Cold Age Sediment in Lower Cambrian of South Sweden

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With 4 Figures, 2 Tables, and 2 Plates

LINDSTRÖM, Maurits: Cold Age Sediment in Lower Cambrian of South Sweden. – Geologica et Palaeontologica 6: 9—23, 4 Abb., 2 Tab., 2 Taf., Marburg, 15. 8. 1972.

The Hardeberga Sandstone of Simrishamn contains ice-push lineations and structures implying frozen sediment. Large wave ripples, parting lineations, zircon concentrates, etc., indicate environment from outer nearshore, intertidal and swash zone. Open sea was to the S. Lower Cambrian carbonates of central to SW Europe could not be coeval with this, unless widely separated in pre-Caledonian geography. The findings seem to fit with a paleomagnetic South Pole in South or East Europe.

Der Hardeberga-Sandstein von Simrishamn enthält u. a. durch Eisschub entstandene Lineare. Große Seegangsrippeln, Strömungslineare, Lamellen mit Zirkonseifen usw. deuten Flachwasser, Gezeiten- und Brandungszone an. Offenes Meer war im S. Die unterkambrische Karbonatprovinz von Südeuropa bis zur Lausitz ist entweder nicht gleichaltrig mit dem Hardeberga-Sandstein oder war in der präkaledonischen Geographie von diesem weit entfernt.

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Introduction

Structures recently found in Lower Cambrian sandstones in the Simrisham area, southernmost Sweden, are believed to have been formed under the influence of sea-ice. If this interpretation is correct, it has a number of paleoclimatological, stratigraphical, and paleogeographical consequences. The combination of structures that might characterize an ancient, arctic or subarctic beach is, taken alone, of sedimentological interest.

Geological background

Simrishamn is a sea-port in the southeast part of Scania, the southernmost province of Sweden. Geologically, the Simrishamn area is situated in the boundary zone between the Baltic Shield, which is an extensive craton of Precambrian age, and the North Sea Basin (in the sense of SORGENFREI 1969). The North Sea Basin is a trough-and-rise area with a persistent tendency to subside. It has a thick succession of sediments beginning with Upper Precambrian.

The Lower Cambrian sandstone of Simrishamn is about 120 m thick. It is transgressive on Precambrian gneiss that ist but slightly weathered. LINDSTRÖM & STAUDE (1971) divided it into six Formations (Table 1).

The whole succession except the lowermost part of the Lunkaberg Sandstone contains trace fossils, mainly of the U-shaped *Diplocraterion* type. The Vik Sandstone is particularly rich in *Diplocraterion* and vertical tube-like trace fossils known as *Skolithos*. Some beds of this formation are strongly bioturbate. The Hardeberga Sandstone is generally poor in traces of animal activity, although a few characteristic forms, for instance, *Syringomorpha*, have been found in it.

Table 1: Stratigraphy of the Lower Cambrian Sandstones of SE Scania, according to LINDSTRÖM & STAUDE 1971.

Stratigraphic unit	Approximate thickness (m)
Lower Cambrian siltstone and limestone	1
Rispebjerg Sandstone	1
Norretorp Glauconitic Sandstone	4
Hardeberga Sandstone	25
Brantevik Glauconitic Sandstone	3
Vik Sandstone	25
Lunkaberg Sandstone	60
Precambrian gneiss	

The Hardeberga Sandstone is a white, medium to fine grained quartzite with minor amounts of feldspar. ASKLUND (1927) regarded certain sandstones with traces *(Skolithos)* as probably Eocambrian (uppermost Precambrian) and was alleged by WESTERGÅRD (1931) to have suggested an Eocambrian age for the sandstones immediately below the Hardeberga Sandstone. This idea (which I have failed to find in ASKLUND's paper) was rejected by WESTERGÅRD (1931) who saw the trace fossils as indicators of Cambrian age. Yet the same trace fossils occur in the Norwegian Ringsaker Quartzite, which is regarded as Eocambrian by SKJESETH (1963). BERGSTRÖM (1970) found probable resting traces of trilobites in the Hardeberga Sandstone of western Scania. He regarded this as evidence of a Cambrian age for the Hardeberga Sandstone as well as possibly for the Ringsaker Quartzite.

While some doubt may still remain whether the sandstones below the Hardeberga Sandstone are Cambrian or latest Precambrian, the existing evidence speaks for an assignment of the Hardeberga Sandstone itself to the Lower Cambrian. The Norretorp Glauconitic Sandstone has yielded trilobites belonging to the zone of *Holmia torelli* that is next to the lowest of the Lower Cambrian trilobite zone of Scandinavia (BERGSTRÖM 1970). The Rispebjerg Sandstone shows evidence of starved sedimentation (discontinuity surfaces, widely distributed enrichment of phosphatic material and pyrite). It marks the final stage of sandy terrigenous sedimentation. The upper Lower Cambrian is thin in most Scandinavian areas. Limestone beds are a characteristic feature of this part of the succession.

