus*, serve as substrate for several brown algae (*Laminaria hyperborea, Fucus serratus, Chorda filum*) and *Corallina officinalis* (Pl. 82/2). During storms, when the bouyancy of the algae was high enough, the rhodoliths were dragged onto the intertidal flats. This kelp-rafting or algal-weed-rafting process caused a temporary dense accumulation of stranded redeposited Holocene rhodoliths along the luv flanks of outer sandbars (see Pl. 81/3). Here the rhodoliths are disaggregated to algal

Plate 80 — High-boreal to subarctic maerl deposits of northern Norway - Carbonate sedimentary facies from the skerry area of Troms

Fig. 1. View of the skerry area of Hillesøy (upper right), Sommarøy (central right), and Edøy (upper left) from Ornfløya Mt. (154 m.a.s.l.), Brensholmen area. The arrow indicates the elevated strandflat along the eastern coastline of Hillesøy..

Fig. 2. Autochthonous maerl bank facies from the southern entrance of the tidal current influenced sound between Sommarøy and Brensholmen. The dredge haul (Station 48) was taken from a flat plateau, ranging from 10 to 11 m water depth. The tips of the valves of *Modiolus modiolus* (Valve length: 15 cm) are encrusted by crustose coralline algae. Furthermore, ophiuroids (*Ophiopholis aculeata*), echinoids (*Strongylocentrotus droebachiensis*), and filamentous rhodophyta are visible.

Fig. 3. Irregularly formed rhodolith, as a result of intergrowth of several small rhodoliths (length: 15 cm; dryweight: 220 g). The cryptic habitats of this rhodolith type are colonized by bivalves (*Chlamys islandica, Modiolus modiolus*) and brachiopods (*Hemithyris psittacea*). Filamentous rhodophyta settle on the light-exposed surfaces.

Fig. 4. Autochthonous muddy algal gravel facies from the sound south of Sommarøy (Station 4; water depth: 19 m). The algal material consists of living rhodoliths originating from adjacent maerl bank facies, and of dead rhodolith fragments, embedded in a muddy sand or sandy mud substrate. The length of the arrow is 12 cm.

Fig. 5. Parautochthonous clean algal gravel facies from the highest subtidal zone of the southern coast of Sommarøy. This facies is often comprised of Recent and Holocene algal gravels. The length of the *Macoma balthica*-valve is 1.8 cm.

Fig. 6. Veneer of *Corallina*-gastropod rudites, resting on wave exposed crystalline rocks at Jevik (Hillesøy). Different trash line directions indicate a high mobility of this facies. The length of the spade is 1.20 m.

Fig. 7. Belt of fucoid algae, fringing the crystalline rocks at Jevika (Hillesøy). The algal leaves provide habitats for rich gastropod populations which contribute to the *Corallina*-gastropod rudite facies postmortally.

ig. 8. Tidal rock-pools with colonies of *Corallina officinalis*, which contribute to the *Corallina*-gastropod rudite facies postmortally. The colonies are surrounded by the fucoid alga *Ascophyllum nodosum*. In the foreground, conceptacles of *Fucus spiralis* are visible. The length of the bottle is 35 cm.


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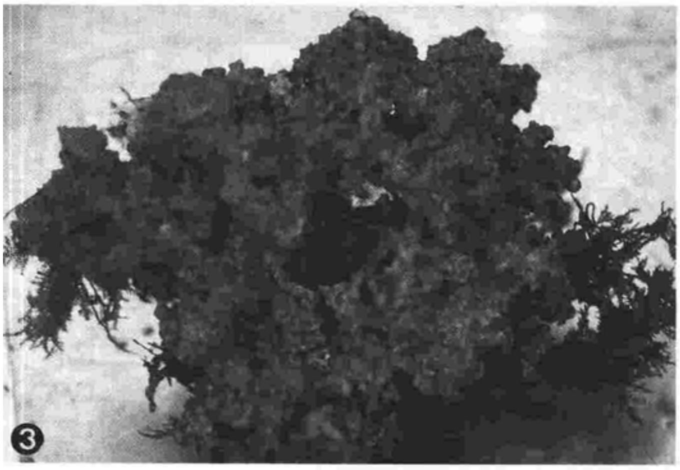
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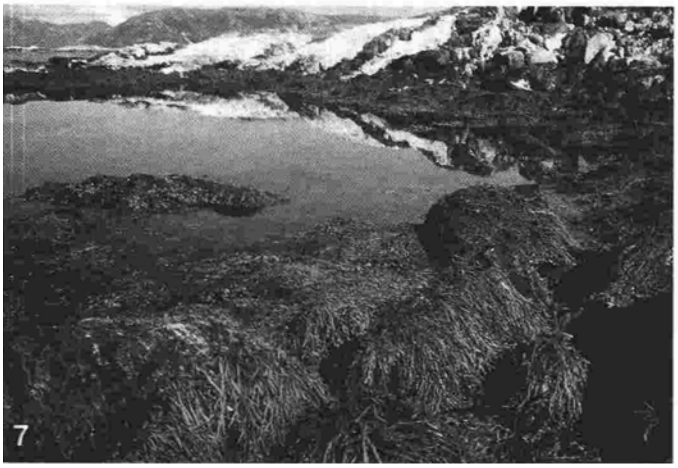
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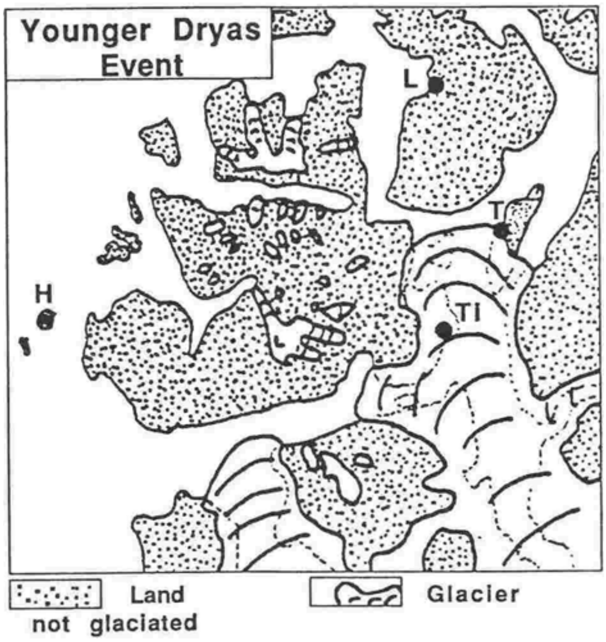

Fig. 13. Glacial limits at the Younger Dryas period (Late Weichselian) in the area investigated according to Vorren & Rønnevik (1980). Almost all of the skerry area (H) was drowned at that time. During deglaciation in the Early Holocene, glaciomarine diamicts were deposited in an iceberg-environment. These diamicts were overlain by carbonate deposits during the Late Holocene, as has been shown from Tromsøy Profiles I and II (T; Fig. 10) and Tisnes (Ti; Fig. 11). The deposits from the Lyfjorden (L) locality were used by Hald & Vorren (1983) to reconstruct a Holocene shore-level displacement curve. (For orientation see Fig. 1)

gravel deposits by mechanical destruction (Fig. 12; see Pl. 81/4). This algal-rafting process is a common mode of redeposition in temperate regions of both hemispheres (Kudrass 1974, Gilbert 1984, Woodborne et al. 1989).

