Ice-marked Sand Grains in the Lower Ordovician of Sweden

Maurits LINDSTRÖM

With 2 Figures, 1 Table, and 1 Plate

LINDSTRÖM, Maurits: Ice-marked Sand Grains i the Lower Ordovician of Sweden. – Geologica et Palaeontologica 6: 25–31, 2 Abb., 1 Tab., 1 Taf., Marburg, 15. 8. 1972.
Of 19 grains of quartz sand recovered from a Lower Ordovician Latorpian sample of pelagic limestone from Sweden, otherwise very poor in clastic material, 12 showed what is recognized as good evidence of glacial abrasion. The grains probably were dropped from ice rafts. This indicates Early Ordovician local ice reaching the sea in a sand dominated area to the south of Scandinavia.
12 von 19 Körnern von Quarz-Sand, die in einer Kalkprobe aus der Latorp-Stufe (Unterordoviz: Arenig) von Schweden gefunden wurden, zeigten unter REM für eindeutig gehaltene Spuren der Glazial-Abrasion. Die Körner, wohl von einer lokalen Vereisung in sandigen Sedimentationsgebieten südlich Skandinaviens stammend, wurden wahrscheinlich mit Treibeis transportiert. Kaltes Klima könnte einige Besonderheiten der unterordovizischen Cephalopodenkalke (Diskontinuitätsflächen u. a.) mit erklären.

Anschrift des Verfassers: Prof. Dr. M. LINDSTRÖM, Fachbereich Geowissenschaften der Philipps-Universität, D-3550 Marburg, Lahnberge.

Introduction

Quartz sand morphoscopy, the technique of deciphering the history of sand grains from their surface texture, has in later years become a well-established discipline (KRINSLEY & FUNNELL, 1965). The Scanning Electron Microscope (SEM) has made these studies easier and provided them with a reliable quantitative base. Features shown by grain surfaces may be diagnostic of aeolian, beach, or glacial environments of sedimentation (KRINSLEY & DONAHUE, 1968). A sample of quartz sand grains from the Lower Ordovician "Orthoceratite Limestone" of Sweden shows indications of glacial grinding. If the interpretation is correct, the sand may have been transported from land by drift ice. Since this appears to be the first evidence of ice activity in the Early Ordovician, the case merits discussion in a rather broad context.

Grain features and interpretation

KRINSLEY & MARGOLIS (1969) described the diagnostic features of the different environments in a brief and comprehensive paper. The following list of morphologic details is abstracted, with a few omissions, from their paper.

1. Littoral
   a) Evidence of spalling
   b) Small, V-shaped impact indentitions
   c) Grooves or scratches that may consist of aligned pits
   e) Etch marks (may be very deep and may be bounded by crystallographic surfaces)
2. Aeolian
   a) Small, more or less deep-reaching blocks breaking away and leaving irregular, meandering ridges
   b) Concentric, size-graded arcs on small, conchoidal fracture-planes
   c) Flat, more or less deeply pitted surfaces
3. Glacial
   a) Conchoidal breakage patterns of very different sizes
   b) High relief
   e) Semiparallel striations
   f) Imbricated breakage-blocks
   g) Irregular, small-scale indentations of the breakage-steps

Several of the glacial features are probably different aspects of a single phenomenon, viz. conchoidal fracturing with offsets. In general, the aeolian and littoral grains are more smoothly rounded than glacial grains. The latter show a high relief bounded by conchoidal breakages. KRINSLEY & MARGOLIS state, in the case of glacial grains, that the observation of four or more of the above textures over large areas of a single grain according to their experience may be taken as adequate evidence of glacial origin. The method is currently being used for studies of the Tertiary to Pleistocene sequence of glaciations, as revealed by ice rafted sand grains in sediments of the deep ocean (see, for instance, MARGOLIS & KENNETT, 1970, KENT, OPDYKE & EWING, 1971). HILLEFORS (1971) uses grain morphoscopy in the identification of glacial grains.