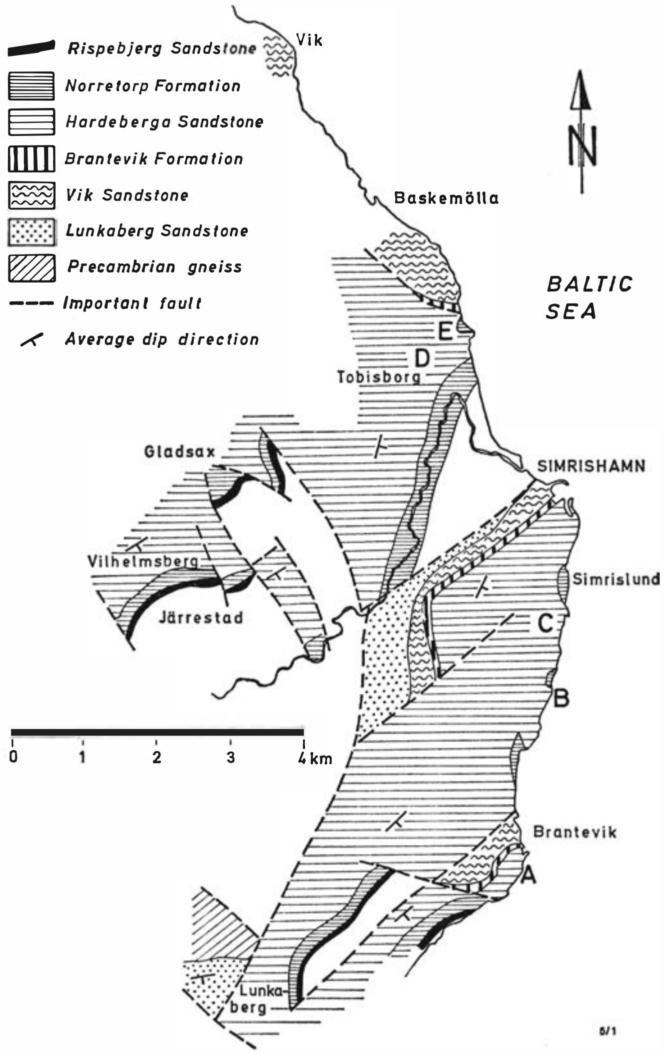

Fig. 1: Geology of the Simrishamn area according to LINDSTRÖM & STAUDE 1971. Formations younger than the Rispebjerg Sandstone are left blank. A–E are localities referred to in the text.

The Baltic Shield north of the investigated area might lack the Hardeberga Sandstone and equivalent beds. For instance, the provinces of Västergötland and Närke in south-central Sweden were probably not permanently transgressed until *Holmia torelli* time (BERGSTRÖM 1970).

In the Middle Cambrian a monotonous black shale facies, beginning in peripheral areas like Scania, gradually spread over the Baltic Shield. This is the only facies represented in the Upper Cambrian (HENNINGSMOEN 1969, LINDSTRÖM 1971).

The structures discussed in this paper were found in the uppermost part of the Hardeberga Sandstone. VORTISCH (manuscript) is describing related features occurring at the contact between the Hardeberga and Norretorp formations.

Previous observations

Various sedimentary structures in the Vik and Hardeberga formations were described by LINDSTRÖM (1967). Foremost of these structures were round collapse structures, called "funnel grabens". The funnel grabens may be as much as 200 m wide and over 50 m deep, although the majority are much smaller. They occur almost exclusively in the so-called Tobisborg Block northeast of Simrishamn. One instance, to be further discussed below, was found in a quarry at Simrislund south of Simrishamn.

The funnel grabens were interpreted as essentially tectonic features. They were thought to be due to the withdrawal of unconsolidated sand from the lower part of the succession into tectonic fissures in the Precambrian basement. Among the arguments for this interpretation one may mention the existence of sandstone dikes in the Precambrian in various places in southern Scandinavia. It was demonstrated that collapse movements took place at least as late as the Late Cambrian. This proves that processes that contributed to form these structures operated a very long time after sedimentation. It is also important that the sandstones remained fairly weak at this late stage.

In close connection with the funnel grabens there are plugs of structureless or contorted sandstone cutting across the bedding, intrastratal brecciation in the Vik Sandstone, crests evidently due to upwelling of sand from fractures, and clastic intraformational dikes. All of these structures were found north of Simrishamn.

A further structure reported in the same paper consisted of straight, parallel grooves and ridges found on bedding planes at three localities, one north and two south of Simrishamn. They were described as forming a penetrative fabric in a thin sheet of sandstone. It was noted that they have irregular cross sections and occur in bundles of different sizes, and that there is no cataclasis of sand grains. It was suggested that they were formed through nearly horizontal slip within the sandstone beds before these were completely cemented. No further explanation was given. This structure was the point of departure of the present study.

Probable ice-push structures

The lineations were found in the uppermost beds of the Hardeberga Sandstone. As noted by LINDSTRÖM (1967) they occur in patches. Within each patch they form a continuous fabric. One occurrence is near Tobisborg north of Simrishamn, at UTM coordinate VB 57905936 (Fig. 1, E). Another is on the shore just south of the dolerite dike at Simrislund, south of Simrishamn. The third, and most important occurrence is 1.2 km farther to the south (Fig. 1, B). At all three occurrences the lineations strike at approximately N 20° E. At the localities to the south of Simrislund the lineations are partly covered by overlying sandstone beds. Thus, they are internal structures of the sandstone. At the southernmost locality they are cut by a set of cross-beds interpreted as the fill of a shallow channel. This circumstance speaks against the earlier interpretation that they formed by late movements within the Lower Cambrian sandstones. The patchy occurrence of the lineations is another evidence against this earlier interpretation. Preserved parts of some lineations are over 2 m long. If horizontal movement of this amount occurred within the bedded sequence, its traces would probably have been continuous over greater areas.