In the tidal inlet of Måsvik (Loc. 8; Fig. 1), a raised Holocene Rhodolith-*M. modiolus* thanatocoenosis is also exposed slightly above the low water tide mark (Pl. 82/7). Here, *Modiolus modiolus* is found in life position with valve pairs, which exhibit gerontic valve characteristics (Pl. 82/8). Radiocarbon dated ages of a rhodolith and a *M. modiolus* in life position are available, with 4,530 ± 75 YBP and 4,450 ± 70 YBP, respectively. This is slightly younger than the rhodolith ages of Avløysbukta and Langenes Profile II.

4 DISCUSSION

Crustose coralline algal growth has been observed at many locations along the rocky coastline of Norway (Foslie 1895).

Plate 81 High-boreal to subarctic maerl deposits of northern Norway - Carbonate sedimentary facies from the skerry area of Troms, northern Norway

Fig. 1. View of the tidal inlet of Avløysbukta, eastern coast of Hillesøy during low tide. The entrance of this inlet is blocked by a sandbar (central part). The tidal flat is drained by a tidal channel fed by run-off waters from the Hillesøy mounts (211 meters above sea level.). Raised Holocene terraces surround the inlet.

Fig. 2. Trash line zonation on a strand flat of Avløysbukta (Hillesøy). Dark trash lines reveal heavy mineral components, bright trash lines consist of abraded algal gravel and/or mollusc and echinoderm fragments. The width of the strand is approximately 8 m.

Fig. 3. Detail from the luv flank of the outer sandbar from the Avløysbukta tidal flat (see Pl. 81/1). Here, numerous algal-rafted rhodoliths of Holocene age are stranded and subsequently fragmented. The photographed section has a width of 2 m.

Fig. 4. Fragmented algal gravel, forming gravel sheets on the lee flank of the outer sandbar. Almost all of the algal gravel are of Holocene age.

Fig. 5. Settlement of *Mytilus edulis* from the Måsvik tidal flat on Rebbenesøy. The settlement exists on a small ridge, consisting of trapped sediment particles which were transported by shifting tidal currents. Additionally, pellets produced by bivalves and gastropods are found here. The bivalves are colonized by thin filamentous green algal mats, which serve as a habitat for *Littorina*-snails. The length of the pencil is 20 cm.

Fig. 6. Coquina-lag deposit facies from the strandflat west of Brensholmen. The dredge haul was taken from 41 to 43 m water depth (Station 46). Infaunal clams of *Cyprina islandica* were winnowed and subsequently colonized by a diverse fouling-community, consisting of *Balanus balanus*, *Hemithyris psittacea*, *Macandrevia cranium*, *Terebratulina retusa*, sponges, bryozoans, hydrozoans, and filamentous rhodophyta. As a result of a long exposure on the sediment surface, the valves of *C. islandica* are heavily infested by endolithic organisms (see Pl. 83/13-14). The length of the arrow is 12 cm.

Fig. 7. Fjord cobble encrusting coralline algal biotope from outer Kaldfjorden (Kvaløy). The crustose coralline algae live in the high subtidal zone at a water depth of 3 to 7 m below mean tide level. In the foreground the deepest part of the *Fucus spiralis*-belt is visible. The algal crusts are predated by echinoids (*Strongylocentrotus droebachiensis*), chitonids, and acmaeid gastropods. The photographed section has a width of approximately of 1.50 m.

Fig. 8. Detail of a single cobble taken from the high subtidal zone of outer Kaldfjorden. The surface is colonized by dense well-rounded bushes of *Corallina officinalis*. On the cobble flanks, thick crusts of coralline algae form pronounced 'microtrottoirs'.


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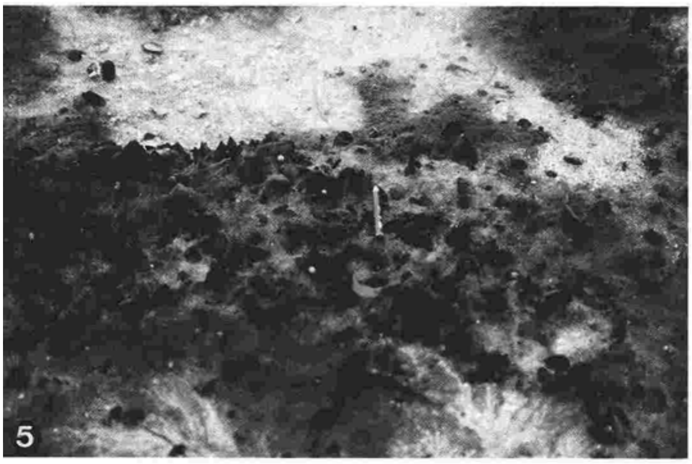
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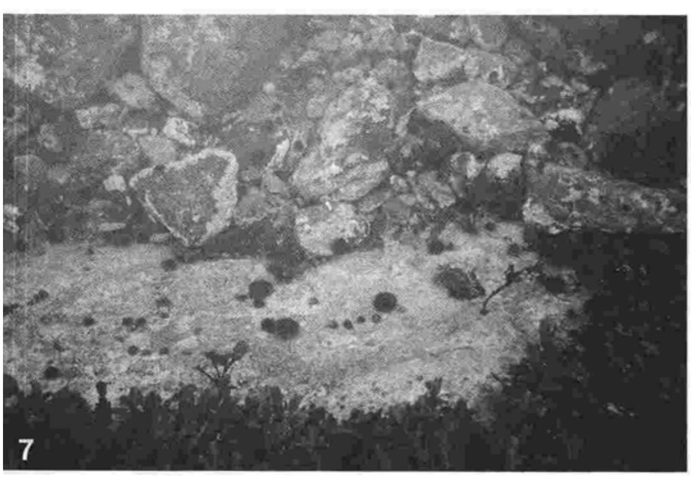
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However, luxuriant growth of coralline algae resulting in maerl banks shows a much more restricted distribution pattern. This indicates that maerl bank communities are strongly controlled by specific environmental constraints with defined ecologic preferences. With this in mind, coralline algae are useful tools for reconstructing past well-determined paleoceanographic constellations viewed on a large and on a small scale (ADEY 1976, WRAY 1979). Generally, coralline algae are restricted to the photic zone. The deepest living coralline algae in the area investigated were sampled from 38 m (Sommarøy) and 74 m water depth (Malangsgrunnen shelf bank). The coralline algae living in these maximum depths form only thin crusts. Rhodoliths with intergrowth of branched thalli are restricted to a narrow water depth interval from 9 m to 20 m controlled by the intensity of light penetration. Crustose coralline algae living at shallower depths tend to produce epilithic crusts with marked 'micro-trottoirs' at the flanks of pebbles (Pl. 81/8). In areas with strong current exposure they are replaced by articulated coralline algae. A comprehensive study on light and temperature conditions versus growth rate of crustose coralline algae by ADEY (1970, 1971) indicated a major influence of these parameters on species distribution which vary from coast to fjord sites along the Norwegian coastline. Results from our observations in addition to ADEY's data indicate that rhodolith environments are controlled by multiple constraints:

(1) Lack of terrigenous dilution, e.g. the fjord troughs have to act as effective sediment traps.

(2) Shifting medium current regimes forced by tides and not by waves.

(3) Flat bottom conditions surrounded by a structured topography, providing partial protection from strong open ocean waves but still facilating the development of intermediate current strength.

