



Ooidal ironstones and laminated ferruginous deposits from the Silurian of the Carnic Alps, Austria

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ABSTRACT - Distinct ooidal horizons and diverse laminated ferruginous structures are reported from the Silurian of the Carinthian Carnic Alps. The former were recovered in forms of centimetric horizons at the base of a single section (Rauchkofel Boden). The Carnic Alps reports are the only record in the Silurian from the European sector of the Northern Gondwana margin. Ooids consist mostly of chamosite, goethite and mixtures thereof with subordinate amounts of apatite. Laminated ferruginous deposits are present in the majority of the investigated sections and are represented either by rare "stromatolite-like" structures or by abundant banded iron-rich fossil coatings, mostly around trilobites and cephalopods. Both types are composed of calcareous laminae alternating with layers rich in iron silicates or oxides (chamosite, goethite, and magnetite).

All these deposits can tentatively be regarded as microbial. Magnetite coatings revealed peculiar filaments of possible organic nature, closely resembling fungal hyphae.

RIASSUNTO - [Livelli ad ooidi di ferro e depositi ferruginosi laminati nel Siluriano delle Alpi Carniche, Austria] - Vengono qui segnalati e descritti nel Siluriano della Carinzia (Alpi Carniche Austriache) alcuni orizzonti ad ooidi e particolari strutture ferruginose laminate. I livelli ad ooidi di ferro delle Alpi Carniche costituiscono l'unica testimonianza di questo tipo nel Siluriano dell'intero settore europeo del margine nord-gondwaniano. Essi hanno spessore centimetrico e sono presenti nella sezione di Rauchkofel Boden. Gli ooidi sono costituiti principalmente da chamosite, goethite o da combinazioni di entrambe, in associazione con minori quantitativi di apatite.

I depositi ferruginosi laminati sono invece presenti nella maggior parte delle sezioni investigate sotto forma sia di rare strutture simili a stromatoliti che di rivestimenti ferruginosi zonati che si sviluppano principalmente attorno a trilobiti e cefalopodi, ma che possono essere presenti anche attorno ad altri organismi. Entrambi i depositi sono costituiti da alternanze di bande calcaree con livelli ricchi di silicati od ossidi di ferro (chamosite, goethite e magnetite).

Tutte queste strutture sono qui considerate di probabile origine microbica. Alcuni rivestimenti di fossili, preservati in magnetite, hanno evidenziato la presenza di filamenti di possibile origine organica, che ricordano le ife fungine.

"A Wolfgang Hamann,
grande maestro di vita ed amico sincero"

INTRODUCTION

Ooidal ironstones are well known in the Ordovician of several SW Europe areas (Portugal, Spain, France, Bohemia, Thuringia, ...) where they formed at mid to high latitudes mostly on the margins of Gondwana (Young, 1989b). Silurian occurrences from the same geographic sector are, on the contrary, very rare. Llandovery and Upper Ludlow oolitic ironstones were reported in Algeria (respectively Tindouf Basin and Hoggar) by Guerrak (1987). They were included within a widespread Oolitic Ironstone Belt containing numerous Paleozoic ironstone occurrences also in Ordovician, Devonian and earliest Carboniferous times (Guerrak, 1987, 1988). Oolitic ironstones are also known from Lower Silurian sequences of North America (Schoen, 1964).

The origin and environment of iron ooids has long been the subject of speculation and discussion. Though general agreement exists concerning moderate to very shallow waters and general non-deposition conditions

in condensate sequences (Burkhalter, 1995), discussion still exists on the hydrodynamic regime of the waters, which has been inferred to be low-energy (e.g. Gygi, 1981) as well as turbulent (e.g. Hallam, 1975), and also been related (e.g. Hallam & Bradshaw, 1979; Van Houten & Purucker, 1984; Bayer et al., 1985; McGhee & Bayer, 1985; Teysse, 1989; Young, 1989a) or not related (e.g. James & Van Houten, 1979) to sea-level fluctuations. In the former case, iron ooids have been variously interpreted as having formed at sea-level lowstands (e.g. Dreesen, 1989; Madon, 1992), during transgressions (e.g. Young, 1989b; Chan, 1992; Burkhalter, 1995; Taylor et al., 2002) or at maximum flooding surfaces (e.g. Young, 1992). Heikoop et al. (1996) reported modern primary iron ooids in reef areas characterized by venting of hydrothermal waters.

The inorganic or organic mode of formation is strongly debated as well. Even the source of the iron is controversial, derived alternatively from lateritic weathering of close-by densely vegetated landmasses (e.g. Taylor, 1951; Bubenicek, 1961; Hallam, 1975; Hallam & Bradshaw, 1979; Gygi, 1981; Van Houten & Purucker, 1984; Van Houten, 1985; Young, 1989), volcanism (e.g. Dreesen, 1989; Sturesson, 1992;

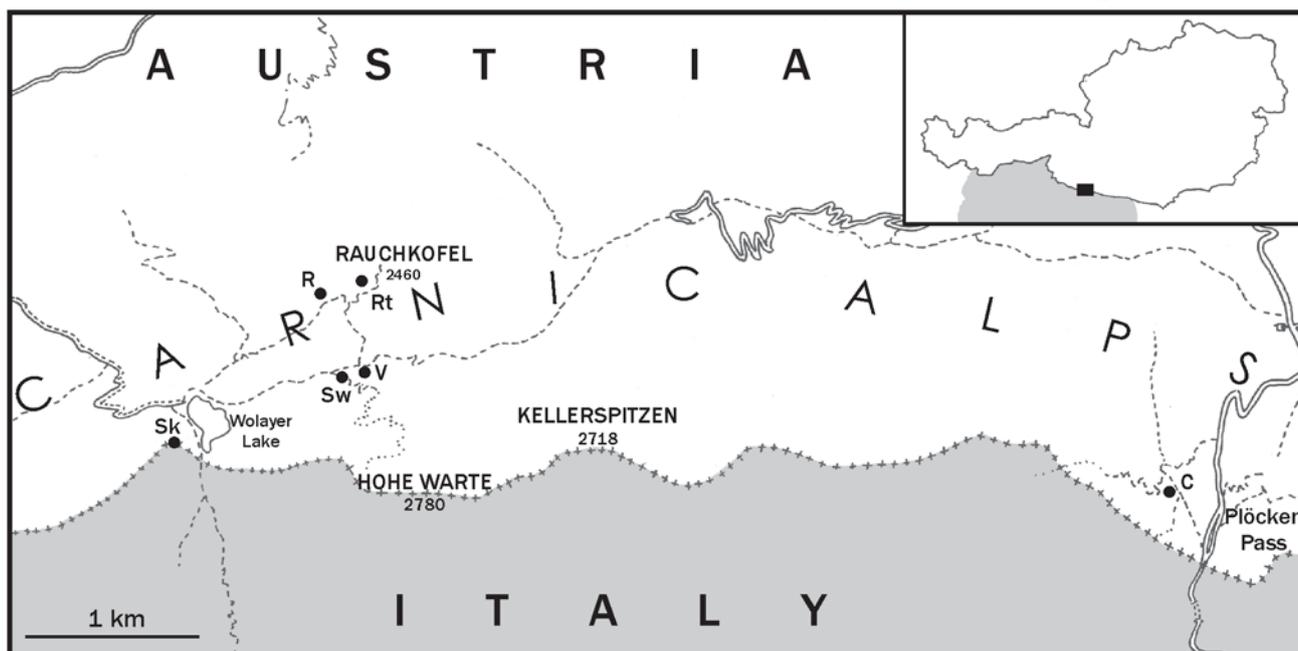


Fig. 1 - Location map of the study area. Sk: Seekopf Section; Sw: Seewarte Section; V: Valentintörl Section; R: Rauckofel Boden Section; Rt: Rauckofel Bodentörl Section; C: Cellon Section.

Sturesson et al., 2000) and direct precipitation from exhalative fluids (Kimberley, 1989, 1994). Several models for the genesis (direct precipitation from fluids, precipitation from a gel, transformation of a kaolinite/goethite mixture) of the iron minerals contained in ironstones have been discussed by Young (1989a).

Goethite and berthierine/chamosite are the dominant mineralogies of iron ooids (Burkhalter, 1995). In a classic paper, Porrenga (1967) associated specific depths and bottom-water temperatures to recent chamosite and goethite recovered from fecal pellets and fillings of foraminifera and other organisms. He associated authigenic chamosite with tropical shallow water with a temperature higher than 20°C (10-50 m and 25-27°C in the Niger delta), while at depths lower than 10 m goethite was dominant, occasionally associated with small amounts of chamosite and probably representing the oxidation product of reworked chamosite grains. Because chamositic minerals are unstable in the presence of free oxygen (Curtis & Spears, 1968; Van Houten & Purucker, 1984; Burkhalter, 1995), goethite has primarily been associated with an oxidizing environment and chamosite with a mildly reducing one (Berner, 1981; Van Houten & Purucker, 1984; Curtis, 1985).

As regards microbialites, Burne & Moore (1987) defined them as the "organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation".

Iron-rich microbialites are well known in the literature. Thin stromatolitic crusts, up to 10 cm thick and with abundant iron oxides, have been reported, for instance, in condensed sequences of the Devonian of the eastern Anti-Atlas (Morocco) by Wendt et al. (1984)

and Wendt (1988). Ferruginous microbialites are reported and described by Burkhalter (1995) from the Jurassic of Switzerland.

Ferruginous microstromatolites and multilayered mineralized coatings have been reported from several red European Paleozoic and Mesozoic limestones (Préat et al., 2000; Mamet & Préat, 2003 and references therein). Most of the iron is believed to be the result of microbially (iron-bacteria and fungi) induced precipitation at about 50-100 m depth, in quiet marine waters close or below the storm-wave base and below the photic zone having anoxic to dysaerobic conditions where iron and manganese are in a soluble reduced state.

Iron stromatolites attributed to fungi were described by Kretzschmar (1982). Bacteria, fungi, algae, and (or) cyanobacteria, acting independently or together as a community, are involved in the formation of biogenic coated grains (Jones, 1991).