Sand grains are mostly scarce in the pelagic cephalopod limestones of Early Ordovician age that occur in extensive areas in northern Europe. A number of well-preserved grains of quartz sand in the size range 0.3–0.5 mm were found in a limestone bed exposed in the coastal cliffs at Horns Udde, in southeastern Sweden. The bed (J bed at 12 m, section of LINDSTRÖM, 1963, Pl. 1) was dated by conodonts as belonging to a level just above the range of *Stolodus stola* in the middle-upper part of the Lower Arenigian (Lower Ordovician) Billingen Substage of the Latorpian Stage. Twenty-two apparently well-preserved grains, some with spots of thin, ferrugineous stain, were collected and subjected to detailed study with the SEM.

The grains were numbered 1–22. Grains 7, 15, and 20 turned out to be in all probability feldspar (dense, intersecting cleavage). The features of the grains are listed in Table 1. Twelve grains were interpreted as glacial. Grains 1, 5, 8, and 17 show minor facets belonging to earlier abraison cycles. On grains 1 and 17, these facets indicate beach environment, probably with relatively low energy, because the surfaces are smooth. Grain 5 shows deeply pitted facets very similar to those found on beach grains (GEES, 1969). These features are evidently due to the combined effects of impact and solution. Preserved older facets on grain 8 show features that indicate aeolian action. Grain 19 shows glacial features overprinted on faces formed by neocrystallization.

Table 1: Features shown by Lower Ordovician grains of quartz sand. The features are numbered according to the list on p. 00.

Grain	Main features	Interpretation	Subordinate features
1	3 a–b, e–f	Glacial	1 a–c, e
2	2 a–c	Aeolian	
3	1 b–c	Littoral	
4	2 a–c	Aeolian	
5	3 a–b, e–g	Glacial	1 e
6	2 a–c	Aeolian	
7	Feldspar		
8	3 a–b, e–g	Glacial	2 a, c
9	3 a–b, e–f	Glacial	
10	3 a–b, e–f	Glacial	
11	3 a–b, e–f	Glacial	
12	1 b–c	Littoral	
13	3 a–b, e–g	Glacial	
14	2 a, c	Aeolian	
15	Feldspar		
16	3 a–b, e–g	Glacial	
17	3 a–b, e–g	Glacial	1 b–c
18	2 a, c	Aeolian	
19	3 a, e–f	Glacial	Recrystallized
20	Feldspar		
21	3 a–b, f	Glacial	
22	3 a–b, e–f	Glacial	

Post-glacial processes have left marks on grains 1, 10, and 21. Grains 1 and 10 show solution pitting on the breakage surfaces. Solution pits found on grain 1 are shallow and rounded, and have diameters about 0.2 μ. Grain 10 has steps and triangular pits evidently corresponding to crystal faces. This pitting might have been formed through prolonged exposure to quiet sea-water. Grain 10 furthermore shows some rounding of certain sharp edges, perhaps due to abrasion. Grain 21 shows consistent smoothing of all edges, possibly due to dissolution or early diagenetic processes. While the pits of grain 1 and the smoothing of grain 21 might have developed at the site of ultimate sedimentation, grain 10 has marks of mechanical abrasion (glacial?) formed after the solution pitting.

Mode of origin and emplacement

The available population of sand grains is small. This is due to the circumstance that sand grains are generally sparse, and grains with well-preserved surfaces have to be long sought for, in the studied limestone sequence. Of the 19 quartz grains, 12 show features that form by crushing and grinding, mechanisms to which few sand grains are subjected in nature outside the glacial environment. While one or two grains with crush marks might conceivably be fortuitous, the twelve grains found are regarded as evidence.

In the matter of transport of the grains, it is obvious that different means have to be considered. Floating algae, animals, and bottom currents are for choice in addition to ice rafts. Of these, bottom currents may be the least likely. A thin veneer of marly mud occurred scattered in places all over the sea-bed, and the intervening carbonate surfaces, though partially hard-ground, had deep, densely crowded pits (LINDSTRÖM, 1963). Thus, sand grains traveling over the sea-bed would very soon have been trapped. The choice between algae and animals is immaterial here. Neither can, perhaps, be excluded, though the animal alternative appears the less likely of the two. Ice rafts would provide the most plausible transportation for ice-shaped particles. This has been the mechanism suggested for ice-worn grains found in Tertiary to Pleistocene oceanic sediments (MARGOLIS & KENNETT, 1970). On the other hand, ice rafts might be expected to have transported coarser and more abundant material than has actually been found. This might speak in favour of a more sporadically occurring and less competent, perhaps indeed a biological, agent.

