SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 819 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 81 NR 5

MANFRED DWORATZEK

SEDIMENTOLOGY AND PETROLOGY OF CARBONATE INTERCALATIONS IN THE UPPER CAMBRIAN OLENID SHALE FACIES OF SOUTHERN SWEDEN

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Black, kerogen-rich shales were very slowly deposited in a large area of northern Europe throughout the Late Cambrian. They contain a low diversity fauna of mainly olenid trilobites with, on occasion, coquinoid layes of a single species of articulate brachiopod. Intercalations of black limestone were lithified, to a great extent by early diagenesis, thereby preserving much of the early mineralogy of the fine-grained siliciclastics included in the carbonates. Outside the limestones later diagenesis has led to some increase of the content of K-feldspar. Early lithification is indicated by early displaced limestone concretions, and by discontinuity surfaces with deeply dissected topography. Larger clasts were moved mainly by gravity; the current activity within the basin was neither strong enough to move major clasts or to create directional fabrics, nor capable of providing the sea-bed with oxygenated water. Among the structures described is *pillar spar:* zones or seams of major, highly elongate, parallel calcite crystals that by growing could force the sedimentary lamination apart; growth of pillar spar took place in a very organic-rich sediment, while exchange was still going on with the sea water. Two facies realms can be distinguished in the otherwise monotonous facies: one realm was close to submarine, bioproductive rises, with relatively strong carbonate deposition, including bioclastics, and slow deposition of fine-grained siliciclastics, the other was characterized by slow carbonate deposition and less slow deposition of fine-grained siliciclastics, at somewhat greater depth. An upwelling regime is postulated for the Late Cambrian throughout the investigated areas.

INTRODUCTION

The epicontinental black shale facies of southern Sweden has a long history of economic exploitation that has resulted in numerous quarry exposures in different parts of the country (Andersson *et al.* 1985). Due to economic pressure at the beginning of World War II, an oil production plant was built in Kvarntorp in the Närke region where black shales with 8% oil contents occur (Schjånberg 1951). During the 1970s, the economic interest in the black shales, especially those of the Billingen region, increased again. Uranium contents of approximately 300 ppm and near-economic contents of, among others, vanadium, chromium, copper, and nickel are the main reasons for this interest (Dahlman & Gee 1977, Andersson *et al.* 1983).

One of the earliest and till now most comprehensive geoscientific papers on the Swedish black shale facies was written by Westergård (1922). Even though his paper focusses on the biostratigraphy of the Upper Cambrian, Westergård also made numerous observations on gross sedimentary structures which led to the interpretation that the black shale facies of southern Sweden was deposited in shallow water during transgressive and regressive phases of a sea on the Baltic Shield. Subsequent papers by Westergård (1940, 1942, 1943, 1944 a & b, 1947) represent a completion of his basic work published in 1922. As for the biostratigraphic aspect, the papers of Westergård and a more recent monograph by Henningsmoen (1957) are of great importance because they allow a reliable dating of each trilobite-bearing bed.

In spite of the weak theoretical foundation, the shallow water hypothesis for the deposition of the Upper Cambrian black shale has not been seriously challenged so far (see, for instance, Frebold 1928 a & b, Hansen 1938, Wetzel 1947, Hadding 1958, Thickpenny 1984). The wide extent and very monotonous character of a sediment series deposited during several (approximately 20) million years do, however, not necessarily point to shallow water deposits (Lindström 1971). Several recent papers deal with geochemical and mineralogical aspects without entering on a detailed discussion of the genesis of the facies (Armands 1972, Bjørlykke 1974, Edling 1974, Dypvik & Brunfelt 1976, Bjørlykke & Englund 1979).

The Cambrian and the alum shales in Scandinavia were comprehensively discussed in the papers by Thorslund (1960), Martinsson (1974), Andersson *et al.* (1985), and Bergström & Gee (1985).

Detailed investigations of the sedimentological aspects of the Upper Cambrian black shale facies of southern Sweden were initiated by the author in 1977. It quickly became apparent that analytical work on the carbonate intercalations in the black shales would be very important for the interpretation of the sedimentary environment and the diagenetic history of the sediments. Therefore, it was decided to put the main emphasis on these carbonate intercalations rather than on the geochemistry and petrology of the black shale, as was originally intended. Preliminary results were presented 1979 and 1982 (Lindström & Dworatzek 1979, Dworatzek 1979, Dworatzek 1982). This paper represents a comprehensive version of the author's thesis (Dworatzek 1985).

STRATIGRAPHIC OBSERVATIONS

The fauna of the Upper Cambrian black shale of Sweden is characterized by extremely low diversity but general abundance of individuals. In the lower parts of the sections investigated, the dominating element of the faunal community is a species of the trilobite family Agnostidae. Usually, each interval of the upper parts of the sections is characterized by the dominance of one species of the family Olenidae, with other species occurring subordinately, mostly also olenids. The frequency of olenids in the Acado-Baltic province and the possibility that they offer to subdivide Upper Cambrian sections in Scandinavia led to the name Olenid shale for the sedimentary sequence. This term is used in the following text in order to discriminate the Upper

Cambrian part of the black shale facies which also comprises Middle Cambrian and Lower Ordovician members.

Within a narrow stratigraphic range, a few layers of the Upper Cambrian are characterized by the articulate brachiopod *Orusia lenticularis*. Other groups of animals are only poorly represented. Instances of such groups are sponges, ostracods and other non-trilobite arthropods (Müller 1983), and conodonts (Müller 1959). The existence of animal groups without preservable parts cannot be excluded.

Based upon the abundant and mostly well-preserved trilobite material, a subdivision of the Upper Cambrian Olenid shale into six zones is possible. These zones comprise 32 subzones. It is likely that further subzones can be distinguished (Henningsmoen 1957). In this paper, the Upper Cambrian is subdivided into eight zones (Fig. 1). Zone V is subdivided into zones Va-c (*Peltura* zones of Henningsmoen 1957).

The investigated sections are situated in an extensive area on the Baltic Shield in southern Sweden (Fig. 2). Selected outcrops were surveyed and systematically sampled in the areas Kinnekulle, Billingen, Närke, and Öland. Single samples for sedimentological investigation were additionally taken in several minor outcrops that are not mentioned in the description of sections. Numerical values of section locations in the following refer to ''Rikets nät'' in the maps ''Topografiska kartan över Sverige'' on the scale 1:50 000.

Wherever it seemed reasonable several sections from the same area are described together in the following text. The description of carbonate intercalations is emphasized. The bedding is generally horizontal and tectonically undeformed in all sections investigated. The shale is very finely laminated on the mm scale and opens up as discrete, thin sheets when weathered (''paper shale''). The investigated sections are presented schematically in Fig. 3.

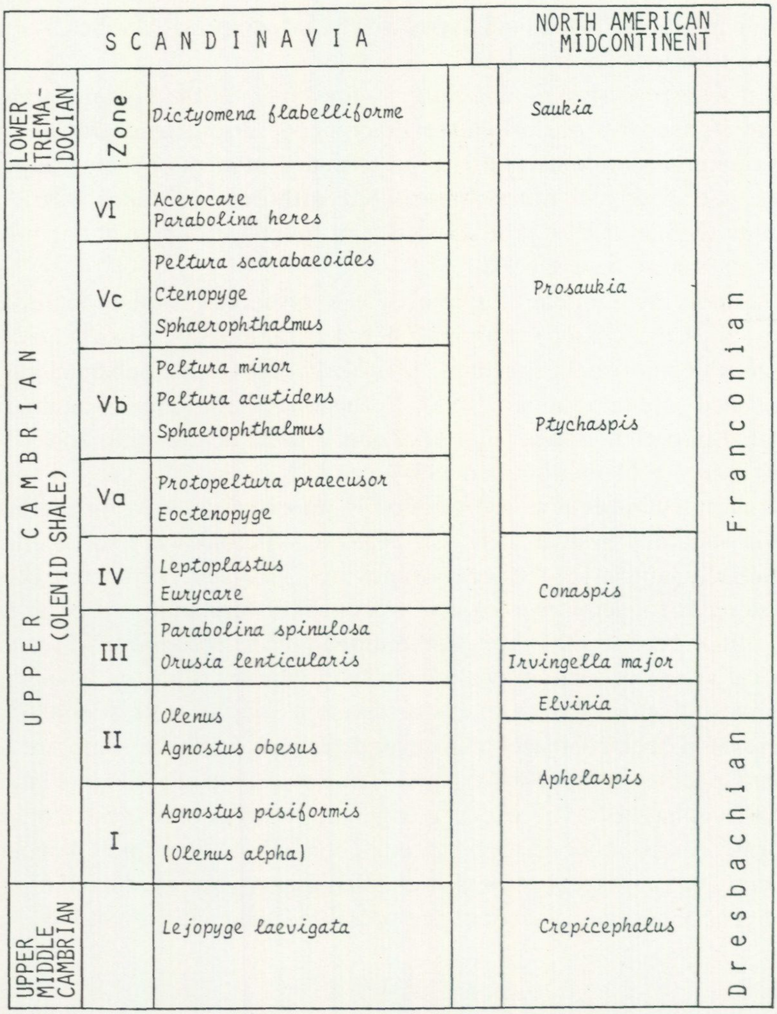
KINNEKULLE

Trolmen – Map-sheet Skara NW (57850/99750)
Abandoned quarry at the western side of Kinnekulle.
Thickness of section: 9.85 m. Zones represented: I–III, Vb, Vc.

Blomberg – Map-sheet Skara NW (55900/93250)
Abandoned quarry at the western side of Kinnekulle.
Thickness of section: 7.65 m. Zones represented: I–III, Vb, Vc.

Haggården – Map-sheet Skara NW (61750/96200)
Abandoned quarry at the western side of Kinnekulle.
Thickness of section: 7.70 m. Zones represented: II–IV, Vb, Vc.

The three sections referred to above show various common features and can be described together.



SCANDINAVIA			NORTH AMERICAN MIDCONTINENT	
LOWER TREMADOCIAN	Zone	*Dictyomena flabelliforme*	*Saukia*	Franconian
UPPER CAMBRIAN (OLENID SHALE)	VI	*Acerocare* *Parabolina heres*	*Prosaukia*	
	Vc	*Peltura scarabaeoides* *Ctenopyge* *Sphaerophthalmus*		
	Vb	*Peltura minor* *Peltura acutidens* *Sphaerophthalmus*	*Ptychaspis*	
	Va	*Protopeltura praecusor* *Eoctenopyge*		
	IV	*Leptoplastus* *Eurycare*	*Conaspis*	
	III	*Parabolina spinulosa* *Orusia lenticularis*	*Irvingella major*	
	II	*Olenus* *Agnostus obesus*	*Elvinia* *Aphelaspis*	Dresbachian
	I	*Agnostus pisiformis* (*Olenus alpha*)		
UPPER MIDDLE CAMBRIAN		*Lejopyge laevigata*	*Crepicephalus*	

Fig. 1. Zonation of the Scandinavian Upper Cambrian, and correlation with North American Midcontinent (slightly modified from Henningsmoen 1957). Note that the fossils listed under the different zones are taxa that were stratigraphically important for the present study, which in several cases are different from those by which the zones are usually named.

Zone I (Trolmen: 9.85–8.15 m, Blomberg: 7.65–6.40 m, Haggården: not outcropping). The basal part of zone I with *Agnostus pisiformis* consists of isolated black limestone lenses with sparse fauna. It is overlain by a continuous limestone bed which contains in its lower part horizontally laminated dark layers rich in *Agnostus pisiformis* and faintly laminated light grey agnostid shell layers. Overlying this bed, a fine-grained black carbonate bed several tens of cm thick and poor in fossils occurs. In the outcrop area of Trolmen, the upper part of this bed shows pit-like structures that are filled with angu-

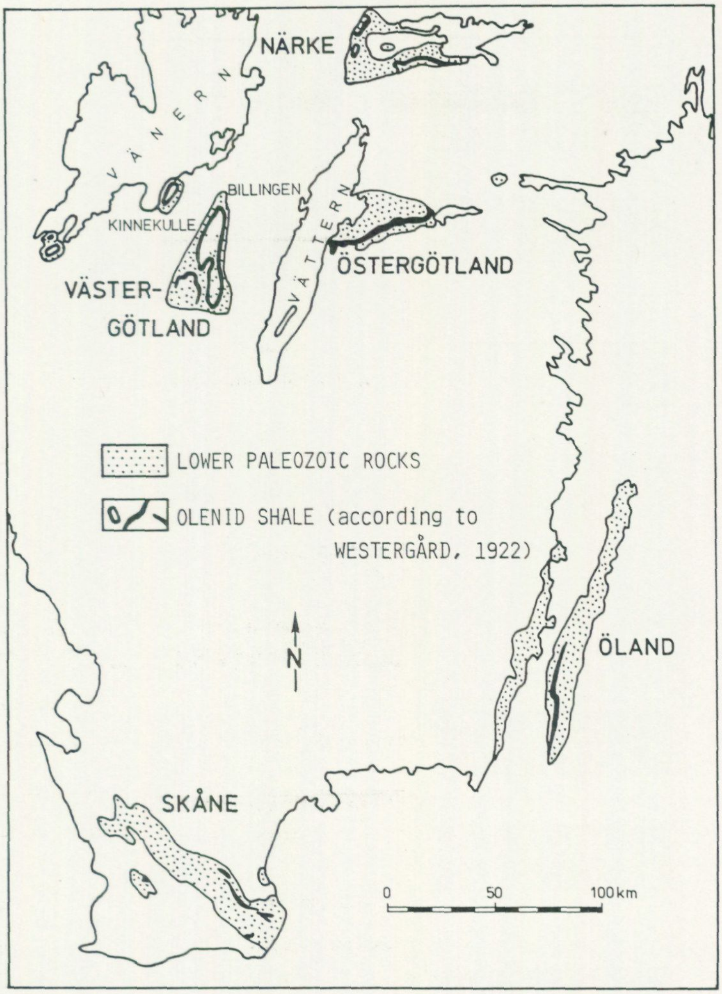


Fig. 2. Regional distribution of Upper Cambrian Olenid shale in south Sweden (after Westergård 1922).

lar, subrounded, and rounded clasts of bituminous limestone that are lithologically identical with the host layer and have the same faunal contents (see p. 20). Zone I terminates with a characteristic carbonate bed that, on weathering, yields a gritty texture. The fossil content of this bed is sparse. The lower boundary is horizontal which indicates that sedimentary thickness was adapted to underlying structures before this boundary formed.

Zone II (Trolmen: 8.15–7.55 m, Blomberg: 6.40–5.90 m, Haggården: 7.70–6.60 m). The upper part of the ”gritty-weathering” carbonate bed con-

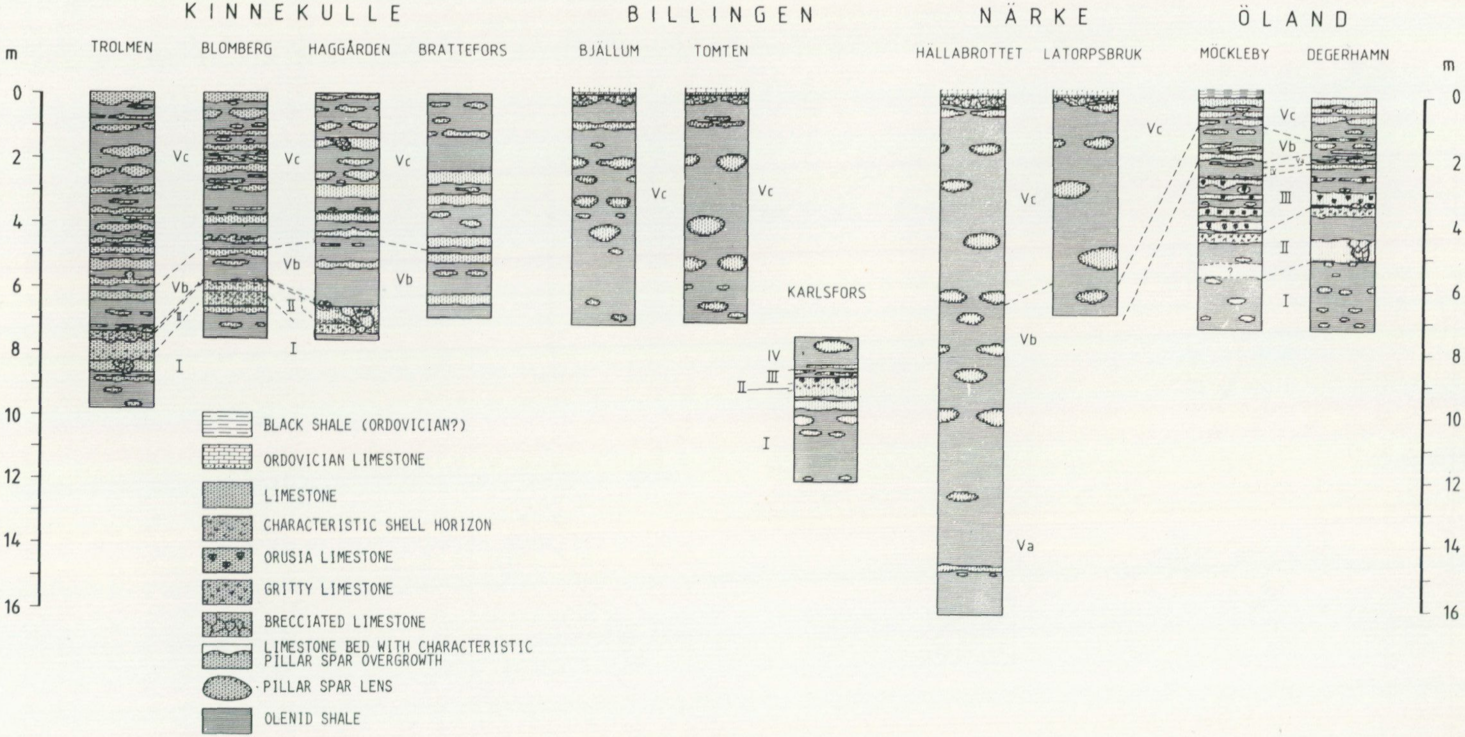


Fig. 3. Simplified stratigraphic sections of the principal outcrops studied.

tains the first laminae that are rich in *Olenus*. The section continues with a fine-grained black carbonate sequence with few fossils, and irregular bedding planes that in several cases are covered with about 10 cm thick *Olenus* coquinas with light brownish grey colour. Scour-and-fill structures were observed in this sequence. The upper boundary is horizontal and flat. Locally, structures similar to sandstone mounds (Baldwin & Johnson 1977) were observed. A detailed description of the *Olenus* bed of Trolmen is given in the chapter on sedimentary structures (p. 25). In the Haggården outcrop the top surface of the *Olenus* bed has developed pits filled with local limestone fragments, *Olenus gibbosus*, and abundant *Orusia*. Phosphatization of the top of the *Olenus* bed frequently occurs throughout the Kinnekulle area.

Zone III (Trolmen: 7.55–7.45 m, Blomberg: 5.90–5.85 m, Haggården: 6.70–6.60 m). Zone III with *Orusia lenticularis* and *Parabolina spinulosa* is only sporadically represented by large flat limestone clasts at the upper boundary of the *Olenus* bed. Pits filled with *Orusia* occur at the top of the *Olenus* bed at Haggården but are otherwise rare.

Zone IV. This zone could not be identified as a discrete unit during my field work. Only within the *Orusia*-rich infillings at Haggården a few cranidia of *Leptoplastus ovatus* were identified.

Zone Va. This zone was not identified. According to Westergård (1922) the total thickness of zones III to Va does not exceed 0.8 m in the Kinnekulle area.

Zone Vb (Trolmen: 7.45–6.10 m, Blomberg: 5.85–4.85 m, Haggården: c. 5.65 m). Zone Vb with *Peltura aucutidens, Peltura minor* and *Sphaerophthalmus alatus* is represented throughout the Kinnekulle area. Carbonate lenses and, in places, thin continuous layers of limestone, contain abundant whitish and brownish speckled coquinoid beds consisting largely of *Sphaerophthalmus;* also, less fossiliferous dark beds with parallel lamination. *Sphaerophthalmus* predominates over *Peltura*.

Zone Vc (Trolmen: 6.10–0 m, Blomberg: 4.85–0 m, Haggården: 4.60–0 m). Zone Vc with *Peltura scarabaeoides scarabaeoides, P. scarabaeoides westergaardi, Sphaerophthalmus major,* and *S. humilis* begins with a condensed sequence consisting of heaped limestone concretions. This horizon is strikingly developed in the Blomberg outcrop and will be described in some detail in the chapter on sedimentary structures (p. 30). The limestone concretions contain *Sphaerophthalmus alatus* that as a rule is quite rare. Towards the top the three sections contain numerous lenses and beds of limestone. A good many bioclastic layers, about 1 cm thick and containing *Sphaerophthalmus* in great abundance, alternate with horizontally laminated and dark grey to almost black layers that besides *Sphaerophthalmus* mostly contain abundant cranidia and pygidia of *Peltura*. In addition to horizontal lamination, the coquinoid layers in particular contain other, frequently discontinuous forms of lamination. No crossbedding was, however, identified.

Synsedimentary thrust structures occur on the western side of Kinnekulle, whereas at the eastern side of this area there are also slide breccias. Irregularly shaped chert intercalations occur sporadically in the upper part of zone Vc in the Trolmen section. The sections of Blomberg and Haggården terminate at a morphological edge with a thick bed containing abundant fragments of *P. scarabaeoides scarabaeoides* and *P. s. westergaardi*. The upper part of zone Vc in the Trolmen section contains *P. s. westergaardi* and some fragments of *Agnostus rudis holmi*. A parallel-laminated limestone with *Peltura paradoxa, Parabolina megalops*, and abundant *Parabolina lobata* forms the termination of this section. Trilobite cranidia occur in abundance and are mostly turned "convex-down".

Zone VI. According to Westergård (1922), zone VI with *Parabolina heres* is locally represented in the Kinnekulle area with a maximum thickness of 0.6 m.

The Lower Ordovician Dictyonema shale is missing in the Kinnekulle area.

Brattefors – Map-sheet Skara NW (60400/94150)
Quarry at the southeastern side of Kinnekulle.
Thickness of section: 7.00 m. Zones represented: Vb, Vc.

