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Deep-water limestones from the Devonian-Carboniferous of the Carnic Alps, Austria

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ABSTRACT

The central Carnic Alps contain continuous sedimentary carbonate sequences that extend through the Devonian and lowermost part of the Carboniferous. Some sediments were deposited near mean sea level; other cephalopod-bearing facies were laid down in deeper water. Red mottled cephalopod limestones are continuous into the Upper Devonian. Grey cephalopod limestones, containing derived shallow-water calcarenites, occur in the Devonian and grade upwards into turbidite-free cephalopod limestones of Early Carboniferous age. These deep-water limestones are characterized by evidence of early lithification and solution, and by the presence of a characteristic fauna. Interpretation of their depositional depth is based on present-day compensation depths for aragonite and calcite: the original sediments apparently resembled modern pelagic oozes. Sedimentological and palaeontological criteria indicate a progressive deepening of the basinal areas accompanied by continuous growth of platform carbonates at the basin edge until Late Devonian time when the shallow-water areas subsided.

INTRODUCTION

The Carnic Alps contain essentially continuous sedimentary sequences extending through the whole Devonian into the Lower Carboniferous. The sections discussed in this paper occur in the central Carnic Alps, to the east and west of the Plöcken Pass of the Bundesland Kärnten in South Central Austria and small parts of the province Udine of Northern Italy (Fig. 1). Detailed descriptions of localities, lithologies and microfacies are given in Bandel (1972).

The sections on which this study is based are parts of an allochthonous structural unit which was subjected to tectonic movements in the Hercynian and Alpine orogenies. Broad palaeogeographic reconstructions can therefore only be made with certain reservations. Limestones are present throughout, and clastics are notably absent. From lowermost Devonian to the lower Upper Devonian (Frasnian) a shallow-water facies can be distinguished from a deeper-water facies. Turbidites, composed of material derived from these shallow-water areas, occur within the deeper-water facies.

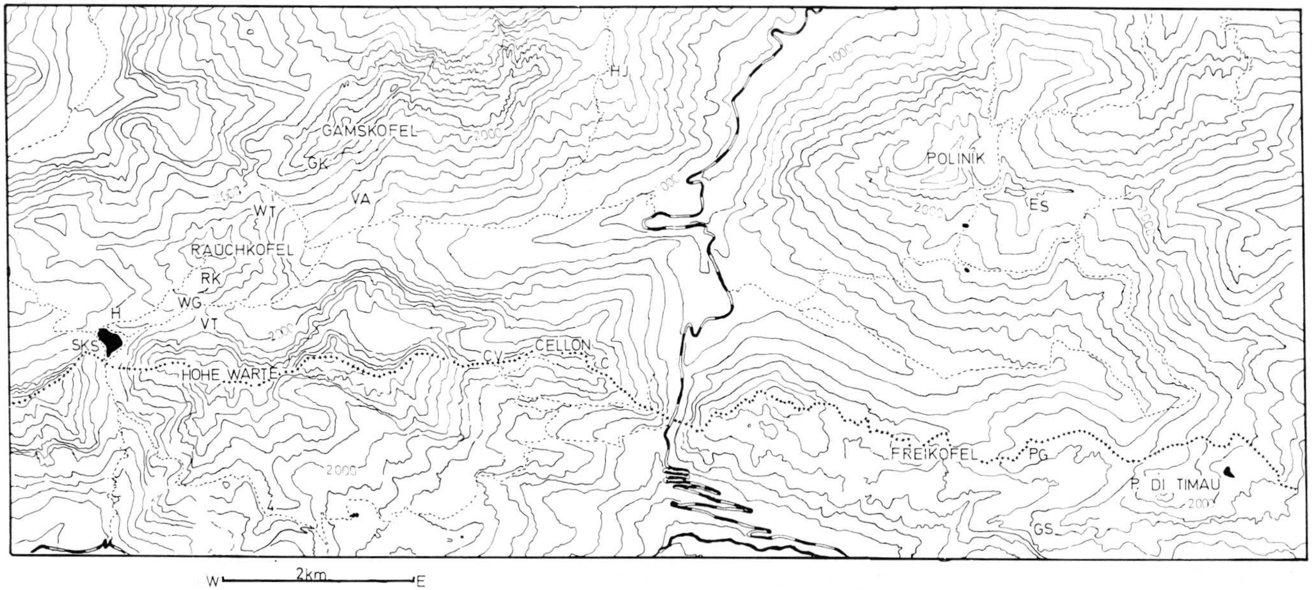


Fig. 1. Map of the area around the Plöcken Pass in the Central Carnic Alps. The location of each section is noted with its initial letters: SKS, Seekopfsockel; H, Hütte; WG, Wolayer Gletscher; VT, Valentin-Törl; RK, Rauchkofelboden; (Wolayer Lake sections): WT, Woderner Törl; CV, Cresta Verda; ES, Elferspitz; PG, Pal Grande; GS, Gamspitz.

Facies interpretations (Bandel, 1969, 1972) of the tectonically isolated 'Schuppen' can establish a palaeogeographic picture restricted to the central Carnic Alps. The deposits of deep-water origin are of two types, (a) pelagic limestones and (b) pelagic limestones with interbedded calcareous turbidites (redeposited or allodapic limestones of Meischner, 1964).

PELAGIC LIMESTONES WITH RARE REDEPOSITED BEDS

Description

Pelagic limestones associated with rare redeposited beds crop out at the localities of Seekopfsockel; Hütte; Wolayer-Gletscher; Valentintörl; Rauchkofelboden (Bandel, 1972). Stratigraphically, these Devonian pelagic limestones can be divided into five facies.

Fig. 2. Deep-water limestones mostly without redeposited beds at their outcrop at the Seekopf-Sockel. The Italian-Austrian border is situated at the small hut above the Wolayer Lake. The basal massive limestone bed is of pre-Devonian age. The tectonic unit is under- and overlain by Carboniferous shales and sandstones. The tectonic unit seen above contains mainly Lower Devonian shallow-water limestones.

Grauer Orthocerenkalk (grey limestone with abundant orthocone cephalopods)

The Silurian-Devonian boundary is situated within or at the base of well-bedded grey limestones characterized by the presence of numerous orthocone cephalopods which show a constant preferred orientation (pointed ends towards the south-south-west). The limestones are biomicrites with 5–60% biogenic material (mostly ostracod, tentaculitids, and Radiolaria). Although the sediment has been strongly bioturbated the original fine-stratification is preserved. Skeletal remains often show borings and evidence of bioturbation. Burrows are preserved in their original shape and have not been compacted (Fig. 12).

'Roter Flaser- und Knollenkalk' (red nodular limestone with and without shale interbeds)

The basal grey limestones slowly grade into red limestones. In the lower part of the sequence the red limestones consist of very regular nodular layers and thin continuous limestone beds with irregular upper and lower surfaces separated by red shales. The micritic nodules and beds are generally pink to light red and make up the bulk of the rock while the mudstone matrix is dark red. This matrix may include layers of abundant crinoid fragments, some small tabulate coral colonies, cephalopods and small angular micrite pebbles. In upper parts of the sequence shaly interbeds are absent but thick shaly partings follow bedding planes, while stylolites running at an angle to bedding planes show highly irregular indented sutures that contain only little insoluble residue. The limestones are biomicrites containing up to 30% biogenic material [mostly tentaculitids, Radiolaria, and ostracods (Fig. 11)]. The red colour of the limestones is caused by low concentrations of a haematite stain. A characteristic feature of these red limestones is the presence of rounded to angular intraclasts (up to 2 cm in diameter) which have a slightly lower insoluble residue than the surrounding limestone matrix. The boundaries of the clasts are generally perfectly sharp, mostly enriched with ferruginous minerals and commonly truncate fossils (Figs 4, 5). Stylolites may or may not form part of these surfaces. Many of these nodules are compound. Some of the clasts are coated with ferromanganese crusts similar to those described by Tucker (1973a, b, 1974) from Upper Devonian sediments of the Montagne Noire. Commonly these ferromanganese crusts show the development of colloform structures. Lattices of echinoderm skeletons, chambers of calcareous Foraminifera, intraseptal voids in tabulate corals and cephalopods, the interior of styliolinid shells, the early whorls of gastropods and borings in skeletal fragments are commonly filled with ferruginous material (Figs 6, 8). Skeletal fragments may also have a light external coating but massive concentric crusts with mushroom-like projections may also occur. Bioturbation has usually destroyed all internal stratification in these limestones but abundant geopetal structures in the fillings of burrows and the inside of fossil shells are present (Fig. 12). Only large skeletal fragments of cephalopods, continuous pieces of crinoid stems, and coral colonies are preserved parallel to the original bedding plane or in growth position. All burrow structures are preserved without any sign of compaction.