The lineations consist of grooves and ridges that are parallel and perfectly straight (Pl. 1, Fig. 1 and 4). The depth of the grooves may amount to a few centimetres. A thin sheet of sandstone may be involved in forming rod-like lineations. The structures are fairly coarse. There appears to be no corresponding grain fabric. The sandstone is medium to fine grained. Thin sections show that there is no cataclasis.

Patches of lineations found at the localities south of Simrislund are associated with small strips of deformed sediment suggesting thrust-faults. These features strike east-west and indicate an over-riding movement towards the north. Like the lineations, they are overprinted by younger sedimentary structures. Thus, they were formed before the end of the sedimentation of the Hardeberga Sandstone.

Parallel, straight sedimentary lineations of a roughly similar kind occur as "groove marks" in turbiditic sequences. Such marks may form the interface between a muddy bed and an overlying bed with coarser texture. The structures described above occur entirely within sandstone. The environment of sedimentation was not turbiditic but, as will be shown in the following text, most likely high-energy beach.

A possible process that might be capable of forming the combination of structures described above appears to be ice-push on a frozen beach. HUME & SCHALK (1964) described and figured similar grooves from a beach in northern Alaska. Since the postulated ice-push evidently came from the south, the open sea must have been in this direction. This agrees with observations discussed below.

Frozen sediments

A number of structures formed during the sedimentation suggest that certain deposits were firmer and more cohesive than one can normally observe in fresh clastic beds. This might be due to consolidation by freezing.

The outcrop 1.2 km south of Simrislund (Fig. 1, B) has a mud pebble breccia occurring as a thin but extensive sheet with irregular topography and poorly defined lateral boundaries. Although the sheet as a whole appears to have been slightly deformed by processes operating in different directions, the mud pebbles as a rule are not crumpled.

This circumstance together with the lack of unidirectional deformation, makes it unlikely that the structure is a slump breccia. Several of the mud pebbles preserved as molds in the sandstone have dimensions of 0.4–0.8 m. They may be either angular or slightly rounded (Pl. 1, Fig. 6). Mud pebbles of this size are not normally encountered in transported material. It is suggested that they were moved in a frozen condition, either independently or attached to ice float. Instances of the latter mechanism are described for instance by DIONNE (1968 and 1969).

On the shore southeast of the southernmost house-group, "kvarteret Svanen" in Brantevik (Fig. 1, A) there are exposures of the uppermost beds of the Hardeberga Sandstone. At the base of this outcrop there is an extensive bedding-plane of the white, medium to fine grained, quartzitic sandstone that is the normal lithology of the Hardeberga Formation. There is a persistent set of long, symmetrical ripples with wavelengths of about 0.6 m, striking about west-east.

This rippled surface has a few pits filled with coarse sandstone to fine conglomerate. The pits were formed after the ripples and cut sharply into the bedding-plane. The northern walls of the pits are vertical. The pits have elongated outlines, with the long axis at about N 60° W–S 60° E. They are 0.4–2.5 m long and 0.15–1.5 m wide. Above the surface with the ripples and pits there follow further beds of cross-bedded, medium to fine grained sandstone.

Since there are no signs of deformation adjacent to the pits, it is believed that these were formed by scour rather than cryoturbation or irregular load. The discordant nature of the pits, and the coarse grain of their filling, show that the rippled surface was relatively firm when the pits were formed. This would have been the case if it was frozen. The same effect might conceivably appear if the sediment surface was held together by an algal mat. This has been suggested to explain the coherence of certain sandy layers (BRADSHAW 1966, GEVERS and others 1971). However, there is no independent evidence of abundant algal growth in the Hardeberga Sandstone. The whole formation is extremely poor in organic or organically derived material. In this as in other respects it is a typical sandy nearshore deposit.

The east-west ripples mentioned above have a pattern of about 1–5 cm wide, shallow polygonal concavities separated by low, poorly defined ridges (Pl. 2, Fig. 5). This is especially obvious at the ripple crests. The structures show no preferred direction. On one point a trace fossil, consisting of a pair of parallel furrows (trilobite trace?) has been widened and lost details in connection with the formation of the pitting. The pattern of shallow pits is evidently due to a corrosive process of some kind. Since this corrosion affected the sediment surface before deposition of the overlying beds and was not followed by disintegration of the structure, it is again suggested that the surface was consolidated, most likely by freezing. If freezing occurred, the pitting might be most easily explained as due to superficial thawing of the frozen bed.

The sandstone bedding planes south of Brantevik show numerous instances of small synsedimentary faults with vertical movements of at the most some tens of millimeters. These microfaults formed in each instance before sedimentation of the succeeding bed. Their effects are only visible on bedding-planes. They do not continue as joints into the subjacent beds.