Pebbles, otherwise indicators of ice rafting in pelagic sediments, do not occur. The sediment is a part of an extensive sheet of very slowly deposited, pelagic limestone (LINDSTRÖM, 1971, MÄNNIL, 1966). The fossil fauna of this limestone is poor in species. It is doubtful if it contained any important sessile, benthonic forms. Despite continuously pelagic conditions through most, probably even all, of the Early Ordovician, the average sedimentation of terrigenous material was as low as 2.7×10^{-1} to 2.7×10^{-3} g/cm² in 1000 years (compare LINDSTRÖM, 1971). For the lithology, this means that many of the limestones are relatively pure carbonate. Most of the terrigenous material is clay.

These circumstances put serious restrictions on the glacial interpretation. Ocean currents flowing over the area of deposition of the cephalopod limestones could not have been in contact with a major, stable land ice. Ice rafts could not have come from ice flowing over exposed rock. The ice must have flowed over sandy surfaces. Dune and beach sands were included among the sediments overridden by the ice before it reached its seaward margin, this we can learn from the grain morphoscopy. Sandy surfaces, no doubt, existed in wide areas of Europe in the Early Ordovician. Thus, the Tremadocian to Arenigian of western and southern Europe consist largely of sandstone (Armorican Quartzite).

Paleogeography and source area

Ordovician paleogeography was reconstructed by SPJELDNAES (1961) on the basis of fossil faunas and sediment distribution. The reconstruction shows a South Pole not far to the south of Europe. For the uppermost Ordovician this has been confirmed by the discovery of extensive glacial deposits of latest Ordovician to Early Silurian age in the Sahara (FAIRBRIDGE, 1971, BEUF & al., 1971). ARBEY & TAMAIN (1971) and DANGEARD & DORÉ (1971) suggest that this glaciation for a while extended into southwestern Europe.

A couple of paleomagnetic South Pole determinations for the Cambro-Ordovician are given by BUCUR (1971) based on African material. These indicate a South Pole in White Russia, which is even closer to the area dealt with here. However, this pole position may be considerably in error with reference to present geography. We do not know the amount of orogenic shortening that has taken place in the areas between Africa and White Russia, but it might be great. Correction for this would have to be added to the correction for any uncertainties inherent in the paleomagnetic method.

Fig. 1: Generalized facies and paleogeographic features of Europe in the Arenigian. ● denotes location of sample. Brick pattern = cephalopod limestone facies. Symbols for volcanism in Wales and in the Bohemian Massif. Uncorrected paleomagnetic pole positions indicated by snow flakes, warm climate by sun. Note that the pole positions depend on African data. Continent displacement since the Triassic might imply that the pole positions have to be relocated to the Tethys province, south of the Alps.

If we disregard the paleomagnetic indications and consider the geology, the search for a source of glacial sand in the Arenigian of Europe is a difficult matter. The greatest difficulty is that the Arenigian was one of the longest epochs of the Ordovician but its deposits are very poorly dated in large parts of Europe. This leaves many possibilities open. Since the sand grains are from only one sample we know nothing about the duration of the glacial episode.

On the Baltic Shield itself, sedimentation of the very slow, pelagic type prevailed throughout the Early Ordovician. We can theoretically look for a glacial sediment source in the direction of the Caledonian orogenic belt, extending along the northwestern margin of Europe, in the direction of southwestern and central Europe, and in the direction of the nuclear continental areas contained within the European parts of the Soviet Union. The Caledonides, to take this belt first, include much of the British Isles. On the northwest margin of the British Caledonides we find in the Lower Ordovician the Durness Limestone, obviously a sediment of a relatively warm and shallow sea. The upper part of the Durness Limestone, to judge from its conodonts (HIGGINS, 1967), includes the Arenigian. The Arenigian of the Moffat Geosyncline in southern Scotland comprises chert-shale (LAMONT & LINDSTRÖM, 1957), formed very slowly in a starved basin, and certainly does not show any evidence of proximity to continental ice. Other parts of the Caledonian belt were either orogenic land (Connemara?, see SKEVINGTON & STURT, 1967) or areas of more or less rapid sedimentation of graptolitic mud (Lake District, Wales), in part with volcanics. As noted by SKEVINGTON (1963) the top Tremadocian and basal Arenigian are not known in Britain.