Some burrow systems are filled with many concentric layers of tentaculids, oriented with their long axes parallel to the length of the burrow. The inner cavity of many burrows is still preserved and now filled with sparry calcite. Burrows showing bends or sections parallel to bedding are often partly filled with finely laminated pelletal micrites.

'Grauer Styliolinen-Flaserkalk' (grey limestone with abundant tentaculitids)

In the uppermost Emsian the red limestones change their colour to grey. Ferruginous crusts around clasts and skeletal fragments are present but in the form of pyrite, barely visible in thin section and polished sample. (The crusts are best examined after heating the rock for an hour when the pyrite is oxidized.) Another difference from the red limestones is the occurrence of at least eight graded biosparites (up to 12 cm thick) in the Eifelian. These thin graded beds are strongly bioturbated and their internal structure has been destroyed. The thicker beds show grading with large skeletal remains and clasts in the lower part and a pelsparite in the upper part (Fig. 14).

'*Kalk mit phosphatischen Knollen*' (limestone with phosphatic nodules)

The grey Eifelian styliolinid limestones are overlain by thin beds of Late Devonian age, some of which are composed entirely of tentaculitid shells (Figs 9, 10). Givetian limestones are absent. Directly above the tentaculitid biosparites there occurs a bed with numerous large phosphatic clasts comprising up to 20% of the limestone. The angular phosphatic nodules, up to 10 cm long and 2 cm high, are composed of more than 90% phosphate, the remainder being calcitic skeletal fragments.

Each clast has a layered structure with a dark inner part and lighter outer part. Skeletal fragments in this bed are commonly coated with phosphate, arranged concentrically around small particles and upon the upper surfaces of large fragments. Sometimes such coated skeletal fragments are incorporated into large crusts but never seem to comprise its centre. As well as the inorganic phosphate, a large amount of biogenic phosphate is also present (conodonts, other phosphatic problematics, Arthodira plates, inarticulate brachiopod valves, fish teeth and scales).

'*Goniatiten-Flaserkalk*'

Of all macroscopic fossil remains goniatites are the most common in these limestones. The biomicrites contain up to 50% biogenic debris, mostly radiolarian. Ferruginous coatings and ferromanganese encrustations upon skeletal remains, as well as phosphatic crusts, occur at various horizons. Intraclasts are generally absent but irregular solution surfaces parallel to bedding planes are abundant and mostly coated with ferruginous crusts.

The extinction of pelagic tentaculitids that occurred in the late Frasnian is represented by a particular horizon (1 cm of sediment).

Discussion

'Grauer Orthocerenkalk' is of very variable thickness, at one section beginning at the Silurian-Devonian boundary (Seekopfsockel), elsewhere beginning in the Silurian (Hütte; Rauchkofelboden). Limestones of various compositions and ages are overlain by these grey pelagic sediments. There is no evidence of terrestrial conditions at this disconformity, suggesting that the stratigraphic break was not due to emersion. It is believed that submarine erosion and non-deposition were responsible for these stratigraphic breaks. Areas of erosion and non-deposition are not uncommon in present-day oceans, and strong currents have been recorded from all oceanic depths (Heezen, 1959). The Blake Plateau, for instance, situated at depths between 800 and 1400 m off the south-east coast of the USA is, for this reason, largely free of Recent and Pleistocene sediments.

Organic remains found in the Devonian limestones mainly belong to animals that swam in the open sea. Very stable depositional conditions are indicated by the fact that within different layers of these limestones the shells of orthocone cephalopods show an orientation of their pointed ends toward south-south-west. The same orientation of uncoiled cephalopod shells was measured at different sections on different bedding planes of Lower Devonian limestones of the overlying facies at various stratigraphical positions. These bedding planes belong to the same tectonic unit ('Schuppe') of the Rauchkofelboden-Valentingletscher sections. The extreme uniformity of orientation indicates considerable water depth and a continuity of conditions over many millions of years. These conditions are much more typical of deep-water environments than of those found in shallow water on shelves. Here the traces of larger differences in current directions should be expected in deposits spanning such a long time. The orientation of these large shells also provides evidence for current action within the depositional areas of these and overlying limestones. The lack of compaction in the grey limestones is proved by the preservation of burrow structures and thin fossil shells in their original shape. These suggest very early cementation for the grey limestones. Transitions with overlying facies are gradational. Red nodular limestones (Roter Flaser- und Knollenkalk) occurring in the Lower and Middle Devonian of the Carnic Alps are also developed in the Devonian of the Rheinisches Schiefergebirge, Frankenwald and Thuringia (Germany), and the Montagne Noire, France (Tucker, 1974). Similar lithologies occur in the Alpine Mesozoic (the Jurassic Adnet and Ammonitico Rosso facies and Triassic Hallstatt limestones). Hollmann's (1962) interpretation of the Upper Jurassic Calcare Ammonitico Rosso Superiore at Monte Baldo in North Italy, that is, that the facies formed primarily by submarine solution, can be applied to the Devonian red nodular limestones of the Carnic Alps. The nodules are thus interpreted as solution relicts of carbonate beds formed and subsequently destroyed on the sea floor. These nodules do not show any sign of concentric growth and can not be interpreted as concretions. They are discrete clast-like remnants of former beds which themselves were largely composed of angular solution clasts. The shale surrounding the clasts must at least partly be interpreted as an insoluble residue of limestone beds dissolved completely or to a great extent.

Fossil remains are enriched on some shale bedding planes and show strong evidence of dissolution, being relicts of beds that have been dissolved save for some small angular clasts. Nodular limestones grade into 'Flaserkalk' without a change in texture or composition. This means that here solution did not in general destroy limestone beds completely but left them mainly undissolved. Only undulating, millimetre-thick shale beds, occurring above hardground surfaces, may partly be diagenetically altered clays enriched by dissolution of calcite. The limestones are characterized by the presence of angular and rounded clasts, generally showing lighter colours than the surrounding matrix and which are themselves often compound. Clay mineral contents of these limestones (nodules included) are never higher than 6% if insoluble material enriched on styliolite seams is substracted. Cephalopod shells in general are poorly preserved due to dissolution, partly caused by pressure solution during stylolite formation. Remains of shells that have been redeposited are common. Fresh shells were apparently incorporated into carbonate oozes and filled with the soft mud. During non-deposition the lime-mud was indurated and subsequently dissolved. The fossil was thus exposed to solution which destroyed most of the shell but left the internal filling and septae to be preserved in newly deposited oozes.

There are now many records of lime-mud lithification in present-day oceans between depths of 200 and 3300 m (Bramlette, Faugn & Hurley, 1959; Milliman, 1967; Fischer & Garrison, 1967; Gevirtz & Friedman, 1966; Bartlett & Greggs, 1969; Milliman, Ross & Ku, 1969).

Many indurated Recent beds are commonly intensely bored by organisms and are associated with iron and manganese oxides which may either form a light coating over the surface of the lithified sediment or may take the form of nodules and encrustations. This shows that this type of cementation is active where deposition is virtually absent over a very long period of time. Very slow sedimentation and solution of calcium carbonate were the evidence on which Garrison & Fischer (1969) interpreted the Adnet limestone (Jurassic) as deposits formed in areas with depths up to 4100 m. Continuing sedimentation into progressively deeper water finally resulted in the deposition of radiolarites where calcium carbonate was dissolved (4500–5000 m). In the Devonian sections of the Carnic Alps radiolarian cherts occur in association with the red 'Flaserkalk' facies to the east of the sections discussed in this paper (i.e. at the Hohe Trieb, Schönlaub, 1969; at Findenig, Pölsler, 1969) and Monte Zermula.