An instructive instance was found at the locality just referred to above. At the top of the section, a bedding-plane shows stepped normal faults with distances of 0.1–0.2 m between individual faults. The first impression of this structure is that of a set of ripples. However, the steep flank may be nearly vertical, the cross-section is angular, and the index wavelength/height varies in a manner that rules out any interpretation of the structure as ripples. The micro-faulted surface is overlain by a thin bed of fine gravel, the upper surface of which is smooth (Pl. 1, Fig. 7). The preservation of the exposed micro-faults during transport of fine gravel seems to require a fairly coherent surface. It is suggested that the micro-faults could most easily form if the faulted surface had a certain rigidity. Their preservation under a lamina of fine gravel can only be explained if the surface was firm. VORTISCH (manuscript) describes small, steep-sided stacks and micro-cliffs from the contact surface of the Hardeberga Sandstone with the Norretorp Formation. These structures were preserved in an environment in which lamination with a strong fabric of parting ("current") lineations were formed. For these and other structures requiring great coherence, VORTISCH suggests cementation by ice as a possible explanation.

Collapse structures

LINDSTRÖM (1967) believed that all funnel grabens of the Simrishamn area were formed by an essentially tectonic process. This is still held to be a plausible explanation of the large structures north of Simrishamn. The single instance found south of that town is different. It occurs in the northern part of the quarry at Simrislund (Fig. 1, C). It is a small structure, about 1.3 m deep and about 3 m wide. The subsidence has taken place at subcircular fault-like steps without complete disruption of the bedding (Pl. 2, Fig. 1).

The setting of this collapse structure is the upper part of the Hardeberga Sandstone. Thus, there is over 100 m of sandstone and muddy layers between it and the basement. It is therefore considered unlikely that this isolated structure could be due to movements in the basement. In the context of frost indications found in the Hardeberga Sandstone one may suggest as one possible explanation that the collapse formed over a buried ice block as this melted.

Ice blocks can only be buried in a littoral or terrestrial environment with a relatively high rate of sedimentation. There are indications that the Hardeberga Sandstone was formed in an intertidal zone. At times, sedimentation was probably rapid in some places.

Another explanation that would fit with sedimentation under cold conditions is that the structure formed as a small pingo. This possibility is worth consideration even in the case of the funnel grabens concentrated north of Simrishamn. Similar structures have been described as fossil pingos from the Lower Paleozoic of the Hoggar Massif of Africa (BEUF and others 1971). The African instances are of the same size as the larger funnel grabens north of Simrishamn.

The main argument against interpreting the funnel graben at Simrislund as a pingo structure appears to be its small size. For the structures north of Simrishamn, the interpretation as pingos cannot be so easily dismissed. However, it is unlikely for two reasons. Firstly, the funnel grabens are exposed in the Vik Sandstone as well as in the Hardeberga Sandstone. We do not know how much older than the Hardeberga Sandstone the Vik Sandstone might be. In any case it is deeper than any likely level of pingo formation in Hardeberga Sandstone time. Secondly, collapse movements appear to have continued at least as late as the Late Cambrian. This would appear to give any Lower Cambrian pingos more time than necessary for their melting. However, even so, readjustment processes might have continued in the Lower Cambrian sandstones a long time after the melting of pingos, and the question should perhaps be regarded as open.

Other sediment structures

The Hardeberga Sandstone was deposited in an intertidal environment. This conclusion is supported i.a. by observations on ripples, cross-bedding, parting lineations, shrinkage cracks, etc. The ripples observed at different localities are symmetrical waves with sinusoidal cross sections ("oscillation" ripples). Wave-lengths of all structures are over 0.4 m. Wave-ripples have been studied in outcrops of Hardeberga Sandstone within the Tobisborg Block, in the exposures south of Simrislund, and in the shore cliffs south of the harbour of Brantevik. Particularly extensive surfaces with wave-ripples surround the quarry of Tobisborg (Fig. 1, D). Other outcrops are 100 m southwest and south of this quarry, respectively.

Table 2: Wave-length, wave-height, and length/height (Ripple Index) for large wave-ripples in Hardeberga Sandstone, Tobisborg (Simrishamn). Lengths and heights are in centimeters.

Locality	Number of observations	Arithmetic mean	Maximum	Minimum
		Length		
Quarry	23	89	118	49
SW of quarry	15	63	70	57
		Height		
Quarry	21	8	11.5	4.5
SW of quarry	15	6	7.5	5
		L/H		
Quarry	21	11.1	16.4	7.5
SW of quarry	15	10.7	12.2	8.9

Table 2 shows wave-lengths, heights, and indices for ripples found in the uppermost beds of the Hardeberga Sandstone at Tobisborg. Fig. 2 shows the horizontal distribution and configuration of ripples occurring southwest of the quarry. The aspect of the ripples is shown by Pl. 2, Fig. 8. The locality has been known for several years for the good exposure and preservation and the unusual size of the ripples. These qualities suggest that it may become possible to give a narrow definition of the environment of sedimentation. At the present, formulas developed by TANNER (1967, 1971) may be of some help, if only in a very general and qualitative