Zone Vb (7.00–4.90 m). Zone Vb contains two thick, continuous limestone beds that are rich in fragments of *Peltura minor, P. acutidens,* and *Sphaerophthalmus alatus*. Both beds contain dark layers that are poor in fossils as well as light, coquinoid layers of a milky appearance that contain great quantities of *Sphaerophthalmus*. Between the two beds there is a level containing lenses of black, fine-grained limestone in which fossils are rare.

Zone Vc (4.90–0 m). The section continues upward with a sequence of beds and lenses of limestone that are intercalated with a variable thickness in the Olenid shale. The lenses characteristically occur along certain continuous bedding planes and consist of mainly black, finely laminated, and poorly fossiliferous limestone. Within the lenses there are sporadic occurrences of small, lens-shaped accumulations of trilobite fragments. Throughout the continuous beds there are, on the other hand, certain laminae that are distinguished by a relatively light shade of grey and that contain abundant trilobite fragments, mainly *Sphaerophthalmus major* and *S. humilis*. These laminae alternate with more fine-grained, dark grey to black layers. In places, the limestones contain irregularly shaped chert nodules. The proportion of *Sphaerophthalmus* within the bioclastic fraction decreases markedly in the upper part of the section, and *Peltura scarabaeoides scarabaeoides* becomes the dominant faunal element.

BILLINGEN

Bjällum – Map-sheet Skara SW (71850/71250)
Abandoned quarry at the western side of Billingen approximately 4.5 km SSW of Varnhem.
Thickness of section: 7.20 m. Zones represented: Vc.

Zone Vc (7.20–0 m). The limestones of the lower part of the section (7.20–2.50 m) are mainly represented by horizontally laminated, dark greyish brown, more or less strongly recrystallized lenses that are arranged along horizontally continuous surfaces. Pillar spar (p. 52) frequently occurs in these lenses. At some levels, there are light brownish grey, bioclastic layers that are a few cm thick and consist mainly of *Sphaerophthalmus major* and *S. humilis*. *Peltura* fragments are very subordinate components. The upper part of the section (2.50–0 m) is characterized by limestone intercalations that form continuous beds. The fauna of these beds is dominated by *Peltura scarabaeoides*. In the beds just below the Cambro-Ordovician boundary, cranidia of this trilobite cover certain bedding-planes with convex-down orientations.

The base of the Ordovician consists of a bed of Arenigian age that is rich in glauconite and phosphorite nodules. The Upper Cambrian limestone in contact with this bed is internally brecciated, bleached from above, and heavily impregnated with irregularly shaped pyrite concretions. Irregularly shaped chert nodules locally occur in the limestones at the Cambro-Ordovician boundary.

Tomten – Map-sheet Skara SW (70900/57500)
Quarry in operation approximately 7 km NNE of Falköping.
Thickness of section: 7.10 m. Zones represented: Vc.

Zone Vc (7.10–0 m). In the Tomten section big limestone lenses are distributed along horizons that are laterally continuous through the several hundred meters that the outcrop extends. The lenses predominantly consist of dark brownish grey to black limestone that is frequently strongly recrystallized. The central parts of the lenses are finely laminated and sporadically contain thin, richly fossiliferous layers with fragments of *Peltura scarabaeoides* and *Sphaerophthalmus majusculus*. At the periphery, the lenses show distinct overgrowths with pillar spar. Immediately below the Cambro-Ordovician boundary the limestone forms continuous beds, a few cm thick, and with internal brecciation. These beds contain abundant cranidia of *Peltura scarabaeoides scarabaeoides* and are distinctly bleached from above. The Cambro-Ordovician boundary surface is characterized by corrosion pits that are filled with glauconite and phosphorite pellets, with local pyritization.

Karlsfors – Map-sheet Skara NE (79750/87750)
Small chasm cut by a brook, approximately 3.5 km S of Timmersdala.
Thickness of section: 4.50 m. Zones represented: I–IV.

Zone I (4.50–1.65 m). In the lower half of the outcropping section black fine-grained limestone occurs as lenses in the shale. Several bedding planes within these lenses are rich in fragments of *Agnostus pisiformis*. A continuous carbonate bed, partly with distinct, parallel lamination, follows at approximately 2.25 m. *Agnostus pisiformis* occurs abundantly; cranidia and pygidia mainly show convex-down orientation. The basal part of the overlying continuous carbonate bed contains alternating dark layers with *Agnostus pisiformis* and light layers of milky appearance, with abundant agnostid debris.

Zone II (1.65–1.45 m). The central part of the continuous carbonate bed mentioned in the preceding paragraph has a "gritty" appearance where weathered. This part is rich in *Olenus truncatus* and *Agnostus obesus*.

Zone III (1.45–1.0 m): In the upper part of the above-mentioned bed milky white layers alternate with dark layers with abundant *Orusia lenticularis* and *Parabolina spinulosa*. The boundary between zones II and III is perfectly horizontal and lacks any visible evidence of a hiatus. Along the upper boundary of the continuous carbonate bed there are thin lenses of limestone with parallel lamination and containing *Orusia lenticularis* and *Parabolina spinulosa*.

Zone IV (1.0–0 m). Limestone bodies in the top part of the section are elongated lenticular, and thin. *Eurycare latum* and *Leptoplastus crassicorne* occur in several layers. Above 0.20 m, a level of big lenses of limestone terminates the section. The limestone of the lenses is horizontally laminated and contains bioclastic layers with fragments of *Leptoplastus stenotus* and *L. angustatus*.

NÄRKE

Hällabrottet – Map-sheet Örebro SW (65900/53850)
Abandoned quarry approximately 5 km E of Kumla.
Thickness of section: 16.10 m. Zones represented: Va-Vc.

Zone Va (16.10–c. 13.0 m). At approximately 14.7 m, there is a bed of horizontally laminated, almost black, and fine-grained limestone. At the base of this bed the shale contains small lenses of carbonate. There are very few fossils; only a few fragments of *Ctenopyge flagellifera* helped to identify zone Va. Further lenses of limestone were found at approximately 12.5 m. However, they were not accessible for sampling; their age is therefore uncertain.

Zone Vb (c. 13.0–6.5 m). Big limestone lenses occur at four laterally continuous levels, frequently with a horizontal distance of a couple of meters between the lenses. As a rule the limestone of the lenses is distinctly and horizontally laminated and almost black. Lamination is caused by the alternation of coarser and finer grain. Continuous pyrite laminae were sporadically observed. Identifiable fossils are sparse and mostly consist of cranidia of *Mesoctenopyge tumida* and *Ctenopyge affinis gracilis*. The carbonate lenses are marginally overgrown with pillar spar.

Zone Vc (c. 6.5–0 m). Owing to lack of identifiable fossils and predominance of recrystallization, carbonate lenses occurring at approximately 6.3 m could not be stratigraphically dated. Therefore it remains uncertain whether this level belongs to zone Vb or Vc. The succession here regarded as belonging to Vc has three levels with limestone lenses below approximately the 1 m level. These lenses are lithologically similar to those of zone Vb. The fauna recovered consists of a few solitary fragments of *Peltura scarabaeoides* and *Sphaerophthalmus*. The uppermost 1 m of the section contains two beds of limestone that are locally almost in contact with one another. These two beds show faintly laminated, several centimetres thick, light brownish grey layers that are rich in *Peltura* fragments. The upper carbonate bed shows complex internal brecciation, bleaching, and pyrite impregnation at the contact with the overlying Ordovician.

Latorpsbruk – Map-sheet Örebro SW (53750/73700)
Abandoned quarry approximately 12 km W of Örebro.
Thickness of section. 6.80 m. Zones represented: Vb, Vc.

Zone Vb (6.80–5.90 m). This zone can be identified in a laterally continuous level with big limestone lenses containing fragments of *Peltura minor, Sphaerophthalmus alatus* and *Ctenopyge* sp. As a rule the dark brownish grey to black limestone is strongly recrystallized. The margins of the lenses tend to be overgrown with pillar spar.

Zone Vc (5.90–0 m). The upper part of the section contains three persistent levels of big limestone lenses. The fauna is generally restricted to a few fragments of *Peltura scarabaeoides scarabaeoides* and *Sphaerophthalmus majusculus*. The inner parts of the lenses contain a few thin, light grey, and richly fossiliferous laminae. Even this part of the section is characterized by recrystallization as well as pillar spar. The uppermost limestone bed below the Cambro-Ordovician boundary is internally brecciated. It is bleached from above and strongly pyritized. Fossil contents are restricted to cranidia of *Peltura scarabaeoides scarabaeoides* with convex-down orientation.

ÖLAND

Möckleby – Map-sheet Kristianopel NE (37550/41500)
Abandoned quarry approximately 0.5 km W of S. Möckleby.
Thickness of section: 7.20 m. Zones represented: I-Vc.

Degerhamn – Map-sheet Kristianopel NE (37650/42550)
Abandoned quarry approximately 0.3 km E of Degerhamn cement factory.
Thickness of section: 7.25 m. Zones represented: I-Vc.

These two sections are described together.

Zone I (Möckleby: 7.20–c. 5.60 m, Degerhamn: 7.25–5.10 m. The lower parts of the two sections contain fine-grained dark grey to black limestone lenses that occur either sporadically or arranged at laterally persistent levels. The lenses contain quite thin laminae with abundant *Agnostus pisiformis*.

Zone II (Möckleby: c. 5.60–4.20 m, Degerhamn: 5.10–3.40 m). A carbonate bed that is several tens of centimetres thick forms the lower part of this zone in the Degerhamn outcrop. This bed contains coquinas with *Olenus gibbosus* and *O. truncatus*. It also contains some layers that yield a gritty texture on weathering. Furthermore, there are pit-like structures that penetrate the bed from above and are filled with very fine-grained, nonfossiliferous limestone. The bed with abundant *Olenus* is only sporadically exposed in the Möckleby outcrop. Another characteristic limestone bed marks one of the working levels in both of the old quarries. This bed is bipartite; it consists of two almost equally thick limestone layers that are locally separated by a thin layer of shale. The basal part is characterized by weathering to a gritty texture. This part contains laminae with *Olenus scanicus* and *Agnostus obesus*.

Zone III (Möckleby: 4.20–2.40 m, Degerhamn: 3.40–2.20 m). The central part of the bipartite carbonate bed is dominated by sediment bodies of light, "milky" appearance, consisting almost exclusively of *Orusia lenticularis*. Parts of the bed are conglomerate-like. Intraclasts of *Orusia* coquina frequently exhibit marginal phosphatization. At one place in the Degerhamn outcrop, there is a structure that can be described as a clastic dyke (see the chapter on sedimentary structures, p. 27). The continuous limestone bed ends with *Orusia* coquina of "milky" whitish appearance. Both sections then continue upwards with limestone intercalations that may form either lenses or continuous beds, in either case with abundant *Orusia*. In the upper part of zone III there are also fragments of *Parabolina spinulosa*.

Zone IV (Möckleby: 2.40–2.15 m, Degerhamn: 2.20–2.05 m). The index fauna of this zone is represented in a relatively thin, continuous limestone bed that is light to dark grey, with thick laminae. Immediately above this bed there are flat, thin carbonate lenses with the same fauna.

Zone Va (Möckleby: 2.15–2.00 m, Degerhamn: 2.05–1.75 m). Elongate lenticular carbonate intercalations in the shale characterize this zone. They contain abundant *Eoctenopyge flagellifera*.

Zone Vb (Möckleby: 2.00–0.90 m, Degerhamn: 1.75–1.35 m). The lower part of zone Vb in the Möckleby section is represented by a limestone bed with variable thickness; in the Degerhamn section it is represented by a level of limestone lenses. These limestones are black and fine-grained, and contain thin laminae with *Peltura acutidens* and *Sphaerophthalmus alatus*. In both sections, the upper part of the zone contains elongate carbonate lenses with light, coquinoid layers mainly consisting of fragments of *S. alatus*.

Zone Vc (Möckleby: 0.90–0 m, Degerhamn: 1.35–0 m). Zone Vc with *Peltura scarabaeoides scarabaeoides* and *Sphaerophthalmus humilis* consists of a compact succession of elongate carbonate lenses and carbonate beds with great lateral thickness variation. There are numerous coquinoid layers with a milky whitish colour in these limestones. *S. humilis* mainly is concentrated in the lower part of zone Vc. Fragments of *Peltura* are relatively rare in this part. *Sphaerophthalmus* strongly decreases in the uppermost part, where *P. s. scarabaeoides* covers the bedding-planes.

The Degerhamn section ends with zone Vc at the top of an old quarry wall. The uppermost part of the Möckleby section consists of black shale that is approximately 1 m thick. According to Westergård (1922) the top of the Degerhamn section consisted of a thin layer of Dictyonema shale (lowermost Ordovician) at the time of his investigation. One may suspect that the uppermost shale unit of the Möckleby section is identical with this Dictyonema shale. However, due to the lack of fossils this suspicion could no be verified by the present investigation. The Upper Cambrian zone VI is not represented.

SEDIMENTARY STRUCTURES

A narrowly spaced, parallel lamination is developed in the Olenid shale. No granulometric or mineralogic variation could be identified across the laminae. Weathering leads to disintegration of the shale as large, thin flakes ("paper shale"). No other kinds of sedimentary structure could be observed in the shale. In contrast, the diversity of sedimentary structure is much greater in the intercalated limestones.

The principal structure in all the carbonate beds is *bedding*. Of the structures belonging to this category *parallel lamination* is the most common. It mainly consists of one to several centimetres thick laminae that can be distinguished by their varying contents of organic matter, clayey contaminations, and bioclastic components. The lamination is frequently enhanced by the different degrees of recrystallization of individual laminae. In polished sections parallel lamination is distinguishable through the alternation of light grey to whitish, grain supported biodetrital layers and dark brownish grey, matrix-rich layers (Fig. 4 a, b). Slight undulation of otherwise straight laminae and boundaries is caused by the curvature of trilobite cranidia (Fig. 4 c). A rare feature is the occurrence of exoskeletal fragments of trilobites stacked upon one another by parallel insertion of the fragments into the concavities of adjacent fragments. In these cases, the fragments mostly rest with their convex sides up. Because this structure is a likely result of wave movement, its scarcity indicates that the sediment surface, was, but rarely, subjected to such movement. However, parallel lamination occurs also in the absence of distinct lithological changes. For instance, preferred orientation of trilobite fragments on bedding-planes causes lamination and mostly also planes of parting. This type of lamination is mainly represented in the *Peltura* zones. Some thin carbonate layers are characterized by "convex-down" orientation of *Peltura* cranidia that indicate very calm depositional conditions (Fig. 4 d). Other carbonate layers show *Peltura* cranidia with "convex-up" orientations that were turned over into the more stable position during or after deposition.

In spite of the circumstance that all bioclastic components are transported, *graded bedding* could not be identified in the bioclastic fractions. The explanation for this apparent absence of grading can be sought in the mechanisms of deposition. However, another possible explanation could be that the structure was blurred by diagenetic processes.

Grading is indicated only in a few cases that involve non-carbonate clastics. One thin section (Fig. 5 a) contains a 0.3 mm thick layer with quartz grains of coarse silt size (0.03–0.06 mm) deposited on top of a coquinoid layer with clayey and organic impurities. Above the silty layer there follows another, 1.5 mm thick, coquinoid layer with similar impurities and grading upwards into a further carbonate layer with a greater content of clay and organics. The two last-mentioned carbonate layers contain sporadically dispersed quartz grains with maximum diameters of 0.03 mm.

Another thin section (Fig. 5 b) has a slightly undulating bedding-plane that is regarded as erosional. Its depressions are filled with phosphate spherules (0.1–0.2 mm). The immediately succeeding coquinoid layer also contains phosphate spherules, but with maximum size of 0.1 mm. In both described cases the contact between the basal layer with the coarser particles and the overlying, finer grained layer is gradational.

Cross bedding is extremely rare (Fig. 6).

In certain areas *carbonate breccias* regularly occur at a few stratigraphic levels. A breccia that probably formed by gravity flow occurs in the lower part of the *Peltura* zones in the Haggården outcrop (Fig. 7 a). A fine-grained, approximately 15 cm thick carbonate bed is interrupted over a

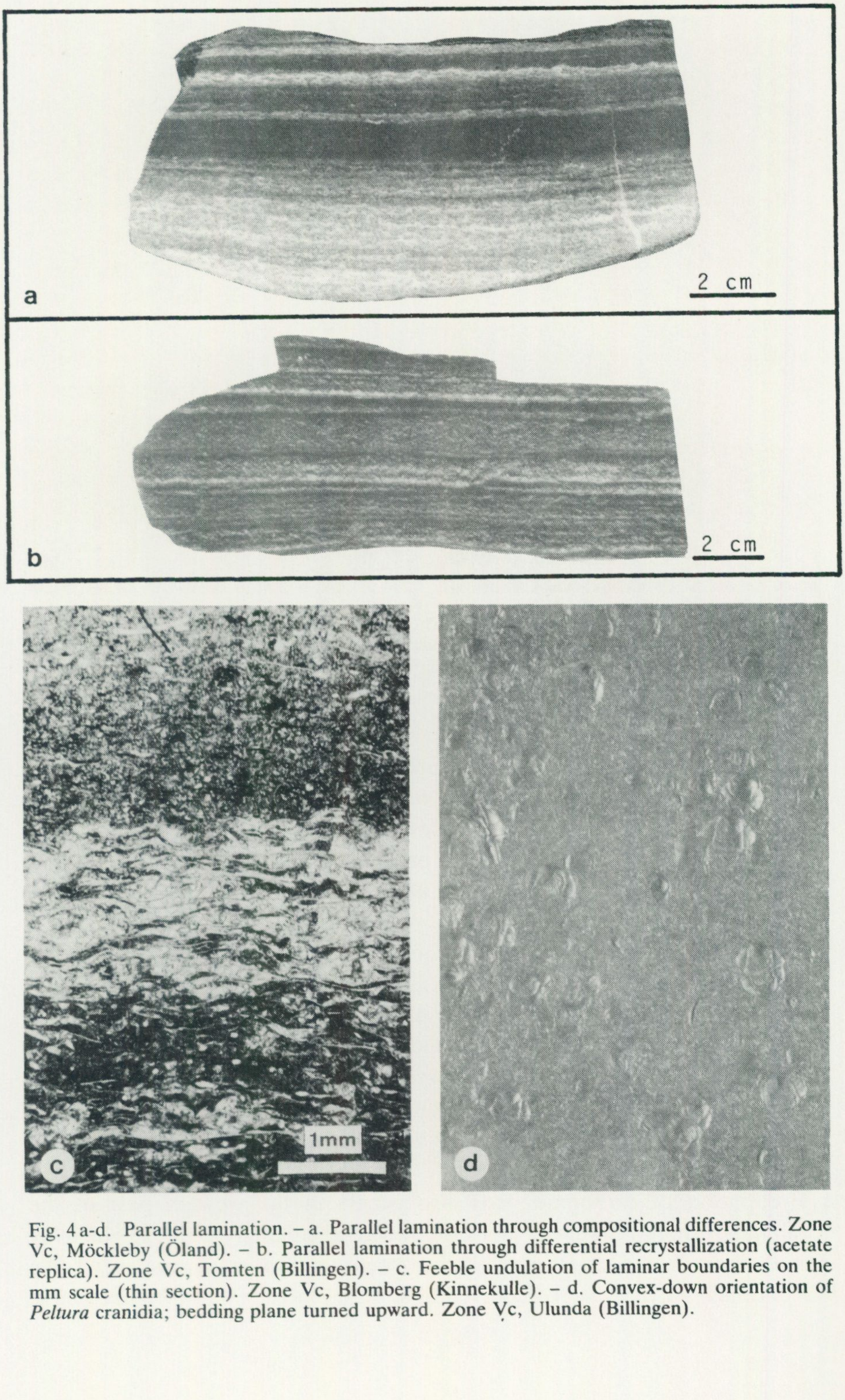


Fig. 4 a-d. Parallel lamination. – a. Parallel lamination through compositional differences. Zone Vc, Möckleby (Öland). – b. Parallel lamination through differential recrystallization (acetate replica). Zone Vc, Tomten (Billingen). – c. Feeble undulation of laminar boundaries on the mm scale (thin section). Zone Vc, Blomberg (Kinnekulle). – d. Convex-down orientation of *Peltura* cranidia; bedding plane turned upward. Zone Vc, Ulunda (Billingen).

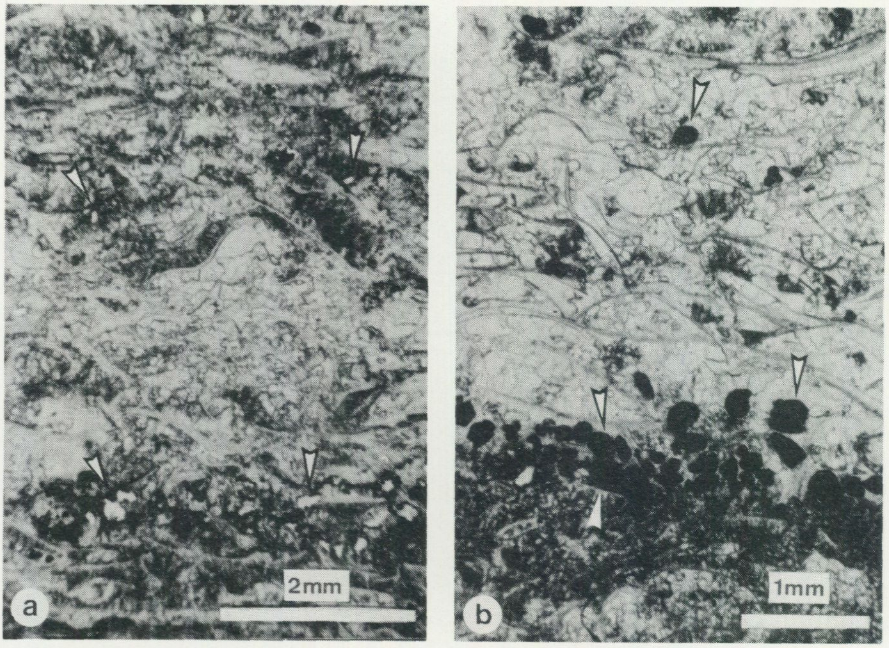


Fig. 5 a, b. Graded bedding in thin sections. The grading involves quartz silt (a: arrows), zone Vc, Tomten (Billingen), and phosphate spherules (b: arrows), zone Vc, Möckleby (Öland).

distance of approximately 30 cm. The space between the irregularly shaped and fracture-like terminations of the carbonate bed is occupied by a brecciated carbonate filling which was furthermore squeezed approximately 15 cm deep into a somewhat coarser grained, underlying part of the bed. A 10 cm thick, lenticular concretion with a diameter of about 1 m in the bedding-plane was rotated into an orientation that is inclined towards the fracture zone and dips into the brecciated sediment.