The optimal combination of these major environmental constraints in a narrow-spaced interval of the photic zone is the principle reason for these restricted occurrences along the entire Norwegian coast. In northern Norway, where extensive rhodolith banks occur, the modern topography of the strandflats provides excellent settings for the luxuriant growth of coralline algae. On the strandflat, with its small-scaled topography (intersected skerries and shoalings of mamillated rocks and sound channels in between), the optimum conditions for maerl-type deposits are found in many places. However, due to ice-isostatic movements of the Scandinavian craton and of eustatic sea level fluctuations during the Holocene, this setting is a rather unique and geologically short-lived situation. Nevertheless, the rapid environmental changes from arctic to boreal conditions in postglacial time are well documented in carbonate facies successions and the evolution of different communities has adapted to these rapid climatic changes.

4.1 Early Holocene to Recent facies successions in the fjord and skerry environment of northern Norway

Parts of the area studied were covered by a final glacial re-advance at the end of the Late Weichselian (Younger

Plate 82 High-boreal to subarctic maerl deposits of northern Norway - Holocene autochthonous and allochthonous carbonate deposits from Troms, northern Norway

Fig. 1. Raised beach ridges at the inner part of the Sandvik inlet on Kvaløy.

Fig. 2. Rhodolith of the subtidal zone of Holocene age, redeposited to the tidal zone at the southeastern coast of Hillesøy. Here, the rhodolith was colonized by Recent *Corallina officinalis*, which is present near the tidal zone in the area investigated. The time-lag between the rhodolith and the basal crusts of the articulated algae is approximately 4,000 to 5,500 years.

Fig. 3. Profile I at Langenes on Tromsøy. This outcrop reveals the lithofacies succession from glaciomarine conditions at the base, to present-day conditions. The boundary between the different sedimentary environments is marked by a pronounced unconformity. The deposits above the unconformity are predominantly comprised of allochthonous barnacle debris and bivalve fragments. The exposed sequence has a thickness of slightly more than 2 m.

Fig. 4. Detail of the Profile I at Langenes (Tromsøy), showing seven *Mya truncata* in life position. These bivalves lived 10 to 20 cm below the unconformity, indicating a former sea bottom that was subsequently covered by foreset beds consisting of barnacle debris. The photographed section has a width of 30 cm.

Fig. 5. Profile II at Langenes on Tromsøy. This section shows the lower rhodolith bank (5,520 ± 80 YBP), that was formed during the *Tapes*-III syngression (see hand). Towards the top, calcareous sandy gravelly layers followed, which were inhabited by *Mya truncata* found in life position. The second rhodolith bank (arrow) was probably formed during the *Tapes*-IV syngression at around 4,500 YBP. The photographed section of Profile II has a thickness of 1,20 m.

Fig. 6. Detail of the Profile II at Langenes (Tromsøy), showing a redeposited Paleozoic metamorphosed carbonate pebble that was colonized by *Balanus balanus*. Additionally, the pebble reveal borings of *Polydora sp.* The camera lens cup has a diameter of 6 cm.

Fig. 7. Raised Holocene subtidal strandflat at Måsvik (Rebbenesøy). The modern tidal flat reveals an in-situ sea bottom of Atlantic stage with numerous *Modiolus modiolus* (Pl. 82/8) and rhodoliths in life position. During the Holocene the skerries (central part of Figure) acted as shoals and were fringed by rhodolith banks.

Fig. 8. *Modiolus modiolus* in life position from the tidal flat of Måsvik (Rebbenesøy). The bivalves yielded an radiocarbon dated age of 4,450 ± 70 YBP. Note, that the valve tips reveal gerontic growth characteristics.


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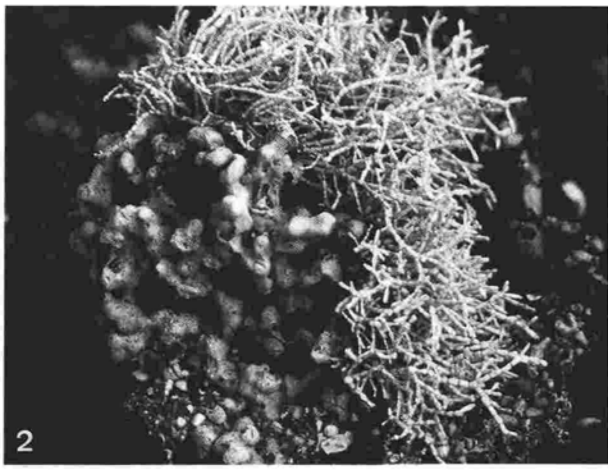
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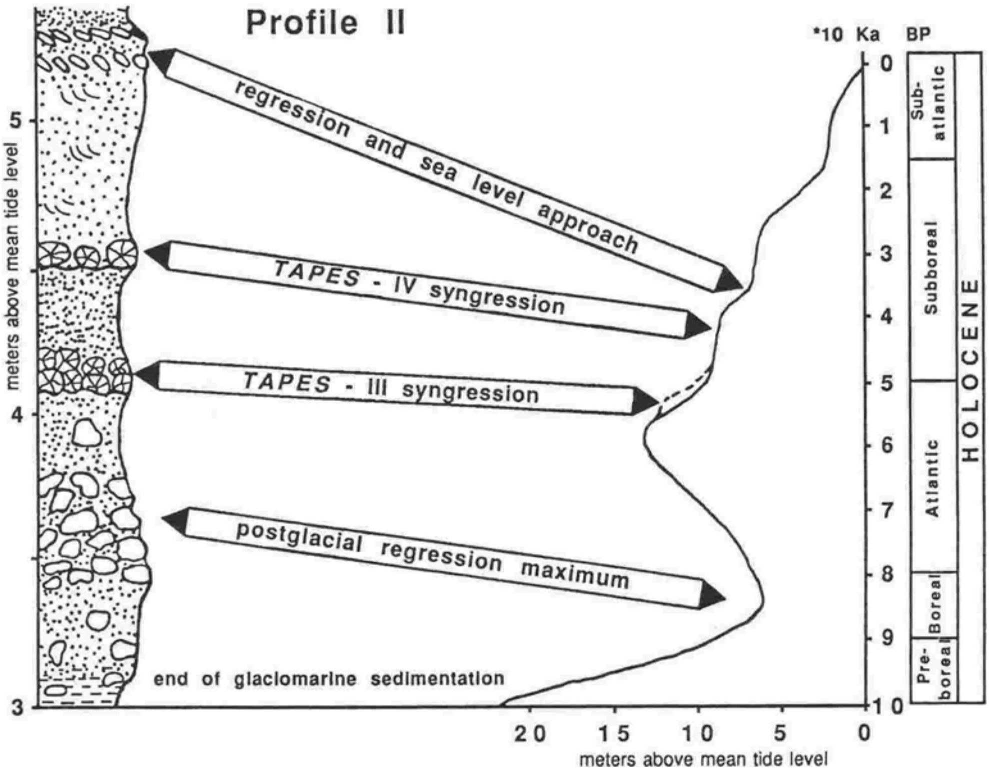


Fig. 14. Correlation of lithological units from Profile II (Fig. 10) with Holocene shore-level displacement rates according to Møller (pers.comm.). The regression minimum of the Boreal stage coincides with the pebble horizon. The autochthonous rhodolith banks have been formed at periods, when regressive tendencies, caused by uplift movements of the crust, were compensated by syngressions. This compensation results in an invariable sea level that facilitate the formation of rhodolith carpets. The dotted line of the *Tapes*-IV-syngression peak is an assumption that must be prooved by detailed shore-level displacement rates at that period. Note, that the shore-level displacement curve gives the altitudes of terraces and beach ridges in the tidal or supratidal zones while the rhodolith banks are situated in the subtidal zone.