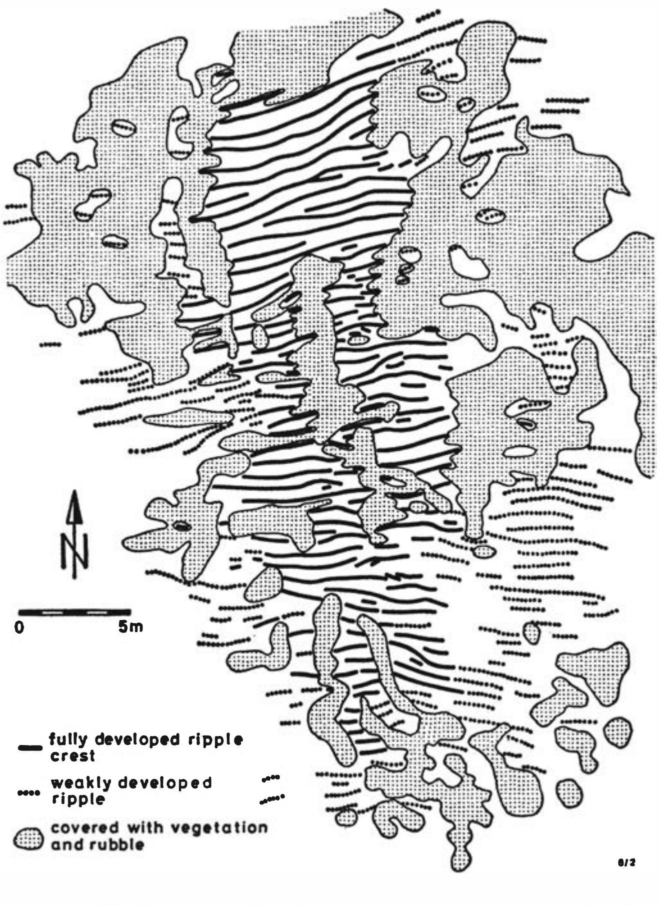

Fig. 2: Field of wave-ripples SW of the Tobisborg quarry. See also Pl. 2 Fig. 8.

way. The ripples being symmetrical, the Ripple Symmetry Index is very near unity. The Ripple Index is just above 10. The ripples are long, and tend to bifurcate. These are characteristics of wave-formed ripples. The wave-lengths of the ripples are so great that, combined with a grain-size of the order of 0.1–0.5 mm, the equations given by TANNER (1971) yield values that must be too great. However, if these values can be accepted as qualitative, the depth of water must have been of the order of a few meters, the wave height over 1 m. What is most important is that the fetch must have been of oceanic dimensions.

These observations are in some part confirmed by the analogy with similar ripples exposed at a tidal beach west of Roscoff at the south coast of the English Channel. Pl. 2, Fig. 7 is given from this beach for comparison. The genesis of these ripples and connected sedimentary structures is being studied by a team from the University of Marburg (LINDSTRÖM, TIETZE, ZANKL, and collaborators). This Bretonic beach is fully exposed to the waves of the Atlantic. The comparison also shows an important difference. The recent ripples studied by us, formed under water during high tide, are eroded in different ways when exposed. The Lower Cambrian ripples of Scania never show the typical signs of such erosion. Thus they probably formed below the intertidal zone.

Cross-laminations observed in the wave-ripples indicate a northerly direction of transport. This is particularly evident south of Simrislund and south of Brantevik. According to NEWTON (1969) wave ripples, though outwardly symmetrical, are polarized internally, owing to a net shoreward transport of sand. If the ripple structures are interpreted according to this observation, one has to assume that the Hardeberga Sandstone of the Simrishamn area was deposited with the shore to the north. The total ripple data thus indicate an extensive open sea to the south. This agrees with the observations on ice-push structures described above.

The Hardeberga Sandstone is divided into beds of commonly 30–100 cm beds thickness. Each bed as a rule is a cross-stratified coset. The cross-stratification is of the trough pi type interpreted by ALLEN (1963) as formed of curved, asymmetrical ripples. It can be observed with the greatest ease along the coastal sector Simrislund-Brantevik, south of Simrishamn. Perhaps significantly, most sets idicate flow in easterly and southeasterly directions.

According to observations at the high-energy, high-tidal-range coast at Roscoff (LINDSTRÖM, TIETZE & ZANKL, work cited above, in progress) ripple-generating flow on the foreshore may be due to the outgoing tide, or to a longshore flow system. Large ripples in the higher energy part near the inlet of a lagoon may be formed by either the outgoing or the rising tide. If the analogy with the Bretonic coast is valid, the cross-stratification found in the Hardeberga Sandstone would be either ebb or longshore structures, for it was definitely not formed within a lagoon. This agrees with the tidal model suggested by KLEIN (1971), who emphasizes the role of ebb runoff currents.

On the other hand, CLIFTON, HUNTER & PHILIPS (1971) show a more complex but perhaps equally relevant situation at a high-energy tidal beach in southern Oregon. Their beach model is characterized by hydrodynamic and sedimentologic regimes (referred to as facies) that migrate with the coming and going of the tide. Wave-induced currents in the outer nearshore zone may generate ripples facing landward. In the inner nearshore zone the wave-generate cross bedding many face seawards. The section is characterized by rapid alternation between planar and cross-stratified beds which thus may face in different directions.