Magnetite of biogenic origin, formed by bacteria and/or other magnetite-precipitating organisms, was reported by Chang & Kirschvink (1989). Bacterial magnetite was described from modern stromatolitic nodules and microbial mats (Chang et al., 1987; Stoltz et al., 1989). Fungi and bacteria, associated with mucilaginous biofilms, were recognized as contributors to the formation of terrestrial oncoids composed of micrite laminae and red clay minerals by Jones (1991) from the Cayman Islands.

A comprehensive study of the biosedimentology, microfacies and taphonomy of the Silurian calcareous sequences of the Austrian Carnic Alps is currently under way (Ferretti & Histon, in prep.). Six sections (Cellon, Rauchkofel Boden, Rauchkofel Bodentörl, Seekopf, Seewarte, Valentintörl; Fig. 1) are being studied

in order to detect the overall paleoecological features of the sector close to the Northern Gondwana margin during the Silurian. The study allowed the discovery of ooidal ironstones in the Rauchkofel Boden Section and of ferruginous “stromatolite-like” deposits in the Seekopf and Rauchkofel Boden sections. Another type of laminated structure, represented by ferruginous “coatings” around skeletal fragments, emerged from the Rauchkofel Boden, Valentintörl, Cellon and Seekopf sections.

All these peculiar structures from the Carnic Alps represent the only record in the Silurian from the European sector of the Northern Gondwana margin. Apart from the preliminary report of Tietz (1976), these occurrences have never been studied in detail. Aim and objective of this paper is to provide a detailed description of the two ooidal horizons and of the ferruginous laminated structures mentioned above, either as “stromatolite-like” structures or as ferruginous fossil coatings. In addition, their mode of origin is discussed, in order to establish its inorganic or organic nature. Finally, possible derived environmental implications for the Carnic Alps area are explored.

REGIONAL SETTING

Paleozoic rocks of the Carnic and Karawanken Alps make up an almost continuous sequence (Middle Ordovician to Late Permian) geographically distributed in a west-east alignment. The Silurian is irregularly exposed within this framework with sequences, often condensed, having a maximum thickness of about 60 m. Numerous sedimentary gaps affect the calcareous sequences at the base of the Silurian and also at the Llandovery/Wenlock boundary and in latest Wenlock times (Schönlaub, 1998).

Limestones (shallow water bioclastic limestones and cephalopod-bearing beds), shales (locally rich in graptolites) and cherts are the main rock types of the Silurian (Schönlaub, 1998). For some time now, the rich faunal content of these rocks has enabled detailed taxonomic and biostratigraphic study of all major groups.

Four different lithofacies have been traditionally attributed to the Silurian of the Carnic Alps, reflecting different depositional depths and hydrodynamic regimes. The “Wolayer Facies” is characterized by fossiliferous limestones rich in orthoconic nautiloids, trilobites, bivalves, small brachiopods, gastropods, crinoids and few corals. The classical sections are located in the Lake Wolayer area. The 28 m thick Rauchkofel Boden Section (Fig. 2) typifies this facies, that would represent the shallowest environment (Schönlaub, 1997). The Silurian is here expressed successively by the Kok Formation, the Cardiola Formation, and the Alticola Limestone.

A shallow to moderately deep marine environment is testified by the “Plöcken Facies” (Flügel et al., 1977) and is best developed in the classic 60 m thick Cellon Section, well known for the conodont biozonation there proposed by Walliser (1964). Lastly, the “Findening Facies” and “Bischofalm Facies” would indicate

respectively transition to or definite deep-water basinal facies. The latter is in fact represented by black siliceous shales, cherty beds and clayish alum shales rich in graptolites, attributed to a starving basinal environment (Schönlaub, 1997).

In general, an overall transgression regime is suggested for the Llandovery-Ludlow interval, while more stable conditions were established in Pridoli times (Schönlaub, 1997). Faunal and sedimentological data would locate the Carnic Alps in a paleolatitudinal position between 30 and 40° S (Schönlaub, 1998).

MATERIAL AND METHODS

Besides “routine” analysis of thin sections and polished slabs, in order to study all of these structures in detail, analyses have been performed using a scanning-electron microscope (SEM), energy-dispersive spectrometer (EDS), X-rays, and Gandolfi

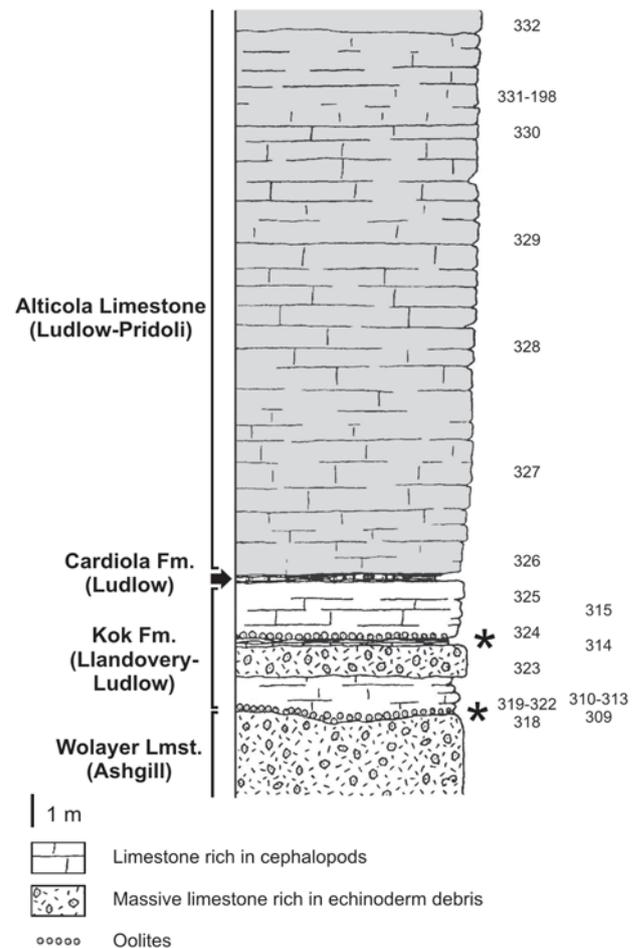


Fig. 2 - Generalised stratigraphy of the Silurian in the Rauchkofel Boden Section. Asterisks mark the position of the two iron-ooidal horizons described in the text, the upper one just next to a sequence of nodular layers (level 324 A to M) (modified after Ferretti et al., 1999). For sample location, see Schönlaub (1980).

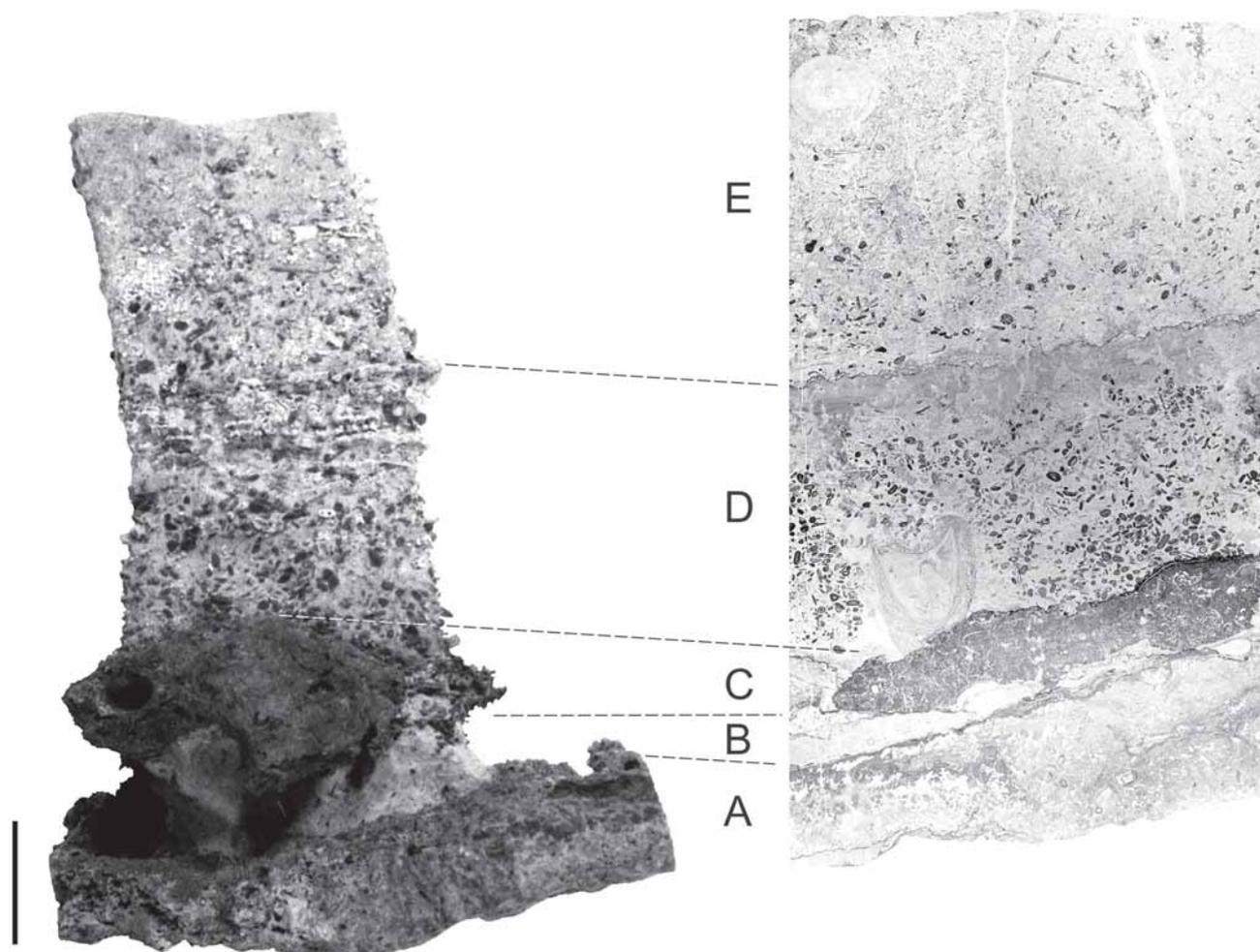


Fig. 3 - Nodular layers (A-E) immediately above the Ordovician, Rauchkofel Boden Middle Trench (RBMT). Scale bar = 1 cm.

camera. In this way, microstructure features and chemical composition can be identified.