Gravity flow breccias of the same general kind and extent are typical for the eastern part of the Kinnekulle area. This kind of breccia indicates that mechanical instability, probably caused by deposition on slightly inclined surfaces, could lead to tearing apart and sliding of sediments. However, such structures also indicate that at least some concretions were already mechanically stable at an early stage of the depositional history, and that more or less non-lithified carbonates existed simultaneously below at least partially lithified concretions.

Brecciation of carbonate beds also occurs in the western part of the Kinnekulle area. However, this brecciation is generally not explained by gravity flow. In the upper part of the *Agnostus pisiformis* zone, karst-like discontinuity surfaces were observed at several places in an otherwise undis-

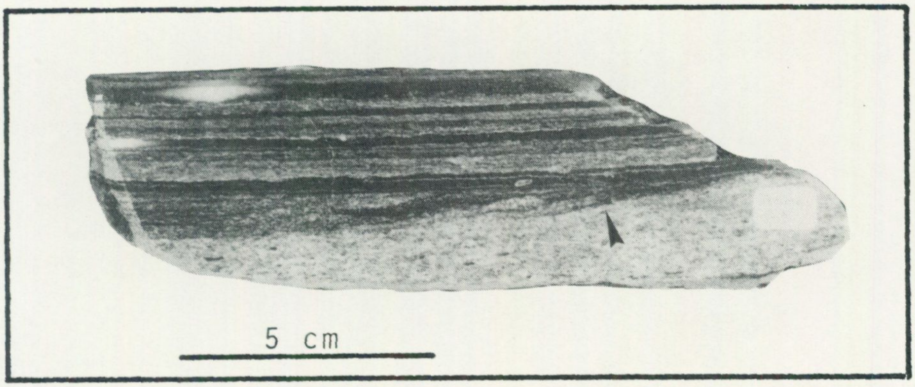


Fig. 6. A suggestion of cross-bedding. Zone Vc, Trolmen (Kinnekulle).

turbed carbonate bed (Fig. 7b). Similar structures were also found in the upper part of the *Agnostus pisiformis* zone on Öland. The brecciated fillings of the pits occurring on these surfaces are lithologically and faunistically identical with the carbonate bed underlying the discontinuity. Because the clasts are of strictly local derivation their presence cannot be taken as evidence of horizontal movement of sediment. Furthermore, karst processes are not known to create structures like those shown in Fig. 7b. As a process that could disintegrate a carbonate bed at an early stage of lithification in some places but would not necessarily result in horizontal movement of the clasts, a shaking of the sediments by earthquakes appears to be a possibility, especially in view of the circumstance that the Late Cambrian was characterized by strong tectonic activity in the Caledonian fold belt (Gee & Sturt 1985).

Together with the evidence of brecciation and reworking of sediments, sedimentary structures were sporadically found that are related to "mud volcanoes" described by Reineck & Singh (1975). Such structures are caused by *gas or fluid escape*. On the scale of the hand specimen they are much more rare than in the thin section but also much more spectacular. One such structure from the *Peltura* zones of the Brattefors outcrop (Kinnekulle) will be described in some detail (Fig. 8a).

On the upper surface of a carbonate bed, approximately 15 cm thick, a low cupola-shaped structure is developed that consists of concentrically arranged rolls that are draped over one another. The weathered fracture plane perpendicular to the bedding shows that the whole carbonate bed is dissected by a network of fine-grained carbonate veins. This fine-grained carbonate is particularly enriched within the concentric rolls and fills the central pipe of the "mud volcano". The pipe filling contains numerous little carbonate flakes that are rich in organic matter. Around these flakes the surrounding carbo-

Fig. 7 a. Slide breccia in lower part of *Peltura* zones in the Haggården outcrop (Kinnekulle). Note the rotated cabonate concretion (arrows).

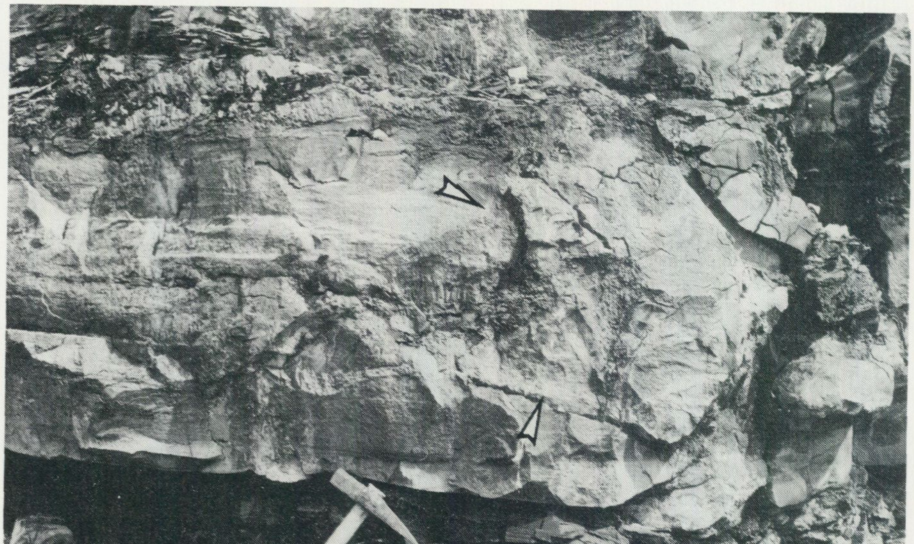


Fig. 7 b. Sedimentary breccia in the *Agnostus pisiformis* zone in the Trolmen outcrop (Kinnekulle).

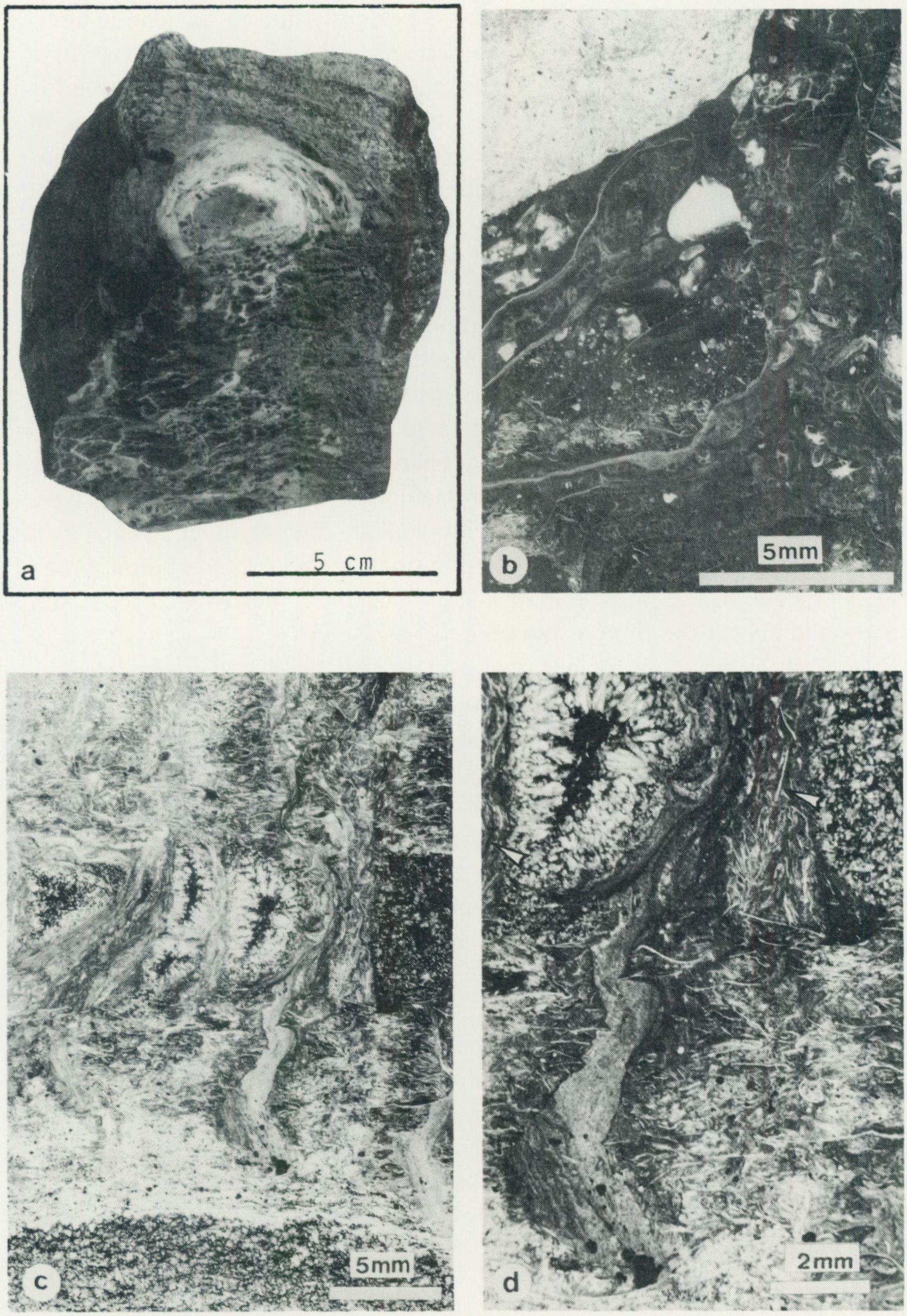


Fig. 8 a-d. Structures probably formed by degassing. – a. Specimen from the *Peltura* zones, Brattefors (Kinnekulle). – b. Thin section from the *Olenus* zone, Trolmen (Kinnekulle). – c. Thin section of degassing structures deformed by compaction, *Peltura* zones (Kinnekulle). – d. Detail of c; note trilobite fragments (arrows) oriented parallel to flow.

nate mud has a coarsening of the grains, evidently due to diagenetic alteration. The lowermost part of the described carbonate bed consists of a coquinoid layer with carbonate mud as matrix. Evidently, part of the muddy matrix was transported toward the sediment surface during the escape of either gas or fluid. The preservation of the structure indicates early lithification and/or calm depositional conditions during and after formation of the structure.

Structures explained by the escape of gas or fluid were also observed in many thin sections. In an example from the *Olenus* zone of the Trolmen outcrop (Fig. 8b), a basal micritic carbonate sediment forms a cone-shaped intrusion into an overlying trilobite-rich sediment. The intrusion is only a few centimetres in diameter and resembles the roots of a tree that converge upwards into a trunk. The micritic carbonate sediment contains some olenid fragments and subrounded as well as rounded intraclasts that evidently originated from the bioclast-rich neighbouring sediment. The intraclasts could have been formed by intrastratal sediment movement. The intrusive upward flow of fine-grained carbonate mud resulted in small-scale flow lamination. Small flakes of shale in the micritic matrix show that the underlying clay was still unconsolidated at the time of intrusion.

The early compaction of gas/fluid escape structures is demonstrated by another example, from the *Peltura* zones of the Kinnekulle area (Fig. 8c). A carbonate bed that is laminated on the cm scale is cut by carbonate mud intrusions perpendicular to the bedding. The intrusions are approximately 2 mm thick and are located at intervals of several millimetres. The mud intrusions contain trilobite fragments the long axes of which are oriented at right angles to the bedding, and evidently parallel to the flow direction of the carbonate mud (Fig. 8d). The mud intrusions exhibit congruent s-shaped folds. The deformation pattern points to plastic deformation by compaction after the intrusion.

According to Reineck & Singh (1975), fast sedimentation at high average rates is a prerequisite for the formation of mud volcanoes. This prerequisite can, however, be excluded in the case of the carbonates of the Olenid shale. Hedberg (1974) described mud volcanoes that were formed through the escape of methane from sediments. Syngenetic, biogenic methane is very likely to have formed in the Olenid shale sediments, and the formation of mud volcanoes and related structures by the escape of gas from non-lithified sediments can thus be expected.

As pointed out above (p. 5) some sedimentary structures in the limestones of the Olenid shale were described and interpreted as regressive-transgressive conglomerates by Westergård (1922). These structures are particularly well developed in the Kinnekulle and Öland areas. They are here interpreted as *condensed sequences* in the sense of Heim (1934). In the

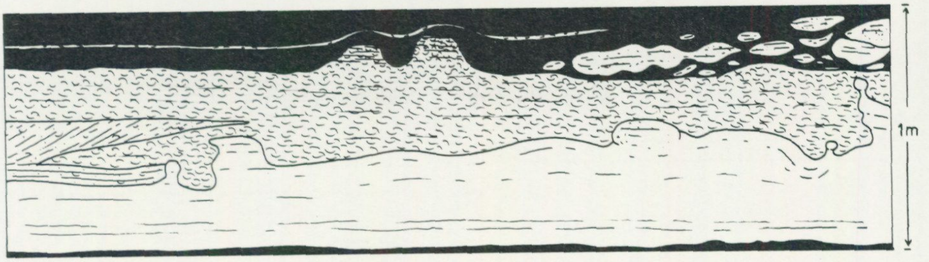


Fig. 9. Schematized representation of the *Olenus* bed of the Trolmen outcrop. For explanation, see text.

following, three examples of the sedimentary complexity caused by condensation are described and interpreted.

The upper part of the *Olenus* bed of the Trolmen outcrop (Kinnekulle) is schematically illustrated by Fig. 9. At the base of the analysed interval we find an almost black, fine-grained limestone with mainly horizontal lamination and with sparse fossils. The upper part of the interval contains a surface with deeply dissected topography (see especially the right part of Fig. 9). Some details of this topography appear to have been delicate and vulnerable to mechanical destruction. The hollow structures are filled with olenid debris. The deposit of trilobite bioclastics can be subdivided into a horizontally laminated, basal portion, with minor clay contamination (see left part of Fig. 9), a portion with weakly developed cross-bedding, and an almost homogeneous and pure carbonate, upper portion that is but feebly bedded.

The upper surface of the *Olenus* bed is horizontal over a distance of about 10 m, but locally it shows structures resembling sandstone mounds (see central part of Fig. 9). An intensive phosphatization occurs on major parts of the surface. In particular, strong phosphatization has affected flat intraclasts with *Orusia lenticularis* that occur sporadically on the bedding-plane.

A model of the genesis of the complex of structures described above is illustrated in Fig. 10. The model comprises the following steps:

(a) Carbonate mud, several tens of centimetres thick, is lithified during early diagenesis. Lithification occurred tens of centimetres below the sediment surface and is suggested to have proceeded from below upwards. In the upper part of the preserved sediment lithification proceeded by radial growth of concretionary ellipsoids.

(b) Due to increased current activity in the overlying water the carbonate mud that still remained non-lithified was removed by erosion. Only the lithified portions remained. The duration of the erosive process is unknown. The upper surface of the preserved deposit does not show any evidence of oxidation or of bioerosion. Massive pyritization is also lack-

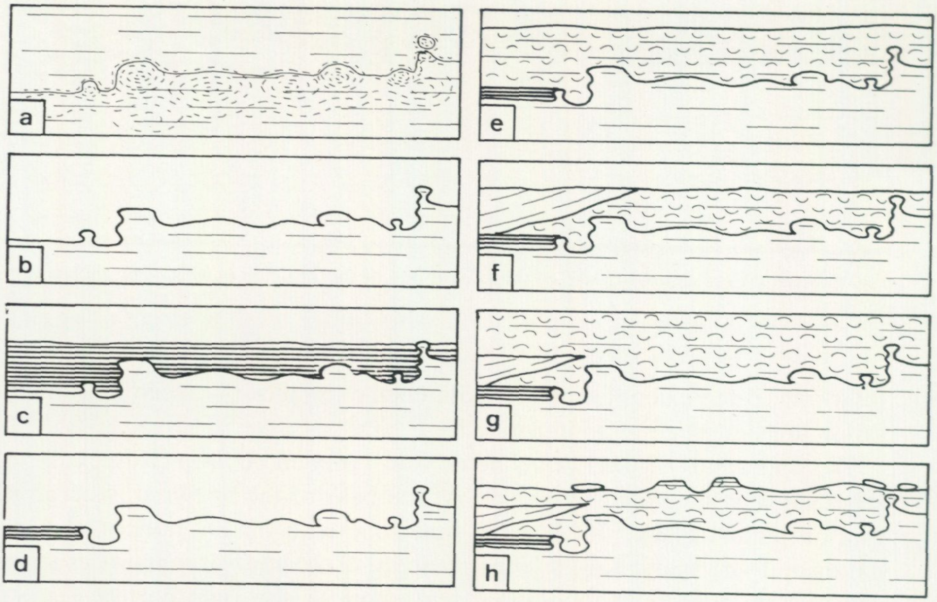


Fig. 10 a-h. Model of the origin of the complex sedimentary structures occurring in the *Olenus* bed of the Trolmen outcrop. For explanations, see the text.

ing, although it occurs on other discontinuity surfaces. The observed structures are not considered sufficiently karst-like to warrant the interpretation that carbonate dissolution was active. In particular, the ellipsoidal concretions are preserved without any signs of chemical attack.

(c-g) The continued depositional history was characterized by the alternation of deposition and erosion of olenid debris. Thus, there developed structures resembling scour-and-fill, which also contain indications of cross-bedding. The bioclastic sediment mostly has a massive structure and only sporadically shows horizontal, coarse lamination. A relatively rapid sequence of episodic events most likely caused the deposition of the bioclastics. Much of the olenid debris could have originated outside the present site of deposition. The transport processes involved winnowing and concentration of the biogenic fraction. The frequent lack of lamination indicates participation of a transport mechanism, such as gravity flow, that prevented laminar arrangement of clasts while the sediment came to rest.

(h) During a late stage of bioclastic deposition structures resembling sandstone mounds (Baldwin & JOhnson 1977) developed at the top of the olenid coquina. Although the superficial morphology suggests diapiric structures, the presence of undisturbed, continuous, and horizontal lamination throughout the structures shows that they are the remnants of an eroded, laminated sediment body. Most likely they were preserved because they had been subjected to differential, early cementation.

The evelopment of the structures referred to above initiated a stage of hardly any net sedimentation. This stage covered the time intervals corresponding to zones III-Va. During this stage intense phosphatization occurred at the top of the bioclastic deposit. Early, blocky calcite cement and trilobite bioclasts were displaced by fine-grained calcium phosphate. Even where fine-grained carbonate concretions reach close to the bed surface their marginal parts are phosphatized. The stage of phosphatization at Trolmen did not produce any evidence of bioturbation or any sessile benthos. However, it was coeval with the establishment of low-diversity *Orusia lenticularis* fauna at localities not too distant from Trolmen to yield some bioclastic products.

The *Olenus-Orusia* bed at Degerhamn (Öland) shows a complex picture similar to that of the *Olenus* bed at Trolmen, but also some deviating features (Fig. 11a, b). The bed as a whole is about 60 cm thick. Its basal part consists of medium-grained limestone containing thin layers of *Olenus* fragments and pillar spar at its base. Above this limestone there follows a very fine-grained,but weakly laminated limestone with an irregularly pitted upper surface. The pits are filled with irregular, occasionally also lens-shaped intercalations of *Orusia* bioclastics of milky whitish colour in a surrounding of dark grey, fine-grained limestone, which also contains solitary *Orusia* shells. Clasts of *Orusia* coquina are relatively frequent on top of the pitted surface. These clasts are elongate, platy, with ellipsoidal cross sections. Their margins are phosphatized. The uppermost bed consists of subhorizontally laminated, fine-grained limestone with *Orusia*.

The entire bed is cut by a vertical fracture with sharp boundaries. The fracture is about 5 cm wide and filled with fine-grained limestone. The structure is interpreted as a kind of clastic dyke. The filling of the fracture rises slightly above the top of the bed. It contains a fauna consisting of sparse fragments of *Agnostus obesus* and thus is older than the *Orusia*-carrying, upper part of the fractured bed.

The depositional history of the described bed is interpreted as shown in Fig. 12.

(a) Above a carbonate mud layer (A) a bed (B) containing layers of *Olenus* fragments was deposited, above which a further carbonate mud layer (C) was laid down with but sparse bioclastic contents. Layer A remained non-consolidated, whereas B and C were at least partly lithified at an early stage.

Fig. 11 a. *Olenus-Orusia* bed in the outcrop Degerhamn (Öland). Pencil for scale. Compare with Fig. 11 b.

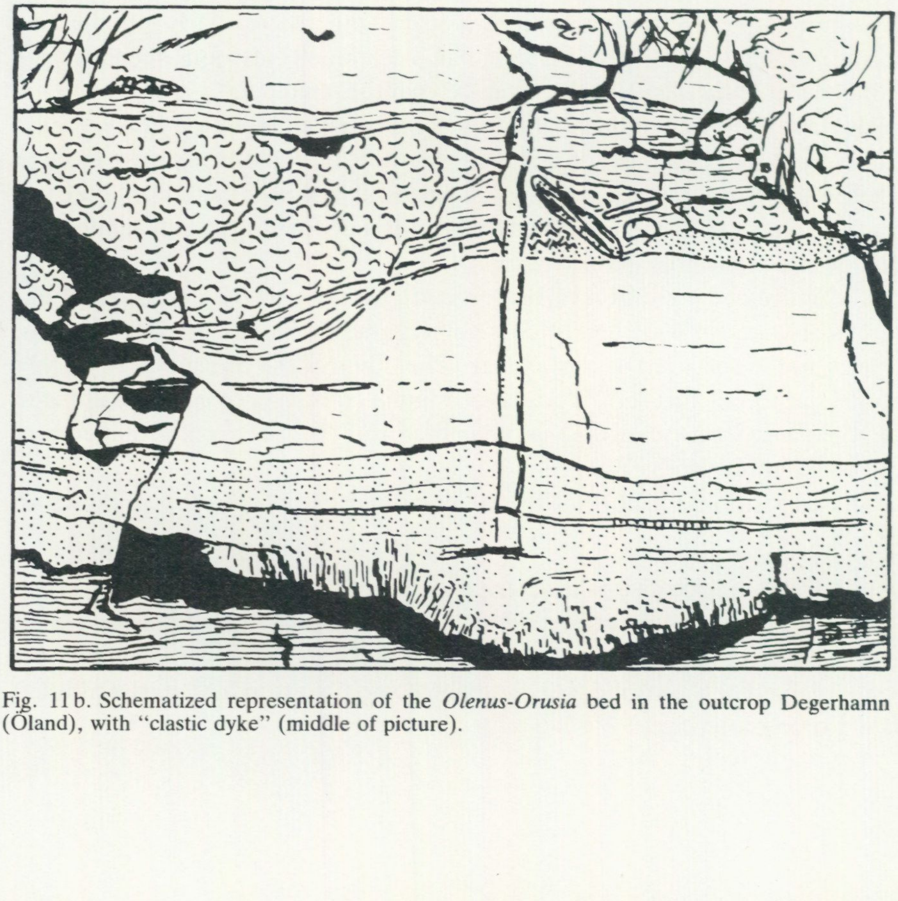


Fig. 11 b. Schematized representation of the *Olenus-Orusia* bed in the outcrop Degerhamn (Öland), with "clastic dyke" (middle of picture).