The red colour of the limestone is due to disseminated haematite and is probably of diagenetic origin. It may have been derived from yellowish to light brown goethite that dehydrated rapidly during diagenesis into red haematite (Berner, 1969). Red colouration in the pelagic Devonian limestones of the Carnic Alps was interpreted by Brinkmann (1935) as typical for rapid subsidence and grey colours of the Kellerwand (shallow-water facies) were connected by him with low rates of subsidence. Normally traces of haematite in limestone are chemically difficult to detect, but in and on the rim of clasts as well as in and on skeletal fragments ferruginous material may be enriched (Figs 5, 6, 8). Hinze & Meischner (1968) described migration of iron-salts to the sedimentary surface of Recent sediments in the North Adriatic. pH and Eh conditions in the bottom muds, influenced by decomposing organic material and the oxygen consumption of burrowing organisms, cause migration of iron-salts towards the surface where oxidizing conditions prevail. A similar mechanism may have concentrated iron oxides on the outside of clasts and on solution surfaces in the limestone. Commonly, ferromanganese crusts on solution clasts show a development of colloform structures (Fig. 4) which were interpreted by Tucker (1973a, b, 1974) as diagenetic alterations of originally undulating crusts. Ferromanganese nodules, as described by Jenkyns (1970) from Jurassic beds, were not encountered, but Upper Devonian crusts from the Montagne Noire (Tucker, 1973a, b) are quite similar to those found in the pelagic limestones in the Carnic Alps from the lowermost Devonian into the Lower Carboniferous.

'Grauer Styliolinen-Flaserkalk' was deposited in similar conditions to the red limestones. The grey colour coincides with the occurrence of a few thin redeposited beds (see below).

After a period of non-deposition that lasted the whole Givetian and earliest Frasnian, thin layers consisting purely of tentaculitid shells formed locally (Figs 9, 10). The thin shells acted as nuclei around which acicular cement grew. Later on the acicular cement was transformed into large angular calcite crystals which contain ghosts of the original needle-like crystal growth. These layers resemble Recent cemented pteropod oozes (Milliman *et al.*, 1969; see also Tucker & Kendall, 1973).

The overlying bed with numerous phosphatic clasts and fossils formed under extremely slow rates of deposition. Phosphatic clasts and encrustations commonly follow hardgrounds recording long stratigraphical gaps (Jaanusson, 1961) or shorter ones (Bromley, 1967). In large nodules or crusts the basic layer grew on the surface of the sediment while the upper ones enlarged the crust in height and width. Material migrating within the sediment may well have concentrated phosphatic material around certain nuclei in concentric layers, but concentric coating of smaller fragments and one-sided coating of larger particles suggest precipitation of phosphate at the sediment-water interface. Crusts around skeletal fragments did not act as nuclei for the phosphatic growth of the larger clasts. Probably phosphatic material was delivered by upwelling carbon dioxide-rich waters.

At the Findenig, to the east of the sections considered here, 4 m of Givetian slump deposits occur (Pölsler, 1969), while at the Hohe Trieb, the Givetian is represented by 8 m of graded limestone within a sequence of radiolarites (Schönlaub, 1969). At the Poludnik, further east still, the Givetian is absent or very thin (Skala, 1969).

Sediments of the upper Frasnian are of particular interest and often contain lithologically curious layers (Buggisch, 1972). Buggisch studied the Kellwasserkalk in many parts of the Hercynian Geosyncline and found a very widespread occurrence of limestones rich in conodonts, tentaculitids, ostracods, goniatites, orthocone cephalopods, and fish remains (especially of pelagic Arthrodira which at that time were distributed world-wide). These fossils also characterize the 'Kalk mit phosphatischen Krusten' from the Carnic Alps. However, within the Kellwasser limestones, bioturbation is absent and there are no benthonic organisms, while in the Frasnian limestones of the Carnic Alps, corals, gastropods, bivalves, and inarticulate brachiopods are present.

With continuous sedimentation from the latest Frasnian into the late Famennian 'Goniatitenkalk', the record of deposition at these sections ends, but it is probable that pelagic sedimentation continued into the Early Carboniferous.

PELAGIC LIMESTONES WITH COMMON REDEPOSITED BEDS

Description

Devonian pelagic limestones associated with limestone turbidites occur to the west of the Plöckenpass (Woderner-Törl, Valentin-Alm, Cellon, Cresta di Colinetta) and to the east (Freikofel, Gamsspitz, Pal Grande, Pizzo di Timau, Elferspitz). Details are given in Bandel (1972).

'*Grauer Styliolinen-Flaserkalk mit turbiditischen Einlagerungen*' (Grey tentaculitid limestone with redeposited beds)

Grey pelagic limestones interleaved with graded, coarse-grained beds range from the Siegenian (Cellon) to the middle Eifelian (Woderner-Törl, Cellon, Freikofel). Gradations with 'roter Flaserkalk' are observable in the Lower Devonian of the Elferspitz. Gradations to 'grauer Orthocerenkalk' are present in the lower Emsian of the Woderner-Törl and the Siegenian of the Cellon.

The grey pelagic limestones are biomicrites containing between 10 and 30% biogenic material (mostly Radiolaria and tentaculitids). Apart from their colour the limestones are very similar to the 'roter Flaserkalk' and are particularly rich in intraclasts measuring up to 2 cm in diameter, giving the rock a vaguely nodular appearance. Iron sulphide coatings occur around clasts and skeletal fragments. Internal stratification has been completely destroyed by bioturbation. In upper Emsian and lower Eifelian deposits intraclasts are less common but irregular solution surfaces are found in great numbers. Authochtonous domed-shaped coral colonies, with diameters up to 20 cm, are found attached to the hardground surfaces.

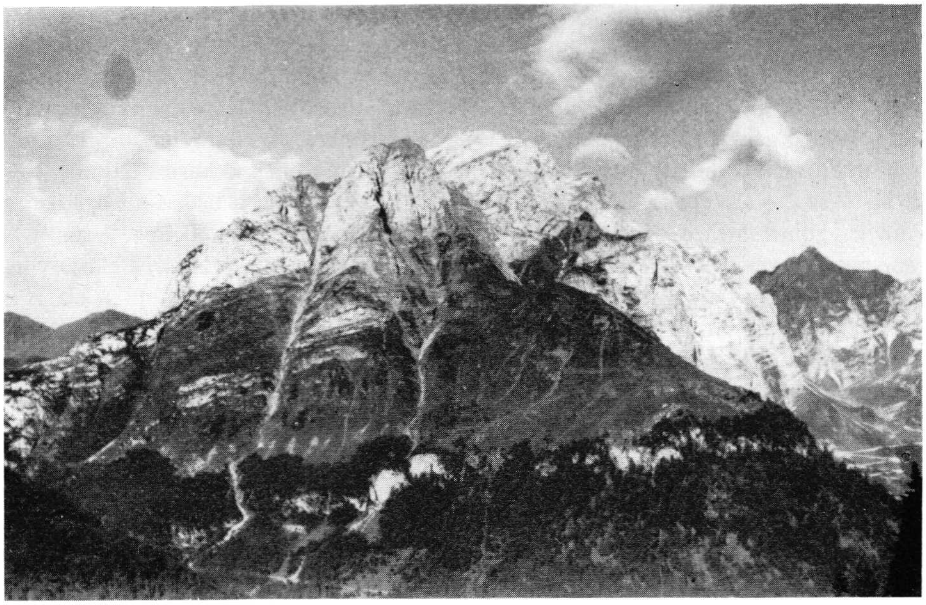


Fig. 3. Deep-water limestones containing redeposited beds at their outcrop at the Cellon, seen from the Polinik.