Dryas Event, e.g. 10,600-10,200 YBP). The limits of the ice margin reached Tromsøy and the eastern entrance of the Rystraumen (Andersen 1968) (Fig. 13). A short time later, at 9,100 YBP, the Tisnes area situated 4 km south of Tromsøy, was already deglaciated. According to Corner (1980), periods of relatively rapid, climatically induced, glacier retreat appear to have occurred around 10,100 ± 150 YBP and 9,700 YBP in the Lyngen-Storfjord area, which is situated about 50 km east of Tromsøy. Due to the onset of isostatic uplift, a pronounced regression is observed in all of Scandinavia. The shorelines, deduced from shore displacement curves, were about 30 m higher than they are today at 10,350 YBP (Corner 1980, Hald & Vorren 1983). The shore-level displacement rate was at least 1.25 m/100 yr during the Early Holocene regression (Hald & Vorren 1983). The glaciomarine diamicts from Tisnes and Tromsøy Profiles I and II were deposited during the deglaciation period. Thick-valved *Mya truncata* and *Hiatella arctica* are characteristic representatives of a community that developed during times when the glacier front retreated on land and the rates of sedimentation were moderate (Syvitski et al. 1989). Regressive tendencies are indicated by coarsening up sequences of the diamicts. Fine clastic sediment was winnowed as a result of increased bottom currents.

A model for the evolution of relative sea level fluctuations during the Holocene has been proposed by Hald & Vorren (1983) and Møller (pers. comm.) for the Lyfjorden and Sommarøy areas (Fig. 9 and Fig. 14). According to these shore level displacement curves the regression maximum occurs between 9,000 and 8,500 YBP in the Boreal stage (Møller 1987). At Lyfjorden, as well as on Sommarøy the relative sea level during the time of maximum regression was about 4 to 5 m higher than today (Hald & Vorren 1983, Møller 1989). During regression the strandflat, as well as the fjord shoulders, pass through the depth interval which is hospitable for the luxuriant growth of coralline algae. Water temperatures were already comparable to present-day temperatures, at least on the shelf off Troms (Vorren et al. 1988). However, there is no evidence of Boreal stage maerl deposits. Possibly the suspension load in the fjords was still too high at that time. This factor has to be ruled out for the skerry area, because the fjord troughs act as sediment traps, ensuring that no major terrigenous input was deposited on the shelf off Troms (Vorren et al. 1989). It appears that climate *per se* can not be regarded as a major control factor for the onset of high-boreal to subarctic carbonate sedimentation. We assume that the regressive shore level displacement rate was too rapid for the rhodolith forming coralline algae to keep pace with the sea level fluctuations. A similar situation is envisaged for the succeeding transgressive phase, lasting from 8,000 to at least 6,600 YBP. According to Hald & Vorren (1983), the rate of shore level displacement was 0.5 m/100 yr. The *Tapes*-transgression began in the Atlantic period and lasted to the early stage of the Subboreal. Four transgression maxima have been found: TI-6,600 YBP, TII-6,250 YBP, TIII-5,500 YBP, and TIV-4,500 YBP (Marthinussen 1962).

Possibly, the thin epilithic coralline algal crusts covering the pebbles in the Tromsøy Profile II represent older *Tapes* stages when the sea level was at least 10 m higher than today. The oldest maerl deposits we have dated come from Hillesøy and Tromsøy Profile II, with 5,450 ± 60 YBP and 5,520 ± 80 YBP respectively (Tab. 1). These radiocarbon datings coincide with stage TIII. The autochthonous rhodoliths and in-situ *Modiolus modiolus* from Måsvik lived at the time of TIV-maximum. Based on the shore line displacement curves kindly provided by Møller (pers. comm.) and Hald & Vorren (1983), the autochthonous maerl banks from Hillesøy, Måsvik, as well as from Tromsøy, were formed in a water depth of 8 to 13 m. This fits well the observed modern water depths of the maerl bank facies and demonstrates their suitabilty as a tool for reconstructing past environments. The raised shore lines from Hillesøy, Sommarøy, and Brensholmen may coincide with syngressions during the Late Subboreal stage and the Early Subatlantic stage (Figs. 7-9). No autochthonous maerl banks of these younger stages are known. Refering to the shore level displacement rates, these possibly existing banks are situated now below modern sea level.

4.2 Generalized facies model of high-boreal to subarctic maerl deposits in northern Norway

The maerl deposits of northern Norway are formed in an environmental setting that has been strongly affected by uplift movements of the underlying crust (Mörner 1979). Due to the rapid sea level fluctuations, the autochthonous maerl banks were comparatively short-lived. Under favorable physical conditions, the coralline algal banks developed only during times of reduced shore level displacement rates, which occurred during relative sea level stillstands when eustatic sea level rise (syngressions) compensated crustal uplift movement. According to Mörner (1979, 1981), the relative sea level fluctuations of Scandinavia during Holocene times can be divided into two steps, a typical glacial isostatic uplift period with rapid (exponential) sea level fluctuations and a linear uplift period. The latter started at 6,000 YBP at the end of the *Tapes*-transgression maxima (Møller 1986). Holocene maerl bank formation coincides with eustatic high-stands (syngressions) at 5,500 YBP and 4,500 YBP.

Due to specific characteristics of glacial morphology, generally steep sloped features prevail, e.g. the fjord flanks, but flat elements are likewise present (strandflat, fjord shoulders). This implies that during rapid shore-line displacement rates carbonate production by coralline algae was not able to keep pace with fluctuations because the specific strandflat morphology was only established at distinct levels. This topography resulted in a more or less insular occurrence of Holocene carbonate facies. On a large scale, areas of extended autochthonous maerl deposition possibly shifted over a great latitude along the entire Norwegian coast during the Holocene. More regionally, the insular appearance of Holocene and Recent autochthonous maerl deposits can be studied east of Hillesøy. The raised terraces (up to 6.75 m a.m.t.l.) and the autochthonous maerl bank facies accumulated during the Atlantic stage, indicating a vast accumulation of carbonate, predominantly by coralline algae. The geometry of the autochthonous maerl bank facies is developed both linear (parallel to current axis) and circular (rock fringe occurrence). Today no noteworthy amounts of living coralline algae can be found in the subtidal east of Hillesøy. A well-developed maerl bank facies is located in the sound area between Sommarøy and Kvaløy today, where all conditions are most favorable for its growth.

5.3 Comparison with other maerl facies models

We have proposed a schematic facies model for maerl deposits in northern Norway in a regressive scenario of an interactive sea level and ice-isostatic uplift. A contrasting facies model was proposed for boreal coralline algal biotopes from the Irish Mannin Bay by Bosence (1980). Here, transgressive sea level fluctuations and an increasing complexity of the topography of the shoreline provide optimal environmental conditions for the luxuriant growth of maerl producing algae. Another model pointing in the same direction was proposed by Wilson (1988). His model relates temporal changes in the faunal composition of shell gravels during a transgression on the continental shelf around the British Isles to a shoreward migration of carbonate bedform zones. The same can be concluded for the maerl producing areas in the nearshore zone of western Ireland (Bosence 1980) as well as of Norway. When terrigenous sediment supply was sparse during transgression widespread carbonate deposits of different compositions with laterally shifting facies belts due to changes in habitats, relief and water depths can be formed on the shelves.

On coasts affected by a regression (e.g., in northern Norway), the resulting carbonate facies belts gained more and more an insular or disjunct character. Under these regressive conditions new maerl biotopes can also develop if the underlying topography and the hydrographic settings offer a suitable environment. Summarizing, we predict a complete retreat of the maerl facies when the strandflat area of northern Norway has vanished by emergence. Areas without the protection provided by the small islands in nearshore skerry areas conditions are not suitable for extensive growth of coralline algal banks because of the strength of open ocean wave scour and bottom currents (e.g., the rather flat banks of the outer shelf off Troms).