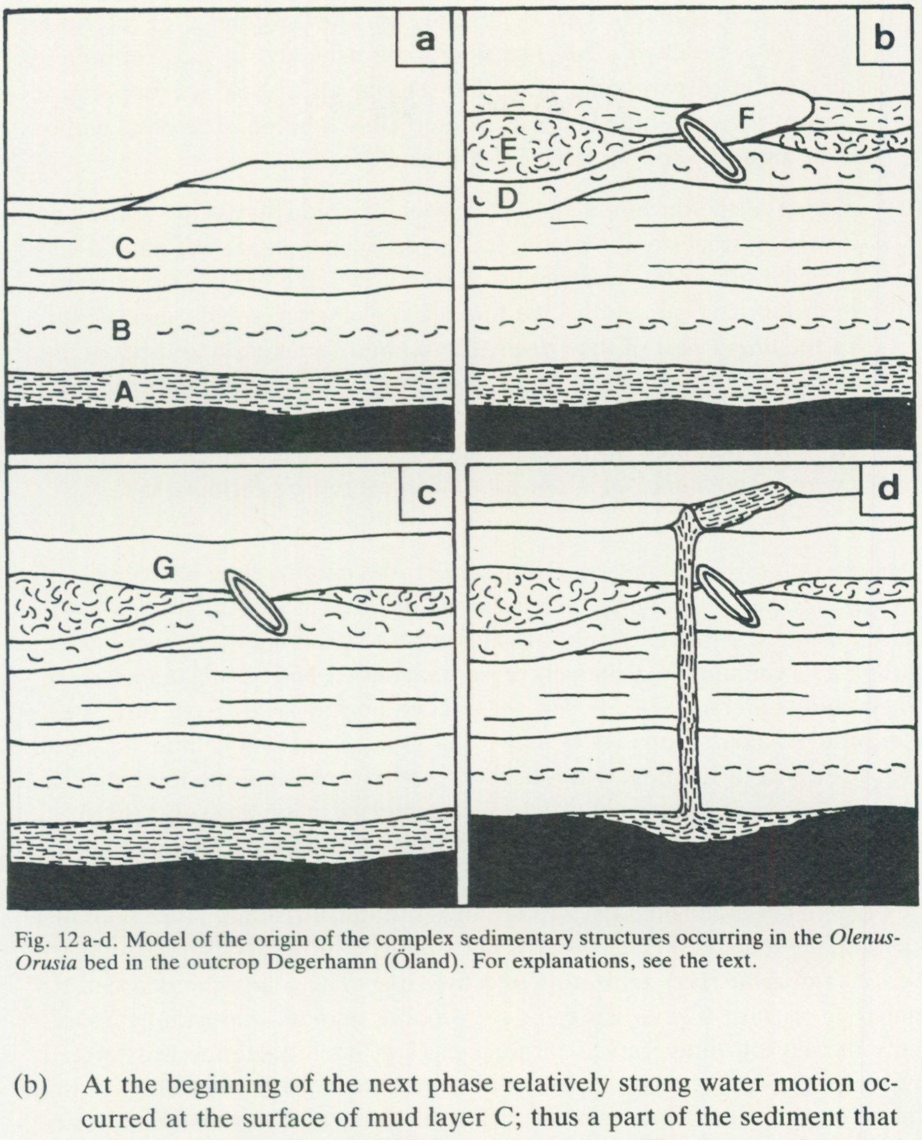


Fig. 12 a-d. Model of the origin of the complex sedimentary structures occurring in the *Olenus-Orusia* bed in the outcrop Degerhamn (Öland). For explanations, see the text.

(b) At the beginning of the next phase relatively strong water motion occurred at the surface of mud layer C; thus a part of the sediment that was but incompletely lithified was removed. The present irregular surface of C was developed. The erosive phase was followed by deposition of carbonate mud (D) with abundant *Orusia*, barely cemented *Orusia* coquina (E), and superficially phosphatized intraclasts (F). The thin, platy, and apparently fragile shapes of the intraclasts make transport by strong currents appear unlikely. Therefore, and because of the absence of lamination in the matrix mud, gravity flow can be considered a plausible mechanism of emplacement of sediment D-F. The distance of transport probably was not very great.

(c) After comparatively fast deposition of D-F sedimenation at lower rates was resumed. This phase was characterized by the continuous deposition of carbonate mud (G). During this phase the uppermost part of the limestone bed was incompletely lithified. The basal carbonate mud (A) still remained non-consolidated.

(d) Owing to the development of horizontal tension across the entire bed a vertical fracture was produced through which the mobile mud A was injected upwards. According to Reineck & Singh (1975), shock waves and slumping can lead to the formation of fractures and clastic dykes. In the upper part of the *Olenus-Orusia* bed the irregular stratification, the shape of intraclasts, and the mixture of lithologies indicate that, at least temporarily, gravity flow contributed to sediment transport, although slumping in the strict sense did not develop. Local displacement of sediments may also have been caused by earthquakes.

In the outcrop of Blomberg (Kinnekulle), the base of zone Vc consists of a limestone bed of varying thickness, at the most about 30 cm. At some places this bed consists of an accumulation of round clasts of fine-grained carbonate swimming in a coarsely crystalline matrix and having diameters of 20 cm and less (Fig. 13 a). A few tens of centimetres away from the latter, somewhat smaller, round clasts may occur in a coarsely crystalline matrix in the upper part of the bed, whereas the lower part consists of a mass of continuous, fine-grained limestone of the kind occurring in the clasts (Fig. 13 b).

Polished sections show that the fine-grained clasts are concretions with almost elliptical cross sections that may be more or less elongate. Their meridional planes are inclined at various angles to the horizontal layering of the surrounding sediments (Fig. 14 a, b). The surrounding matrix evidently underwent neomorphic recrystallization to coarse spar. The coarse-grained sparitic matrix in its turn fills an irregular yet broadly rounded topography apparently incised into fine-grained carbonate. That this topography was formed by erosion of horizontally bedded sediment can be demonstrated with the aid of an approximately 1 cm thick, whitish lamina that was repeatedly identified in the upper part of upward projections of the baseal fine-grained carbonate layer. This lamina contains what could be peloids (if so, the only established occurrence in the Olenid shale carbonates), phosphate spherules, and bioclasts (Fig. 14 a-c). The preservation of the original orientation of the bedding is furthermore confirmed by mainly horizontal orientation of trilobite fragments in the otherwise almost structureless, fine-grained carbonate.

The described carbonate projections are interpreted as erosion remnants consisting of early lithified carbonate mud layers. The depositional history of the carbonate bed is interpreted in Fig. 15.

Fig. 13 a. Conglomerate-like level in the outcrop Blomberg (Kinnekulle). Base of zone Vc.

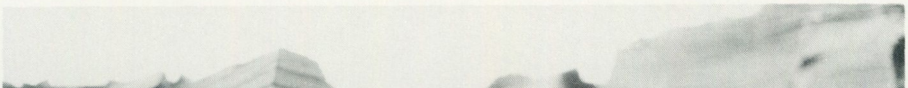


Fig. 13 b. Base of zone Vc in the outcrop Blomberg (Kinnekulle). Compare with Fig. 13 a.

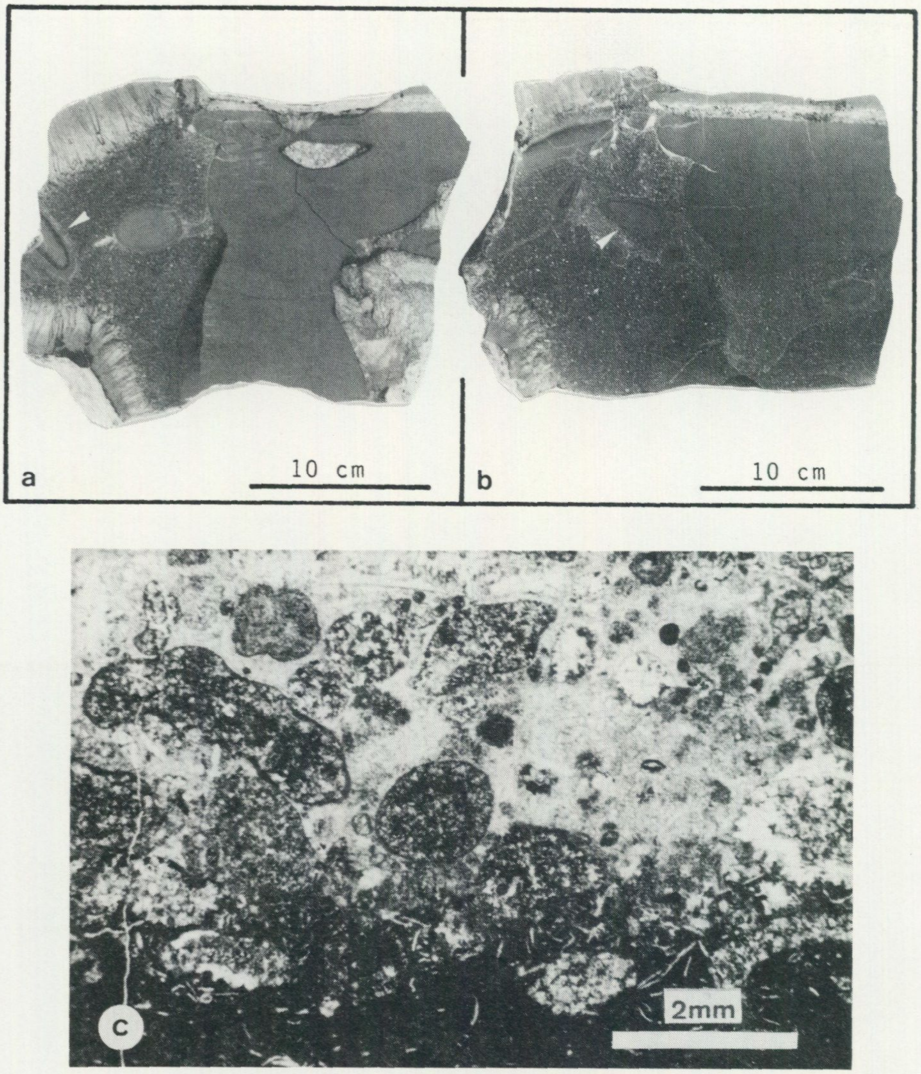


Fig. 14 a-c. Conglomerate-like level in the outcrop Blomberg (Kinnekulle). – a, b. Polished sections; note small, elliptical and obliquely oriented concretions (arrows) and whitish, horizontal peloid (?) layer. – c. Detail of thin section of peloid (?) layer.

(a) During a phase of undisturbed deposition of carbonate mud, a layer several tens of centimetres thick was deposited on underlying non-carbonate mud. The deposition of carbonate mud was interrupted for a while by the deposition of a coarser grained layer with peloids(?). Thereafter, deposition of carbonate mud was reestablished.

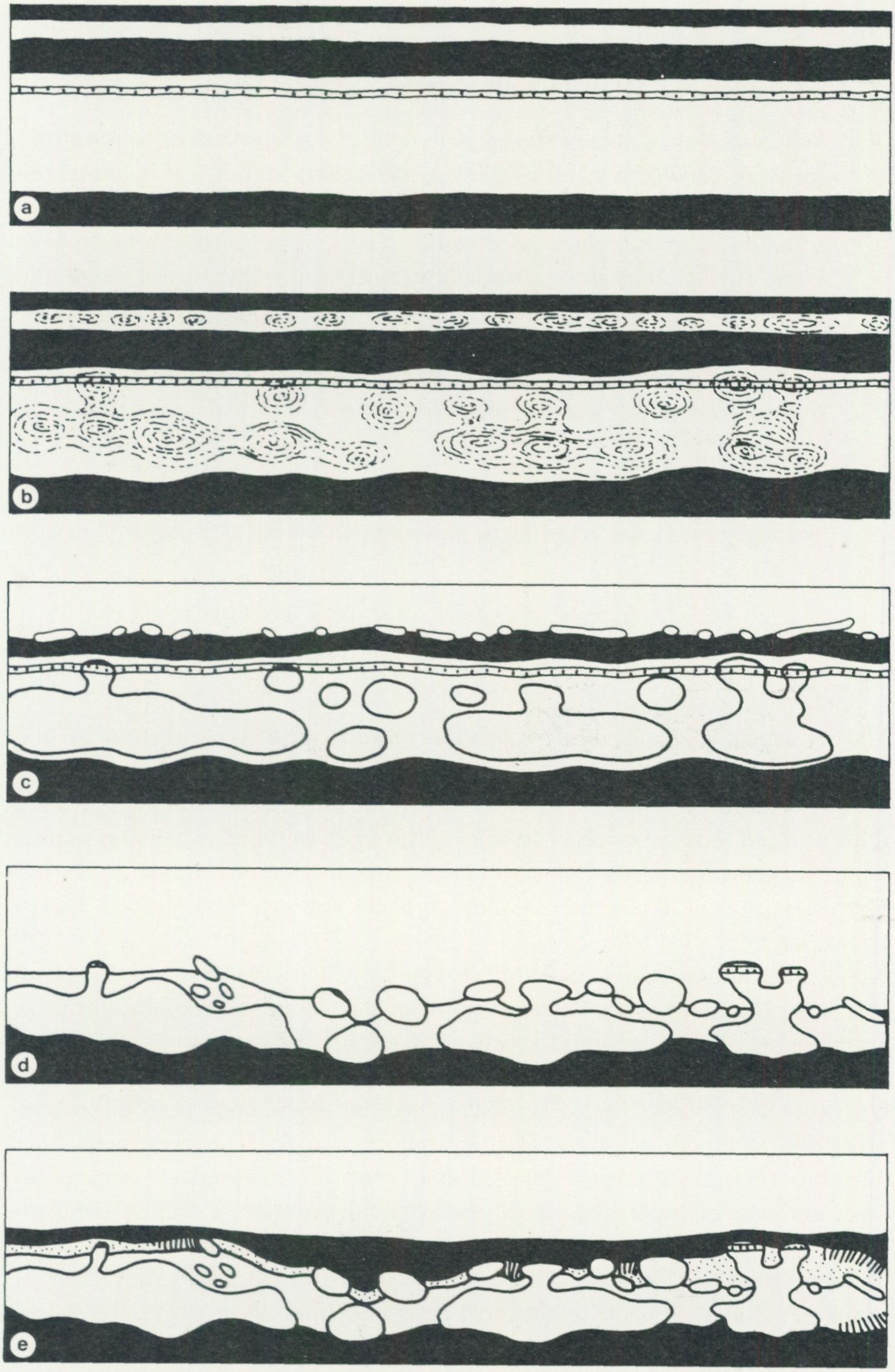


Fig. 15 a-e. Model of the origin of the conglomerate-like level in the outcrop Blomberg (Kinnekulle), zone Vc. For explanations, see the text.

(b) Either during or after deposition of the layers referred to under (a), lithification began, starting from different centers of concretionary nucleation and the basal portion of the bed.

(c-d) When the lower part of the carbonate mud was lithified, either continuously or in discrete, ellipsoidal patches, and higher levels contained isolated, lithified ellipsoids of smaller size, the remaining non-lithified sediment was subjected to erosion. The eroding currents must have been strong enough to bring into suspension the fine-grained and presumably somewhat cohesive sediment. The small concretions present in the upper part of the deposit were trapped by the surface relief of the lower carbonate horizon and thus remained close to where they had formed. Later on they became embedded in a new generation of sediment.

(e) At a later stage, this last generation of sediment recrystallized into the coarse-grained sparitic matrix that now surrounds the major clasts.

LENTICULAR CARBONATE BEDS AND CONCRETIONARY CARBONATES

The lenticular shape of many carbonate beds is most likely caused by diagenesis rather than by conditions prevailing during deposition. This is demonstrated below by an example from the Haggården outcrop. A 5 cm thick trilobite coquina occurs in two lenses each of which is several metres long. Between the lenses the shell bed disappears over a distance of several metres. It occurs as an intercalation in a continuous, dark greyish brown carbonate bed.

The complete carbonate bed is approximately 5 cm thinner where the coquinoid layer is lacking. About halfway between the terminations of the lenticular occurrences of the coquinoid layer, a thickening of the host limestone bed to "normal" thickness was observed. A polished section through a sample from this point shows that a lenticular segment of the coquinoid layer is represented again in the zone of thickening (Fig. 16). The coquinoid layer evidently represents a single depositional event. It originated as a continuous layer and was disrupted by either erosion or dissolution. Of these two processes, only dissolution could have created structures symmetrical about the horizontal plane. Because the lenticles are characterized by this kind of symmetry the responsible agent must be dissolution, not erosion. Bjørlykke (1973) described similar discontinuous carbonate beds in the Upper Cambrian of the Oslo region which, according to his interpretation, also indicate early diagenetic dissolution.

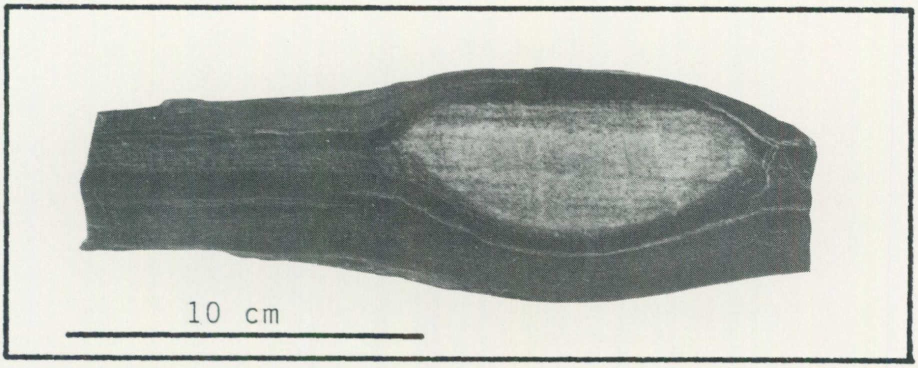


Fig. 16. Thin coquinoid bed partly preserved as solution relic within dark, poorly fossiliferous limestone. Zone Vc. Haggården (Kinnekulle).

In other outcrops (for instance, Trolmen) it was found that structurally identical limestone beds occurred within lenticular bodies that had moved vertically relative to one another. The movements include small overthrusts. Continuous carbonate beds below and above such overlapping structures are not deformed. These relations indicate that early diagenetic lithification of carbonate beds was responsible for the formation of lenticular bodies.

The concretionary carbonates discussed in this paper are lenticular, spherical, or occasionally irregularly discoidal, blackish to brownish grey, fine-grained carbonate inclusions in the Olenid shale.

In the basal parts of the Olenid shale, especially in the *Agnostus pisiformis* zone, numerous limestone concretions occur, while in the upper parts they are less frequently represented. The longer diameters of lenticular concretions vary from tens of centimetres to about 1 m. The short axes rarely exceed 30 cm. When weathered the lenticular concretions usually show faintly sculptured contour lines parallel to the layering.

The bedding planes of the surrounding shale are draped around the concretions. The fine-grained, homogenous composition of many concretions is obvious in fresh fracture planes that as a rule are conchoidal. No internal structures, such as for instance bedding, are visible in these cases. Only rarely does one find light layers rich in trilobite fragments. Such layers render visible a bedding that completely traverses the concretions parallel to their longer, horizontal diameters. They are cut off at the periphery of the concretions and cannot be identified in the surrounding shale. Septarian cracks (see, for instance, Hudson 1978) were not found in any of the analyzed concretions.

Spherical concretions reach diameters of only about 10–30 cm. Weathered fracture planes show concentric lines that differ slightly in colour. These lines

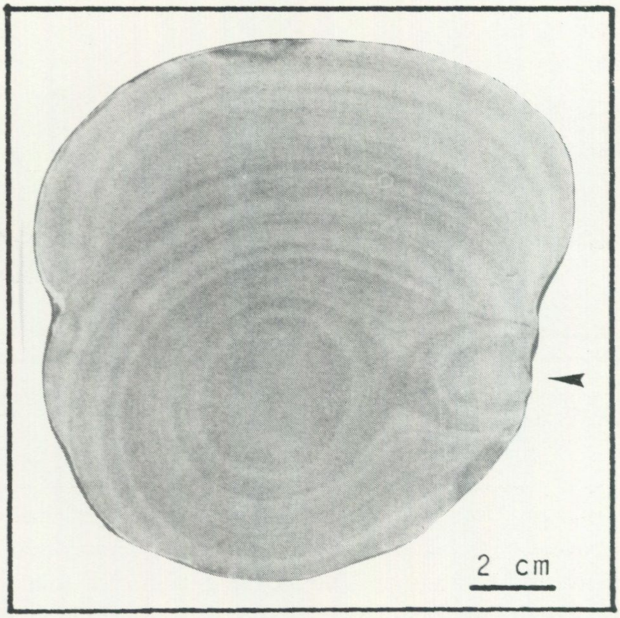


Fig. 17. Polyphase growth of concretion, with indication of early partial solution. Zone Vb, Blomberg (Kinnekulle).

become more evident in acetate peels of polished and etched specimens. They are caused by inconspicuous variations in grain size, and by differences in the non-carbonate fraction. There is no evidence of growth of spherical concretions under conditions of increasing compaction of surrounding mud. Therefore it is assumed that these concretions, in particular, formed close to the sediment surface at an early stage of diagenesis.