The grey, 1–200 cm thick redeposited beds, rich in bitumen and poor in insoluble residue (below 1%, mostly consisting of authigenic quartz crystals), are distributed at random in these sections. They are composed of coarse-grained material, mostly echinoderm fragments, and exhibit good graded bedding. Other beds are composed of more diversified skeletal remains and may contain a basal layer of clasts, of the same type as those in the interbedded pelagic micrites. Clasts, large fragments of corals, stromatolitic algal remains, stromatoporoids, thick-shelled brachiopods, bryozoan colonies and other organic fragments disturb the grading at the base of a unit, while grading in upper parts is clearly visible. All these beds have been invaded by boring and burrowing organisms from above. Bioturbation penetrated to a maximum depth of 10 cm with increased intensity in the uppermost centimetres. Beds thinner than 10 cm are bioturbated to such an extent that they can only be detected with difficulty; those thinner than a few centimetres often only survived as coarse-grained burrow fills.

'Lithoklastkalk'

From the middle Eifelian to the late Frasnian only graded beds, one on top of the other, were deposited in these sections (Woderner-Törl, Cellon, Freikofel, Pizzo di Timau). Gradational beds from the lower basic tentaculitid limestones to the 'Lithoklastkalk' show higher density of graded beds with progressively fewer micrites between them. First biomicrites disappear, later pelmicrites and in some Givetian and lowermost Frasnian sections (Cellon, Freikofel) a climax is reached when even pelsparite disappears. From there on the tendency is reversed toward more fine-grained intermissions. In the late Frasnian a change in facies took place, accompanied by a change of colour from grey to red.

Skeletal fragments in the 'Lithoklastkalk' commonly have micritic envelopes. Composition of these beds is similar to that of the graded limestones interbedded with the tentaculitid limestones, apart from a higher content of pellets. The lithoclast limestones are bio-pelsparites with 10–50% pellets and 1–70% biogenic material of which 0–70% are echinoderms and 1–10% calcispheres. A characteristic feature of these limestones is the presence of large lithoclasts found at the base of almost every one of these 20–200 cm-thick graded beds. The basement for a bed is always formed by an irregular surface which is also the top of the graded bed below. Usually the lower part of a bed is rich in echinoderm (crinoid) fragments and large clasts which may be rounded (if smaller than 2 cm in diameter) or angular. The angular clasts are up to 6 cm thick, up to 50 cm wide and long, and never show any preferred orientation in the basal layers of these graded beds. Most clasts are bored parallel to the short sides. The borings may penetrate the whole thickness of a clast or continue only 1–2 cm into it. Fillings of these tunnels often show geopetal structures which are in accordance with stratification of the sequence. The internal structure of the clasts consists of stratified layers of pelmicrites or pelsparites parallel to the long sides and vertical to the thin edges. Except for bioturbation no deformation of stratification within clasts was noted. The lower part of each lithoclast bed is not graded because of the variable size of components, but higher up, echinoderm fragments grade into more pelletoidal sediment containing numerous calcispheres and Radiolaria. In the upper Eifelian some irregular bedding surfaces at the top of graded layers, and lithoclasts at the base of the next graded layer, are coated with phosphatic crusts and impregnations. Phosphatic material surrounds clasts, and clasts within clasts, as a thin rim; it forms many layered nodules, fills spaces within skeletal fragments, boreholes in clasts, and coats hardground surfaces (Fig. 15).

At the Woderner-Törl section spaces between lithoclasts at the base of a graded layer are filled with numerous valves of inarticulate brachiopods.

'*Bunter Radiolarienkalk*' (vari-coloured limestone with numerous Radiolaria)

In the upper Frasnian and the lowermost Famennian biomicrites with 5–10% biogenic material are interleaved with graded beds (mostly up to about 15 cm in thickness).

In the micrites, apart from characteristic radiolarians, numerous calcispheres, echinoderms, ostracods, small gastropods, cephalopods and trilobites are present. The limestone colours are variable (grey to light red and pink and brown) and clasts of these colours (and black also) occur at the base of the interbedded graded limestones. Biogenic material, clasts and hardgrounds commonly show ferruginous impregnations and may be encrusted with ferromanganese oxide. The graded pelsparites usually overlie an irregular surface with many sharp and rounded projections and tunnels leading down into the micrite (Fig. 14). Famennian pelagic micrites contain numerous strongly bioturbated pelsparite and pelmicrite beds, always less than 2 cm thick. Some of these limestones ('Flaserkalk mit *Stromatactis* Strukturen', Pal Grande) contain numerous bedding-parallel cavities (up to 2 cm high) filled with fibrous calcite that grew from all walls. Most of the cavities are shaped like flattened cushions or tubes. They have a smooth floor consisting of laminated micrite and an irregular roof. Often they form large bodies along bedding planes and resemble sheet cracks. However, even if they cover more than a square metre, they do not form a continuous cavity but rather a network of communicating tubes and cushions with pillars and walls between them. In smaller cavities a continuation of sediment-filled uncompacted burrow tubes with fibrous calcite-filled cavities can be seen. Commonly, vertical tunnels may lead from one oval cavity into another situated above, or horizontal tunnels may connect neighbouring cavities.

'Goniatiten-Flaserkalk'

Some beds of the micrites below this facies contain numerous goniatites (Cresta di Colinetta) and can be considered as gradational from 'Radiolarien-Flaserkalk' to the 'Goniatiten-Flaserkalk'. In the uppermost Famennian (Pal Grande) and the Lower Carboniferous (Cresta Verde, Colinetta di sopra) limestones characterized by goniatites are similar to those of the Fammenian from Wolayer See.

With deposits of limestone in this facies the carbonate sedimentation that characterized the pre-orogenic Palaeozoic history of the Carnic Alps came to an end.

In the goniatite limestones biogenic material, with a predominance of radiolarians, comprises up to 50% of the rock. In other respects the fauna is similar to that of the limestones below except for the presence of more benthonic organisms such as corals, Foraminifera and crinoids. Many biogenic fragments are encrusted with phosphate and in other layers with ferromanganese oxides. Clasts are rare, and graded biosparites are absent. Irregular bedding-plane surfaces are commonly encrusted and impregnated by ferruginous material. Adjacent skeletal remains may be strongly corroded or well preserved. Irregular hardground surfaces (relief up to 4 cm) are overlain by argillaceous layers. From such surfaces, tunnels with clay-coated walls extend vertically into the sediment.

Discussion

'Grauer Orthocerenkalk', similar to that of the Wolayer lake sections but interleaved with redeposited beds, is characteristic of the Lower Devonian up to the base of the 'Grauer Styliolinen-Flaserkalk'. The environment of deposition of the styliolinid limestone facies must have been very similar to that of the 'roter Flaserkalk' apart from the frequent incursions of turbidity currents.

The fine-grained texture of Liassic grey pelagic limestones was considered by Jurgan (1969) to indicate deposition in a quiet milieu without current activity. In the autumn of 1969, on a field trip in the northern Adriatic Sea, D. Meischner demonstrated to us that in Recent sediments originally coarse-grained carbonate material may be transformed into fine lime muds by the activity of dissolving and sediment-ingesting organisms. This mechanism of biological maceration of skeletal particles was active in the Devonian pelagic limestones of the Carnic Alps. Strong bioturbation, destroying an original fine stratification, is indicative of the existence of a rich endobenthonic fauna. Broken skeletal fragments and shells are bored to such an extent that only a thin outer skin has survived; this is a further indication of the action of biological grinding of skeletal remains to yield the fine-grained texture that characterizes these beds (Figs 6, 7).

Fabricius (1961) explained the difference in colour between Liassic red and grey faces in pelagic limestones as an effect of different sedimentation rates, grey colours produced under high rates of sedimentation, when complete decomposition of organic matter could not take place. The abundance of solution clasts suspended in the micritic matrix of limestones found between redeposited beds in the Lower Devonian sections of the Carnic Alps suggests an alternative interpretation. History of deposition started

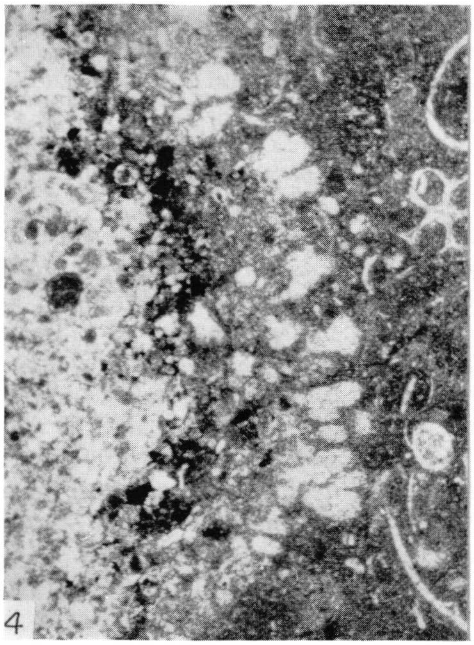


Fig. 4. Solution clast with club-like overgrowths. × 30. Thin section. (Frasnian of Hütte Section.)