It is probable that the vertical range and horizontal extent of the intertidal area influences the structures. Runoff structures are likely to be particularly important on extensive tidal flats with great differences between high and low tides. The investigated sediment sequence may have formed in such an environment. Since all other evidence points to an open sea in a southerly or southeasterly direction, the current bedding is unlikely to have formed in an outer nearshore environment with waves coming from the west or northwest. Current, or parting lineations (ALLEN 1968, STOKES 1968) were found within the Hardeberga Sandstone at the locality 1.2 km south of Simrislund and in the Norretorp Sandstone immediately overlying the Hardeberga Sandstone at several localities (LINDSTRÖM & STAUDE 1970, VORTISCH MS). There is a general consensus that parting lineations form parallel to upper regime flow (ALLEN 1966, 1968, PICARD & HULEN 1969, WILLIAMS 1971). It is a trivial observation born out also by current work at the Bretonic coast (LINDSTRÖM, TIETZE, ZANKL, and collaborators) that such flow may occur during ebb runoff. However, CLIFTON and others (1971) demonstrate that the water movement in the swash zone of a high-energy beach may show features of the upper flow regime, and that this may generate parting lineations. Whereas the structures observed in finely laminated Norretorp Sandstone are perhaps most likely to have been generated by ebb runoff (VORTISCH MS), the parting lineations of the Hardeberga Sandstone, as discussed below (p. 15) might have been formed in the swash zone.

Irregularly branching, small-scale shrinkage cracks have been observed in clayey partings and in clay pebbles in the Hardeberga Sandstone (particularly south of Brantevik) and in the underlying Brantevik Sandstone. Shrinkage cracks are mostly taken as evidence of desiccation. Though other explanations are conceivable, for instance boudinage and load-adjustment, the conventional interpretation seems to be the most likely one. In the present case it would speak for an intertidal environment.

Trace fossils are mostly rare in the Hardeberga Sandstone. They are absent in the uppermost part. However, a smaller than usual form of the burrow *Diplocraterion* may occur on isolated patches at levels below the ice-push structures, and the serially arranged tubes of *Syringomorpa*, mostly resedimented, are, though far from abundant, the characteristic fossil of the lower and main part of the formation. The enigmatic trail *Scolicia* has been found in at least two localities.

HADDING (1929) found some surfaces of the Hardeberga Sandstone south of Brantevik to be pitted in a manner recalling raindrop marks. This structure was also referred to by REGNÉLL (1960). The pits are irregular, a few millimeters wide and deep, and entirely cover the surfaces on which they occur. Characteristically, they occur on the upper parts of cross-bedding laminae and die out toward the lower parts. Since the pitting may occur on several laminae of a cross-bedding set, it must have been initiated under water and/or sediment. Thus, it cannot represent raindrop marks. Its occurrence in the upper parts of cross-beds suggests that it might have formed as marks of gas bubbles. According to HOYT & HENRY (1964), bubbles may develop in sand in the upper part of the tidal zone. They form in dry sand when this is covered with water. The bubbles, according to the authors cited, may either be disruptive or concentrated along laminae. They may grow to a size of one-half inch. They are described as densely crowded and as resembling raindrop marks.