In some cases it was evident that concretionary growth concurrently started at several places lying close together in the same bed. Such instances of competitive concretionary growth would lead to the formation of irregular concretions with diameters of not many centimetres. Concretions that grew faster than others could finally enclose adjoining ones. After interruptions concretionary growth could locally continue at the peripheries of irregularly shaped concretions. Such multistage growth could even involve the partial dissolution of already formed portions of concretions. An example of multistage growth of concretions is shown in Fig. 17.

Concretionary growth at closely neighbouring levels could also lead to vertical connections between the levels. The formation of this kind of structure frequently began with a basal concretionary level consisting of horizontally fused concretions with an undulating or, more rarely, planar boundary against the underlying shale. The upper boundary of such basal concretionary levels usually consists of adjoining convex-up shapes. At a somewhat higher level one frequently finds numerous smaller, spherical to ellipsoidal concretions that are connected with the basal level by carbonate stubs that look rather like tree trunks rising from the basal carbonate level. Such stubs are interpreted as remnants of a once continuous bed of carbonate mud. Early lithification affected in particular the lower portion of this bed as well as those portions connecting the overlying concretions with the base of the bed. At a later stage the non-lithified portions were eroded, leaving the concretions perched on the stubs that remained.

THE FAUNA AND ITS BEARING ON THE DEPOSITIONAL ENVIRONMENT

A differentiated interpretation of the marine environment of the Olenid shale sea is hampered by the low differentiation of the fauna itself. The monotony of the Late Cambrian fauna certainly implies that the ecological conditions offered by this epicontinental sea were extremely restrictive for a long time, as is evident also from the lithofacies. Therefore, any hints of the possible existence of various modes of living among the preserved biota are the more interesting.

The fauna of zone I consists almost exclusively of agnostids, and some members of this enigmatic trilobite group are met with even in younger beds. The prevailing opinion that the agnostids generally were blind was commented on by Bergström (1973) with qualified scepticism. According to him, their habitat was not necessarily located below the photic zone. Bergström (1973) leaves it an open question whether agnostids were pelagic or benthic. Considering some of their morphological characteristics an ectoparasitic mode of living can possibly not be excluded, even though the large amounts of individuals in many deposits may argue against this possibility.

According to Bergström (1973) the high contents of organic matter in the Olenid shale may be explained by the existence of abundant pelagic algae; perhaps the agnostids led an epiplanktonic life on such algae. To G. & R. Hahn (1975) this interpretation is, however, unlikely. According to Robison (1975) most agnostids are likely to have been actively swimming organisms of the open sea. Robison (1975) discusses the possibility that different types of agnostids may have lived at different depth ranges at the same time.

As repeatedly emphasized, the dominant faunal element throughout most of the Late Cambrian consists of olenid trilobites. Henningsmoen (1957) distinguished three morphological types of olenid exoskeleton. The *Olenus* type indicates a slightly restricted capability of active swimming. The morphology of the *Peltura* type shows the characteristics of a strong, active swimmer, while the *Ctenopyge* type is related to a more passive, planktonic mode of living. The three types possess a very thin mineralized exoskeleton as a common adaptive feature for a life as plankton.

As regards the possibility of stagnant, anoxic conditions close to the sediment surface, Henningsmoen (1957) tends to the opinion that many olenids were able by active swimming to change from a ventilated biotope at a higher level in the sea to a lower, hostile but more nutritious one closer to the sea-bed, and that they were able even to stay there for a short time. According to Henningsmoen, the prevailing occurrence of olenids in the Upper Cambrian may be related to their good adaptation to stagnant sea waters.

Bergström (1973) argues that the shape of the dorsal shield is not alone decisive for the way of living of its bearer, but that the degree of active swimming abilities also depends on the development of the muscular system underneath the rhachis. After considering the significance of other morphological elements he arrives at the conclusion that most of the olenids were pelagic organisms that probably lived on planktonic algae.

Rudwick (1965) gave a general review of the ecology and paleoecology of the brachiopods. Most brachiopods are and were benthic organisms some of which might have been able to settle on muddy sea-floor. Most recent brachiopods seem to prefer chilly or moderately warm, predominantly calm waters of continental shelf areas.

The possibly epiplanktonic mode of life of some brachiopods was discussed in several papers (Paul 1939, Havlicek 1967, Spjeldnaes 1967, and Bergström 1968). Concerning the mode of life of the articulate brachiopod *Orusia lenticularis*, Bergström (1980) and Bergström & Gee (1985) suggest that *Orusia* represents a benthic brachiopod since it may occur together with benthic asaphid trilobites.

Inferences regarding the character of the Late Cambrian epicontinental sea can be drawn from stratigraphic outcrop sections, various sedimentary structures, and interpretations concerning modes of living and habitats of the Late Cambrian fauna given in the literature. The following general characteristics of the fauna are considered relevant.

1. Preserved outcrops of Olenid shale contain a fauna that may be rich in individuals but shows extremely little diversity, both on the species level and on higher taxonomic levels.
2. The faunal remains are mainly allochthonous; this is valid also for the *Orusia* fauna.
3. The bioclasts do not show any evidence of biogenic corrosion.
4. With the exception of (mainly allochthonous) *Orusia* coquinas no evidence of the existence of benthic animals was observed.
5. The occurrence of a brachiopod fauna (*Orusia*) is limited in time and extends over wide areas.
6. *Peltura* shows less abundance of individuals but more persistent occurrence than other trilobite genera.

The observations summarized under 1–6 are interpreted as follows. Restricted conditions predominated in the known depositional area, thereby preventing the development of diversified faunas. Furthermore, the establishment of megafaunas close to the sediment surface was prevented during most of the Late Cambrian, presumably because anoxic conditions prevailed at the sediment-water contact. The trilobite fauna could have been either actively swimming or epiplanktonic; *Orusia lenticularis* most likely had a benthic mode of life.

However, the predominantly transported character of the fossil fauna indicates that possibly more favourable conditions of living existed outside the areas in which the Olenid shale is now exposed. For instance, the conditions could have been "favourable" because the anoxic bottom water layer was relatively thin or conditions at the sea-bed were at least temporarily oxic. Even if the entire trilobite fauna were capable of active swimming, the principal nutrient reservoirs could have existed in water layers close to the sea-bed. If this was the case much of the fauna probably was drawn to the bottom waters even though this required a certain tolerance of conditions that would have been toxic to other animal communities (Henningsmoen 1957). It would have been an advantage if the diving time through any existing, anoxic water layer to the bottom was short.

The abrupt appearances and equally abrupt vanishing of *Orusia* as dominant faunal component point to significant disturbances in the evolution of the Olenidan sea. Because the first assumption about the living habitat of any articulate brachiopod is that it represents sessile benthos, the *Orusia* intervals would signal phases of habitable sea-bed, possibly with better oxygenation than during the rest of the Late Cambrian.

The accumulation of *Orusia* shells coincides with phosphatization of the carbonate sediments in the Öland and Västergötland sites of deposition (p. 27). This phosphatization is an indictor of increased production and decomposition of organic matter and hence probably an indicator of a change to more oxic conditions. However, this interpretation is fully valid only for the areas in which *Orusia* lived, which, as pointed out above (p. 38), were not necessarily the same as the areas of known deposition of Olenid shale. The latter areas might have remained quite inhospitable. In this context it is significant that not even the relatively good conditions in the hypothetical source areas of biogenic carbonate sufficed to produce a diversified fauna.

In a stratified water body with hypoxic to anoxic bottom water, any existing topographic rise will offer the ecologic advantage of a reduced distance between the redoxcline and the sea-bed. During phases of lowered redoxcline or generally better aeration of the water-body such areas will remain the most advantageous for carbonate production by organisms living near the sea-bed. Baltoscandia, in the Early Paleozoic (as today), doubtlessly had rises as well as lower terrain; consistent thickness differences in the stratigraphic successions of the various areas are otherwise inexplicable. Thus it appears reasonable to assume that some areas were more suitable than others for the development of faunas near the sea-bed, and that there might have been areas that were more hospitable than those in which sediments are preserved. Indeed, sediments deposited on rises are more likely to have been removed by penecontemporaneous and later erosion than those laid down in deeper (and less hospitable) areas.

The existence of intrabasinal highs and temporarily better aeration of sea water in the Olenidan sea were also briefly discussed in papers by Dworatzek (1979), Lindström & Dworatzek (1979), Bergström (1981), Bergström & Gee (1985), and Andersson *et al*. (1985).

As compared to other olenids, the amount of *Peltura* individuals is relatively limited. However, *Peltura* remains are found with almost constant frequency across the entire area of deposition. In Närke and Billingen the frequent convex-down orientation of *Peltura* cranidia indicates that the cranidia sank through quiet water, and that they were not transported by bottom currents. Thus, they were either transported in the superficial part of the water column, for instance by storms, before sinking through quiet water, or they lived above the sediment surfaces on which they occur as fossils. Although the mostly good sorting of *Peltura* cranidia makes the former alternative appear plausible, the second is not excluded.

Sphaerophthalmus occurs together with *Peltura* but tends to be concentrated in certain areas, where it can even be rock-forming. Such areas are close to the boundaries of preserved depositional basins, for instace on Kinnekulle and Öland. The difference in mode of occurrence of the two trilobite genera indicates differences of preferred habitat. Because *Peltura* is the more uniformly distributed fossil, the living trilobite might indeed have preferred the surface waters that extend over the entire depositional area. Thus, the frequency distributions rather favour the second alternative referred to in the preceding paragraph.

SEDIMENTOLOGICAL EVIDENCE OF DEPOSITIONAL ENVIRONMENT

An important feature, shared by all studied outcrops, is the lack of non-carbonate grain sizes greater than silt. This circumstance is interesting in view of Westergård's (1922) opinion that the Olenid shale is a shallow water deposit. Although this opinion has been shared by various authors, the arguments in its favour have never been presented in any detail.

If the investigated sites of deposition of Olenid shale were located within the littoral zone for a long enough time, erosion would locally have exposed the Lower Cambrian sandy clastics that occur only 10–20 m below the top of the Olenid shale. This would have resulted in sporadically intercalated sand layers. However, such sand layers are lacking. The siliciclastic silt and clay fractions of the Olenid shale can be interpreted as slowly deposited suspension load (the clay fraction) and as aeolian (much of the silt) derived from distant areas. The contribution of volcanic components is likely although it cannot be proved.

The argument for shallow to intertidal deposition is further weakened by the circumstance that no levels of oxidation are preserved within the facies throughout the Upper Cambrian, corresponding to several million years. This generalization includes the bioclastic packstones and the diastems which instead are very frequently enriched in sulphide. In the littoral zone one would expect oxidation to be a frequently occurring phenomenon.

As was shown above (p. 39), a certain amount of ventilation of the bottom water is perhaps the most likely at the time of zone III. However, even the "pebbles" described by Westergård (1922) from this zone cannot be taken as indications of the formation of basal conglomerates (p. 24).

The analysis of the outcrop sections offers a possibility to discriminate two consistently different types of sediment sequence. The sections of the Öland and Kinnekulle areas (exception: Brattefors) are in the following characterized under Type I, the sections of the Billingen and Närke areas under Type II.

The outcrops of *Type I* are characterized by relatively high proportions of limestone (about 50%), mostly represented by continuous beds. Slide breccias, cross-beds (though weakly developed), clastic dykes and condensed sequences occur in addition to the "normal" horizontal lamination. Some of the limestone beds are almost exclusively composed of trilobite coquinas (packstones) with abundant and spacious pore cement. The acid insoluble residue of the limestones rarely exceeds 10%. Concretionary lenses and pillar spar lenses are much less frequent than in Type II.

The outcrops of *Type II* are characterized by relatively low proportions of limestone (mostly less than 30%) and by greater thicknesses of the aggregate succession. Continuous limestone beds are less frequent than large concretionary lenses, in particular of pillar spar, arranged along particular levels. The characteristic sedimentary structure is strictly horizontal lamination. Only the carbonates in contact with the Ordovician show multiple internal brecciation. Rock forming shell layers are the exception. The average content of acid insoluble residue of the limestone is about 15%.

The differences between sediment sequences Type I and II together with their geographical distributions offer the possibility of conclusions concerning the differentiation of the sedimentary environment. As discussed above it appears unlikely that the area of deposition was uniformly populated with the Upper Cambrian fauna. It was assumed (p. 39) that a significant pro-

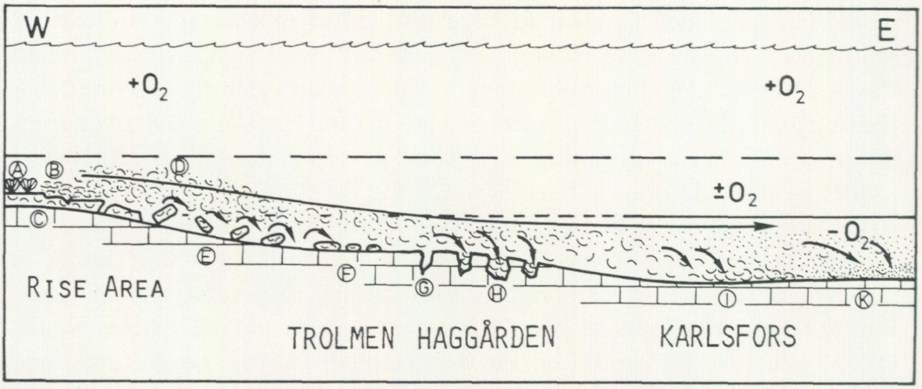


Fig. 18. Model of the process of sedimentation in the area Kinnekulle to Billingen, zone III. – A. *Orusia* fauna in situ. – B. Shell deposit *in situ.* – C. partial early lithification of shel deposit. – D. Transport of shell and fine-grained clastics by currents. – E. Breakage and bedload transport of early lithified sediment. – F. Deposition of early lithified sediment clasts. – G. Sliding causes breaking up of *Olenus* bed. – H. Widened fractures function as sediment traps. – I. Sedimentation of *Orusia* shell in more quiet water. – K. Sedimentation of silt and clay in quiet water.

portion of the bioproduction occurred in rise areas. The complex inventory of sediment structures, bioclastic packstones, and relatively low clay and silt contents in the carbonates point to stronger current and wave energies in the depositional areas of Kinnekulle and Öland than in those of Närke and Billingen.

Greater water motion usually causes better ventilation, but this effect in the present cases is not reflected by bioturbation or any other signs of a diversified, benthic fauna. Therefore, it is suggested that the greater hydraulic energy does not represent normal and continuous conditions in the area but rather sporadic and, as it were, catastrophic events to which the afflicted areas were especially prone because of their situation. Certain structures are doubtlessly due to gravity movement that may have been released by earthquake shocks or by waves (p. 21).

Decreasing transport energies are expected with increasing depth or with greater distance from the inclined surfaces where movements were released. Sites of deposition distant from rises (sediment sequence Type II) received coarse-grained bioclastics only sporadically and in small quantities. However, these sites were preferred by the deposition of suspended clay and silty clastics.

Fig. 18 summarizes this discussion by giving a model for the Kinnekulle area and the outcrop of Karlsfors in the Billingen area, during the time corresponding to zone III.

The rise model and the local relations described above explain certain sedimentary structures occurring in zone Vc. A few bedded carbonate levels

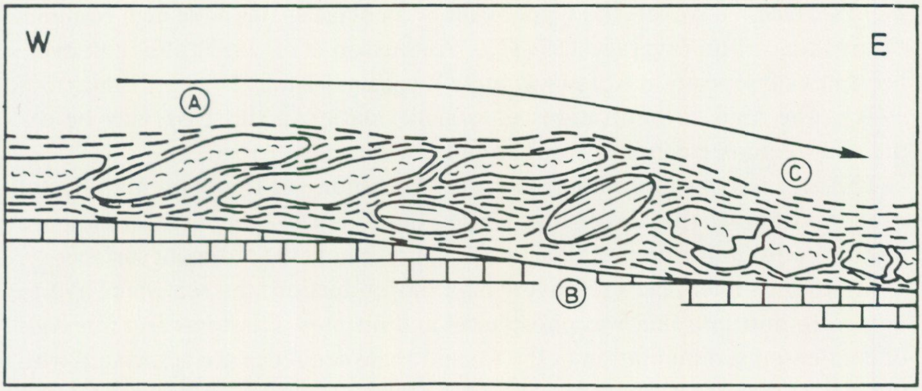


Fig. 19. Gravity flow structures in zone Vc of the Kinnekulle area. – A. Thrust. – B. Rotated concretion. – C. Breccia.

occurring in this zone at the western side of Kinnekulle contain thrust structures, while small debris flow breccias occur at the same level at the eastern side (Fig. 19; see also p. 20).

TOWARD A DEPOSITIONAL MODEL FOR THE UPPER CAMBRIAN BLACK SHALE

In a review paper Demaison & Moore (1980) discuss the conditions that are considered significant for the deposition of black shales. Accumulation of marine sediments rich in organic matter usually occurs in water bodies with insufficient oxygen to oxidize organic detritus before this becomes embedded in the bottom sediments. As far as Cambrian sediments are concerned this rule probably applies only to organic matter produced within the water bodies, because in the absence of vascular plants the terrestrial contribution may have been negligible.

The concentration of oxygen in the open sea depends on oxygen concentration in the atmosphere, water circulation, and rate of oxygen consumption by organic processes and the decay of organic matter. Whether organic matter is completely oxidized or not before getting embedded in the sediment depends not only on the concentration of oxygen in the sea water but also on the duration of exposure of the organic substance to the oxidizing environment.

Heath *et al.* (1977) show that in sea waters having permanent excess of oxygen the speed of sedimentation is an important factor in the preservation of organic matter. High rates of deposition favor the preservation of organic matter in the sediment, because they contribute to protect once deposited organic compounds from the oxidizing influence of waters close to the sediment surface. However, the Upper Cambrian black shales have high contents of organic carbon (average 15% C_{org}, Andersson *et al.* 1983) although average rates of deposition were extremely low (max. 1 mm/1 000 a., Lindström 1971). The high concentrations of organic matter in this case may be explained by anoxic conditions in the bottom water layer.

The absence of bioturbation and the allochthony of the great majority of preserved faunal remains in the Upper Cambrian of southern Sweden are interpreted as indications of such anoxic conditions at the sediment surface.

In order to maintain a relatively high bioproduction, the sea water had to be rich in nutrients, such as phosphates and nitrates. Diastems and intervals of condensed sedimentation in the Olenid shale sequence are associated with the development of phosphate components and/or phosphatization of the sediment. The *Orusia lenticularis* zone contains characteristic examples of this phenomenon. As shown by Burnett (1977, 1980) phosphates may preferably be deposited in the transitional zone between anoxic and oxic sea water. Burnett draws his examples from organic rich sedimentation off the present coast of Peru. The connection between the existence of hypoxic to anoxic zones (oxygen minimum layers) and the concentration of phosphates in the transitional zone to oxic sea waters, occurring in upwelling regimes in particular, commonly serves as an explanation for the formation of phosphates in marine sediments. It is discussed in a number of modern papers (Braisier 1980, Burnett *et al.* 1983, Demaison & Moore 1980, Lindström & Vortisch 1983, Parrish & Ziegler 1983).

Thus, Braisier (1980) assumes, in agreement with a model developed by Berry & Wilde (1978), that a continuous vertical rise of the oxygen minimum zone occurred in the area of the Baltic Shield during the Cambrian. The model states that the rise was connected with global climatic warming and transgression of the sea. Braisier (1980) suggests that the oxygen minimum zone may have had upwelling as one important cause. He also offers the interesting suggestion that low rates of deposition may be related to landward directed currents connected with the upwelling.

Demaison & Moore (1980) show that upwelling waters commonly do not come from deeper than 200 m. Oxygen minimum zones developing below upwelling waters therefore rarely have their upper boundary below 200 m. Lindström & Vortisch (1983) suggest that the Baltic Shield was a deep shelf during deposition of the Lower Ordovician "Orthoceratite limestone", with many depositional areas at depths of as much as 500 m. Assuming that the topography of the Precambrian basement resembled the present one, these authors furthermore suggest that certain areas of production of bioclastics could have risen 300 m higher than the depositional areas. A similar rise and basin model was suggested by Dworatzek (1979) in order to explain *Orusia* shell beds in the Upper Cambrian, however, without suggestions about water depth in metres. If water depths during the Late Cambrian resembled those suggested for the Early Ordovician, the sea that covered the Baltic Shield may well have contained an upwelling system of the kind suggested by Braisier (1980), as well as rises that were less deficient in oxygen. This statement could apply even if both average water depths and topographic contrasts were somewhat less than those suggested for the Early Ordovician sea by Lindström & Vortisch (1983).

The association of high contents of organic matter in the sediment and the development of phosphate, during periods of diastem development and sediment condensation is regarded as an indication in favor of the upwelling hypothesis.

The Cambrian of the Baltic Shield is a transgressive succession (Thorslund 1960). Predominantly sandy facies were laid down in the littoral to infralittoral during the latest Precambrian to Middle Cambrian. During the Middle Cambrian the transgression continued with the spread of black shale facies from the western and southern marginal areas of the Baltic Shield. The explanation for this shift of facies probably is that the transgression caused the upper margin of an oxygen minimum zone to rise above shelf level. Those areas of the western and southern parts of the Baltic Shield that were situated near the open ocean were the first to come under the influence of oxygen depletion (Fig. 20 a).

At the beginning of the Late Cambrian the oxygen minimum zone finally covered the entire area of deposition discussed in this paper, and even rise areas were located within it (Fig. 20 b). However, the thickness of the hypoxic to anoxic water layer above the rises was not great enough to prohibit the establishment of trilobite fauna.

Due to eustatic regression during the Late Cambrian – especially in the *Orusia lenticularis* interval – the upper margin of the oxygen minimum zone was temporarily lowered far enough for oxygen-dependent organisms to establish themselves on the rises (Fig. 20 c). Such declines of sea level are documented e.g. by high concentrations of phosphate and by stratigraphic condensation. However, these regressive phases were of limited effect, because only a very specialized fauna occurs in the present outcrop areas. Indications of the establishment of diversified, oxygen-dependent bottom faunas are absent.