Fig. 5. Solution clast with ferruginous coating. × 30. Thin section. (Emsian of Seekopfsockel Section.)

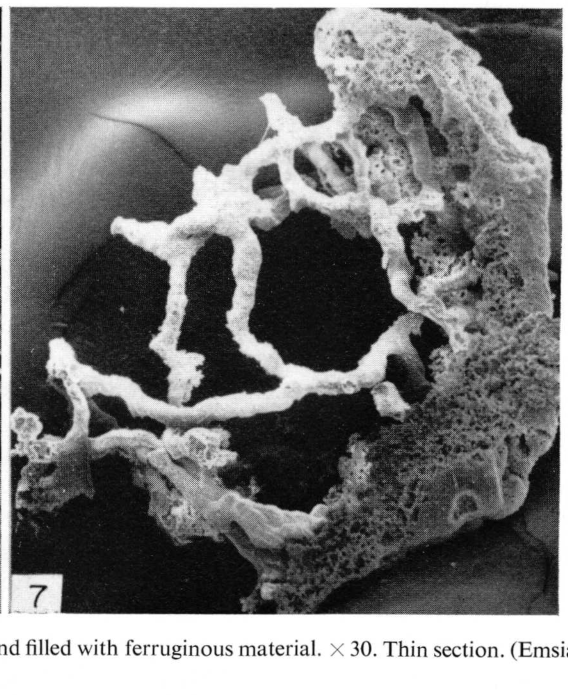


Fig. 6. Thick fragment of shell bored and filled with ferruginous material. × 30. Thin section. (Emsian of Wolayer Törl.)

Fig. 7. Dissolved crinoid ossicle with clay-filled borings. × 45. Gold-coated and photographed with the stereoscan electron microscope. (Lower Carboniferous of Cresta Verde.)

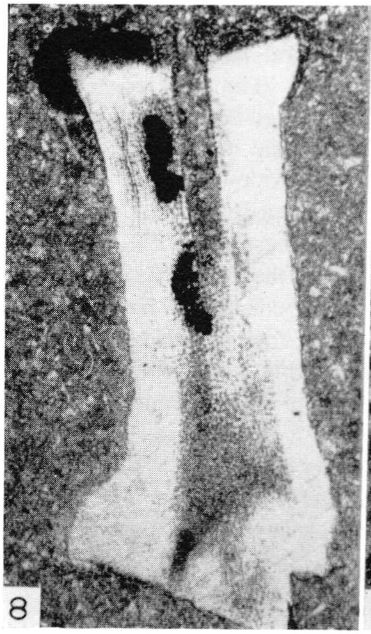
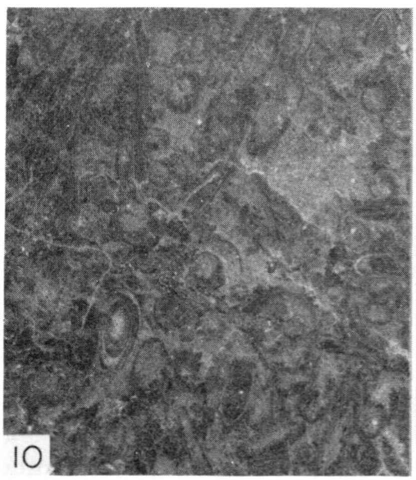


Fig. 8. Crinoid fragment with ferruginous lattice-fillings and ferromanganese crust on the outside. $\times$30. Thin section. (Eifelian, Hütte Section.)

Fig. 9. Pure tentaculitid biosparite consisting of the shells and their overgrowths. $\times$30. Thin section. (Frasnian, Wolayer Gletscher.)



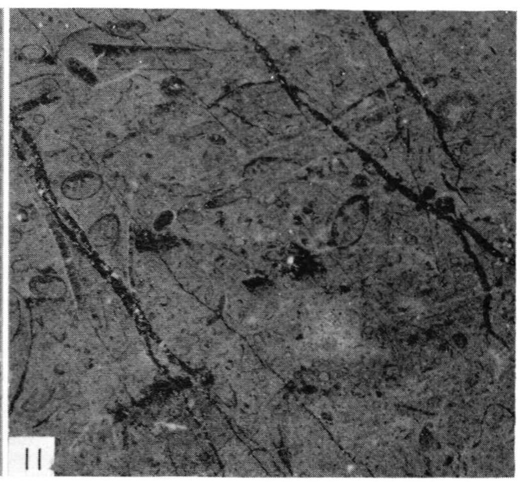


Fig. 10. Tentaculitid biosparite. Negative print from acetate peel. $\times$30. (Frasnian, Wolayer Gletscher.)

Fig. 11. Typical 'Styliolinen-Flaserkalk' biomicrite. $\times$30. Acetate peel. (Eifelian, Seekopfsockel Section).

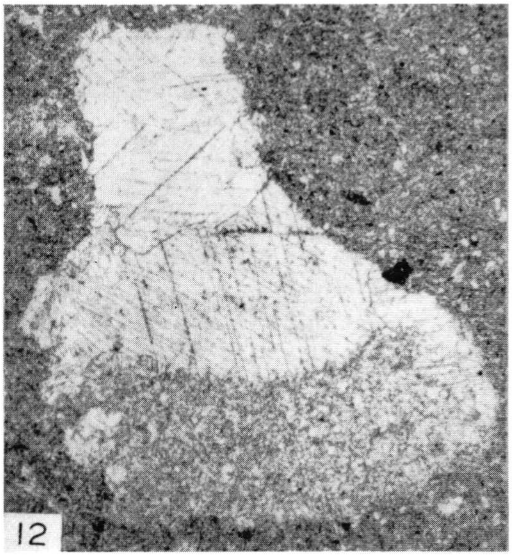
here with sedimentation of lime ooze followed by a long time of non-deposition. Subsequently, bioturbation, induration and dissolution followed each other and left only solution clasts, preserved when new deposition began. This left enough time for oxidation and decomposition of all organic compounds. The grey colours of this facies must therefore be related to the influence of redeposited beds, and it is suggested that their deposition resulted in an enrichment of organic material to the bottom sediments. This would cause a transformation of iron-oxides into sulphides which, along with the bituminous material, provide the grey pigment of these rocks.

Recent sediments in many respects resembling the limestone turbidites from the Carnic Alps have been described by Davies (1968) from the abyssal Gulf of Mexico. In these deep-sea oozes 2–120 cm thick, light carbonate beds occur. They are graded, show an erosive base, often contain micritic pellets at their basal layers, are only bioturbated in the uppermost section, and are separated from each other by pelagic oozes. The thickness and composition of these beds is variable and they contain dominantly benthonic shallow-water remains mixed with few pelagic components.

All these characteristics can be seen in graded beds in Devonian sections. It can therefore be concluded that in their origin they parallel those beds found in modern deposits of the Gulf of Mexico. The skeletal fragments of the graded beds from the Gulf of Mexico derive from the shallow-water area of the Campeche Bank and were carried in suspension currents to abyssal depths. Close to their source area they are frequent and thick, away from it they are more scarce and thin. Turbidity currents move fast and far and cover distances up to 500 miles in the Gulf of Mexico.