In the Norwegian Caledonides the Tremadocian to Arenigian include i.a. thick greenstone volcanics, thick graptolitic shales, and clastics of varying degrees of coarseness (see, for instance, HOLTEDAHL, 1960, and CHALOUPSKY, 1970). To summarize, the Caledonides might not have had the right climate for land ice, they contain sediments that must have been deposited far from any land ice, and they would, if glaciated, have yielded a great deal of coarse erratics.

From southwestern and central Europe the Ordovician Baltic Shield was separated by a belt of mainly graptolitic mud that extended from the Oslo area through souhernmost Sweden into northern Germany (see, for instance, STÖRMER, 1967). It is conceivable that this area may occasionally have been crossed by rafts carrying sand. The source area would then have to be sought farther south. Lower Ordovician is known from the Ardennes, the Armorican Massif of western France, Montagne Noire, the Bohemian Massif including marginal areas in Bavaria and Thuringia, and the Holy Cross Mountains. The sequence in all these areas is clastic, dominated by sand.

In the Ardennes the youngest dated beds are Tremadocian. In the Armorican Massif, Tremadocian coarse clastics are known from the Ancenis Synclinorium (CAVET, 1970). The Lower Ordovician for the rest is dominated by a relatively pure, quartzitic to subarkosic sandstone (Armorican Quartzite) that may be over 500 m thick. The top of this sandstone may belong within the Arenigian (CAVET, 1970). The Armorican Quartzite is known for its wide distribution. For instance, it occurs in the Ordovician sections of Spain and Portugal. The Lower Ordovician of Montagne Noire has been discussed by DEAN (1966). He describes a succession of fossiliferous shales, sandstones, and mudstones with a collective thickness of over 400 m, all of Early Arenigian age.

The Bavarian and Thuringian Lower Ordovician has been summarized by SDZUY (1971). Though there are great facies variations with this small area, one can generalize by stating that the Tremadocian to Lower Arenigian is several hundred and may be over thousand meters thick. It is shaly to sandy and may contain abundant volcanics. Possibly, volcanic pebbles should be expected to be dropped from ice rafts coming from this area.

The Tremadocian and Arenigian is missing in some places in Bohemia. Elsewhere these series are mainly shaly and may contain volcanics (HAVLIČEK & ŠNAJDR, 1955). This area, like the previous one, is an unlikely source for the glacial material under discussion.

By comparison with the areas referred to above, the Holy Cross Mountains have a thin Lower Ordovician succession. The Tremadocian may be missing, or consists of graptolitic shale, chert, or glauconitic sandstone. The Arenigian is transgressive. It is sandy to shaly, rich in glauconite, and may contain reworked older sediments in a basal conglomerate. These conditions have been briefly described by TOMCZYK (1971). The area has sedimentary and faunistic affinities to the Baltic Shield. The sparse and fully marine sedimentation makes it unlikely that the area was greatly influenced by land ice.

The Ordovician of Russia and Ukraine is poorly known. It is known, however, that the system is underlain by Cambrian and late Precambrian clastics, of which the Cambrian are largely sandy, whereas the Precambrian contains much unweathered pebble material. The Lower Ordovician may be missing. A further complication is that the Ukrainian Shield, with extensive exposure of Precambrian crystalline rocks, formed a rising area during much of the Paleozoic. It would probably have contributed pebble erratics to any land ice within this area.

To sum up, a derivation of the sand grains, as the only ice-transported material, from the east (Russia and Ukraine) is unlikely, from the south (Bohemian Massif) is probably impossible, from the southwest (Armorican Quartzites area) appears possible, and from the west and north (Caledonian belt) is impossible.