FERRUGINOUS OIDS

Ooidal ironstones occur in the Rauchkofel Boden Section at two distinct levels, immediately above the Ordovician/Silurian boundary and in early Ludlow times, as thin discontinuous layers respectively at the base and within the Kok Formation (Fig. 2). Following Burkhalter (1995), the term “ooidal ironstone”

(Kimberley, 1978; Young, 1989a) is used herein as a general term for rock types containing >5% ferruginous ooids, independently of thickness and lateral extent of the unit (in the original definition of Kimberley of 1978, the term “ironstone” was limited to a rock having more than 15 weight per cent of iron, independently from its age).

Ordovician/Silurian Boundary

The contact of the Silurian with the Ordovician exposed at the Rauchkofel Boden Section is markedly irregular and undulose. Limestones of Wenlock age

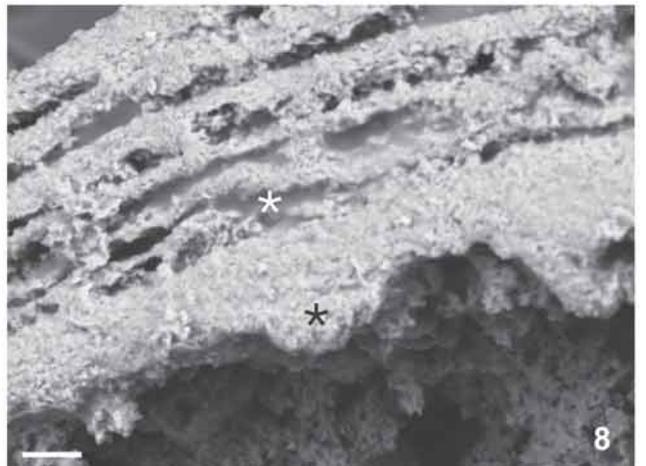
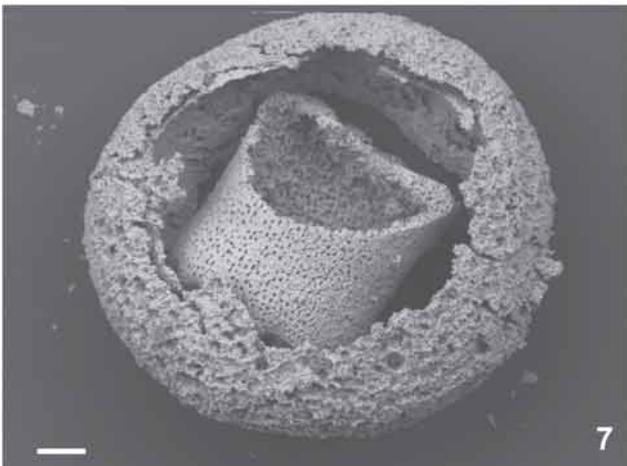
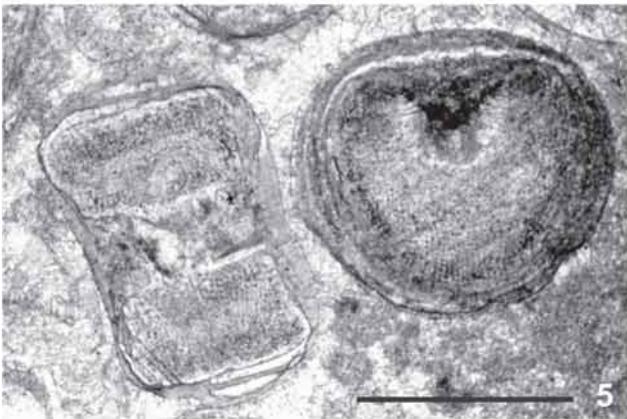
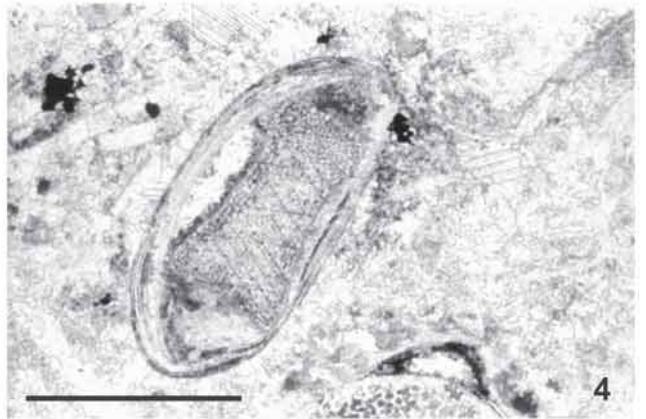
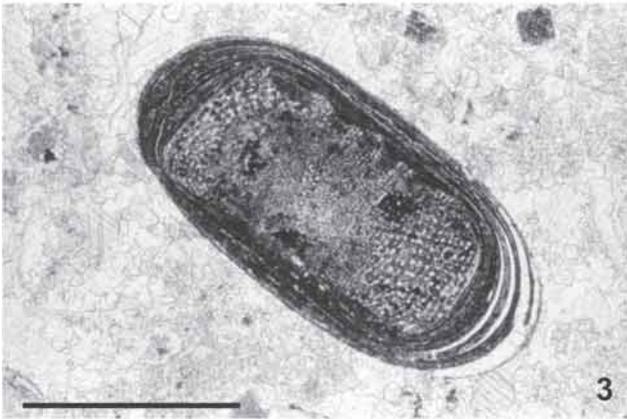
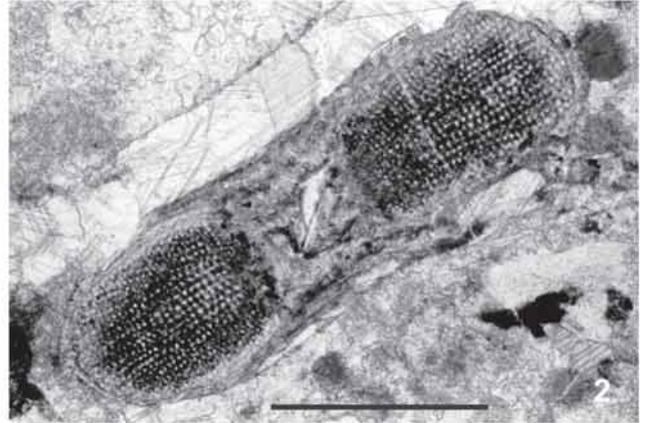
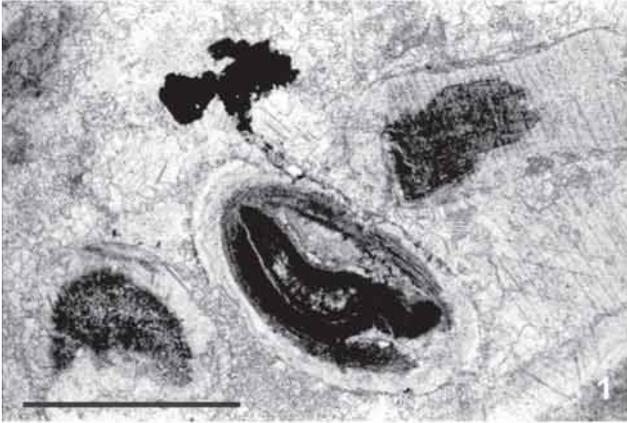
EXPLANATION OF PLATE 1

Varieties of iron ooids, Kok Formation, Rauchkofel Boden Middle Trench.

Figs. 1-6 - Thin-section photomicrographs of chamositic ooids mostly around echinoderm fragments (2-5) and rarer trilobite fragments (1, in the centre). White bands are made of sparite/microsparite. Note in 6) either homogeneous (dark arrow) or finely laminated (white arrow) ooids. All photos taken with transmitted plane-polarized light. Scale bar = 0.5 mm.

Fig. 7 - SEM image of chamosite ooids around ?echinoderm fragment. Scale bar = 100 µm.

Fig. 8 - Detail of fig. 7. Dark asterisk marks chamosite, white asterisk marks goethite. Scale bar = 20 µm.