Towards the end of the Late Cambrian a general lowering of the sea level probably occurred across the entire southern Baltic Shield, and the influence of upwelling shifted to the south. The state of oxygenation of the seawater on the Baltic Shield toward the end of the Late Cambrian may have been similar to that obtaining in the Middle Cambrian (Fig. 20 a). The comparatively low topography of the Baltic Shield during the Late Cambrian, and ocean currents generally directed towards the west and northwest, contri-

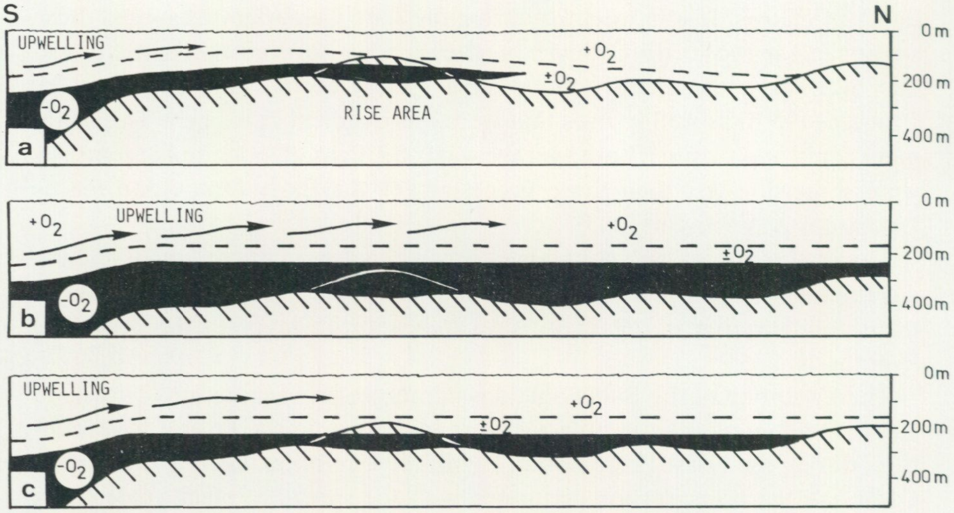


Fig. 20 a-c. Model of history of sedimentation and spatial variation of layering of sea water from Middle Cambrian to end of Late Cambrian. c. Sealevel lows in Late Cambrian.

buted to keep the sedimentation rates low (see Braisier 1980). Any land derived siliciclastic deposition of sand and coarser sizes appears to have been limited to sublittoral strips the remains of which are no longer preserved.

CARBONATE DIAGENESIS

The Olenid shale contains abundant evidence of early lithification of carbonate. However, the investigation of thin sections also revealed evidence of subsequent diagenetic alteration. In the following discussion special attention will be given to "pillar spar" and "pillar spar lenses".

The carbonates will be divided into clean carbonate and contaminated carbonate, based on studies of thin sections.

Clean carbonate contains low amounts of organic matter and clay. The biogenic fraction of the analyzed clean carbonates predominantly consists of trilobite fragments. Fragmentation occurred before final deposition. Indications of breakage or deformation of skeletal fragments after deposition are absent in the thin sections. This circumstance indicates that most of the carbonate sediments had already reached a comparatively high degree of lithification before compaction of the Olenid shale took place. Thus, it is assumed that the present thickness of carbonate nearly corresponds to the original one.

In some of the thin sections cements were identified on the basis of fabric criteria given by Bathurst (1971). The occurrence of cements that are likely to be morphologically unaltered is sometimes observed between skeletal com-

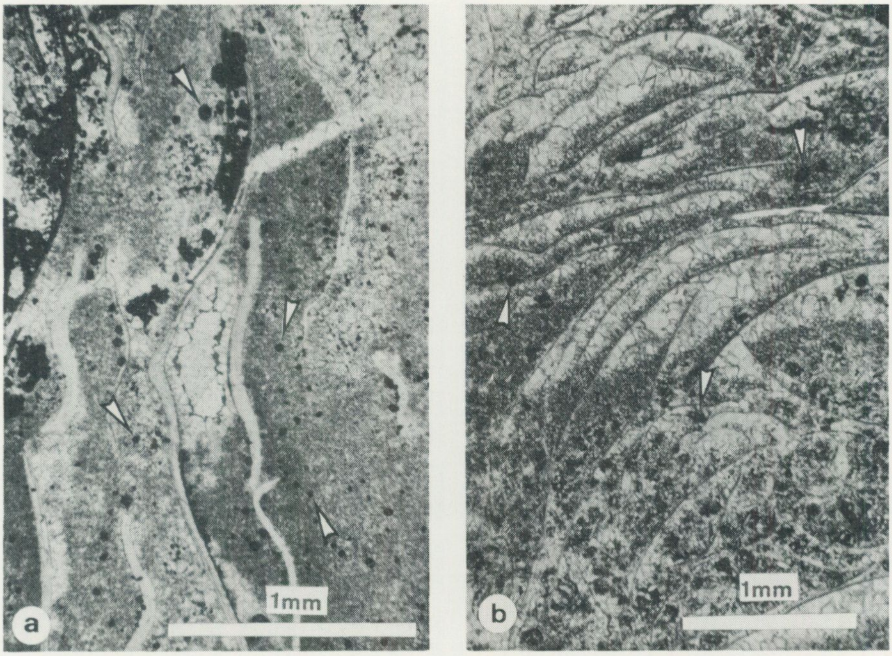
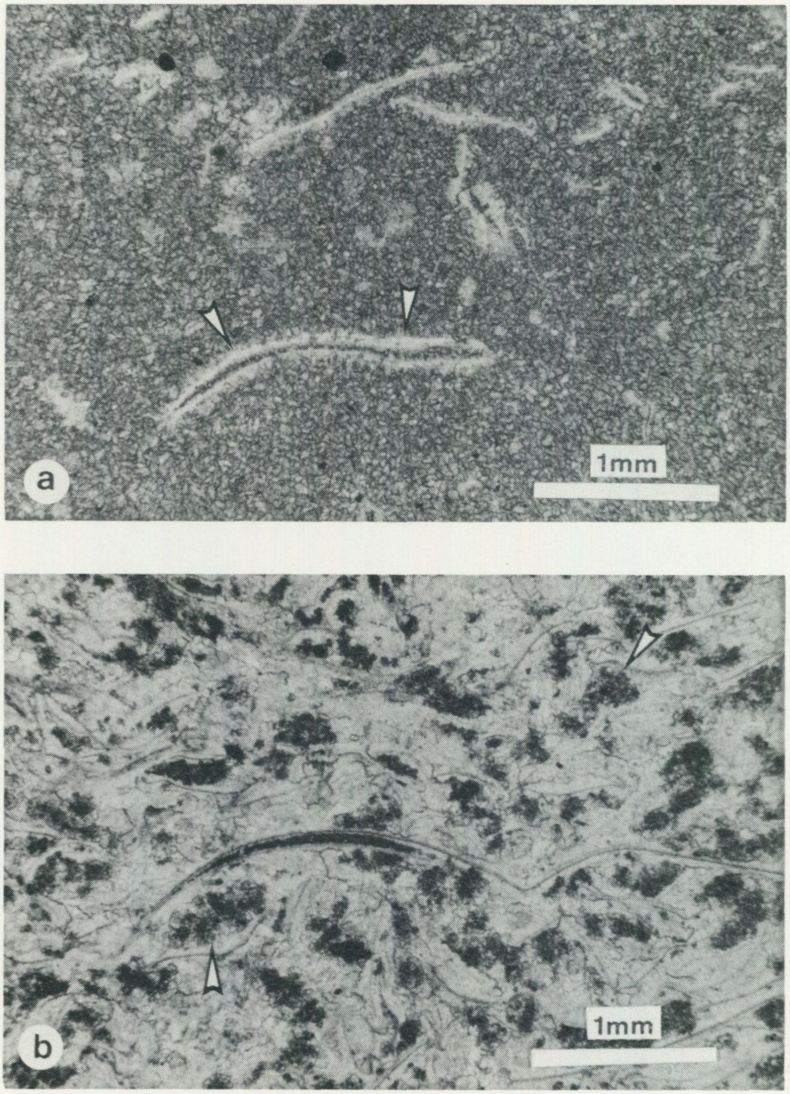


Fig. 21 a, b. Carbonate cementation. – a. Drusy and blocky calcite cement between trilobite fragments in fine-grained matrix (middle of picture); note the framboidal pyrite (arrows). Zone II, Trolmen (Kinnekulle). – b. Umbrella effect in grain-supported fabric; note the framboidal (arrows). Zone Vc, Möckleby (Öland).

ponents lying close together, particularly in matrix supported fabrics (Fig. 21 a). Pores left between such components during deposition may have been preserved from the infiltration of fine-grained matrix. In most cases these pores are filled with two, occasionally with three different generations of cement.

In such cases a first cement resembling "dog-tooth" cement grew on the smooth trilobite surfaces, followed by a second generation of drusy calcite cement. The final stage of this phase of cementation is characterized by slight contaminations at the growing tips of individual crystals. Finally, the remaining pore space was filled with large, blocky calcite crystals.

Staining tests (Evamy 1969) failed to yield positive indications of iron in the different generations of calcite cement. The intensive activity of sulphate reducing bacteria in the matrix mud, which contributed to the early formation of iron sulphide, might possibly have consumed available iron ions during the process of cementation. This suggestion is supported by the frequent occurrence of framboidal pyrite in the fine-grained matrix. On the other hand, the reduction of sulphate indicated by this occurrence of pyrite



might possibly have created conditions favorable for the early cementation of carbonate (Berner 1966, Lindström 1980; see below, p. 57).

The occurrence of "umbrella effects" (Wilson 1975) is frequently observed in grain-supported fabrics (Fig. 21 b) and is interpreted as evidence for early cementation. In the present context the effect consists of sparite occurring below trilobite components with convex-upward orientation. A characteristic coarsening upwards can be observed in this sparite. The microsparite occurring near the margin of the spar filled pore spaces is lightly contaminated

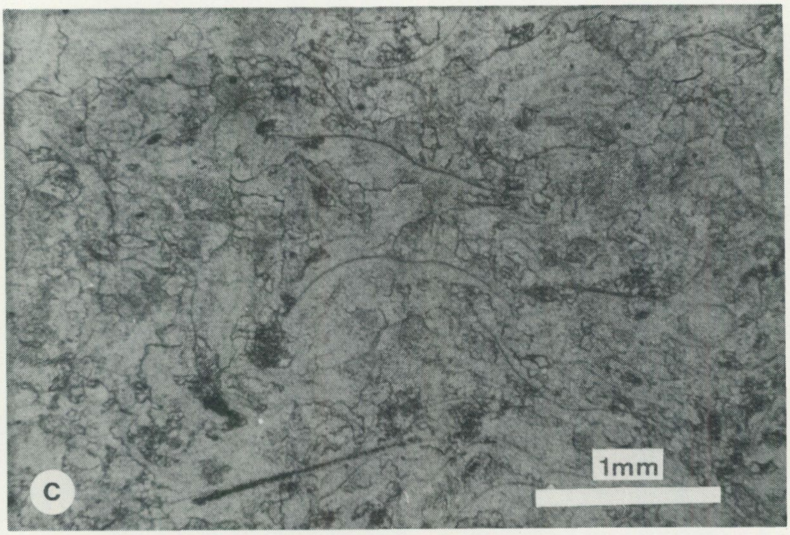
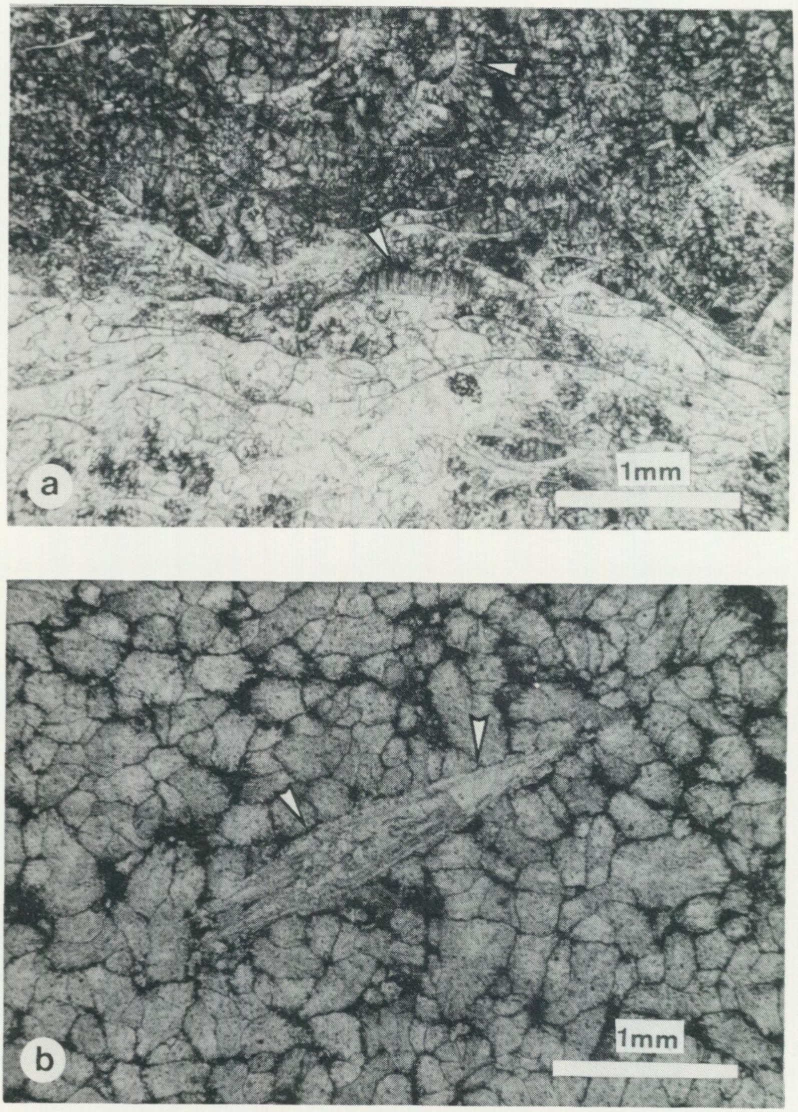


Fig. 22 a-c. Recrystallization – a. Microsparite. Thin sheets of micrite replicate altered skeletal fragments, with clear surrounding zones that might represent relics of early cement. Zone Vc, Tomten (Billingen). – b. Pseudosparite overprinted on bioclastics and early cement. Note "nests" of microsparite (arrows) that indicate the presence of remains of primary matrix. Zone Vc, Tomten (Billingen). – c. Pseudosparite. Zone Vc, Haggården (Kinnekulle).

with clay and organic matter. The mode of occurrence of this contaminated microsparite indicates that it represents recrystallized, fine-grained matrix that had not been completely winnowed out of the bioclastic layers.

The existence of early cementation in carbonate muds is indicated by observations on sediment breccias. However, actual observations of cement are only sporadically possible in the finer grained deposits. This circumstance is explained mainly by subsequent recrystallization of most of the early lithified carbonates.

In a number of cases it is hardly possible to distinguish cements and fabrics formed through neomorphic processes. The enlargement of grains seems to have played an important part in several of the analyzed samples. Thus, the originally micritic matrix was changed to microsparite (Fig. 22 a) in many matrix supported fabrics. Together with the occurrence of microsparite, an alteration of skeletal components caused by dissolution is frequently observed. The occurrence of shell fragments is frequently documented only by thin seams of dust or micrite, which delineate the shapes of the bioclasts. Stalky calcite crystals, about 0.1 mm long, that might represent the relics of earlier cements, are oriented perpendicular to and in direct contact with these seams. Skeletal components and cement are to some extent obscured by coarse pseudosparite that has developed on matrix existing in certain grain-



supported fabrics. The original occurrence of matrix in such cases may be documented by small enclaves of microspar that are slightly contaminated with clay and organic matter (Fig. 22 b). Even pure, grain-supported fabrics have in many cases been transformed by pseudosparites in which bioclasts and/or earlier cements can hardly be identified (Fig. 22 c).

In the case of *contaminated carbonates* the fabrics of samples differ from those described above. According to the first visual impression these samples contain high amounts of organic matter and clay. The presence of organic

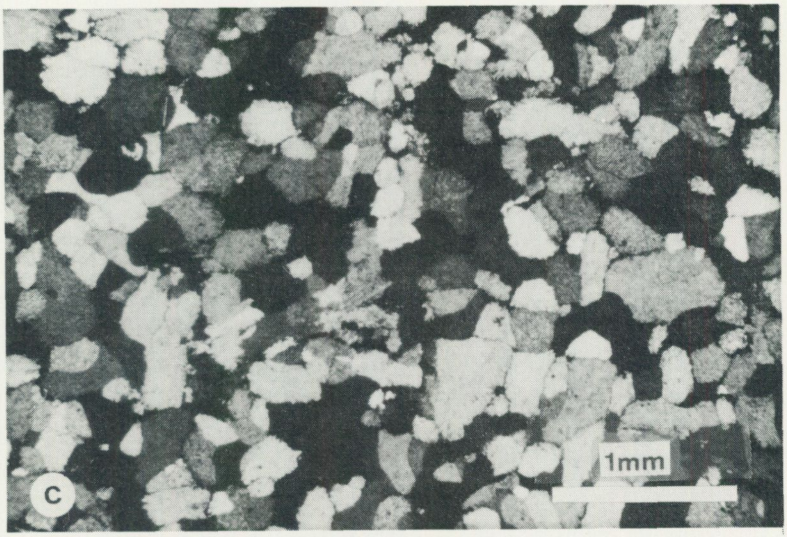


Fig. 23 a-c. Contaminated carbonate. – a. Elongate calcite crystals grown perpendicularly from skeletal fragments (arrows) in clayey-organic contaminated laminae. Zone Vc, Möckleby (Öland). – b. Granular spar mosaic in carbonate concretion. Note bioclast (arrows). Zone II, Trolmen (Kinnekulle). – c. Same as 24 b; crossed Nicols.

matter, indicated by a distinctive brown colour in the thin sections, appears to have caused the development of characteristic fabrics.

One fabric consists of impure calcite crystals about 0.2–0.4 mm long and with diameters of about 0.04 to 0.08 mm (Fig. 23a). These crystals are oriented with their longitudinal axes perpendicular to the substrate, which may consist for instance of skeletal components, embedded in layers rich in clay and organic matter. The optical axes of the crystals are also oriented approximately perpendicular to the substrate. The crystals terminate against thin organic-clayey seams that also extend into the fabric as boundaries between individual crystals. The seams may follow straight lines, but they may also form rugged and toothed shapes. Ends of crystals may have somewhat curved, frill-like extensions.

Another fabric feature of the contaminated carbonates is that the preservation of skeletal components usually is worse than in the clean carbonates.

The matrix of contaminated carbonates commonly consists of a mosaic of granular, in parts highly contaminated spars with diameters of 0.025–0.125 mm. The outer margins of these spars are frequently dissected in a frill-like fashion into extensions surrounded by organic-clayey seams. The same granular spar mosaic is also characteristic of the internal structure of concretions (Fig. 23b, c) that must be interpreted as results of early lithification because they have been physically displaced within the sediment. The question whether the calcite actually occurring in contaminated carbonate and in concretions represents early cementation products, recrystallized modifications of such products, or products of late diagenesis is, however, left open.

The term "*pillar spar*" is used here for columnar, dark greyish brown calcite crystals that are arranged parallel to each other, that have lengths varying between a few millimetres and as much as hundreds of millimetres, and that show internal structures resembling cone-in-cone. The outer appearance and arrangement especially of the larger pillar spars (some centimetres) remind of pillar basalt. This is the reason why the term was chosen. A new term is preferred because pillar spar only superficially resembles other long, subparallel carbonate crystals described in the literature.

Pillar spar occurs with sediments with high concentrations of organic matter, such as the Olenid shale. The structure preferably occurs at the upper and lower margins of lenses (Fig. 24 a) and layers (Fig. 24 b) of carbonate in the Olenid shale facies. It also occurs, although less spectacularly, around highly bituminous inclusions in the carbonates. The following description of typical features of pillar spar is based on such instances.

Fig. 25, a and b, shows a flat, highly bituminous inclusion, about 2 cm long and 1–1.5 cm thick, that is oriented horizontally and parallel to the bedding within almost unfossiliferous microsparite. This inclusion is surrounded by pillar spar with about 2.5 mm long and 0.2–0.4 mm thick crystals. The long axes of the crystals are oriented more or less perpendicularly to the outer margin of the inclusion, and crystal growth evidently started from the microsparite matrix in the direction of the inclusion. The contact between the basis of individual crystals and the microsparite matrix is sharp and planar. It circumscribes the bituminous inclusion usually at a distance of about 2.5 mm (equalling the length of the pillar spar crystals).

At the contact between pillar spar and matrix, the described structure has an approximately 0.1 mm thin seam of more or less clean, tiny calcite crystals. The coarser, long pillar spar crystals grew with U- or V-shaped bases from this seam. The spaces between the basal terminations of the major pillar spar crystals are filled with up to about 0.5 mm long, contaminated calcite crystals mostly irregular in shape. These crystals are also regarded as pillar spar. The boundaries between individual pillar spar crystals are mainly irregularly shaped and marked with dust seams. The individual crystals have thin, internal seams of contaminations that form acute cones with the apices directed towards the crystal bases. These structures give the crystals a frilled appearance, especially where they join the seams of impurities between the individual crystals. The terminations of the pillar spar crystals towards the bituminous inclusions are straight to slightly curved and appear slightly frilled at higher magnifications. A zone of transition into the inclusion of feathery appearance was observed at some places.

Fig. 24 a. Pillar spar on upper and lower margins of major carbonate lens. Haggården (Kinnekulle).