5 CONCLUSIONS

Carbonate sediments are common along the northern coastal areas, particularly in skerry and sound environments. Their distribution patterns reflect the strong imprint of hydrographic and topographic controls.

The maerl producing biotopes are developed in the photic zone on the plain strandflat or on fjord shoulders that are wave-protected but influenced by tidal currents. The mollusc-echinoderm arenite facies and the *Corallina*-gastropod rudite facies cover the sea bottom and strand areas of the wave-exposed parts of the strandflat or the fjord bottoms, which are affected by strong tidal currents. Relict terrigenous sediments containing a coquina lag deposit facies are present on the tidal current as well as on the wave-affected strandflat that is situated below the photic zone. A terrigenous mud facies is restricted to the deep fjord troughs.

Radiocarbon dated autochthonous rhodoliths and bivalves collected from raised Holocene outcrops indicate a control by postglacial sea level fluctuations. The oldest autochthonous rhodolith banks developed in a period when a boreal climate was already established. The onset of carbonate sedimentation coincides with a phase of reduced shore level displacement rates which began at around 6,000 YBP. The linear uplift rates that can be deduced from that time caused a regressive scenario that was compensated by syngressions. During these periods stable hydrographic and topographic conditions lasted over sufficient time for coralline algae to produce maerl banks.

ACKNOWLEDGMENTS

We thank the Institute for Geology and Biology, the Geological Department of the Tromsø Museum, and the Station of Marine Biology of the University of Tromsø for

Plate 83 High-boreal to subarctic maerl deposits of northern Norway - Growth forms of coralline algae and other carbonate build-ups with characteristic types of carbonate sediments and bioerosional features

Fig. 1. A Recent nodular rhodolith from a dredge haul in Kvalsundet (Station 65, water depth: 15 to 20 m). The maximum length is 15 cm and the dryweight is 317 g. This rhodolith is colonized by bushy colonies of the bryozoan *Dendrobeania murrayana*.

Fig. 2. A densely branched spheroidal rhodolith from the Måsvik tidal flat. This rhodolith was taken from 15 cm below mean tide level (Sample M 15C) and yielded an age of 4,530 ± 75 YBP. The diameter is 11 cm and the dryweight is 437 g.

Fig. 3. A Recent open-branched rhodolith from the inner skerry area of Hillesøy and Sommarøy. The diameter is 6 cm and the dryweight is 36 g (Station 11; water depth: 17 m).

Fig. 4. Recent crustose coralline algae, encrusting a valve of *Modiolus modiolus* from a dredge haul in Rystraumen (Station 50; water depth: 18 to 26 m). The length of the valve is 10 cm.

Fig. 5. A winnowed valve of *Cyprina islandica* from the sound west of Brensholmen. This sample was taken from the coquina-lag deposit facies that is situated in the photic zone. Here, the dominant encrusters are thick coralline algal crusts (Station 47; water depth: 23 to 32 m). The width of the valve is 8 cm.

Fig. 6. A winnowed valve of *Cyprina islandica* from the sound west of Brensholmen. This sample was taken from the coquina-lag deposit facies that is situated below the zone of luxuriant growth conditions of coralline algae. The dominant encrusters are barnacles (*Balanus balanus*) (Station 46; water depth: 41 to 43 m). The width of the valve is 7.5 cm.

Fig. 7. A colony of sabellarid polychaetes from a dredge haul (Station 49; water depth: 59 to 63 m). The calcareous worm-tube colonies were bored by bivalves (*Hiatella arctica*) and colonized by ophiuroids (*Ophiopholis aculeata*), encrusting sponges, bryozoans, barnacles (*Balanus balanus*), serpulid polychaetes and caprellid crustaceans. The maximum length of the colony is 20 cm and the dryweight is 191 g.

Fig. 8. Detail of the sabellarid colony, showing the dense arrangement of the filigran meshwork. The scale bar is 2 mm.

Fig. 9. Detail of the mollusc-echinoderm arenite facies from the eastern flank of Edøy (Station 30; water depth: 8 m). The well-sorted sand is predominantly comprised of bivalve (1) and echinoid (2) fragments. Of minor importance are fragments of gastropods (3), asteroids (4), ophiuroids, and benthonic foraminifers (5). Width of section is 3 cm.

Fig. 10. Detail of the *Corallina*-gastropod rudite facies (1, 2) from Jevika on Hillesøy (Sample J 3). This type of sediment is indicative for wave exposed hardrock localities, which are fringed by a broad *Fucus*-belt. Furthermore, echinoid (3), spirorbid (4), bivalve (5), and barnacle (6) fragments, as well as coarse terrigenous components (7) are visible. Width of section is 3 cm.

Fig. 11. Coarse fraction (>2000 µm) from a beach ridge on Rebbenesøy, consisting of abraded algal gravel (Sample LE 1). Width of section is 3 cm.

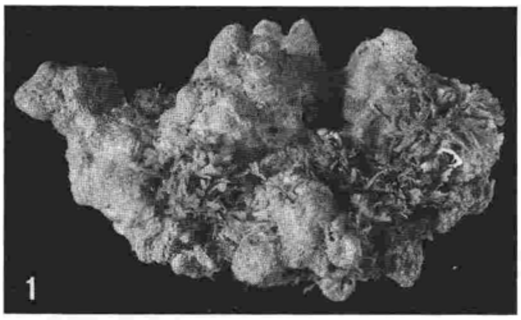
Fig. 12. Sample (HK 11C) was taken from a short core of the Avløysbukta tidal flat. The sediment predominantly consists of echinoderm plates (1), spines (2), and teeth (3) (*Strongylocentrotus droebachiensis*), as well as of barnacle plates (4) (*Balanus balanus*). This type of deposit is found close to exposed crystalline rocks and can be compared with the *Corallina*-gastropod rudite facies. Width of section is 3 cm.

Fig. 13. Radiography of a *Cyprina islandica* valve that was heavily infested by boring sponges (*Cliona sp.*) and phoronids (Station 46; see Pl. 81/6 for further information). The width of the valve is 8 cm.

Fig. 14. SEM-photography of the entrance of a *Cliona* borehole on a valve of *Chlamys islandica*. The pitted outfit of the ultrastructure of the clam is a result of etching activities of the boring sponge, that leads to the formation of charcteristic micrite-chips. The scale bar is 100 µm.

Fig. 15. SEM-photography of *Cibicides lobatulus*. Total view of the abraded test. The scale bar is 100 µm.