(levels 310 and 319, *Oz. sagitta sagitta* Zone; for sample numbers see Fig. 2 and Schönlaub, 1980) were reported as resting directly on the Wolayer Limestone of Ashgill age (*A. ordovicicus* Zone; Ferretti & Schönlaub, 2001). A small new exposure (Rauchkofel Boden Middle Trench, RBMT) revealed a series of centimetric iron-rich nodular oolitic levels (ooidal pack-ironstones to grain-ironstones) immediately above the Ordovician, preserved in basal pockets of the Wolayer Limestone. These levels are attributed to the late Llandovery on the basis of conodonts (*Pt. amorphognathoides* Zone). Cephalopods, often having telescoped shells, are the only macrofossils recognisable in the field. The ooidal ironstone is strongly discontinuous and, as the outcrop is limited, it is impossible to estimate its lateral extent. Nevertheless, it is also present at the base of layers 310 (newly assigned to the *Pt. celloni* Zone) and 319. The most complete sequence from the RBMT exposure has a total thickness of about 10 cm and is shown in Fig. 3. A 1 cm thick nodular black-brownish level is present immediately above the Ordovician limestone (level A of Fig. 3). Phosphatised (Figs. 4a, c) and chamositic ooids, which have nucleated almost exclusively around echinoderm fragments, are present. The ooid nuclei still retain their original calcareous composition, having rare chamosite at their outer margin. Apatite and chamosite as well as rare barite crystals are present in the matrix. Chamosite appears to be present also amongst individual nodules of level A. This phosphatic horizon is followed by an irregular, nodular, max. 1 cm thick, pale-grey layer (level B of Fig. 3). It is made up of a strongly recrystallised packstone of echinoderm debris, trilobites and cephalopods in a fine calcareous matrix. Rare bivalves, ostracodes and gastropods also occur. No oolites are present. Apatite is present in this level as rare arborescent forms. Thickness reduction of transversal sections of cephalopod shells testifies to strong dissolution in level B. A second dark brown phosphatised nodular level (level C of Fig. 3), slightly thicker and more homogeneous than level B, is discontinuously present immediately above level B. Phosphatisation is more pronounced here as, together with a matrix composed only of apatite, even the fossil shells are made (entirely or partially) of apatite. If compared to level A, the fauna is more varied here, with abundant echinoderms and subordinate trilobites, ostracodes, bivalves, gastropods, cephalopod shell fragments, and sponge spiculae. No oolites occur in level C. Levels D and E (Fig. 3) are the most typical ooidal ironstone layers. They are separated by a 1 cm ferruginous “stromatolite-like” horizon, made of alternating laminae of calcite and chamosite/goethite. Level D is a 3 cm ooidal pack-ironstone to grain-ironstone having a calcareous matrix and an undulating lower boundary. Ooids are moderately to well sorted, subspherical to subvoidal in shape, and range from 0.3 to 1.5 mm long. Ooids are either homogeneous or finely laminated (Pl. 1, fig. 6). The cortex consists of uniform chamosite or concentric layers of chamosite (and subordinate goethite) and calcite (Figs. 4b, d). Individual cortical laminae have a thickness averaging

10-50 µm. Chamosite ooids may be altered to ferric oxides, both as dark-brown bands inside the cortex, or small blotches scattered or concentrated at the outer edge of the cortex. Some ooids with a calcareous cortex were also recovered at the top of level D. Ooid nuclei are represented mostly by ferruginous crinoid ossicles and spines, rarer trilobite or cephalopod fragments, and parts of broken ferruginous ooids. The original calcareous composition of ooid nuclei is generally maintained, apart from a slight chamosite marginal enrichment within calcareous ooids. Ooids with a cortex made of chamosite around phosphatised bioclasts were recovered from the conodont residue and most probably belong to this level. Equidimensional ostracodes and thin-shelled bivalves, often articulated, echinoderm debris, trilobites, small cephalopods, gastropods, rare brachiopods, and muellerisphaerida are associated with ooids inside these levels, constituting local well-sorted coquinas. Relatively large cephalopods, present both in levels D and E, may show peculiar iron-banded “coatings” (see below) rich in chamosite in level D and goethite in level E. Bivalves, gastropods and ostracodes may have iron-oxide blotches inside or around the shell; echinoderms are often ferruginised. Phosphorus, dominant element of levels A and C, was revealed only as a point-like element inside the matrix. Level E is 3 cm thick. Chamositic ooids are still present, but not as abundant as in the level below. They have the same morphological features as in level D. In addition, their oxidation is much more frequent. Bioclasts, of the same types as in level D, are dominant here.

Levels B and C may be absent in places, whereas level A appears more continuous overlying the Ordovician. Only part of the RBMT succession (levels C, D, and E) is present at the base of layers 310 and 319.

Early Ludlow

A second iron enrichment occurs around level 324, as millimetric horizons within a 50 cm sequence of centimetric nodular layers (Fig. 2; levels 324 A to M). These levels consist of bioclastic packstones and well sorted grainstones that are intercalated with iron-rich crusts. Cephalopods are the only large faunal elements, often with telescoped shells. Equidimensional bioclasts consist of the remains of gastropods, echinoderms, bivalves and ostracodes (either articulated or non-articulated), trilobites and rare brachiopods. The matrix may be either micritic (locally pelleted) or bioclastic towards the top in packstones and, finally, well-sorted and winnowed grainstones (levels G and M). These last levels reveal a peculiarly high-iron content, mostly in the form of an opaque iron-oxide rim around organisms (echinoderms, bivalves, ostracodes, small cephalopods, trilobites, etc.) giving a dark-reddish colour to the fossil profile. These “coated-grains” range between 0.5 and 2 mm in size. Some of them still preserve green chamosite portions inside the outer iron-rich layer or even bear a distinct lamination. Other “coated-grains” are represented by brilliant-green superficially coated shell-fragments (echinoderms, bivalves, ostracodes, etc.) and fade to the coating

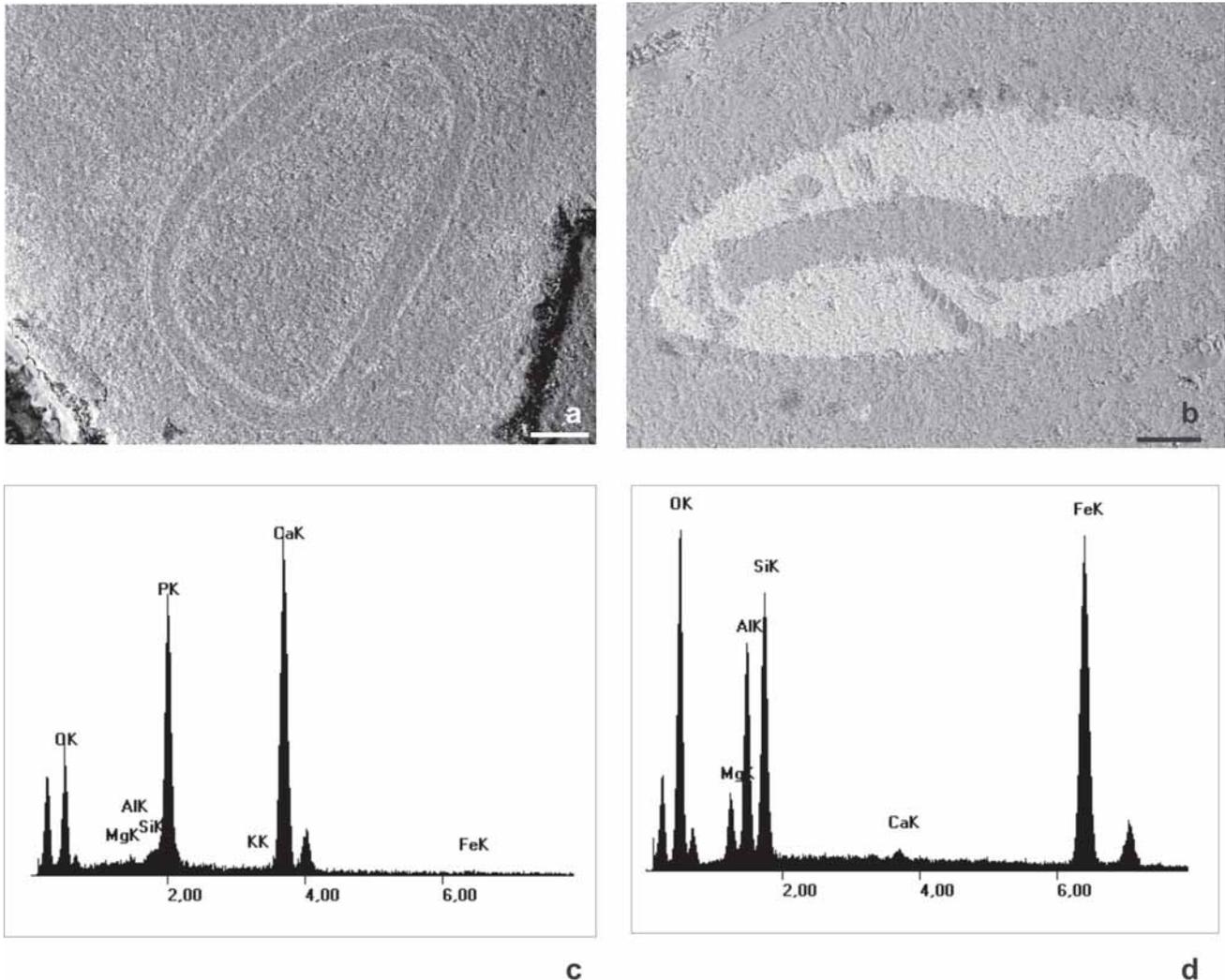


Fig. 4 - Composition of ooids.

a, c - Backscattered image and spectrum of phosphatised ooid around echinoderm fragment, RBMT, level A. Cortical laminae are made of apatite (white lines, spectrum c) and calcite (dark lines). Note the enrichment of chamosite (lighter area) towards the borders of the oolite nucleus.

b, d - Backscattered image and spectrum of chamositic ooid around trilobite fragment, RBMT, level D. Ooid cortex (lighter area) is made of chamosite (spectrum d).

(a) (b) Scale bars = 100 μm .

structure described below. Chamosite sediment is also often preserved in sheltered areas below and within the shells.

A further centimetric phosphatic horizon, rich in bivalves, gastropods and echinoderm fragments and strongly associated with chamosite, caps the sequence.

LAMINATED FERRUGINOUS DEPOSITS

Peculiar ferruginous “stromatolite-like” laminar structures (Seekopf and Rauchkofel Boden sections) and banded ferruginous “coatings” around fossils (Valentintörl, Rauchkofel Boden, Cellon and Seekopf sections) are present in the studied localities. Coatings from only the first two sections are described here.

These deposits could be inorganic or organic in origin, or a mixture of these two origins. A detailed description is given in the next sections with special emphasis on the features that suggest they might be, at least in part, microbial.

“Stromatolite-like” structures

“Stromatolite-like” structures (Pl. 2) were found immediately above the Late Ordovician Wolayer Limestone. The Seekopf Section exposes local reddish laminar patches (Pl. 2, fig. 1), with diameter ranging from 2-3 to over 20 cm, now preserved only in small depressions at the top of the Wolayer Limestone due to the strong erosion suffered by the unit. Conodonts indicate that these structures are early Ludlow in age (*K. crassa* conodont Zone).