The very thick and fairly homogeneous Armorican Quartzites may have covered much wider areas than those in which they are now preserved. If parts of these sandy expanses were temporarily glaciated, much like the Lower Paleozoic sandy formations of the Sahara at the turn of the Ordovician and Silurian, the moraines produced would have consisted exclusively of sand. The uppermost part of the Armorican Quartzite of Crozon contains structures believed to have been formed in a littoral, tidal environment (BABIN & PLUSQUELLEC, 1969). It is here suggested that some of these structures, in particular those described by BRADSHAW (1966) would hardly have been preserved in such an environment unless the surface was cemented. In analogy with the Lower Cambrian Hardeberga Sandstone of Sweden, where similar structures have to be explained (LINDSTRÖM, 1972, VORTISCH, manuscript in press), one may suggest that the structures of the Armorican Quartzite, if truly littoral, were ice-cemented. The Hardeberga Sandstone contains more positive evidence of frost and sea-ice activity. As regards lithology, sedimentary structures, trace fossils, and adjacent facies the two compared sandstone formations are strikingly similar. If truly littoral conditions existed when the upper part of the Armorican Quartzite was deposited in certain areas, nearby areas must have been land. Such areas, if temporarily glaciated, may have delivered sand of the kind discussed.

Sedimentologic consequences of a cold climate

The cephalopod limestone in which the sand grains were found was laid down on a sea-bottom on which the situation for carbonate sedimentation was precarious. Carbonate was very slowly deposited and then dissolved and again precipitated in the pores of the sediment. Dissolution of limestone occurred on the sea-bed at frequent intervals (JAANUSSON, 1961, LINDSTRÖM, 1963, 1971). These processes brought about the formation of microkarst-like discontinuity surfaces. To explain them, HADDING (1958) invoked the periodic influx of cold currents. The present discovery suggests that HADDINGS hypothesis may contain some truth, and that climatically induced fluctuations of the compensation depth of calcite might explain some peculiarities of the limestones in question. Restrictive climatic conditions might also explain the specialized nature of the fauna, the absence of all major, benthonic forms, and the small number of species represented. If the climate might have been cool in northern Europe in the Early Ordovician, it appears to have become warmer in the Middle and Late Ordovician. The evidence for this amelioration of climate consists i.a. in the growth of calcareous reefs.

Summary and conclusions

12 of 19 grains of quartz sand found in a sample of Lower Arenigian cephalopod limestone from Sweden were found to have been shaped essentially by crushing and grinding.

Experience, and theoretical considerations, show that these mechanisms normally work only in the basal parts of a land ice (cited works by KRINSLEY and collaborators).

The cephalopod limestone in this case is a pelagic facies formed in an extensive area during millions of years of extremely slow sedimentation. The so far unique discovery of ice-shaped sand grains in this facies raises considerable problems as regards nature of the occurrence, as regards means of transportation, as regards provenience, as regards paleogeographic implications, and as regards consequences for biotopes and sedimentation.

The most puzzling circumstance about the occurrence is perhaps that no other exotic material has been observed until now, either within the cephalopod limestones themselves or in stratigraphically and geographically adjacent facies.

With this in view it has to be emphasized that there is no doubt that the sand grains were derived from within the limestone sample, and that this sample belonged to the stratigraphic succession. The limestone was dated by conodonts, and mineral coating on parts of the sand grains is characteristic of the limestone. The micropaleontologic technique employed in dealing with the limestone was a normal one designed to prevent contamination.

The grains were probably transported by rafting, rather than by bottom currents. The nature of the raft might be important. If it was algal, this might explain both the scarcity of the occurrence and the absence of coarser grains. However, since the grains would have come from a glacial environment, the discussion has centered on the assumption that the grains were transported by an ice raft.

In this case the source of the grains must have been in a glaciated area in which practically nothing but sand occurred. Similar conditions must have existed in connection with the probably much more important Saharan glaciation in the Late Ordovician – Early Silurian (BEUF & al., 1971, FAIRBRIDGE, 1971). It is suggested that the source area was within the wider Armorican Quartzite area. The ice might have left few traces in a sequence of mainly sands, and the main glaciated area might have been outside the exposures now remaining of the Armorican Quartzite. We do not, for instance, know how far the Armorican Quartzite may originally have extended to the east.

Paleogeographically, the area from which the sand came needs not to have been at the South Pole itself but might have been at some distance from that pole. This implies that great parts of Europe were at times fairly cold. The sea covering the Baltic Shield in the Arenigian might have been a cold sea. This would help to explain the slowness of carbonate sedimentation and the frequent formation of surfaces of carbonate solution in the Arenigian cephalopod limestones. It might also explain why the fauna is so specialized and poor in species.