Fig. 16. Detail of the algal and fungi bored test of *Cibicides lobatulus*. The sample was taken from the tidal inlet of Avløysbukta, Hillesøy (Sample H 14). The scale bar is 30 µm.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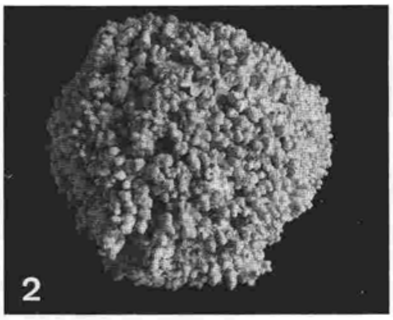
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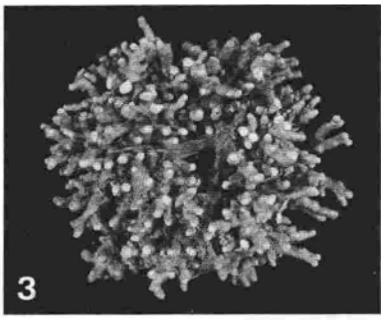
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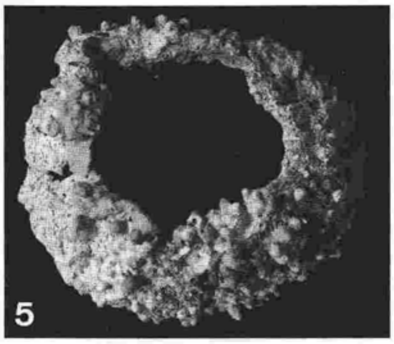
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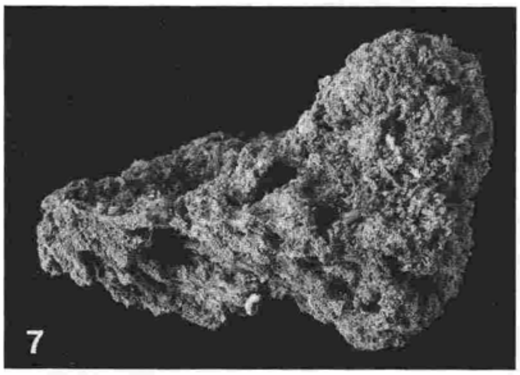
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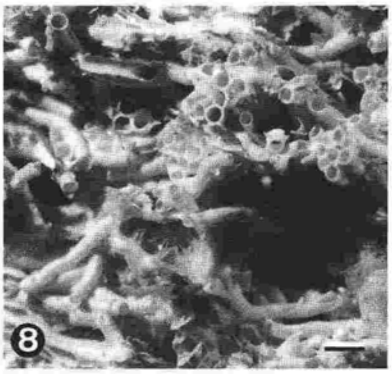
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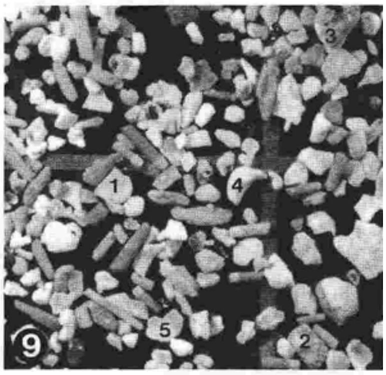
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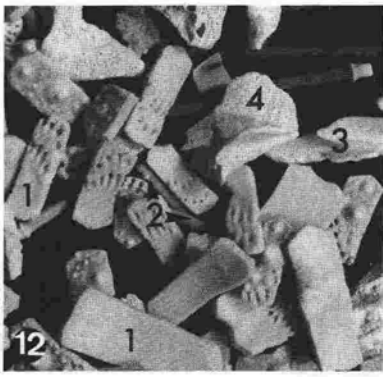
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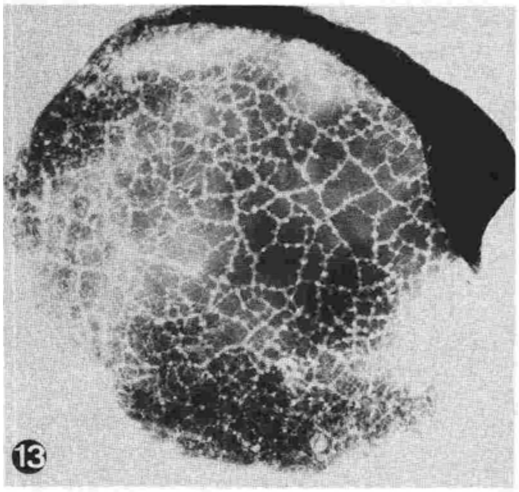
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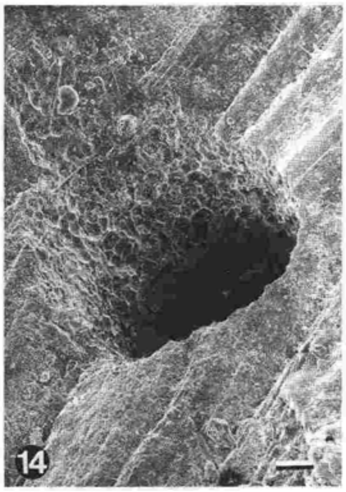
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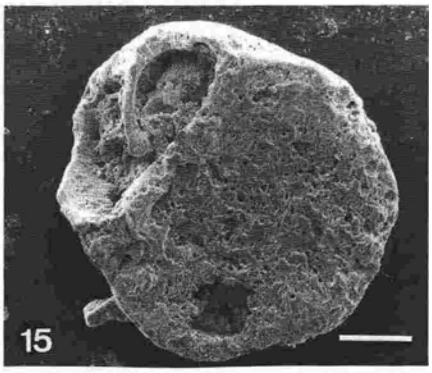
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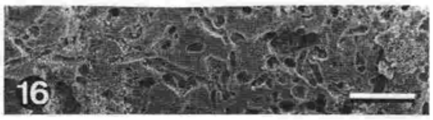
16

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REFERENCES

Adey, W.H. (1970): The effects of light and temperature on growth rates in boreal-subarctic crustose corallines. – J. Phycol., **6**, 269-276, 7 Figs., 1 Tab., Baltimore

-- (1971): The sublittoral distribution of crustose corallines on the Norwegian coast.– Sarsia, **46**, 41-58, 21 Figs., Bergen

-- (1976): Crustose coralline algae as microenvironmental indicators for the Tertiary. – In: Gray, J. & Boucot, A.J.: Historical biogeography, plate tectonics, and the changing environment.– 459-464, 2 Figs., 1 Tab., Corvallis (Oregon State University Press)

Adey, W.H. & Adey, P.J. (1973): Studies on the biosystematics and ecology of the epilithic crustose corallinaceae of the British Isles. – Br. phycol. J., **8**, 343-407, 71 Figs., London

Adey, W.H. & Macintyre, I.G. (1973): Crustose coralline algae: A re-evaluation in the geological sciences. – Geol. Soc. Am. Bull., **84**, 883-904, 31 Figs., 6 Tabs., Boulder

Adey, W.H. & McKibbin, D.L. (1970): Studies on the maerl species *Phymatolithon calcareum* (Pallas) nov. comb. and *Lithothamnium corallioides* Crouan in the Ria de Vigo. – Bot. Mar., **8**, 100-106, 16 Figs., Washington

Akpan, E.B. & Farrow, G.E. (1985): Shell bioerosion in high-latitude low energy environments: Firths of Clyde and Lorne, Scotland. – Marine Geology, **67**, 139-150, 8 Figs., Amsterdam

Andersen, B.G. (1968): Glacial geology of western Troms, north Norway. – Norges Geol. Undersøk., **256**, 1-160, 3 Pls., 29 Figs., 7 Tabs., Oslo

Berthois, L. & Guilcher, A. (1959): Les bancs de Saint Marc et du Moulin Blanc (Rade de Brest) et remarques sur la sedimentation du Maerl (*Lithothamnion calcareum*).– Cahiers Océanographiques, **11**, 13-23, 4 Pls., Paris

Bosence, D.W.J. (1977): Ecological studies on two carbonate sediment-producing algae. – In: Flügel, E. (Ed.): Fossil Algae. – 270-278, 1 Pl., 4 Figs, Berlin (Springer)

-- (1979): Live and dead faunas from coralline algal gravels, Co. Galway. – Palaeontology, **22/2** 449-478, 2 Pls., 5 Figs., 7 Tabs., London