The origin of skeletal material in the redeposited beds of the Carnic Alps is easily recognized. They are remains of benthonic organisms clearly of shallow-water origin as found in the same tectonic unit of the central Carnic Alps at the same stratigraphic position (Fig. 13). Indices of derivation from shallow-water environments are skeletal materials with micritic envelopes which suggest water depth no greater than 60 m (Swinchatt, 1969; Bathurst, 1967; Winland, 1968). Besides this evidence, skeletal remains of many organisms characteristic of reef, fore-reef and back-reef deposits can be determined from redeposited beds (e.g. crinoids, corals, algal crusts, oncolites, calcispheres, brachiopods and bryozoa). The composition of resedimented beds reflects the history of shallow-water deposition, where in Early Devonian times crinoid limestones were more common whereas in Middle Devonian times pelletoid sediments were more abundant (Bandel, 1969, 1972).

The erosive force of a turbidity current diminishes with the distance from the source area, a fact that is well documented in pelagic deposits from the Carnic Alps. Strong erosive forces were active at the deposition of the 'Lithoklastkalk' where the largest components are found at the base of graded beds. Strong currents must still have been active during the deposition of the Lower Devonian graded beds at the Cellon section because they are rather coarse-grained at the base with unsorted skeletal fragments and large lithoclasts. At the Lower Devonian Gamspitz section, however, lithoclasts are not as common and graded beds are mainly composed of well-sorted crinoid fragments. In the Lower Devonian of the Woderner-Törl section redeposited beds make up less of the rock column than in previously mentioned sections. Emplacement of Eifelian resedimented beds occurred furthest away from the source area at the Wolayer Lake sections. Here the admixture of pelagic components is prominent but currents were still strong enough to pick up solution clasts and skeletal fragments from the sea bottom and incorporate them into the basal part of resedimented beds.



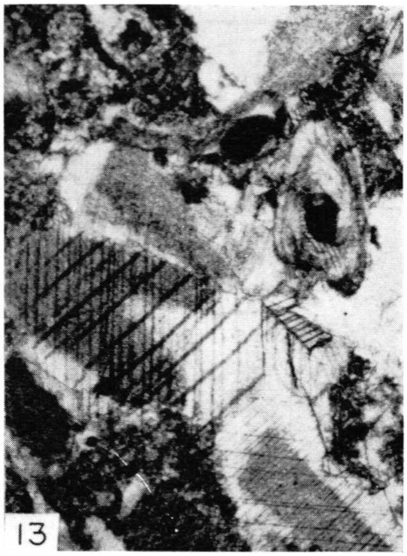


Fig. 12. Burrow filled at the bottom with fine-grained sediment and at the top with calcite spar. ×30. Thin section. (Emsian, Cellon Section.)

Fig. 13. Redeposited bed whose basal part shows mainly echinoderm remains with their overgrowths forming most of the sparite matrix. ×30. Thin section. (Eifelian, Freikofel Section.)

Meischner (1964) introduced the term 'allodapic' for those limestones emplaced by turbidity currents. The beds found in the Carnic Alps fit into his definition of 'allodapic' limestones if it is somewhat broadened. Differences between Meischner's examples of the Kulmplattenkalk and Devonian Flinz from the Rheinisches Schiefergebirge can be seen in that with the limestones here described: (a) the area of deposition was not poorly supplied with oxygen but showed oxidizing conditions; (b) the authochtonous pelagic (basinal) sediments interbedded with the turbidites were carbonate oozes, and not clays; (c) the basinal deposits were not soft but largely cemented and thus inhibited erosion by the turbidity currents. Sea-floor solution produced indurated pelagic limestone clasts, which were subsequently incorporated into the turbidity-current deposits. (d) Rich benthonic faunas were present in the carbonate oozes of the Carnic Alps, which led to bioturbation of the upper parts of the limestone turbidites.

Similar graded limestone beds composed of shallow-water carbonate particles have been described by Winterer & Murphy (1960) from the Silurian of Nevada, Carozzi & Frost (1966) from the Silurian of Indiana, Tucker (1969) from the Devonian of Cornwall, Garrison & Fischer (1969), Jurgan (1969), and Flügel & Pölsler (1965) from the Jurassic of the northern Alps.

The upper parts of graded beds of the 'Lithoklastkalk' facies were exposed to sea water until emplacement of a new bed by turbidity currents. During these very long time intervals hardgrounds were formed due to lithification, solution and boring. This early diagenetic cementation in the sense of Zankl (1969) created a bottom sediment with more than one indurated layer, whose upper level consisted of more or less loose slabs. These could be picked up by the following turbidity current and incorporated into the lower part of the newly deposited bed. Water had access from almost

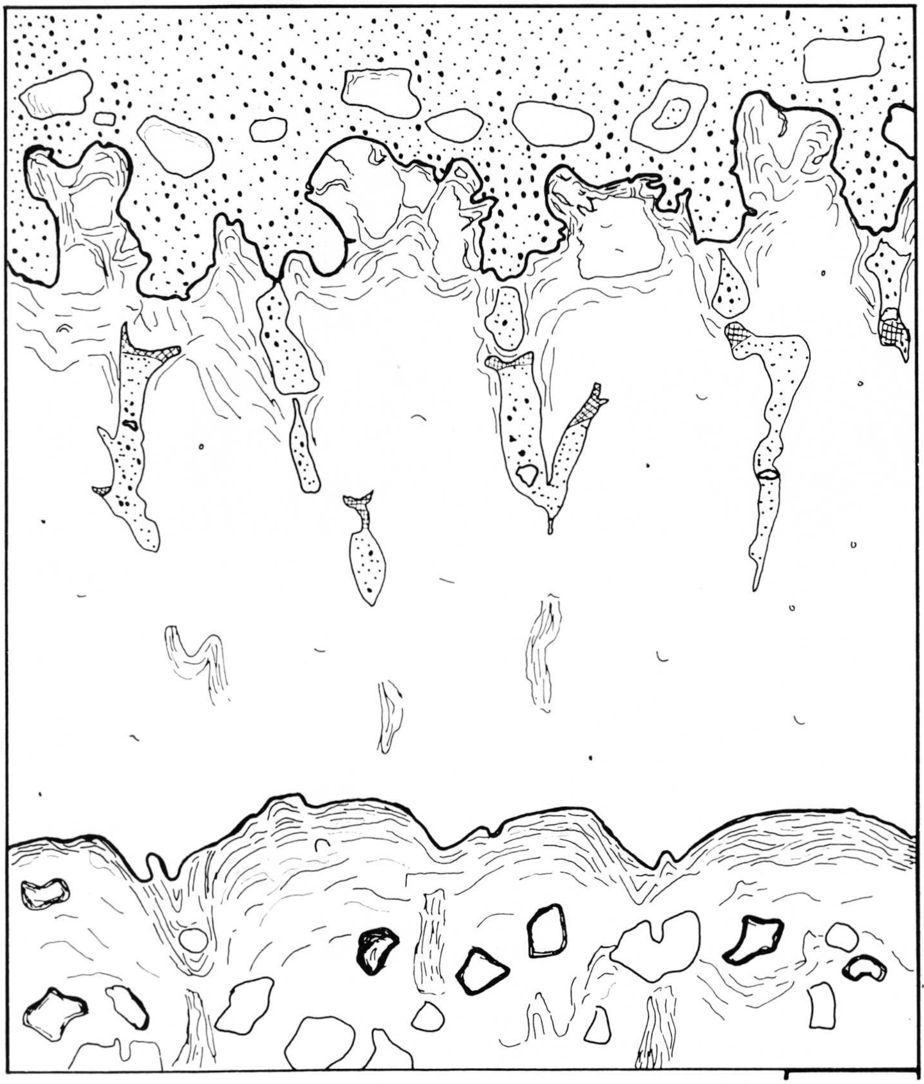


Fig. 14. Hardground surface preserved by redeposited bed. The upper surface is enriched with ferruginous material. The bed below is bioturbated and contains no solution clasts. The base is formed by another hardground surface encrusted with more ferruginous material than the upper one. Here the limestone also contains abundant solution clasts with thick encrustations of ferruginous material. Scale at the base = 1 cm.

all sides to the surface of these slabs as documented by boring and encrustation with phosphatic material. Sometimes solution and cementation continued to such an extent that the cemented upper slab layer itself was composed of earlier solution fragments (Fig. 15). Clay minerals and ferruginous materials were not enriched on the solution surfaces because (as analysis shows) only up to 0·2% of the rock consists of insolubles with most of it in the form of authigenic quartz crystals. In this respect