The question of Early Ordovician climate and sedimentation is being followed up along four lines, in cooperation with colleagues at the Marburg University. Isotope paleotemperature investigations on the Arenigian limestones of Sweden are being carried out in cooperation with Dr. H. FRIEDRICHSEN. The clay mineralogy of the succession is being investigated by Prof. H.-H. LOHSE and Dipl.-Geol. W. VORTISCH. The detailed stratigraphy of the relevant sections is being established by means of conodonts, in cooperation with Prof. W. ZIEGLER. In connection with this work, each sample is systematically searched for quartz grains for further morphoscopic studies.

Acknowledgements

I wish to thank Dr. R. CHRISTENHUSZ for patient and skilled work at the SEM as well as for stimulating discussion. Prof. D. KRINSLEY and Dr. K.-W. TIETZE have given advice and encouragement. The work has been financed from Deutsche Forschungsgemeinschaft Project Li 174/2. The Cambridge Stereoscan electron microscope used for this study was donated to the Philipps University of Marburg by the Volkswagenwerk Foundation.

References

ARBEY, Francois & TAMAIN, Guy (1971): Existence d'une glaciation siluro-ordovicienne en Sierra Morena (Espagne). — C. R. Acad. Sci. Paris (D) **272**: 1721–1723, Paris.

BABIN, Claude & PLUSQUELLEC, Y. (1969): "Ripple-marks" actuels et fossiles. — Penn ar Bed, N. Ser. **7**: 34–40, Quimper.

BEUF, Serge; BIJU-DUVAL, Bernard; DE CHARPAL, Olivier; ROGNON, Pierre; GARIEL, Olivier & BENNACEF, Abdelkrim (1971): Les grès du paléozoique inférieur au Sahara. Sédimentation et discontinuités. Evolution structurale d'un craton. — Publ. Inst. Français Pétrole, Coll. "Science et technique du pétrole" **18**, 464 p., Paris.

BRADSHAW, J. D. (1966): An unusual sedimentary structure indicative of shallow water conditions in the Grès Armoricain of Finistère (France). — Sedimentology **7**: 149–154, Amsterdam.

BUCUR, Ileana (1971): Etude paléomagnétique d'une formation sédimentaire du Sahara algérien, d'âge cambro-ordovicien. — Ann. Géophys. **27**: 255–261, Paris.

CAVET, P. (1970): Chalonnes-sur-Loire. Carte géologique à 1/50000. Notice explicative. — 32 p., Nancy.

CHALOUPSKY, Josef (1970): Geology of the Hølonda-Hjulsjøen area, Trondheim region. — Norges Geol. Unders. **266**: 277–304, Oslo.

DANGEARD, Louis & DORÉ, Francis (1971): Faciès glaciaires de l'ordovicien supérieur en Normandie. — Mém. B. R. G. M. **73**: 119–127, Paris.

DEAN, W. T. (1966): The Lower Ordovician stratigraphy and trilobites of the Landeyran Valley and the neighbouring district of the Montagne Noire, south-western France. — Bull. Brit. Mus. (Nat. Hist.), Geol. **12**: 245–353, London.

FAIRBRIDGE, Rhodes W. (1971): Upper Ordovician glaciation in Northwest Africa? Reply. — Geol. Soc. Amer. Bull. **82**: 269–274, Boulder.

GEES, R. A. (1969): Surface Textures of Quartz Sand Grains from Various Depositional Environments. — Beitr. elektronenmikroskop. Direktabb. Oberfl. **2**: 283–297, Karlsruhe.

HADDING, Assar (1958): Hidden hiatuses and related phenomena. Some lithological problems. — Kungl. Fysiogr. Sällsk. Lund Förhandl. **28**: 159–171, Lund.

HAVLÍČEK, Vladimír & ŠNAJDR, Milan (1955): Some Problems of the Paleogeography of the Central Bohemian Ordovician. — Sborn. Ústředn. Ústav Geol. **21** (Odd. Geol.): 449–518, Praha.

HIGGINS, Alan C. (1967): The age of the Durine Member of the Durness Limestone Formation at Durness. — Scott. Jour. Geol. **3**: 382–388, Edinburgh.