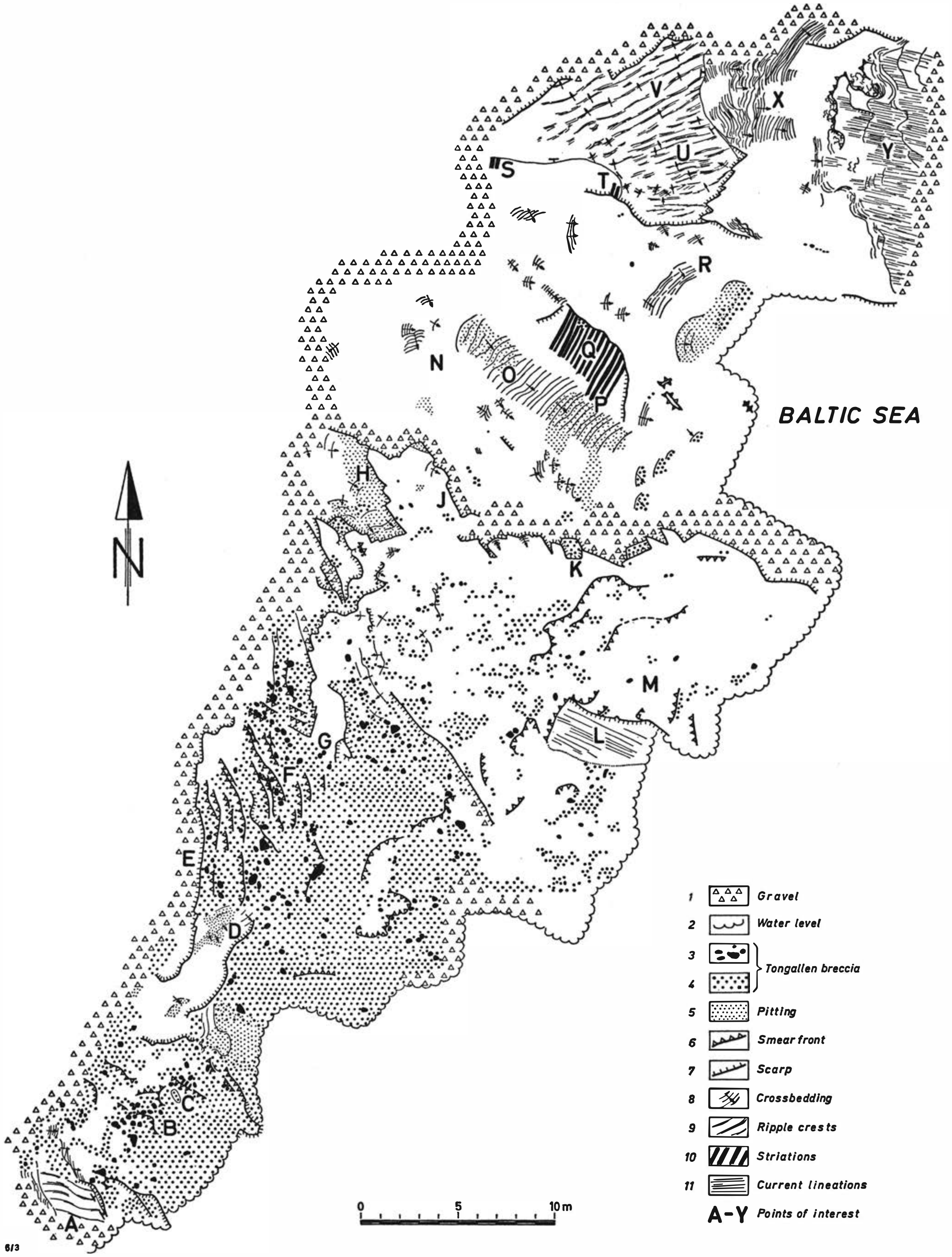

Fig. 3: Outcrop 1.2 km S of Simrislund (Fig. 1, B). The extent of recent beach gravel (1) and water level (2) may change somewhat. The larger slabs within the clay pebble (Tongallen) breccia (3) are distinguished individually. The pitting (4) is of the type that has been referred to as raindrop marks and might represent marks of trapped gas bubbles. The "smear fronts" (6) are small thrust-like structures; the triangles point towards the thrust unit. The small scarps (7) cut the bedding; the hatches point towards the underlying bed.

The main outcrop between Simrislund and Brantevik

Because of the unique importance of the grooves found in the middle of the outcrop (Fig. 1, B), a detailed description and discussion of relevant features has to be given here. This should clarify the structural and probable causal relations. The outcrop is bounded to the east by the sea and to the west, north, and south by beach gravel. It can be divided into six parts that represent different phases of sedimentation. At the northern end of the outcrop the oldest part is a *wave-rippled suface* (Fig. 3, U–V). The ripples have wave-lengths of 40–80 cm. Cross laminations facing towards the north-northwest are exposed by slight erosion of the ripple crests (see the foregoing discussion of large wave-ripples).

To the south this surface is overlain by a quartzite bed of varying thickness, amounting locally to a few tens of centimeters. This quartzite is the *ice-pushed unit* (N–T of Fig. 3). It is a homogeneous, mostly massive white quartzite with a relatively smooth upper surface. Its contact S–T with the wave-rippled surface shows signs of northward thrusting without grain-fracturing. At S and T there are north-striking striae. Pi-type cross-bedding occurs at different points (e.g. N and R). It generally progrades eastwards and southeastwards. At O there is a train of cross-beds with a low dip suggesting a channel. The cross-beds are pitted. The pitting may be transitonal to surfaces covered by what looks like small clay-pebbles. According to the discussion given on p. 13 the pitting may have formed as gas bubbles within the sediment.

The striations described in a previous section appear at Q. To the north they are covered by a higher part of the unit. To the south, at R, they were found to be older than the train of crossbeds O. This relation proves the important circumstance that striae were formed at or near the sediment surface before the sedimentation of the Hardeberga Sandstone came to its stop.

Above the ice-pushed unit there follows a roughly 1 m thick *quartzite bed with scattered clay pebbles* (G–M). This bed is weakly cross-laminated, with current directions generally toward the southeast (particularly evident at the pitted surface, H). The upper surface is generally smooth, with some patches relatively rich in flat, more or less rounded clay-pebbles. Within the bed, for instance at K, there is a parting that is very rich in clay pebbles. This parting, however, is not extensive enough to be present 8 m farther west, at J.

A seaward-dipping surface (L) with parting lineations striking at about S 67° E is interpreted as the remainder of a southeast-facing swash zone. Clifton and others (1971) have discussed similar structures from a recent beach of high energy.

To the south of the quartzite with scattered clay pebbles there is an extensive, somewhat *irregular surface rich in clay pebbles* (B–F) some of which are very large. In the eastern part of the outcrop the upper surface of the bed G–M passes into the surface with abundant clay pebbles. The same condition is plainly visible just to the west of G. To the east of G, however, the quartzite bed G–M rests with obvious sedimentary contact on the clay pebble layer B–F which then, probably, continues northwards under the uppermost layer of G–M, to reappear at K. It is absent in the layer G–M at J. Evidently the upper, western parts of G–M were sedimented after deposition of the clay pebble layer B–F.

Most clay pebbles are small and rounded. However, angular pebbles are common, and many reach sizes over 20 cm. The largest clay flake measures about 80 cm along its longest axis. The larger clay flakes were often laid down over smaller ones. Thus, they are not in situ. The whole arrangement of the pebbles within the layer is somewhat chaotic. However, they were spread out as a thin layer. Thus, the layer cannot be interpreted as a flow breccia. The larger, more or less angular flakes could probably only have been transported in a frozen condition, perhaps attached to ice blocks. It is noteworthy that they do not show shrinkage fractures. Such fractures would almost certainly have occurred in the larger flakes had they been formed by the normal breaking up by waves or currents of a dry clay layer. A wet bed of clay might perhaps disintegrate into coherent flakes of this size if it were frozen but not otherwise. It is assumed therefore that the clay clasts were strewn in a frozen condition, presumably over a gently sloping beach.