-- (1980): Sedimentary facies, production rates and facies models for recent coralline algal gravels, Co. Galway, Ireland. – Geol. J., **15**, 91-111, 1 Pl., 7 Figs., 4 Tabs., Liverpool

-- (1983a): Description and classification of rhodoliths (rhodoids, rhodolites).– In: Peryt, T. (Ed.): Coated Grains. – 217-224, 4 Figs., 1 Tab., Berlin (Springer)

-- (1983b): The occurrence and ecology of recent rhodoliths - A review. – In: Peryt, T. (Ed.): Coated Grains. – 225-242, 5 Figs., 1 Tab., Berlin (Springer)

Cabioch, J. (1966): Contribution à l'Étude morphologique, anatomique et systématique de deux Mélobésiées: *Lithothamnium calcareum* (Pallas) Areschoug et *Lithothamnium corallioides* Crouan. – Bot. Mar., **9**, 33-53, 4 Pls., 4 Figs., Hamburg

Chave, K.E. (1967): Recent carbonate sediments - an unconventional view. – J. Geol. Educat., **15/5**, 200-204, 3 Figs., 2 Tabs., Washington

Corner, G.D. (1980): Preboreal deglaciation chronology and marine limits of the Lyngen-Storfjord area, Troms, North Norway. – Boreas, **9**, 239-249, 8 Figs., 1 Tab., Oslo

Dekko, T. & Rokoengen, K. (1980): Submerged beaches off Troms, north Norway. – Inst. Kontinentalsokkelundersøk., **101**, 5-34, 15 Figs., Trondheim

Dullo, W.-C., Moussavian, E. & Brachert, T.C. (1990): The foralgal crust facies of the deeper fore reefs in the Red Sea: A deep diving survey by submersible. – Geobios, **23/3**, 261-281, 4 Pls., 3 Figs., Lyon

Edyvean, R.G.J. & Ford, H. (1987): Growth rates of *Lithophyllum incrustans* (Corallinales, Rhodophyta) from South West Wales. – Br. phycol. J., **22**, 139-146, 5 Figs., 1 Tab., London

Eide, L.I. (1978): Ocean currents on the Halten and Malangsgrunnen banks. – Inst. Kontinentalsokkelundersøk., **97**, 1-302, 132 Figs., Trondheim

Eilertsen, H.C., Falk-Petersen, S., Hopkins, C C.E. & Tande, K. (1981): Ecological investigations on the plankton community of Balsfjorden, northern Norway. – Sarsia, **66**, 25-34, 11 Figs., Bergen

Evers, W. (1962): The problem of coastal genesis, with special reference to the 'strandflat', the 'banks', or 'grounds', and 'deep channels' of the Norwegian and Greenland coasts. – J. Geol., **70**, 621-630, 8 Figs., Chicago

Farrow, G.E., Cucci, M. & Scoffin, T.P. (1978): Calcareous sediments on the nearshore continental shelf of western Scotland. – Proc. R. Soc. Edinburgh, **76B**, 55-75, 5 Pls., 8 Figs., 7 Tabs., Edinburgh

Feyling-Hanssen, R.W. (1955): Stratigraphy of the marine Late Pleistocene of Billefjorden, Vestspitsbergen. – Norsk Polarinst. Skr., **107**, 1-226, 27 Pls., 57 Figs., 3 Tabs., Olso

Foslie, M. (1895): The Norwegian forms of *Lithothamnion*. – Kong. norske Vidensk. Selsk. Skrifter **1894**, 29-209, 23 Pls., Trondheim

Gärtner, H.R.v. (1958): Vorkommen von Serpelriffen nördlich des Polarkreises an der norwegischen Küste. – Geol. Rundsch., **47**, 72-73, 1 Fig., Stuttgart

Gilbert, R. (1984): The movement of gravel by the alga *Fucus vesicolosus* (L.) on an Arctic intertidal flat. – J. Sed. Petrol., **54/2**, 463-468, 5 Figs., Tulsa

Gunatilaka, A. (1977): Recent carbonate sedimentation in Connemara, Western Ireland. – Estuarine Coast. Mar. Sci., **5**, 609-631, 6 Figs., 2 Tabs., London

Hagen, N.T. (1983): Destructive grazing of kelp beds by sea urchins in Vestfjord, northern Norway. – Sarsia, **68**, 177-190, 7 Figs., 2 Tabs., Bergen

Hald, M. & Vorren, T.O. (1983): A shore displacement curve from the Tromsø district, North Norway. – Norsk Geol. Tidsskr., **63**, 103-110, 6 Figs., Oslo

Henrich, R. (1989): Glacial/Interglacial cycles in the Norwegian Sea: Sedimentology, paleoceanography, and evolution of Late Pliocene to Quaternary northern hemisphere climate. – In: Eldholm, O. et al.: Proc. of the Ocean Drilling Program. – Scientific Results, **104**, 189-232, 3 Pls., 24 Figs., 5 Tabs., Washington

-- (1990): Cycles, rhythms, and events in Quaternary Arctic and Antarctic glaciomarine deposits. – In: Bleil, U. & Thiede, J.(Eds.): Geological history of the Polar Oceans: Arctic versus Antarctic. – 213-244, 16 Figs., Kluwer Acad. Press, Netherlands

Hessland, I. (1942): Über subfossile Massenvorkommen von *Corallina officinalis* Linné. – Senckenbergiana leth., **25**, 19-40, 14 Figs., 4 Tabs., Frankfurt

-- (1943): Marine Schalenablagerungen Nord-Bohusläns. – Bull.

Geol. Inst. Uppsala, **31**, 1-346, 4 Pls., 115 Figs., Uppsala

Holtedahl, H. (1962): The problem of coastal genesis, with special reference to the 'strandflat', the 'banks', or 'grounds', and 'deep channels' of the Norwegian and Greenland coasts: a discussion. – J. Geol., **70**, 631-633, Chicago

Johnson, J.H. (1962): The algal genus *Lithothamnium* and its fossil representatives. – Quart. Colorado School of Mines, **57**/1, 1-111, 13 Pls., 14 Tabs., Golden

Kjellmann, F.R. (1883): The algae of the Arctic. – Kongl. Svenska Vetensk. Akad. Handling., **20**/5, 1-350, 31 Pls., Stockholm

Kudrass, H.-R. (1974): Experimental study of nearshore transportation of pebbles with attached algae. – Marine Geology, **16**, M9-M12, 2 Figs., Amsterdam

Lees, A. & Buller, A.T. (1972): Modern temperate-water and warm-water shelf carbonate sediments contrasted. – Marine Geology, **13**, M67-M73, 3 Figs., Amsterdam

Lees, A., Buller, A.T. & Scott, J. (1969): Marine carbonate sedimentation processes, Connemara, Ireland. – Reading Univ. Geol. Repts., **2**, 1-63, 6 Pls., 39 Figs., Dublin

Mangerud, J. & Gulliksen, S. (1975): Apparent radiocarbon ages of recent marine shells from Norway, Spitsbergen, and Arctic Canada. – Quart. Res., **5**, 263-273, 4 Figs., 1 Tab., Washington

Marthinussen, M. (1962): C^{14}-datings referring to shore lines, transgressions, and glacial substages in Northern Norway. – Norges. Geol. Undersøg. Årbog, **215**, 37-67, 2 Pls., 1 Tab., Oslo

Mörner, N.-A. (1979): The Fennoscandian uplift and Late Cenozoic geodynamics: Geological evidence. – Geo Journal, **3**/3, 287-318, 33 Figs., 3 Tabs., Wiesbaden