HILLEFORS, Åke (1971): Deep weathered rock material and sand grains under the Scanning Electron Microscope. — Svensk Geogr. Årsbok **46**: 138–164, Lund.

HOLTEDAHL, Olaf (1960): Geology of Norway. — Norges Geol. Unders. **208**, 540 p., Oslo.

JAANUSSON, Valdar (1961): Discontinuity surfaces in limestones. — Bull. Geol. Inst. Univ. Uppsala **40**: 221–241, Uppsala.

KENT, D.; OPDYKE, N. D. & EWING, M. (1971): Climate Change in the North Pacific using Ice-Rafted Detritus as a Climatic Indicator. — Geol. Soc. Amer. Bull. **82**: 2741–2754, Boulder.

KRINSLEY, David H. & DONAHUE, Jack (1968): Experimental Interpretation of Sand Grain Surface Textures by Electron Microscopy. — Geol. Soc. Amer. Bull. **79**: 743–748, Boulder.

— & FUNNELL, Brian M. (1965): Environment history of quartz sand grains from the Lower and Middle Pleistocene of Norfolk, England. — Quart. Journ. geol. Soc. London **121**: 435–461, London.

— & MARGOLIS, Stanley (1969): A study of quartz sand grain surface textures with the scanning electron microscope. — Trans. New York Acad. Sci. (II) **31**: 457–477, New York.

LAMONT, Archie & LINDSTRÖM, Maurits (1957): Arenigian and Llandeilian Cherts identified in the Southern Uplands of Scotland by means of Conodonts, etc. — Trans. Edinburgh Geol. Soc. **17**: 60–70, Edinburgh.

LINDSTRÖM, Maurits (1963): Sedimentary folds and the development of limestone in an Early Ordovician sea. — Sedimentology **2**: 243–292, Amsterdam.

— (1971): Vom Anfang, Hochstand und Ende eines Epikontinentalmeeres. — Geol. Rundschau **60**: 419–438, Stuttgart.

— (1972): Cold Age Sediment in Lower Cambrian of South Sweden. — Geol. et Palaeontol. **6**: 0–00, Marburg.

МЯННИЛЬ, Р. М.: ИСТОРИЯ РАЗВИТИЯ БАЛТИЙСКОГО БАССЕЙНА В ОРДОВИКЕ. — Eesti NSV Teaduste Akad. geol. Inst., 200 S., 69 Abb., Tallin (Walgus) 1966

MARGOLIS, S. V. & KENNETT, J. P. (1970): Antarctic glaciation during the Tertiary recorded in subantarctic deep-sea cores. — Science **170**: 1085–1087, Washington.

SDZUY, Klaus (1971): The Ordovician in Bavaria. — Mém. B. R. G. M. **73**: 379–390, Paris.

SKEVINGTON, David (1963): A correlation of Ordovician graptolite-bearing sequences. — Geol. Fören. Stockholm Förhandl. **85**: 298–319, Stockholm.

— & STURT, Brian A. (1967): Faunal evidence bearing on the age of Late Cambrian – Early Ordovician metamorphism in Britain and Norway. — Nature **215**: 608–609, London.

SPJELDNAES, Niels (1961): Ordovician climatic zones. – Norsk Geol. Tidsskr. **41**: 45–77, Bergen.

STÖRMER, Leif (1967): Some aspects of the Caledonian geosyncline and foreland west of the Baltic Shield. — Quart. Journ. Geol. Soc. London **123**: 183–214, London.

TOMCZYK, Henryk (1971): The Arenigian transgression in Poland and its relation to earlier formations. — Mém. B. R. G. M. **73**: 423–430, Paris.

Plate 1

A. Grain 10, showing conchoidal breakage surfaces slightly modified by solution pitting and surface recrystallization.

B. Detail of A.

C. Whole view of grain 9.

D. Detail of C, with features 3 a, 3 b, 3 e (lower left corner), and 3 f. The niches contain ferrugineous dust belonging to the matrix.