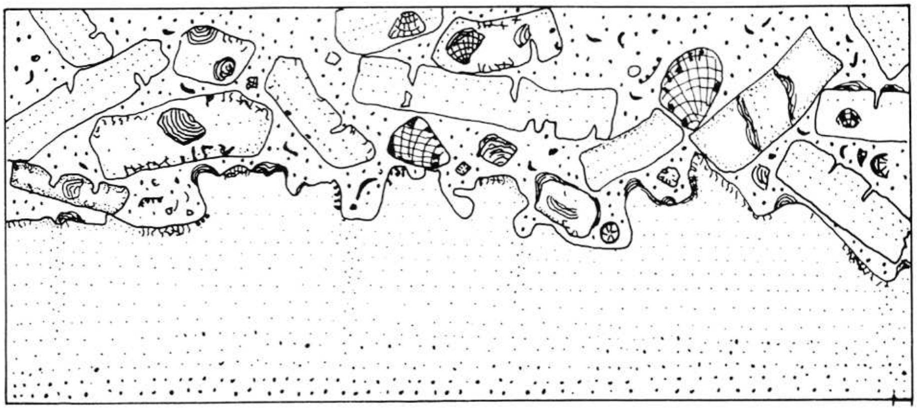


Fig. 15. Base and top of a redeposited bed in the 'Lithoklastkalk' sequence. The angular clasts are bored and encrusted by phosphatic material. Borings and encrustations are also seen on the hard-ground surface and in and on coral and stromatoporoid fragments. Many clasts are compound. Scale at the lower right side = 1 cm.

the contents of insolubles reflect the nature of the source area. Rocks from shallow-water environments contain 0·02–0·6% insolubles comprising mainly quartz crystals.

The continuation of very strong solution and the gradation into micritic pelagic sediment in the stratigraphic column in the Emsian and the Frasnian together with the interleaving radiolarites in sections similar to these in the east (Schönlaub, 1969) indicate formation of the 'Lithoklastkalk' in deep water. However, scattered colonies of stromatoporoids and tabulate corals attached to hardground surfaces may be counted as contrary evidence (H. Flügel, personal communication).

In the upper Frasnian a rapid change in the type of deposition took place, which was directly linked with the submergence of the shallow-water platform which had been the source area for the redeposited beds. From then on resedimented layers became of minor importance. However, quite a lot of thin biosparitic beds are found within the pelagic uppermost Frasnian and lowermost Famennian. The source area of these beds must have been further away at that time than the carbonate platforms active until lower Frasnian times, because the redeposited beds are thinner and show in their composition some admixture of pelagic components. The micrites between the resedimented layers compare well with the Lower Devonian 'roter Flaserkalk' in being composed mainly of differently coloured solution clasts in a matrix slightly richer in clay minerals. Therefore these sediments must be considered as deep-water deposits. Radiolarites within limestones of this composition and age are developed at the Hohe Trieb.

Limestone deposits in the Carnic Alps are continuous into the Lower Carboniferous and may only grade into radiolarites east of these sections. In small tectonically dislocated outcrops, Lower Carboniferous limestones, probably deposited on the former shallow-water platform, give way to 'Goniatiten-Flaserkalk' that shows all features so far described for pelagic limestones (solution-surfaces, rich pelagic fauna, ferruginous crusts). This indicates a subsidence after Frasnian times into considerable depth.

FAUNA OF PELAGIC LIMESTONES

Planktonic organisms

The group 'Calcisphaera' probably includes a number of spherical microfossils of quite different systematic affinity. The more simple forms occur in the pelagic limestones, but the most varied types are found in shallow-water facies (Bandel & Vai, in preparation). Calcitized Radiolaria, as representatives of pelagic free swimming Protozoa which originally had siliceous skeletons, may be found in all the Devonian pelagic-limestone facies in great abundance. They also form the only pelagic component in the uppermost layers of many graded beds in the 'Lithoklastkalk'-facies. Radiolaria were probably the main source of silica for the radiolarites, although recrystallization has commonly obliterated shell outlines (Fig. 16).

By analogy with modern forms, some of the small gastropods (few mm length) may also have had a free-swimming mode of life. The valves of most larval bivalves of today do not generally mineralize except near the end of their larval life. Therefore the small fossil bivalve shells found probably belonged to the benthos. Cephalopods are represented by orthocone shells in the Lower Devonian, orthocone and coiled shells in the middle Devonian and mainly coiled shells in the Upper Devonian. The 'Grauer Orthocerenkalk' is especially rich in orthocone cephalopods, which are also commonly found in the 'Roter Flaserkalk'. Here shell lengths of 1 m were seen. Usually goniatite shell diameters measure only up to a few centimetres and only rare specimens measure over 10 cm. Most of the orthocone nautiloids characteristic of this facies possessed smooth slender shells.

Smooth and ribbed small tentaculitids (*Styliolina, Nowakia* and others) were an important constituent of the pelagic deposits until their extinction in the upper Frasnian. They probably lived like the recent pteropods as free-swimming organisms in the high seas, and accumulations of their tests formed a sediment very similar to indurated modern pteropod oozes (Figs 9, 10; see also Tucker & Kendall, 1973). Their extinction must have produced a great change in marine planktonic fauna because no equivalent faunal element seems to have taken their place in the Late Devonian and Early Carboniferous. Ostracods with ornamented valves (the Entomozoidea) appeared in the Late Devonian and were probably planktonic.

Vertebrate remains in the form of fish teeth, scales, fins, spines and skeletal plates are found in all stratigraphic situations in the sections. Remains of Arthrodira are especially common in the Frasnian phosphate nodule layer. At that time remains of Arthrodira are found on a world-wide scale indicating a pelagic way of life for these fishes. Selachian teeth occur from the Famennian onwards, indicating common occurrence of pelagic sharks since that time.

A planktonic way of life probably has to be considered for the unknown animal that carried conodonts as skeletal elements, otherwise they would not be of such value to stratigraphy (for Carnic Alps, see Bandel & Schönlaub, in preparation).

Benthonic organisms

Shells of multicameral Foraminifera with calcareous shells are common but never abundant. Simple agglutinating Foraminifera are present in great numbers and can be used for correlation (Bandel, 1972). They are interpreted as representatives of the