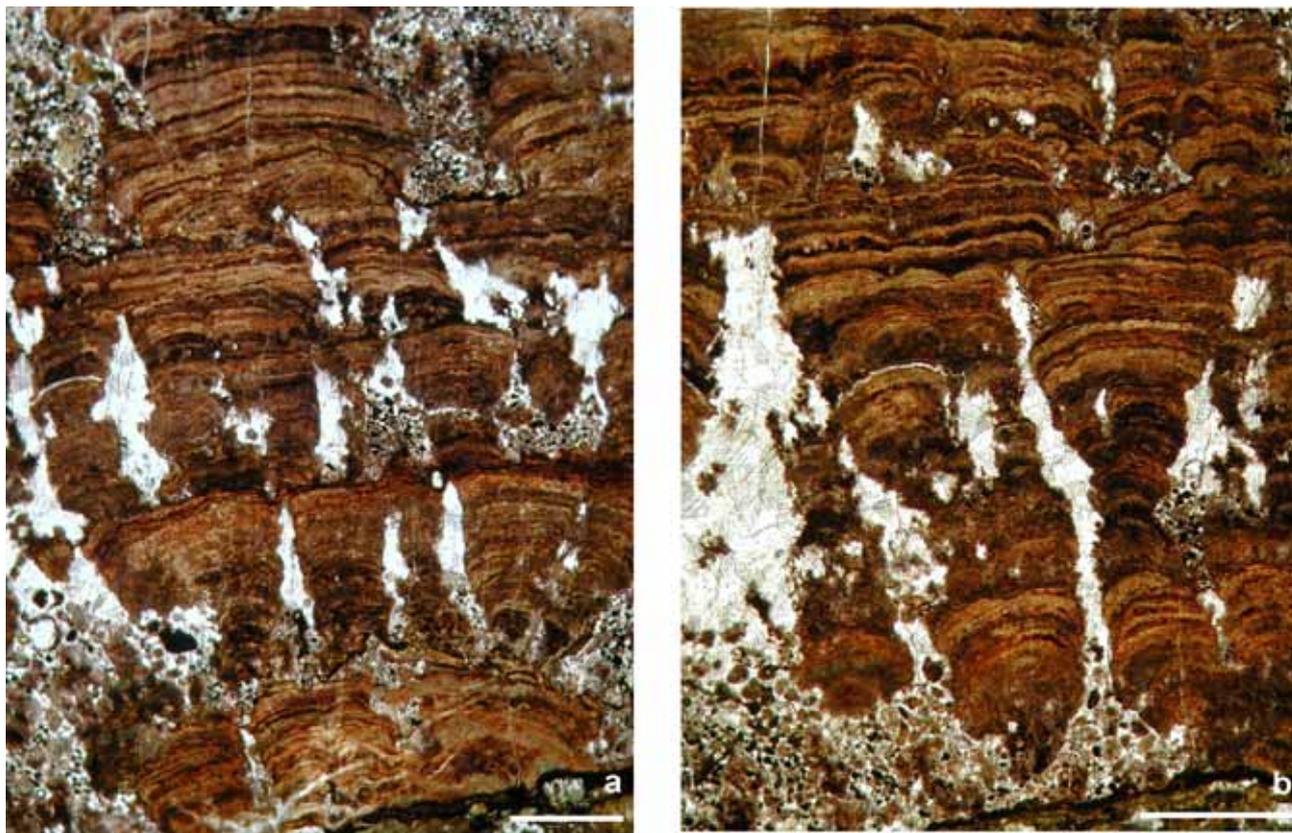


Fig. 5 - "Stromatolite-like" deposits. Microfabric details of the "stromatolite-like" deposits revealing fenestrae rich of peloids at the bottom and sparry cement at the top. Rauchkofel Boden Middle Trench (RBMT). Scale bars = 0.2 mm.

"Stromatolite-like" deposits, dark red in colour, are also present in the RBMT (Pl. 2, fig. 2) at the base of the late Llandovery ooidal ironstone described above. Here they occur only in a small area, 7 cm wide and 1.5 cm high, within the topmost Wolayer Limestone.

The internal fabric of these structures consists of planar to wavy, sometimes discontinuous fine laminae with individual thicknesses ranging from a few to tens of microns. Wavy laminae may evolve into small-scale dome-like structures (Seekopf Section; Pl. 2, fig. 1) or into irregular columnar structures (Rauchkofel Boden Middle Trench; Pl. 2, fig. 2). Fenestrae are common between the columns (Figs. 5a-b), filled by sparry cement at the top and by subrounded chamosite peloids, sometimes oxidised and 50-80 μm in diameter, and clots at the base. At higher magnification, the identification of each single lamina geometry is quite hard. This is especially true for the RBMT material, where laminae

are more irregular than the Seekopf ones and appear organised in yellow-green to red-brown "bundles" confined between deeper-red laminae. Distinct clear microsparitic laminae also occur locally.

COATINGS

Iron-coatings

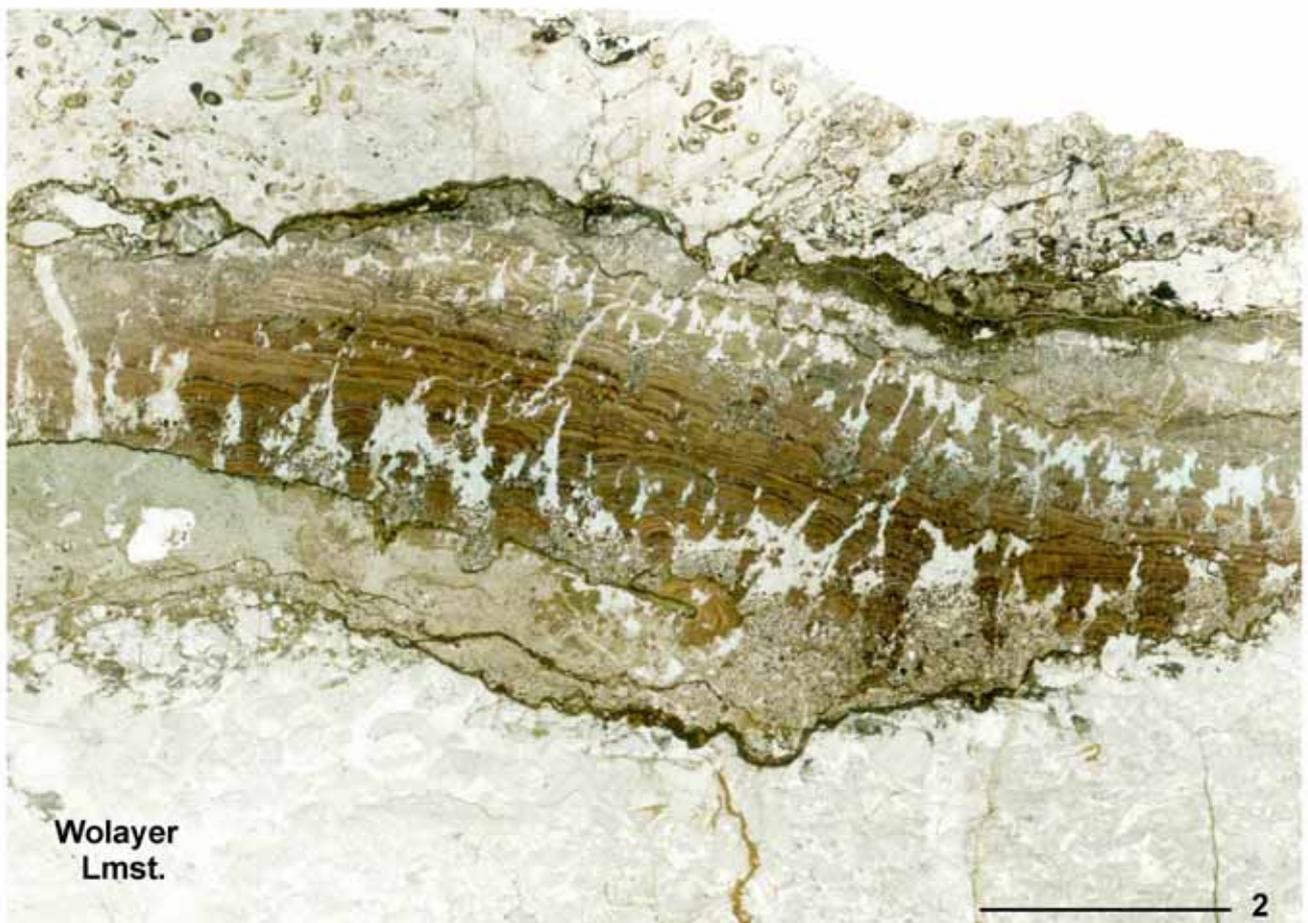
A peculiar feature observed in both the Kok Formation (especially at the top) and the Alticola Limestone is the presence of regular iron-rich laminated coatings around fossils (Pl. 3; Fig. 6). Coatings may be incomplete, consisting of multiple layers surrounding only parts of the shell, or they may envelope the entire particle, having either laminar or homogeneous fabric.

Incomplete coats are more common and are represented by series of small banded domes which mostly develop on the outside of the shell and only

EXPLANATION OF PLATE 2

"Stromatolite-like" structures. Scale bars = 1 cm.

- Fig. 1 - Seekopf Section.
 Fig. 2 - Rauchkofel Boden Middle Trench (RBMT).



rarely on the inside (e.g. cephalopod septa). Typical examples are offered by trilobites which have domes with alternating lamination (*sensu* Monty, 1976) starting from the most prominent parts of the shell or from the shell extremity (Pl. 3, figs. 1-2). Domes grow only on one side of the shell with no preferred orientation with respect to stratification. The coating fabric consists of whitish laminae of granular spar and pseudospar in more or less regular alternation with reddish-brownish (Kok Fm. and Alticola Limestone) to brilliant green (Alticola Limestone) iron-rich laminae. Individual sparry laminae are up to 30 μm thick and appear generally less continuous than the iron-rich laminae. They strictly follow the morphology of the coated shell but with variable thickness. Sparry laminae may occasionally fade laterally, as also evidenced by transversal sections of the domes (Pl. 3, fig. 7). Comparable lamina patterns occur in adjacent domes, as revealed by thicker sparry laminae that occupy the same position. This suggests contemporaneous growth of the coating in diverse parts of the shell.