-- (1981): Crustal movements and geodynamics in Fennoscandia. – Tectonophysics, **71**, 241-251, 4 Figs., Amsterdam

Moussavian, E. (1989): Über die systematische Stellung und die Bestimmungskriterien der Solenoporaceen (Rhodophyceae). – Cour. Forsch. Inst. Senck., **109**, 51-91, Frankfurt

Møller, J.J. (1986): Holocene transgression maximum about 6000 years BP at Ramså, Vesterålen, North Norway. – Norsk geogr. Tidsskr., **40**, 77-84, 8 Figs., 1 Tab., Oslo

-- (1987): Shoreline relation and prehistoric settlement in northern Norway. – Norsk geogr. Tidsskr., **41**, 45-60, 11 Figs., 2 Tabs., Oslo

-- (1989): Geometric simulation and mapping of Holocene relative sea-level changes in northern Norway. – J. Coastal Research, **5**/3, 403-417, 11 Figs., 1 Tab., Charlottesville

Nelson, C.S. (Ed.) (1988): Non-tropical shelf carbonates - modern and ancient. – Sedimentary Geology, **60**, 367 p., 177 Figs., Amsterdam

Pendlebury, D.C. & Dobson, M.R. (1976): Sediment and macrofaunal distributions in the eastern Malin Sea, as determined by side-scan sonar and sampling. – Scott. J. Geol., **11**/4, 315-332, 5 Figs., 1 Tab., Edinburgh

Rokoengen, K., Bell G., Bugge, T., Dekko, T., Gunleiksrud, T., Lien, R., Løfaldli, M. & Vigran, J.O. (1977): Prøvetaking av fjellgrunn og løsmasser utenfor deler av Nord Norge i 1976. – Inst. Kontinentalsokkelundersøk., **91**, 1-65, 26 Figs., Trondheim

Schäfer, P. & Freiwald, A. (1990): Besiedlungsstrategien von Fouling-Gemeinschaften auf lebenden *Chlamys islandica*, Tromsø, Nord-Norwegen. – Nachr. Dt. Geol. Ges., **43**, 86, Hannover

Scoffin, T.P. (1988): The environments of production and deposition of calcareous sediments on the shelf west of Scotland. – In: Nelson, C.S. (Ed.): Non-tropical shelf carbonates - modern and ancient. – Sedimentary Geology, **60**, 107-124, 6 Figs., 1 Tab., Amsterdam

Snell, J.-A. (1968): The *Lithothamnion* community in Nord-Möre, Norway, with notes on the epifauna of *Desmarestia viridis* (Müller). – Sarsia, **31**, 69-74, 1 Tab., 2 Figs., Bergen

Soot-Ryen, T. (1934): Hydrographical investigations in the Tromsø district 1930. – Tromsø Museums Arshefter, **52**, 1-78, 1 Pl., 82 Figs., 28 Tabs., Tromsø

Stearn, C.W., Scoffin, T P. & Martindale, W. (1977): Calcium carbonate budget of a fringing reef on the west coast of Barbados. I. Zonation and productivity. – Bull. Mar. Sci., **27**/3: 479-510, 28 Figs., 11 Tabs., Miami

Sundby, S. (1983): Influence of bottom topography on the circulation at the continental shelf of northern Norway. – Fiskeridir. Skr. Ser. Havforskningsunders., 15 pp., Bergen

Sundet, J.H. (1988): Haneskjellets utbredelser og fangst av haneskjell. – Ottar, **170**, 8-12, 4 Figs., Tromsø

Syvitski, J.P.M., Farrow, G.E., Atkinson, R.J.A., Moore, P.G. & Andrewa, J.T. (1989): Baffin Island fjord macrobenthos: Bottom communities and environmental significance. – Arctic, **42**/3, 232-247, 11 Figs., 4 Tabs., Montreal

Sælen, O.H. (1950): The hydrography of some fjords in northern Norway. – Tromsø Museums Arshefter, **70**/1, 1-93, 10 Pls., 42 Figs., Tromsø

Sætre, H.J. (1972): Strømmålinger i Tromsøysundet og Sandnessundet, februar 1972. – Rep. Norw. Hydrodyn. Lab., 1-20, Trondheim

Sætre, R. & Ljøen, R. (1972): The Norwegian Coastal Current. – Proc. 1st. Int. Conf. on Port and Ocean engineering under arctic conditions, **1**, 514-535, 11 Figs., Trondheim

Thomsen, E.T. & Vorren, T.O. (1986): Macrofaunal palaeoecology and stratigraphy in Late Quaternary shelf sediments off northern Norway. – Palaeogeogr., Palaeoclim., Palaeoecol., **56**, 103-150, 8 Pls., 13 Figs., 3 Tabs., Amsterdam

Vahl, O. (1983): Mucus drifting in the limpet *Helcion (=Patina) pellucidus* (Prosobranchia, Patellidae). – Sarsia, **68**, 209-211, 2 Figs., 1 Tab., Bergen

Vorren, T.O., Hald, M., Edvardsen, M. & Lind-Hansen, O.-W. (1983): Glacigenic sediments and sedimentary environments on continental shelves: General principles with a case study from the Norwegian shelf. – In: Ehlers, J. (Ed.): Glacial deposits in North-West Europe, 61-73, 8 Figs., Rotterdam

Vorren, T.O., Hald, M. & Lebesbye, E. (1988): Late Cenozoic environments in the Barents Sea. – Paleoceanography, **3**/5, 601-612, 7 Figs., Washington

Vorren, T.O., Lebesbye, E., Andreassen, K. & Larsen, K.-B. (1989): Glacigenic sediments on a passive continental margin as exemplified by the Barents Sea. – Marine Geology, **85**, 251-272, 21 Figs., Amsterdam

Vorren, T.O. & Rønnevik, H.C. (1980): Sokkelens naturhistorie. – Ottar, **118**, 9-26, 20 Figs., Tromsø

Wiborg, K.F. (1963): Some observations on the Iceland scallop *Chlamys islandica* (Müller) in Norwegian waters. – Fiskeridir. Skr. Ser. Havforskningsunders., 13/6, 38-53, 12 Figs., 1 Tab., Bergen

Willkomm, H. (1976): Altersbestimmungen im Quartär. Datierungen mit Radiokohlenstoff und anderen kernphysikalischen Methoden. – 276pp., München

Wilson, J.B. (1988): A model for temporal changes in the faunal composition of shell gravels during a transgression on the continental shelf around the British Isles. – In: Nelson, C.S. (Ed.): Non-tropical shelf carbonates - modern and ancient. – Sedimentary Geology, **60**, 95-105, 4 Figs., 1 Tab., Amsterdam

Woelkerling, W.J. (1988): The coralline red algae: An analysis of the genera and subfamilies of nongeniculate corallinaceae. – Brit. Mus. (Nat. Hist.), 268 pp., London (Oxford University Press)

Woodborne, M.W., Rogers, J. & Jarman, N. (1989): The geological significance of kelp-rafted rock along the west coast of South Africa. – Geo-Marine Letters, **9**, 109-118, 13 Figs., New York

Wrage, W. (1937): Wattbildungen an der nordnorwegischen Küste. – Ann. d. Hydr., **65**/3, 97-104, 1 Pl., 18 Figs., Hamburg

Wray, J.L. (1979): Paleoenvironmental reconstructions using benthic calcareous algae. – Bull. Cent. Rech. Explor. Prod. Elf-Aquitaine, **3**/2, 873-879, 6 Figs., Pau

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