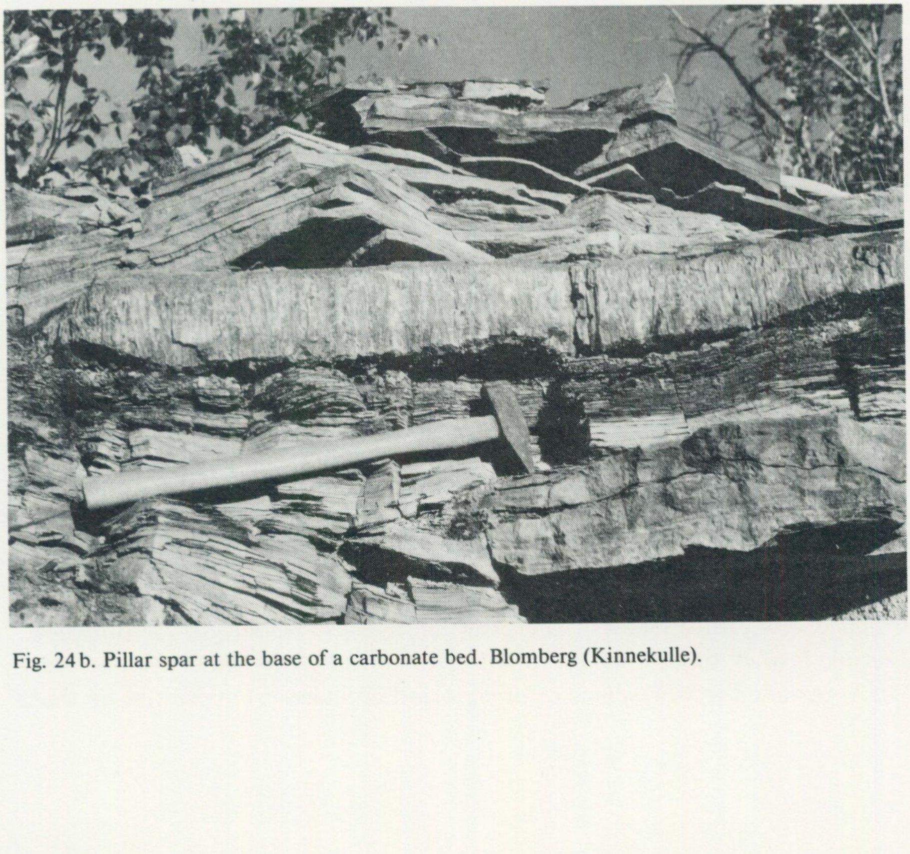


Fig. 24 b. Pillar spar at the base of a carbonate bed. Blomberg (Kinnekulle).

The optical axes of individual crystals are only occasionally oriented parallel to the morphological longitudinal axes of the crystals. Divergencies of 5° to as much as 25° between the orientations of optical and longitudinal axes of crystals are much more frequent. Most crystals show a slightly undulose extinction. In a few cases, straight twin lamellae occur within the crystals.

Several of the above characteristics remind of those described by Kendall & Tucker (1973) as being indicative of radiaxial fibrous calcite. However, there is a lack of such diagnostic features of radiaxial fibrous calcite as convergency of optical axes within individual crystals and convex curvature of twin lamellae towards the substrate. Kendall & Tucker (1973) interpret radiaxial fibrous calcite as products of the recrystallization of early acicular cement (aragonite?) that filled pores in carbonate sediments.

The shape of the space into which the pillar spar grew in the described case precludes the interpretation that we are dealing with pore filling cement; the more likely interpretation appears to be that the bituminous and argillitic matter at the core of the inclusion represents the remains of an angular clast with organic and, perhaps, partly carbonate composition. After lithification of the outer frame, shrinkage of the clast apparently provided the space needed for growth of pillar spar that proceeded at equal rates from all directions. Because there never was an internal void there is no void sediment. Pillar spar possibly grew at the expense of carbonate mud being dissolved within the inclusion.

During this dissolution-reprecipitation process, a continuous disintegration of carbonate and organics occurred within the inclusion. The major part of the organic components was concentrated towards the center of the inclusion. Possibly the growth of pillar spar from the margins of the inclusion was favoured because the growth of drusy or blocky calcite was inhibited within the organic matrix of the inclusion. It is also possible that the alternation of dissolution and reprecipitation at the boundary between carbonate and decomposing organic matter (release of CO_2) might favour the formation of pillar spar.

A further case exemplifies that the formation of pillar spar also occurred at the boundary between laminae with low and high organic contents within the outer parts of lenticular carbonate bodies, and that the growth of pillar spar at the boundary between shale and limestone could culminate with the formation of as much as several centimetres long pillar spar crystals (Fig. 25 c). Small pillar spar crystals started to grow, either individually or as groups, from carbonate laminae that were poor in organics. They grew towards highly contaminated laminae, with the result that these laminae were dragged along the flanks of the growing crystals, in the growth direction. During further growth of the pillar spar crystals, the same laminae were partly included as thin seams of organic and argillaceous impurities between or within individual crystals. The ultimate result of continuing growth of pillar spar was the suppression of the contaminated laminae.

The number of pillar spar crystals and the degree of contamination decrease with growing distance from the laminae at which the growth of pillar spar began. The distal parts of pillar spar crystals therefore are relatively large and pure in the present case. Growth of the distal, enlarged parts of spar crystals perpendicular to the bedding appears to have been unimpeded or even favoured. As a consequence of these processes, there developed a zone of several centimetres thickness consisting of palisade-shaped pillar spar. The contact of this zone with the adjoining shale is mainly sharp but in places also dissected, with a frilled appearance.

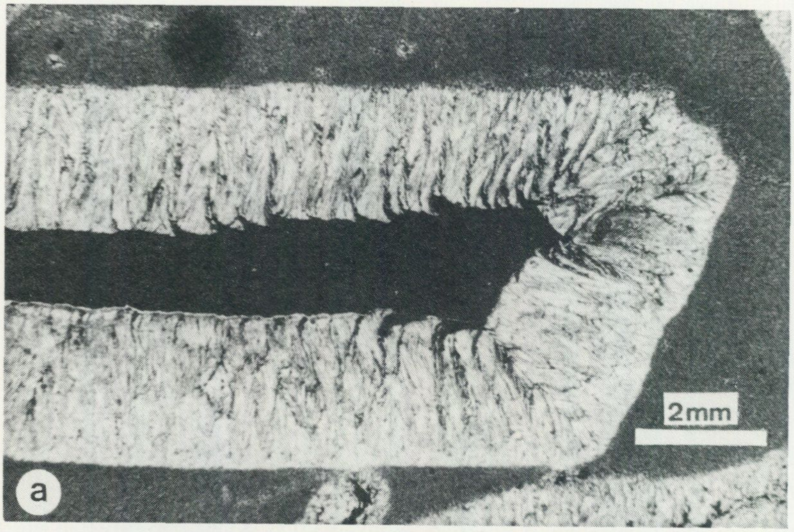
The described case of pillar spar formed at the margin of an already established but poorly delimited carbonate lens. The growth of spar involved extreme secondary inflation of lamination and hence addition of material to the lens. For these reasons it is assumed that the laterial syply of carbonate fróm the adjacent sediment to the lens was necessary for the growth of pillar spar.

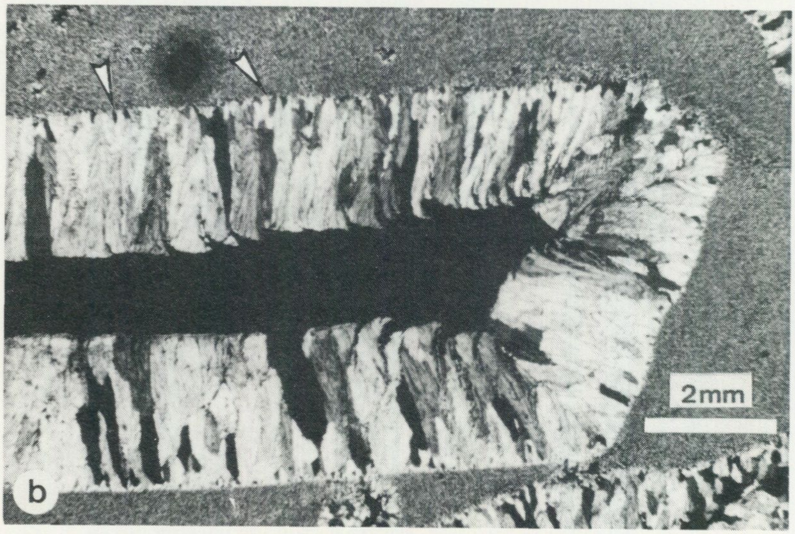
Pillar spar lenses are concretionary bodies that largely consist of radially arranged pillar spar. The occurrence of as much as 10 cm long, pencil-shaped calcite crystals in such lenses may be very conspicuous (Fig. 26a, b). Pillar spar lenses are very similar to the radial-columnar "Riesenkalzitsphaeriten" of the Lower Tertiary lignites of central Germany that were described by Krumbiegel (1959) and by Gallwitz & Krumbiegel (1957), who interpreted them as being of early diagenetic origin. They also highly resemble carbonate nodules, surrounded by secondary sparry calcite, in the Lower Paleozoic of the Oslo region, that were described and discussed by Bjørlykke (1973). According to Bjørlykke (1973), these nodules represent remains of continuous carbonate layers that were formed during a very early diagenetic stage.

Pillar spar lenses are carbonate bodies that are mostly shaped like rotational ellipsoids but are occasionally almost spherical. They can have diameters of several tens of centimetres. In the field they can easily be confused with concretionary carbonate lenses of other inner structure and mode of formation.

The occurrence of pillar spar lenses in the sedimentary succession is comparable with that of other carbonate concretions. They occur preferably in laterally continuous horizons within the shale. The distances between lenses tend to be regular in individual horizons but vary between a few metres and about ten metres from horizon to horizon. The occurrence of pillar spar is mainly restricted to the sites of deposition that are located relatively far from the hypothetical rise areas (e.g., Hällabrottet, Tomten).

The central part of all investigated pillar spar lenses consists of poorly delimited zones of limestone with thin, horizontal and parallel lamination. The laminated limestone is frequently rich in fossils. Lamination is caused





by varying contents of organic matter and clay, and is enhanced by varying degrees of recrystallization. The ellipsoidal to spherical shape of pillar spar lenses is caused by the evenly radial growth of pillar spar.

Pillar spar lenses differ from other described carbonate concretions by the circumstance that calcite instead of filling pores that already existed in the sediment pushed the sedimentary lamination aside by its growth; spar crystals do not contain any vestiges of a sedimentary, pore-supporting framework.

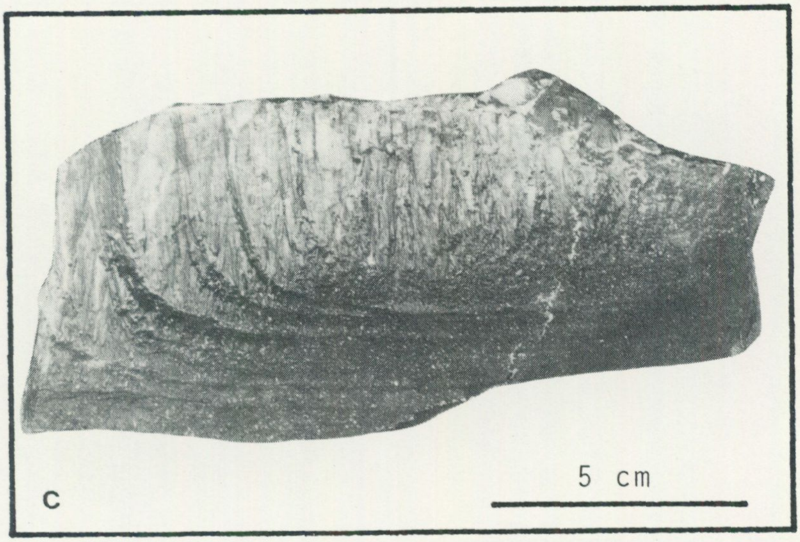


Fig. 25 a-c. Pillar spar. – a. Pillar spar grown about strongly bituminous inclusion in microsparite. Ventlinge (Öland). – b. Same as a, with crossed Nicols. Note small calcite crystals (arrows) at the bases of major crystals of pillar spar. Ventlinge (Öland). – c. Pillar spar in marginal part of lenticular, laminated carbonate body. Zone Vc, Tomten (billingen).

Results of isotope geochemical investigations (compare Dworatzek 1982) point to the early formation of pillar spar lenses in a mainly horizontally circulating pore water system. Irwin *et al.* (1977) showed that the fractionation of carbon isotopes in diagenetically formed carbonates in clayey organic rich sediments depends on the depth of formation. Isotopically light CO_2 ($\delta^{13}C_{PDB}$: 0 to –25‰) is predominantly formed in the zone of bacterial sulphate reduction in the upper ten metres of the sediment, whereas isotopically heavy CO_2 ($\delta^{13}C_{PDB}$: 0 to +15‰) is formed in the zone of bacterial fermentation (10–100 m sediment depth).

Assuming that the primarily deposited shell material and carbonate muds of the Olenid shale facies had carbon isotope compositions close to $\delta^{13}C_{PDB}=0$‰ (value for sea water), carbon isotope values of diagenetic products formed by early dissolution-reprecipitation in the sulphate reduction zone should have shifted towards the negative range. Results of isotope geochemical analyses of pillar spars confirm this assumption and point to the early diagenetic formation of the spars.

A 40 cm thick lens of pillar spar was cut perpendicular to the bedding, and ten samples for stable isotope measurements were taken across the section.

Fig. 27 shows the results of the isotope measurements. Distinctly negative $\delta^{13}C$ values for the central part of the lens point to lithification in the sulphate reducing zone. In relation to the central zone the $\delta^{13}C$ curve is

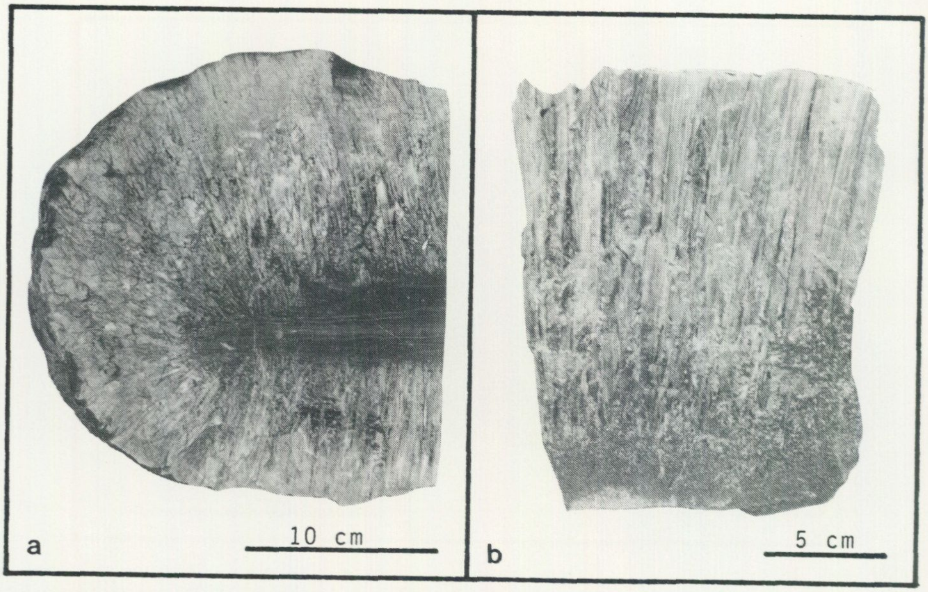


Fig. 26 a, b. Pillar spar lenses. – a. Polished section. Zone Vc, Tomten (Billingen). – b. Pencil thick pillar spar crystals from the outer zone of a pillar spar lens. Zone Vc, Tomten (Billingen).

symmetric, which indicates horizontal migration of solutions in a practically closed system during diagenesis. Variations of the $\delta^{13}C$ curve point to alternating intensities of sulphate reduction and/or contribution by dissolved carbonate sediment during the formation of pillar spar.

Comparable investigations were carried out by Jux & Manze (1979) on Ordovician concretions. Similar variations of $\delta^{13}C$ values were found and also interpreted as indication of the early diagenesis of the concretions analyzed.

As for the *composition of the carbonate fraction* X-ray diffraction bulk analyses of 73 representative samples from the sections Trolmen (Kinnekulle), Bjällum (Billingen), Hällabrottet (Närke), and Möckleby (Öland) show that the main reflection of the carbonate fraction of all samples is very close to 3.035 Å. This indicates that the carbonate phase consists of almost pure (Mg-poor) calcite. Indications of the existence of high-Mg calcite and/or dolomite were not found. These findings are also confirmed by atomic absorption analyses (AAS) of selected samples yielding Mg contents in the range 1805–2544 ppm (1805–2222 ppm for 11 samples of pillar spar, 1994–2282 ppm for 4 samples of "clean" bioclastic layers, 2161–2486 ppm for 4 samples of "contaminated" bioclastic layers, and 2351–2544 ppm for 4 samples of the relatively fine-grained concretions).

These data show that there are no marked quantitative differences of Mg

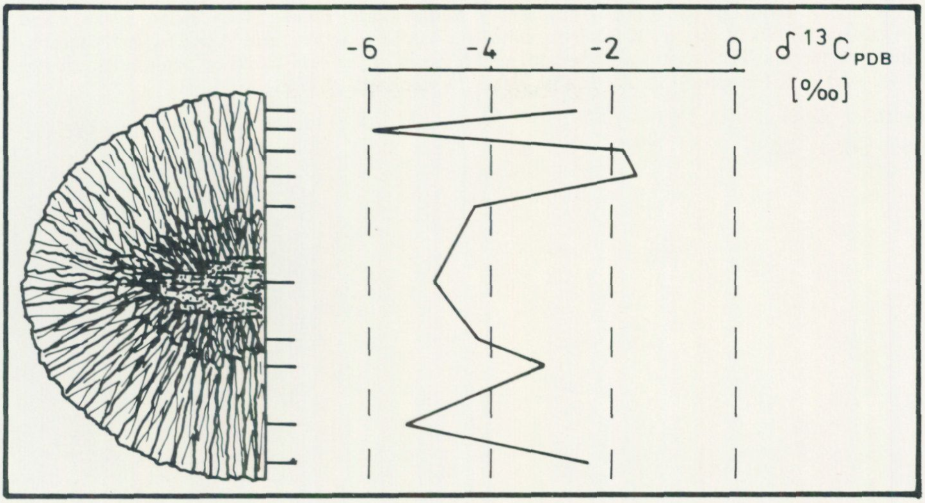


Fig. 27. Variation of carbon isotope ratios in a pillar spar lens. Zone Vc, Tomten (Billingen).

contents of coquinoid layes, concretions, and pillar spar. X-ray analyses also show that the Mg content of calcite does not vary between the areas. All carbonates investigated are calcite. For many of these carbonates early diagenetic formation is indicated (for instance, pillar spar).

Magnesium deficiency in Lower Paleozoic carbonates on the Baltic Shield is a widespread phenomenon and is discussed for the basal Ordovician by Lindström (1980) and for the Paleozoic of the Oslo region by Bjørlykke (1974) and Bjørlykke & Englund (1979).

Early diagenetic calcite is usually only formed at relatively great water depths (about 800 m). In shallow water aragonite and high-Mg calcite are primarily formed. Water depths between about 150 and, at the most, 500 m are assumed for the Late Cambrian Olenid shale sea. In modern oceans these depths most likely would exclude the formation of early diagenetic calcite. This would mean that all observed calcite could be the diagenetic alteration products of early aragonite and/or high-Mg calcite.

As for the pillar spars the alteration of early aragonite can be neither excluded nor proved. During the alteration of high-Mg calcite (for instance as cement in bioclastic layers) Mg should be released and transported away. This is, however, unlikely to have happened, because diagenetic alteration in the carbonates of the Olenid shale apparently proceeded in more or less closed systems (isochemical diagenesis according to Bjørlykke & Englund 1979). Nevertheless the early diagenetic alteration of primary high-Mg calcite cannot be altogether excluded. Another, possibly simpler and more accurate explanation for the low content of Mg in the Upper Cambrian carbon-

TABLE 1. Trolmen (Kinnekulle): Content of acid insoluble residue in carbonate samples and relative contents of quartz, K-feldspar, illite, and kaolinite in the same residues. Relative contents of the four last-mentioned components are given in per cent based on peak height quartz (4.26 Å) + K-feldspar (3.25 Å) + illite (10 Å) + kaolinite (7.17 Å) = 100.

Depth of section (m)	Acid insoluble residue (%)	Quartz	K-Feldspar	Illite	Kaolinite
0,15	14	63	2	14	21
0,75	3	74	5	12	9
1,15	4	64	6	15	15
1,75	3	62	4	18	6
2,20	9	66	7	19	8
3,10	14	75	7	11	7
3,75	12	70	7	14	9
3,95	4	62	8	19	11
4,40	14	69	6	16	9
4,65	10	72	7	12	9
4,80	16	72	8	15	5
5,00	4	47	25	11	17
5,40	2	50	25	23	2
6,00	6	45	13	30	12
6,15	2	51	11	21	17
6,40	1	64	11	18	7
7,30	12	57	12	18	13
7,65	4	47	11	31	11
8,25	11	53	16	27	4
8,50	5	56	15	22	7
9,10	12	39	17	27	17

ates could be that under certain conditions the formation of early, Mg-poor calcite was possible at depths of water between 150 and 500 m.

Rao (1981) and Rao & Green (1982) point to this possibility and prove it by the example of the Berridale Limestone (Lower Permian, Tasmania). This limestone was deposited and cemented at water depths between about 50 and 150 m. Very low water temperatures (less than +3°C) were the prerequisite for the formation of calcite cement in this case.

Another possible explanation for the formation of primary low-Mg calcite cement is that the Mg content of the ocean has fluctuated (Sandberg 1975), and that it was lower in the Late Cambrian than it is now.

MINERALOGY OF INSOLUBLE RESIDUES

The HCl insoluble residues of 73 representative carbonate samples from the four sections Trolmen (Kinnekulle), Bjällum (Billingen), Hällabrottet (Närke), and Möckleby (Öland) were investigated by X-ray diffraction (see Tables 1–4). Petrographic investigations on the same material and SEM analy-

TABLE 2. Bjällum (Billingen): Content of acid insoluble residue in carbonate samples, and relative contents of quartz, K-feldspar, illite, and kaolinite in the same residues, calculated as in Table 1.

Depth of section (m)	Acid insoluble residue (%)	Quartz	K-Feldspar	Illite	Kaolinite
0,20	23	80	1	12	7
0,35	11	60	3	28	9
1,00	4	52	5	31	12
1,65	9	57	12	24	7
2,20	3	57	18	18	7
2,65	12	59	9	27	5
3,20	11	40	17	43	-
3,35	21	64	13	23	-
4,45	7	43	16	41	-
4,90	16	19	19	62	-
6,55	11	53	10	37	-
6,90	9	62	13	25	-
7,00	8	67	11	22	-

ses were carried out in addition to the above investigations. This research showed that the mineralogy of the non-carbonate fraction is very monotonous all over the sedimentation area.