Red laminae are made of goethite. They are generally thinner than the white ones and appear less defined, having in fact a blotchy appearance at larger magnification. It is, in fact, quite difficult to differentiate whether they are made of a single layer or of multiple fused layers. Green laminae are composed of chamosite and appear more continuous and less point-like than the red ones. Some of the latter bear ferric oxide crystals or a definite rim at their outer edge.

Complete coatings have a pustulous or tubercular outer surface and consist either of irregular sparitic and microsparitic laminae alternating with goethite-chamosite layers (Pl. 3, figs. 3-4), or of a homogeneous chamositic/goethitic coat. In the former type, individual laminae show a generally continuous development around the entire grain and give rise to spectacular geometric patterns around skeletal fragments (Pl. 3, fig. 3). The Valentintörl Section offers the best examples with coatings involving mostly benthic forms (trilobites, bryozoans, etc.). Complete banded coatings are present in both the Kok Fm. and the Alticola Limestone. The iron-rich bands are represented preferentially by goethite in the Kok Fm. (Fig. 6) and by chamosite (rarer

goethite) in the Alticola Limestone. In the latter the coatings are more variable. Some coatings in the Kok Fm. also revealed thin phosphate films alternating with calcareous bands. Trilobites and cephalopods are the most common organisms which have been coated, but complete coatings have also been observed on brachiopods and echinoderms. In addition, fragments of the coatings may be present in the matrix (banded white-green or white-red structures).

Homogeneous complete chamosite coatings, brilliant green in colour, are visible at the base of the Alticola Limestone. They closely resemble the unlaminated oolites described at the O/S passage. The green coat may directly cover the shell or be separated by a red layer. Iron-oxide blotches are occasionally present. In some cases there are white partial laminae inside undifferentiated chamosite. A thin goethite layer borders many shells in the Kok Fm., as shells seem to have been subjected to a sort of "rusting". The contemporaneous presence, in the same sample, of shells with "rusted" borders and others with banded coatings could represent preservation of intermediate coating stages. A similar mixed-aspect is given by concurrent banded and homogeneous coatings around the extremities of the same fossil, again possibly reflecting different stages of the coating process (Pl. 3, figs. 5-6).

The outer shell margin of coated trilobites, brachiopods and cephalopods may appear slightly "nibbled" but no true shell perforations have ever been observed. The high iron content of the units where all these coating structures are present is also revealed by frequent iron staining of the shells (more frequent in the Kok Formation) with microborings, for example, in cephalopod and bivalve shells being infilled or echinoderm pores being impregnated by the iron-oxides.

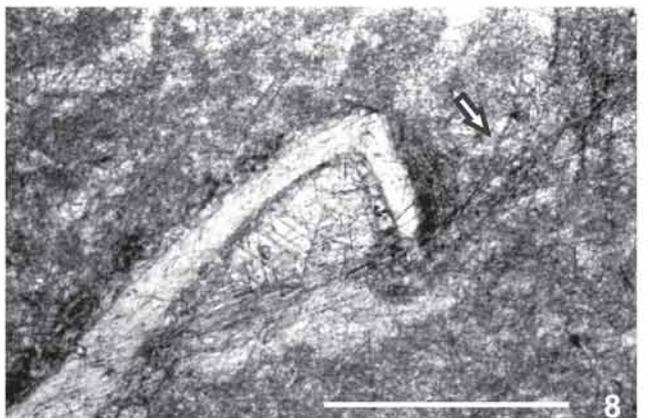
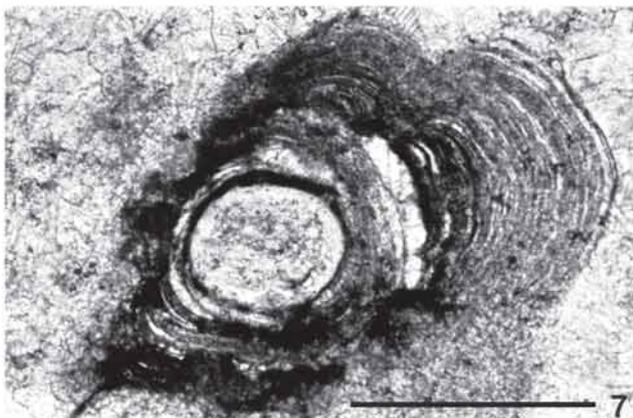
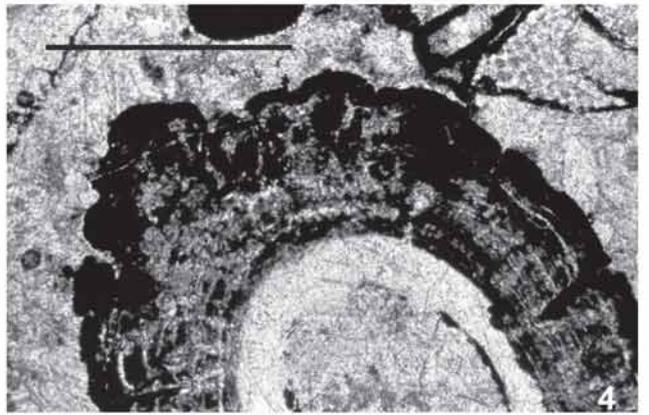
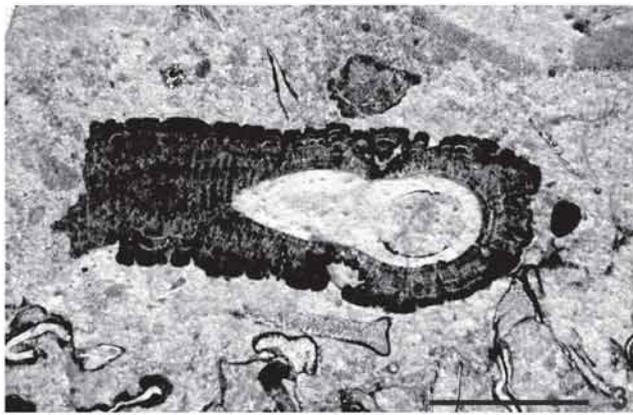
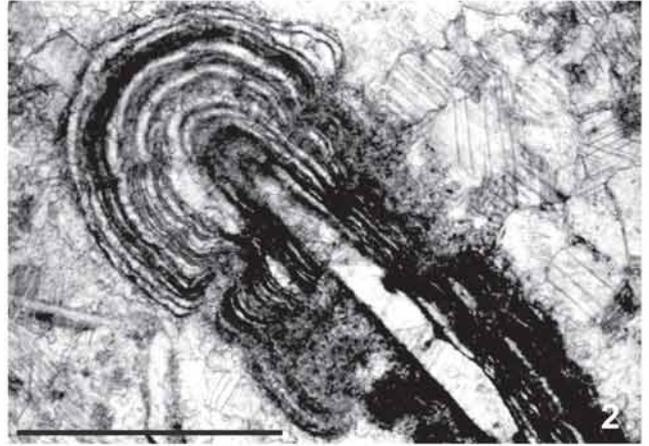
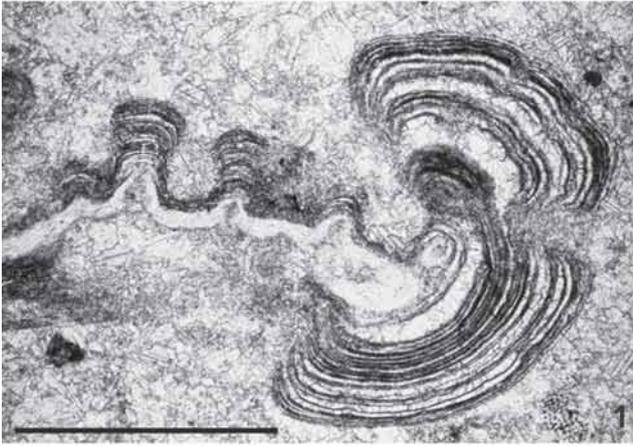
Magnetite Coatings

Rust-coloured ferruginised fossils were picked from the residue of the acid processing of some samples collected at the Valentintörl Section. Spectacular trilobites, preserved in full three-dimensions (Pl. 4, figs. 1, 3, 7), together with rarer echinoderms and

EXPLANATION OF PLATE 3

Iron-rich coatings around skeletal bodies. All photos taken with transmitted plane-polarized light.

- Figs. 1-2 - Incomplete ferruginous coatings around trilobite (1) and ?cephalopod fragment (2). Rauchkofel Boden Section, Kok Fm. Scale bar = 0.5 mm.
- Figs. 3-4 - Complete ferruginous coatings around a trilobite. Valentintörl Section, Kok Fm. Scale bars = respectively 1 mm and 0.5 mm (fig. 4 is a detail of fig. 3).
- Figs. 5-6 - Coatings of diverse maturity showing goethite (dark), chamosite (grey) and calcite (white) developing at the extremities of a trilobite fragment. Rauchkofel Boden Section, Alticola Limestone. Scale bars = respectively 0.5 and 0.1 mm (fig. 6 is a detail of fig. 5).
- Fig. 7 - Coated trilobite; note that light laminae are wavy, eventually discontinuous laterally. Rauchkofel Boden Section, Alticola Limestone. Scale bar = 0.5 mm.
- Fig. 8 - Tiny filaments in the matrix around a trilobite skeleton, Rauchkofel Boden Section, Alticola Limestone. Scale bar = 0.5 mm.