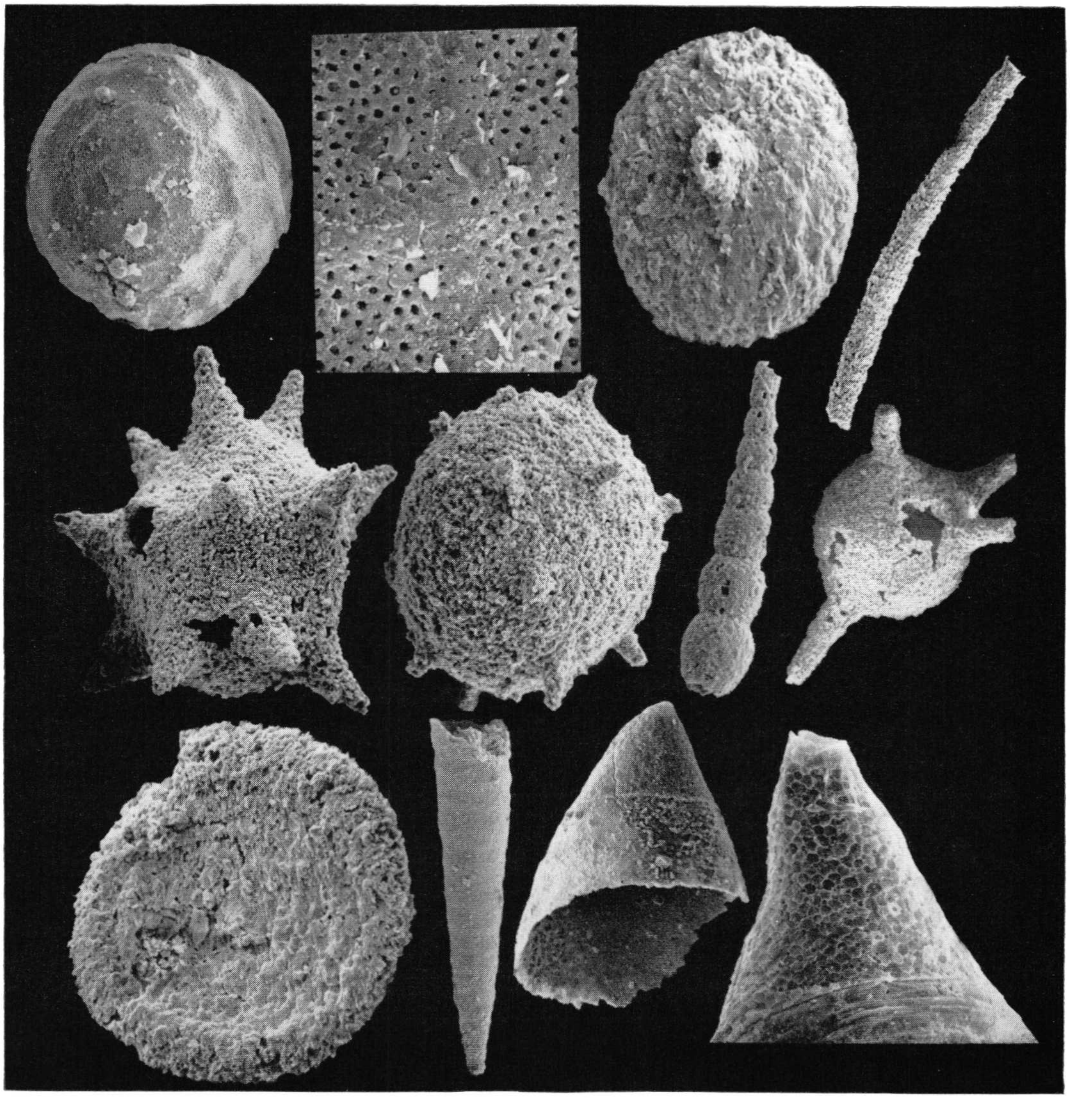


Fig. 16. Scanning electron micrographs of organisms typical for Palaeozoic deep-water limestones. In the upper line from left to right: Radiolaria (× 120), detail of surface (× 300), agglutinating Foraminifera (*Lagenammina*) from the Lower and Middle Devonian (× 102), *Hyperammina* as found in the whole stratigraphial section (× 120). Organisms shown in the middle line all represent agglutinating Foraminifera: *Thurammina* from the whole stratigraphical section (× 60), *Psammosphaera* from the whole stratigraphical section (× 60), *Hyperammina* from the Frasnian to the Lower Carboniferous, *Astrammina* from the whole Devonian. In the lower line: *Ammodiscus* (Foraminifera from the Middle Devonian and Frasnian), *Hyperammina* from Upper Devonian and Lower Carboniferous (× 60), inarticulate branchiopod (cf. *Torynelasma*) from the Lower Devonian to Eifelian (× 120), and apex of another brachiopod (× 240).

vagile and sessile benthos. Free-moving forms lived in the uppermost levels of the substrate and perhaps accompanied burrowing animals further into the sediment. Others encrusted solution clasts and skeletal fragments lying on the sea floor.

Colonies of stromatoporoids and tabulate corals found suitable bottom substrates for settlement even in deeper waters when hardground surfaces were available. Here they settled in single colonies living scattered randomly on the sea floor at great distances from one another. Single polyps of rugose corals (*Syringoxon, Enterolasma*) occur. Some species of these small rugose corals show a very wide stratigraphic range indicating a very uniform living habitat for a long time. They have been recorded in similar Devonian pelagic limestones from the Bosporus to North Spain (Kullmann, personal communication).

Small bivalves and gastropods settled on the bottom of the sea during the whole depositional history of these limestones. As in Recent deep-water oozes they may represent a small-sized fauna with many species.

Inarticulate brachiopods with conical shapes (cf. *Torynelasma*) were common up to the Eifelian (Fig. 16), and *Lingula*-shaped forms are frequent in the whole section, particularly so in the Frasnian.

The trilobites are mostly smooth forms belonging to the Proetida family and the free-swimming spinose varieties are missing. The trilobites present had large eyes and apparently roamed across the sediment. Ostracods are one of the major biogenic benthonic components of these rocks. A rich silicified fauna was found in the lowermost to middle Devonian limestones of the Wolayer-lake sections (Bandel & Becker, in preparation). Very little species change was noted for that time which again indicates very stable environmental conditions for these many millions of years.

Crinoids must have settled on the bottom substrate in a random fashion similar to the corals, but with large distances between single animals. Sometimes large parts of the skeleton of one crinoid are found still connected, but usually single fragments are scattered about, probably as a result of bioturbation.

About 50% of the larger skeletal fragments in the pelagic limestones are bored (Figs 6–8). The range in size and shape of the borings suggests that a variety of organisms were responsible, either making tubes only a fraction of a millimetre across, or up to 1 cm wide. Communicating tunnels of equal width and bottle-shaped holes with only one exit reflect the extremes in shape. It is also likely that many different animal groups have been involved in the bioturbation which is prevalent throughout the pelagic limestones.

RECONSTRUCTION OF THE DEPOSITIONAL ENVIRONMENT

Far from the shallow-water platform purely pelagic deposits accumulated at depths between 200 and 4000 m. Periods of carbonate deposition were followed by times when sedimentation was virtually at a stand-still. Rich benthonic life destroyed all stratification and infaunal organisms produced open burrow systems that aided cementation during non-depositional intervals. After induration, bottom water rich in carbon dioxide and undersaturated with calcium carbonate led to sediment dissolution, aided by boring organisms.

Relicts of dissolved beds were coated by ferruginous crusts and incorporated into the succeeding sediments during renewed deposition; or, if non-deposition continued, were rendered into a clay residue. Hardgrounds were colonized by randomly distributed encrusting Foraminifera, corals and crinoids. Foraminifera, thin-shelled gastropods and bivalves, ostracods and trilobites lived on the sea floor. Single rugose corals and brachiopods formed the sessile benthos of soft substrates. The shells of organisms living in the upper layers of the sea upon their death formed a major part of the sediment, but were partly ground to small unrecognizable particles by the activity of the benthos.

Close to the shallow-water carbonate platform, periodic turbidity currents derived from these banks covered the sea-floor under a layer of sediments. These coarse-grained beds contained much more organic material than the extremely slowly deposited pelagic muds. Benthonic animals only occupied the top few centimetres of turbidites so that organic material was preserved, which altered previously formed ferruginous oxides into iron sulphides.

In upper Eifelian times, sedimentation of fine-grained pelagic oozes ceased, owing to the effects of current activity and dissolution of slowly deposited carbonate material. Only thick beds of shallow-water carbonate brought into this environment by turbidity currents withstood dissolution. Thickness changes from the Cellon (140 m) to Freikofel (94 m) to Woderner-Törl (34 m) to Wolayer Lake (less than 1 m) reflect distances from the source area. Cold up-welling waters undersaturated with calcium carbonate caused strong dissolution of the upper parts of graded turbidite beds. These beds were cemented in layers up to 6 cm thick and then broken up later along cracks with the aid of boring organisms. Soft layers between indurated ones were more easily dissolved leaving great solid slabs on the bottom which were colonized on all sides by boring organisms, colonial stromatoporoids and tabulate corals. These slabs were sometimes encrusted with phosphatic material, possibly supplied by currents. Endobenthonic animals, with the exception of boring organisms, did not find a very suitable substrate for life.

With the disappearance of reefs on the shallow-water platform in the late Frasnian, slow subsidence of the platform occurred and from this time turbidity currents became less important. During most of the Famennian, shallow-water material still contributed to deposition to some extent but supply of this material ceased during the latest Famennian. Furthermore, in the Wolayer Lake area from uppermost Frasnian time, very slowly deposited deep-water carbonate oozes, similar to those described from the Lower Devonian, had been laid down. By latest Devonian and earliest Carboniferous times this type of sedimentation had spread across all depositional environments in the Carnic Alps.

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