Quartz is the most frequent non-carbonate component of all samples. Under the microscope it can only rarely be identified as single, angular silt grains. SEM analyses proved the existence of authigenic quartz grains that are only a few µm long (Fig. 28 a). The main contents of quartz are presumably represented by finly dispersed wind- and/or water-transported particles in the fine silt to clay fraction. Grain size reduction by diagenetically induced solution cannot be excluded.

Feldspar is almost exclusively represented by potassium feldspar very similar to microcline, with a 040 reflection at 3.25 Å. Because of small grain size it cannot as a rule be identified under the light microscope.

Plagioclase is only very sporadically indicated by a weakly developed reflection at 3.20 Å.

Illite occurs in all samples and is the predominant clay mineral. It mainly consists of 2M-illite. The reliable identification of 1M-illite is only rarely possible and is frequently made more difficult by the overlapping of reflections of apatite and (rare) gypsum. The 001 reflection of almost all illites investigated in normal powder preparations shows a weakly developed shoulder towards lower angles. This shoulder indicates transitions from illite to illite with expandable, more strongly hydrated layers. The predominance of 2M-illite indicates that most of the 10 Å clay minerals are of detrital origin.

TABLE 3. Hällabrottet (Närke): Content of acid insoluble residue in carbonate samples, and relative contents of quartz, K-feldspar, illite, and kaolinite in the same residues, calculated as in Table 1.

Depth of section (m)	Acid insoluble residue (%)	Quartz	K-Feldspar	Illite	Kaolinite
0,15	17	69	6	14	11
0,60	5	80	1	15	4
1,55	12	67	8	12	13
2,75	14	59	10	16	15
4,60	21	63	12	13	12
6,25	18	59	10	17	14
6,90	14	62	13	12	13
7,70	17	60	11	15	14
8,65	10	62	11	20	7
10,00	4	64	13	23	-
14,75	20	62	9	13	16
15,00	6	54	9	22	15

Kaolinite can be identified in almost all samples by X-ray diffraction. It is quantitatively, however, less represented than illite. The diagenetic formation of kaolinite is only possible under extraordinary conditions in marine sediments (Vortisch 1980). Therefore, the kaolinite present in the samples is regarded as most likely detrital.

Chlorite cannot be identified with X-ray diffraction in any sample. The lack of chlorite in the Paleozoic black shales of Scandinavia can, according to Bjørlykke & Englund (1979), be explained by the assumption that the black shale sediments originated from "mature" continental source areas in which chlorite had been destroyed by weathering.

Phosphate occurs mainly as very pure calcium apatite. Diagenetically formed phosphate displaces early formed calcite cement and carbonate bioclasts in the condensed sequences (Fig. 28 b). In the biogenic fraction it is bound to conodonts (Fig. 28 c) and to so-called black spheres (Olgun 1985).

Pyrite is more or less strongly represented in all samples (1% to several per cent). It mainly occurs as finely dispersed framboids in amorphous kerogen in the carbonates (Fig. 28 d). Distinct crystals were much less frequently observed. Spectacular pyrite enrichment occurs wherever hiatuses and condensation are indicated. The best example of this kind of occurrence is the Cambro-Ordovician boundary where pyrite can form megascopic concretions.

Sulphates are rare and are only represented by gypsum and baryte. These minerals sporadically occur as idiomorphic crystals. A partial or complete displacement of sulphates by calcite can frequently be observed.

Organic matter forms approximately 10–20 weight per cent of the HCl

TABLE 4. Möckleby (Öland): Content of acid insoluble residue in carbonate samples, and relative contents of quartz, K-feldspar, illite, and kaolinite in the same residues, calculated as in Table 1.

Depth of section (m)	Acid insoluble residue (%)	Quartz	K-Feldspar	Illite	Kaolinite
0,10	10	55	15	30	-
0,20	10	58	7	35	-
0,30	6	56	11	23	10
0,35	5	49	9	36	6
0,40	5	59	11	24	6
0,75	4	61	5	24	10
1,05	3	73	6	12	9
1,55	8	70	9	14	7
1,85	9	72	5	13	10
2,20	1	74	9	11	6
2,30	9	71	6	13	10
2,60	3	65	9	15	11
2,80	4	59	10	20	11
3,15	8	62	7	22	9
3,60	1	65	7	19	9
4,00	2	71	8	13	8
4,15	9	59	9	22	10
4,30	11	60	9	20	11
4,50	9	69	6	15	10
5,05	25	60	13	27	-
5,75	14	42	9	34	15
6,35	13	33	8	42	17
6,80	12	34	9	38	19

insoluble contents of the carbonates. The organic substances in the carbonates occur as finely dispersed, orange brownish, amorphous masses in thin sections.

MINERALOGICAL COMPARISON BETWEEN CARBONATE AND SHALE

If it is correct that the carbonates were lithified during early diagenesis, then this conclusion should also be confirmed by a comparison of the mineral composition of the shale and the insoluble residues of the carbonates.

It should be expected that the intensity of diagenetic alteration in the shale is greater than in the carbonate, because cementation of the carbonate excluded the insoluble residues from later diagenetic influences.

In order to control this assumption, based on X-ray diffraction analyses, semiquantitative mineralogical comparisons were carried out on Olenid shale

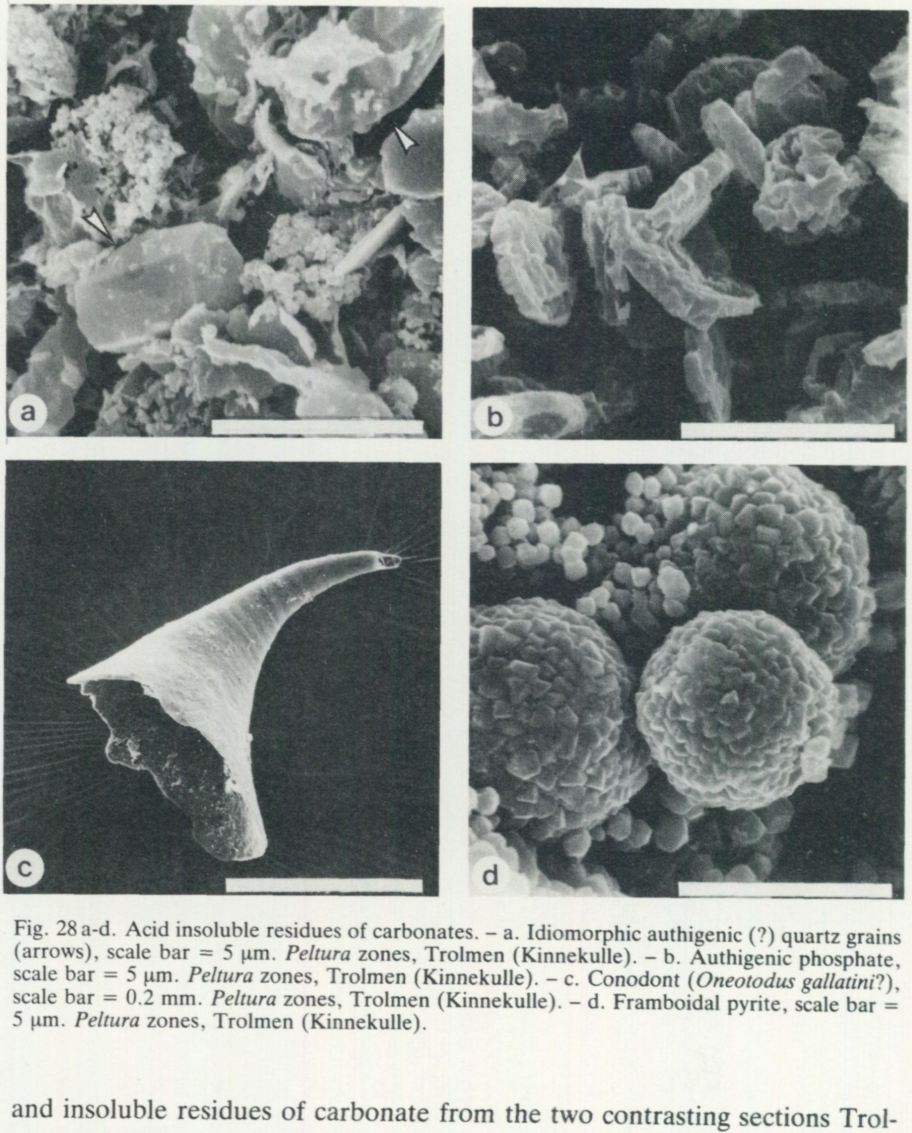


Fig. 28 a-d. Acid insoluble residues of carbonates. – a. Idiomorphic authigenic (?) quartz grains (arrows), scale bar = 5 µm. *Peltura* zones, Trolmen (Kinnekulle). – b. Authigenic phosphate, scale bar = 5 µm. *Peltura* zones, Trolmen (Kinnekulle). – c. Conodont (*Oneotodus gallatini*?), scale bar = 0.2 mm. *Peltura* zones, Trolmen (Kinnekulle). – d. Framboidal pyrite, scale bar = 5 µm. *Peltura* zones, Trolmen (Kinnekulle).

and insoluble residues of carbonate from the two contrasting sections Trolmen and Hällabrottet.

The totals of the reflection intensities of quartz (4.26 Å), potassium feldspar (3.25Å), illite (10Å), and kaolinite (7.17 Å) were equated with 100 and split into percentage values.

The results are presented in Figs. 29 and 30 (see also Tables 1, 3, 5, 6). It turned out that the mineralogy of the shale and that of the insoluble residues of carbonate is very monotonous in space and geological time, even though some differentiation is possible as is shown in the following.

The section of *Hällabrottet* (Fig. 29) which by comparison with the section

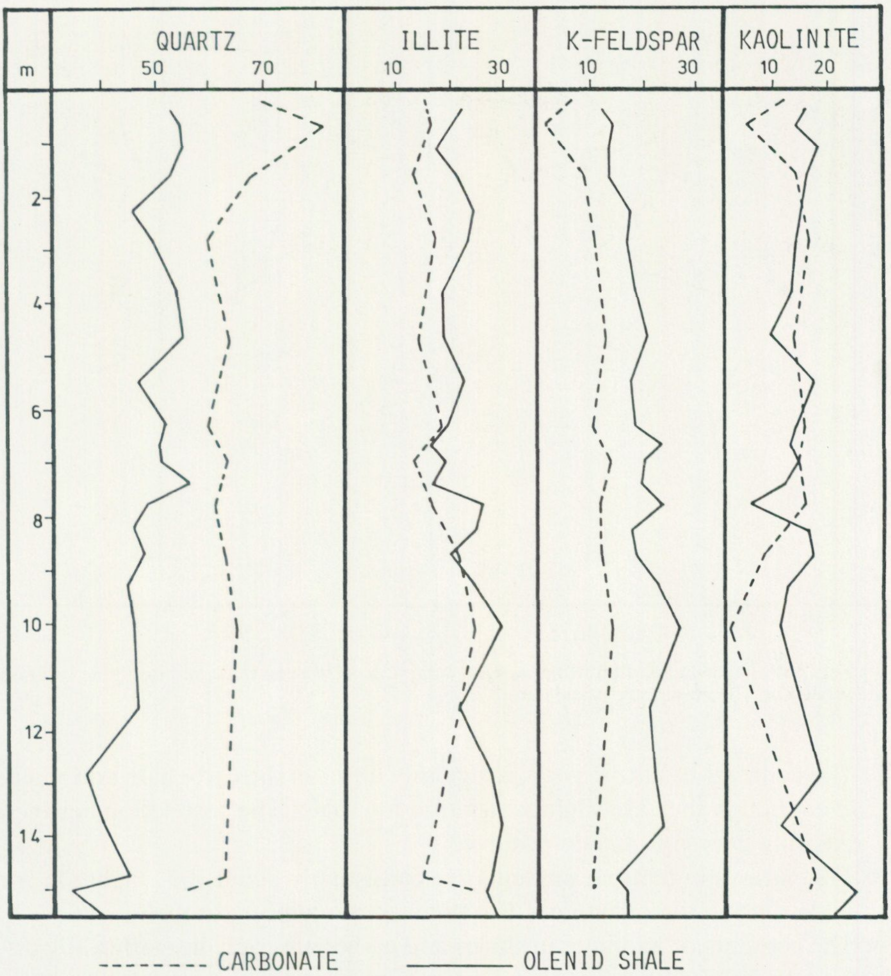


Fig. 29. Hällabrottet (Närke): Mineralogical comparison between shale and insoluble residues of carbonate. Relative contents of quartz, illite, potassium feldspar, and kaolinite, based on the peaks of quartz (4.26 Å), illite (10 Å), K-feldspar (3.25 Å), and kaolinite (7.17 Å). The sum of these peaks for each sample is taken as 100 and the individual peaks are calculated as percentages of this sum.

of Trolmen is characterized by significantly stronger recrystallization of carbonate and by considerably higher proportions of shale yields the following results:

1. The quartz contents of the carbonates are consistently 10–20% higher than in the Olenid shales.
   The quartz curves for carbonate and shale run almost parallel at least in the upper part of the section.

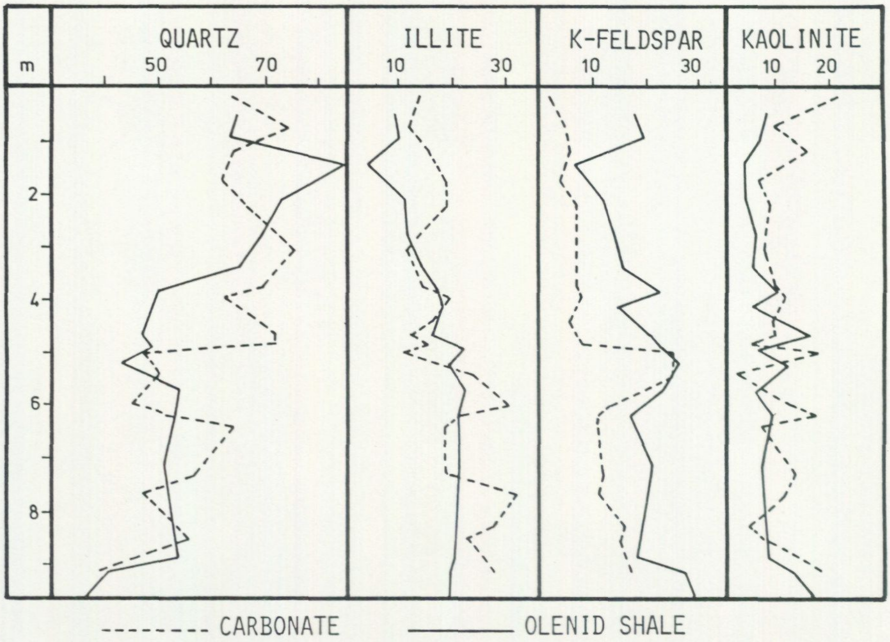


Fig. 30. Trolmen (Kinnekulle): Mineralogical comparison between shale and insoluble residues of carbonate. The curves are calculated as in Fig. 29.

2. The contents of illite do not particularly differ in the carbonate and shale, even though they are slightly higher in the shale. The correlation between the illite curves is mainly positive.
3. The potassium feldspar contents are consistently about 10% higher in the shale than in the carbonate. Both curves run almost parallel.
4. The contents of kaolinite in shales and carbonates only insignificantly differ as a rule. There is an obvious anti-correlation between the kaolinite curve and the potassium feldspar curve for the shale.

The quantitative relation of quartz and illite may be interpreted as being representative of the primary sedimentary quartz-illite composition in the carbonate, supposing that early lithification of the carbonate prevented quantitatively significant alteration.

There are no strong reasons to assume that the primary composition of sediments contributing to the shale at the deposition site of Hällabrottet was significantly different from that of the non-carbonate fraction of the carbonate lenses, both being determined by extended, continuous deposition far from land.

The situation is characterized in particular by the almost parallel curves for shale and carbonate, even though there are considerable absolute vari-

TABLE 5. Trolmen (Kinnekulle): Shale. Relative contents of quartz, K-feldspar, illite, and kaolinite in acid insoluble residues, calculated as in Table 1.

Depth of section (m)	Quartz	K-Feldspar	Illite	Kaolinite
0,50	65	9	18	8
0,95	63	10	20	7
1,45	85	4	7	4
2,10	73	11	12	4
2,80	69	11	14	6
3,40	65	14	16	5
3,85	50	17	23	10
4,10	62	18	15	5
4,65	47	16	21	16
4,90	49	22	23	6
5,20	43	19	26	12
5,70	54	22	23	6
6,15	53	21	17	9
7,15	51	21	21	7
8,85	54	20	18	8
9,10	41	19	27	13
9,60	36	19	29	16

ations especially of quartz and feldspar, to a minor extent also of illite and kaolinite. Obviously the relative decrease of quartz in the shale is causally connected with the relative increse of potassium feldspar and illite. Where the contents of potassium feldspar in the shale is the highest, there is also a significant decrease of kaolinite. This connection was not observed in the carbonates.

If the feldspar in the non-carbonate fraction of the limestones represents the content of primary detrital feldspar, the described relationships are interpreted as being the consequence of potassium feldspar authigenesis (Armands 1972); this would imply the consumption of detrital quartz and/or mobile silicic acid and of detrital kaolinite in the shale (see Hurst & Irwin 1982). This authigenesis should mainly be regarded as a further growth of the primary detrital feldspar fraction. Illite authigenesis also occurs in the shale, although at a lower rate, and also contributed to consumption of the primary quartz.

The circumstance that the illite and feldspar curves for shale and carbonate run parallel suggests that these minerals may have grown at the expense of quartz, even in the limestones, although at a lower rate than in the shale.

The relation carbonate to shale is distinctly higher in the outcrop of *Trolmen* as compared with Hällabrottet. Deposition at Trolmen is marked by a much broader spectrum of variation. Furthermore, the Trolmen section

TABLE 6. Hällabrottet (Närke): Shale. Relative contents of quartz, K-feldspar, illite, and kaolinite in acid insoluble residues, calculated as in Table 1.

Depth of section (m)	Quartz	K-Feldspar	Illite	Kaolinite
0,35	52	12	21	15
0,60	54	14	19	13
1,05	54	13	16	17
1,55	52	13	20	15
2,25	45	17	23	15
2,75	49	16	22	13
3,70	53	18	17	12
4,60	54	20	17	8
5,45	46	17	21	16
6,25	51	18	18	13
6,60	50	23	15	12
6,90	50	19	18	13
7,30	55	19	15	11
7,70	48	23	25	4
8,15	45	17	23	15
8,65	47	18	19	16
9,25	44	22	23	11
10,00	45	26	29	10
11,50	46	20	20	14
12,75	36	21	26	17
13,75	39	23	28	10
14,75	44	14	26	16
15,00	33	16	27	24
15,50	39	16	25	20

covers a stratigraphically larger interval than that of Hällabrottet.

All of these differences contribute to the fact that the semi-quantitative composition of the shale and the non-carbonate fraction of carbonate shows a picture more complex than was the case with Hällabrottet (Fig. 30).

The more complicated findings may generally be considered as an indication that the composition of the primarily accumulated non-carbonate detritus was subjected to more variation at the depositional site of Trolmen than in the area of Hällabrottet. The homogenizing effect of large transport distances and a continuously calm water body might not always have been as important in the area of Trolmen as it was in that of Hällabrottet. However, this comparison can only apply to zones Vb and Vc that are outcropping at Hällabrottet. Furthermore, the degree of diagenetic alteration especially in the shale appears generally to have been lower in the area of Trolmen, whereby a homogenizing effect may have been lost.

This assumption is based for instance on the circumstance that the illite curve for shale and carbonate cross one another quite frequently, unlike the condition found for Hällabrottet. However, the two potassium feldspar curves do keep well apart even in the case of Trolmen. The potassium feldspar contents are markedly higher (about 5–10%) in almost all samples than it is in the adjacent carbonate. The anticorrelation of potassium feldspar and kaolinite in the shale is much less significant than in the case of Hällabrottet. In all probability authigenesis of potassium feldspar in the sense of further growth of detrital feldspar particles also occurred to some extent in the shale of the Trolmen section.

CONCLUSIONS

1. The occurrence of a specialized trilobite fauna poor in species, but rich in individuals and its generally allochthonous character as well as the lack of bioturbation point to hypoxic to anoxic conditions at the sediment surface during the deposition of the Upper Cambrian Olenid shale sequence.
2. High contents of organic matter in the entire shale sequence in spite of generally very low sedimentation rates are further evidence that oxygen supply at the sea-bed was insufficient for destruction of the organic matter.
3. Certain structures can be explained as having formed by degassing, probably the escape of biogenically formed methane from underlying sediments.
4. The occurrence of the articulate brachiopod species *Orusia lenticularis*, and widespread phosphatization of carbonates in conjunction with particular condensed sequences are taken as indications of temporarily more oxic conditions.
5. The distribution of various olenid species and that of *Orusia lenticularis* point to the existence of rises within the depositional area.
6. Slide breccias and small, synsedimentary structures in the vicinity of assumed rises are additional indications that these rises existed.
7. At certain stratigraphic levels localities widely apart have internal brecciation of sedimentary beds without indications of lateral sediment movements. These breccias might indicate earthquakes.
8. The predominance of parallel lamination and the lack of sedimentary structures typical of tidal environments throughout the time and area of Olenid shale deposits exclude deposition in shallow water environment.
9. The monotonous mineralogy of acid insoluble residues of carbonates, the small grain size of siliciclastics (clay to silt size) indicate deposition far from land, probably to no small extent from aeolian transport.
10. The conclusions 1–9 and by analogy with the depositional conditions of the Ordovician Orthoceratite limestone lead to the conclusion that the

Olenid shale sequence was deposited in the domain of an upwelling system in water depths that were permanently below wave base.

11. The carbonates show numerous indications of early diagenetic lithification.
12. "Lenticular bedding" was caused by early diagenetic partial dissolution of carbonate layers.
13. Recrystallization frequently occurs.
14. The formation of the so-called pillar spar is explained by early dissolution – reprecipitation processes under strong anoxia in the contact zone to highly bituminous carbonate inclusions and shale.
15. All carbonate examined is low-Mg calcite. The circumstance that the Mg content is so low remains without explanation.
16. Comparison between the mineralogy of the shale and the siliciclastic residues of the carbonates indicates that continued diagenesis in the shale led to formation of authigenic potassic feldspar.

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