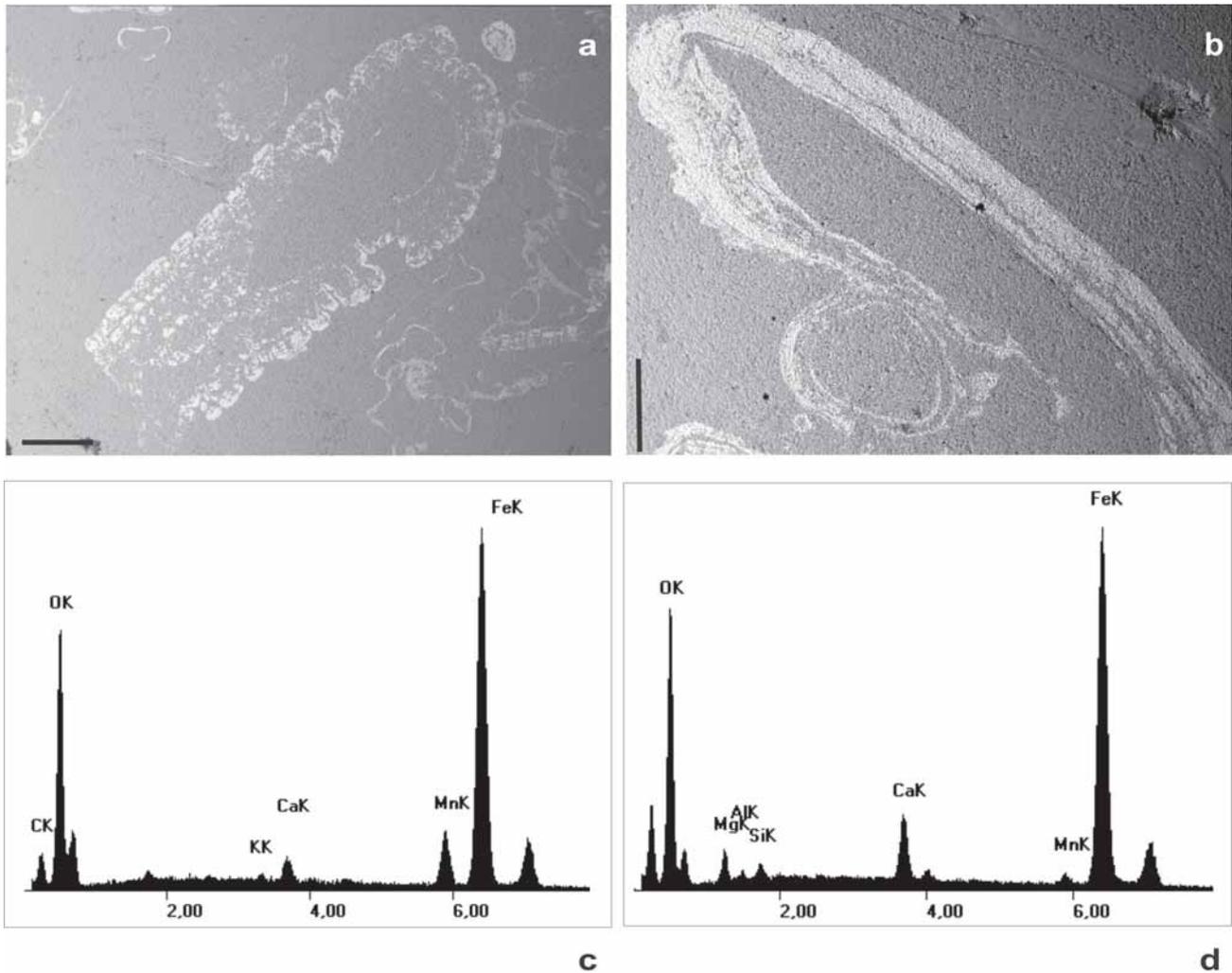


Fig. 6 - Backscattered images and EDS spectri of ferruginous laminated coatings.

a, c - Complete coating (same as Pl. 3, fig. 3), Valentintörl Section, Kok Fm. White laminae of (a): goethite (spectrum in c).

b, d - Complete coating around a cephalopod fragment, RBMT, Kok Fm. White laminae of (b): goethite and possibly minor chamosite (spectrum in d).

(a) (b) Scale bars = 0.5 mm.

gastropods, appeared, still exposing minute details of their shells. According to X-ray analysis, these shells are made of magnetite.

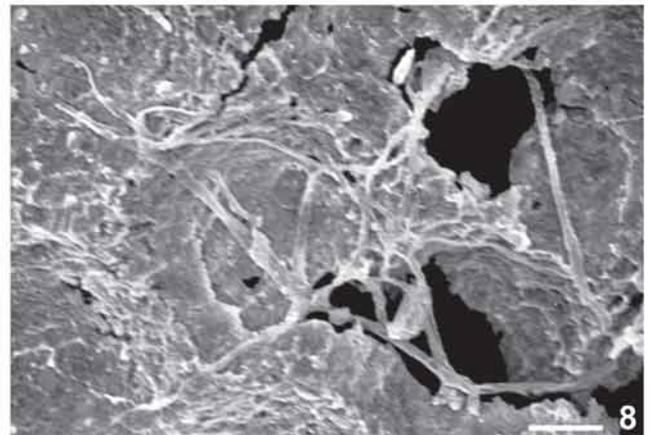
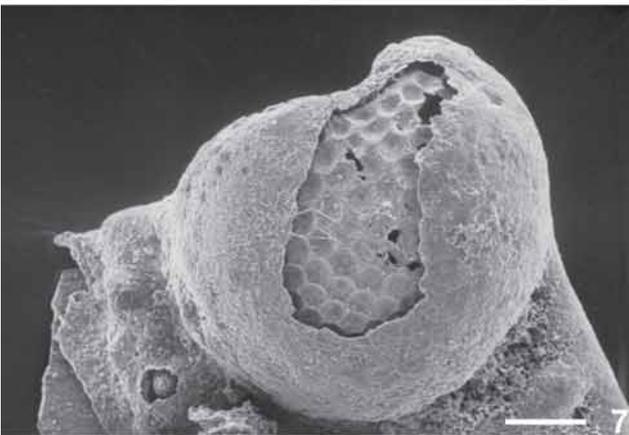
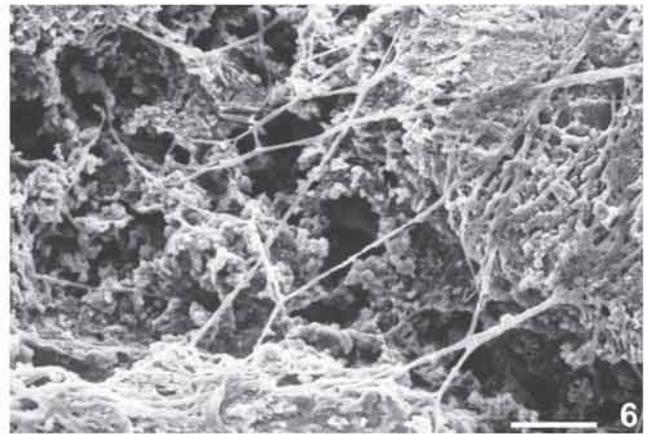
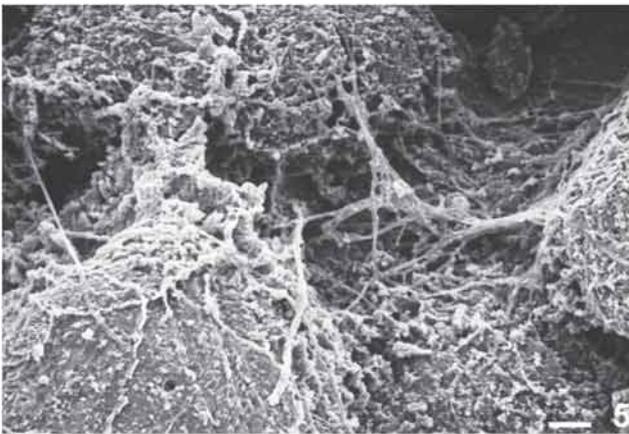
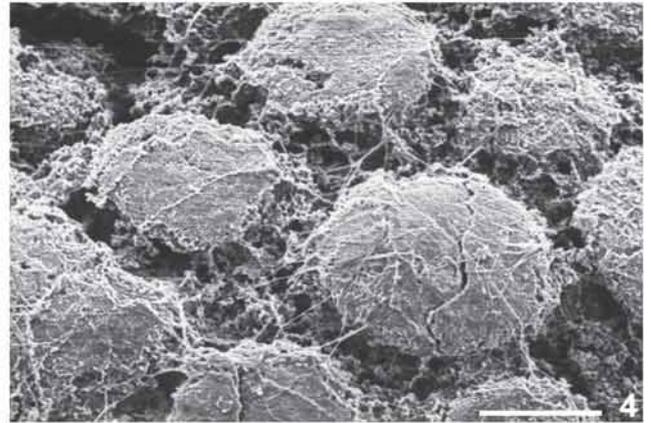
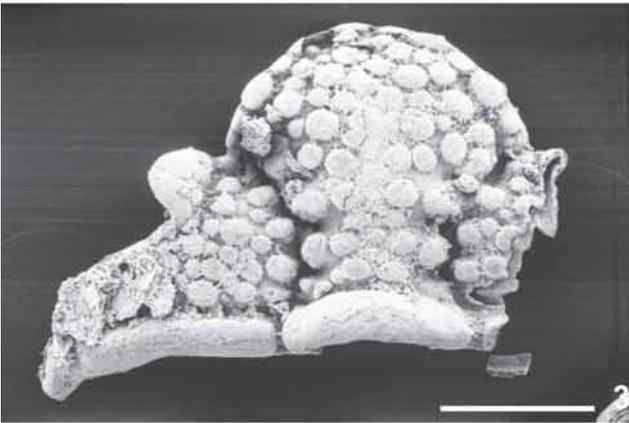
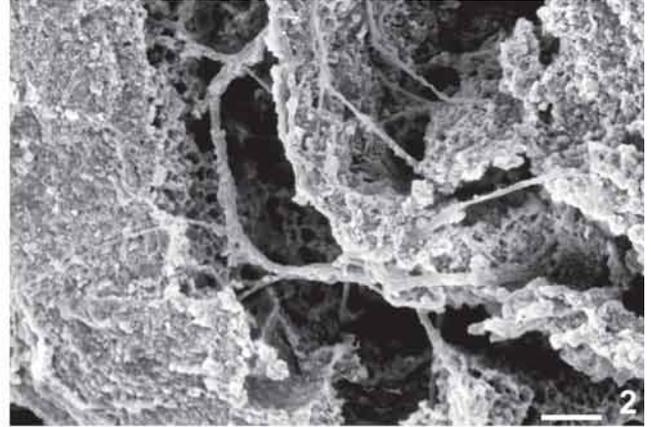
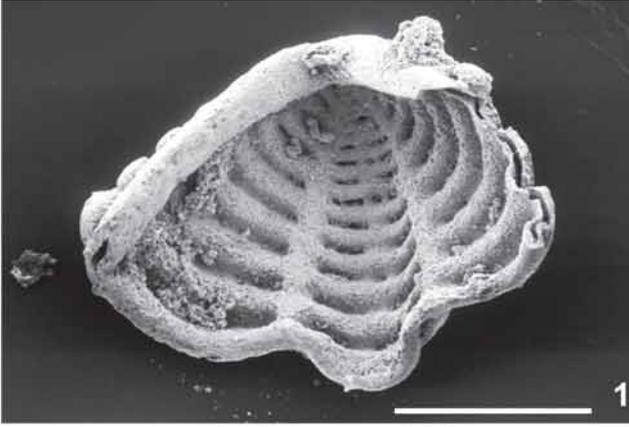
SEM observation revealed the presence of abundant tiny cylindrical thread-like filaments, 1-4 μm across and up to 100 μm long, spread all over the shell surface