E. Whole view of grain 21.

F. Detail of E, showing i.a. imbricated breakage-blocks with smoothed relief.

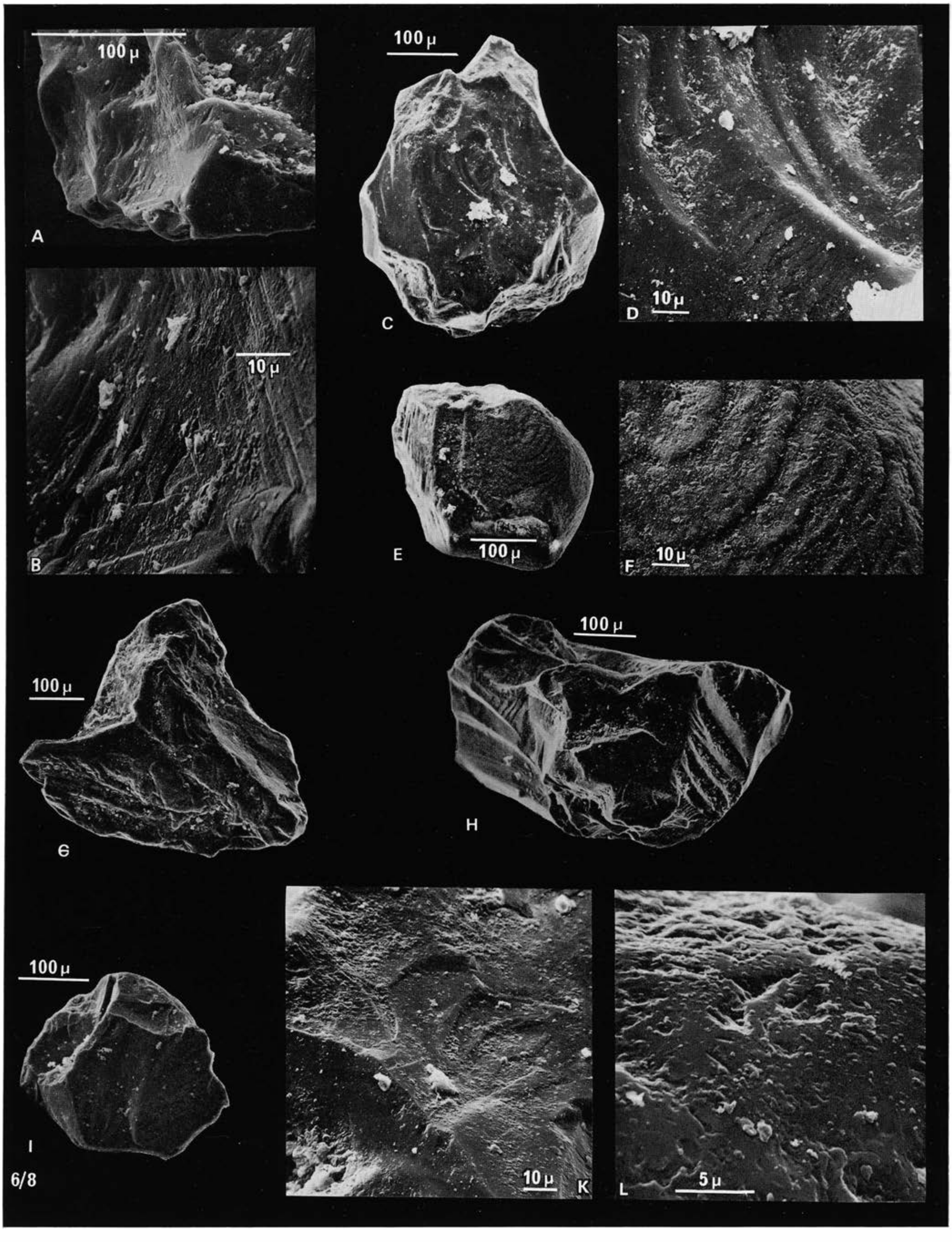
G. Whole view of grain 13.

H. Grain 8, showing different aspects of conchoidal breakage.

I. Whole view of grain 5.

K. Detail of grain 16. Non-calcareous matrix adhering in several places.

L. Detail of grain 12 as instance of non-glacial, probably littoral, grain morphology.


100 µ
A
100 µ
C
10 µ
D
10 µ
B
100 µ
E
10 µ
F
100 µ
G
100 µ
H
100 µ
I
6/8
10 µ
K
5 µ
L