(Pl. 4, figs. 4-6, 8) and within layered structures (Pl. 4, fig. 2). These filaments are homogeneous in width and appear mostly isolated and only locally in bunches. They are deeply inserted in the shell wall. Chemical analysis by electron beam instruments done on these filaments (Fig. 7a) revealed a notable presence of

EXPLANATION OF PLATE 4

SEM micrographs of magnetite skeletal fragments, Valentintörl Section, Kok Fm.

- Fig. 1 - General view of a trilobite pygidium preserved in full three dimensions. Scale bar = 1 mm.
- Fig. 2 - Filaments through cortical layers of a trilobite coating. Scale bar = 20 μm .
- Fig. 3 - General view of a trilobite cephalon showing abundant filaments spread all over the surface. Scale bar = 1 mm.
- Figs. 4-6 - Detailed views of the shell surface of the trilobite illustrated in fig. 3. Note bifurcating filament in fig. 6. Scale bar = 0.1 mm in fig. 4 and 20 μm in figs. 5-6.
- Fig. 7 - General view of a trilobite eye with filaments. Scale bar = 0.1 mm.
- Fig. 8 - Detailed view of the previous shell with filaments all over the eye-lenticles. Scale bar = 10 μm .



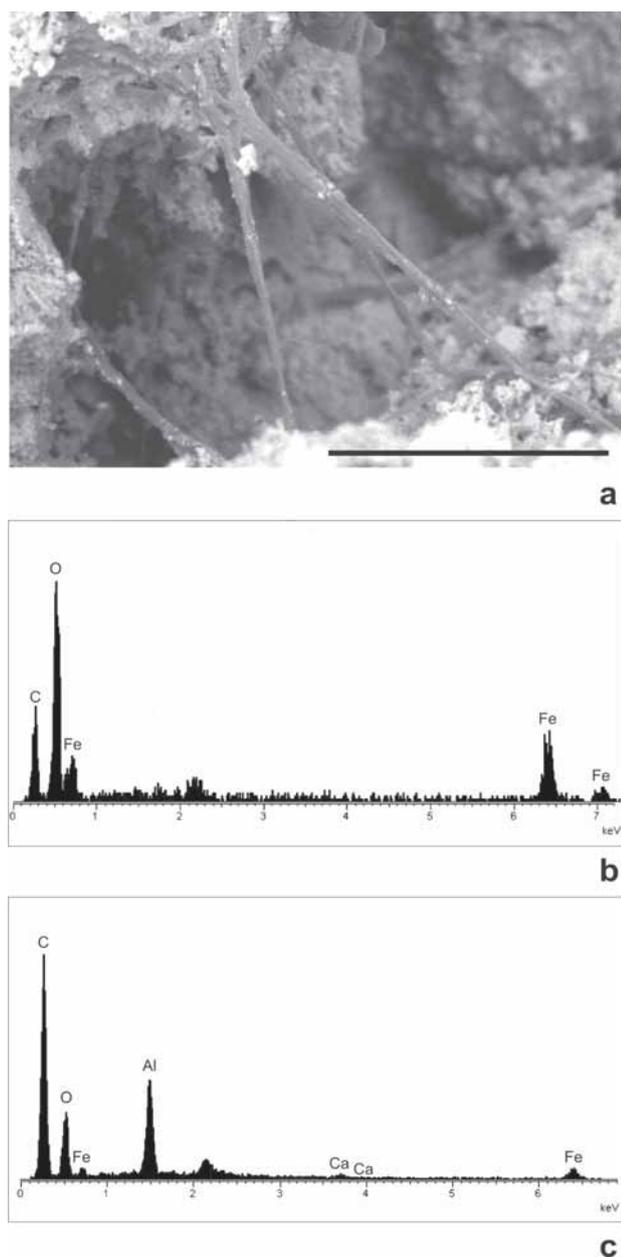


Fig. 7 - Backscattered image and EDS spectri of filaments recovered in magnetite coatings, Valentintörl Section, Kok Fm. a, b - Image and spectrum of filaments associated with a trilobite fragment. Metal coating with gold. Scale bar = 50 µm. c - EDS data of filaments isolated from the shell. No metal coating (Al peak is from the stub).

carbon, oxygen and iron (Fig. 7b). The same composition was also obtained from the analysis done on the shell itself. In order to avoid any possible influence of the coated shell on the results and to get an even more precise signal, some filaments were isolated and placed with distilled water on the stub without using glue or conductor coating. Again, oxygen and iron were revealed as their main constituents (Fig. 7c).

DISCUSSION

Iron ooids, “stromatolite-like” structures and ferruginous coatings have been described in great detail in the previous chapters.

According to Young (1992), ooidal ironstone-producing events occur essentially synchronously over large areas as a response to uniform sedimentary conditions across wide areas of the shelf. In contrast, the ooidal ironstones described in this paper appear to be a local episode in the Silurian of the Northern Gondwana sector. It can only be correlated with difficulty within the Carnic Alps (chamosite ooids were reported by Schönlaub in 1971 at the base of the Seewarte Section while stromatolites and oncolites were reported from the same area by Tietz in 1976) and correlation to other regions is tentative at best. As these ooidal horizons are only preserved in very small depressions of the irregular Ordovician/Silurian boundary, it is possible that similar occurrences were lost due to erosion/non deposition events that affected many other Carnic sequences in Early Silurian times.

The iron oolitic episodes of the Austrian Carnic Alps and associated phosphorite horizons represent initial deposits above a disconformity and clearly indicate condensed sequences implying low sedimentation rates and linkage to sea-level fluctuations (Ferretti & Histon, in prep.). With regard to the source of the iron deposited in the ooidal horizons as well as in the ferruginous laminated structures, no definite answers are yet available. However, it is worth mentioning that numerous thin bentonite layers discovered recently by K. Histon may suggest a relationship with volcanism in areas adjacent to the former depocenter of the Silurian of the Carnic Alps (Histon et al., in press).

The two major features which characterize the ferruginous laminated structures (“stromatolite-like” structures and coatings) described in this paper are the major presence of iron silicates and oxides on one hand and the possible role played by organisms in their formation on the other.

Being distinct microbial fossil generally absent, recognition of inorganic or organic origin for these deposits is often based on general overall appearance of irregular lamination and distinctive microfabrics. The irregular lamination of the “stromatolite-like” deposits described in this paper and their unique microfabric (clots, peloids and fenestrae) strongly support an organic origin. The great irregularity noticed inside coating lamination pattern is in favour of an organic origin even for those structures.

The close mineralogical and micromorphological resemblance of the two types of ferruginous deposits (“stromatolite-like” and coatings) suggests therefore a common biogenic origin for these structures which can tentatively be regarded as microbial deposits.

As regards possible organisms involved in the microbialite formation, the peculiar filaments recovered in the magnetite coatings described in this paper strongly resemble fungal hyphae. Fossil fungi are known from the Precambrian to Recent (Ethridge Glass et al., 1987) and their ability in trapping and binding of loose particles, and in producing microstromatolites, has been

documented by Jones & Pemberton (1987). Fungi might therefore have played a primary role in the genesis of the microbialites described previously but new investigations are needed to exclude finally the possibility that these filaments could be more recent contaminants. Tiny dark filaments, sometimes present in the matrix (Pl. 3, fig. 8), could indicate the involvement also of bacteria in the creation of the laminated structures here discussed.

These diverse laminated structures of the Carnic Alps illustrate different growth stages of a process which develops through periodic deposition, possibly mediated by the action of microorganisms (fungi and bacteria), of a fine chamosite-precursor material as a thin coating (?gel-like) around skeletal fragments (coatings) or as a definite layer ("stromatolite-like" structures) through the trapping and binding of the same detrital material, alternating with calcification stages. The process may have repeated several times, interrupting and resuming on the same grain or on new material. Oxygen fluctuations, possibly associated with sea-level variations, were responsible for the different iron phase preservation.

The iron ooids described in this work undoubtedly share many features (mineralogy, fabric, growth mode, oxidation, etc.) with the ferruginous microbialites. Ferriferous ooids and microbialites might therefore have been the products of the same biogenic activity and a probable common biogenic origin is suggested (see also Dahanayake et al., 1985; Dahanayake & Krumbein, 1986; Burkhalter, 1995).

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