The surfaces B–F and G–M are slightly deformed by low, thrust-like structures that die out laterally. In the western part of the outcrop they are small. They are easily distinguishable only where they deform clay flakes (Pl. 1, Fig. 6). Most of the smallest thrust-like structures, for instance those at E–F, face in an easterly direction. In the eastern part of the outcrop the thrust-like lobes are somewhat larger and tend to face toward the northwest. One might think of at least two explanations for these structures. Those facing toward the east might be due to solifluction down the slope of a beach. The northwest-facing structures might then be due to gentle ice-push in a landward direction, applied directly to the sediment surface. Another, perhaps more plausible explanation is that all the thrust-like structures were formed by ice-push that was effective at slightly different times and in different directions. This agrees with the beach topography suggested by the distribution of clay pebbles. According to this hypothesis the sediment surface was practically horizontal and equally exposed to ice-push from several directions when the structures were formed.

At one point (C) a small thrust-like structure facing north occurs in combination with grooves of the same kind as those at Q, only much weaker and not equally perceptible at all angles of illumination. Here ice-push from the south is the favoured explanation.

Cross-bedding is poorly developed in the area B–F. Where it can be observed, the foresets face eastward and southeastward. At the southern limit of the B–F surface cross-bed sets belonging to B–F have an erosive contact against the southernmost exposed unit of the outcrop, A.

A is a surface with wave ripples of the same kind as those at U–V. The ripples strike in east-westerly directions. They have wave-lengths of about 50 cm. The age-relations of beds and structures within the outcrop make it seem likely that the ripples of A were formed during the same narrow time interval as those at U–V.

It remains to deal with the unit X–Y at the northeastern end of the outcrop. This, essentially, is a cross-bed set with an estimated thickness of over 1 m and east-facing foresets. There is a sharp erosive contact against the surface U–V. Since the unit X–Y is also clearly younger than the unit N–T, it is one of the youngest structures of the outcrop. The easternmost foresets are planar and dip eastwards about 10° steeper than the major bedding-planes of the outcrop. The laminae, about 3–10 mm thick, consist of medium grained quartz sand and mainly finer grained zircon (LINDSTRÖM & VORTISCH, work in progress). The zircon occurs as basal concentrates, in some cases however as dominant mineral, in the laminae. Parting lineations on all laminae strike at about S 75° E (Pl. 1, Fig. 3).

As indicated above (p. 15) it is regarded as probable that the parting lineations formed in the swash zone of a high-energy beach. The alternative, that they formed by ebb runoff on the bed of a tidal creek, is ruled out by the circumstance that they developed on laminae with an appreciable dip. CLIFTON, HUNTER & PHILLIPS (1971) described similar laminae with current lineations from the swash zone of an Oregon beach. They also reported on instances in which the laminae had heavy minerals concentrated in their lower parts.

The top of the cross-bed set at X–Y is discordantly cut by patches of sandstone with strongly contorted bedding. In places the foreset laminae are deformed at their upper edges. Above the X–Y cross-bed set, separated from this by a narrow band of recent beach gravel, there follow a few thick, massive beds of light grey to white quartzite. These form the top of the Hardeberga Sandstone at this locality.

The interpretations given above can be summarized as follows. All sediments of the outcrop were laid down in the nearshore and intertidal zones. The oldest structures are wave ripples (A and U–V) formed in not too shallow water by waves coming from the south and southeast. These were covered or partly eroded during the sedimentation of a sheet of cross-bedded sand. This sand was pushed by heavy ice from south-southwest (grooves, particularly at Q). For this to happen the sediment surface may have had to be laid dry, perhaps by ebb. At later stages seaward-dipping cross-beds were formed either by ebb currents or by wave activity on the landward side of the surf zone (compare CLIFTON and others, 1971).

If the pitting of cross-beds is correctly interpreted as marks left by gas bubbles, the sediment must have remained in the intertidal zone. At one instance, the surface was strewn with clay flakes that were probably frozen, eventually also attached to ice. Occasionally, gentle ice-push took place from west, south, and southeast. In the later phases of the recorded sedimentation the sediment was washed by waves coming from the east-southeast. At least during low tide it was exposed in the swash zone. This phase generated parting lineations and concentrates of zircon.

Paleogeographic implications

The described structures indicate that the Hardeberga Sandstone of southeastern Scania was laid down as part of a sandy shore that must have extended round the Baltic Shield in the Lower Cambrian. To the south and southeast, in terms of present geography, there was an extensive open sea. Tides and wave exposure were strong. The climate was cold enough for sea ice to form. How cold it was cannot be put into precise terms. According to EKMAN (1953, p. 184) sessile animals are either very rare or entirely lacking in the intertidal zone of high-arctic beaches. They are less rare in the low-arctic intertidal zones. As mentioned (p. 13) *Diplocraterion* and *Syringomorpha*, both obviously traces of sessile benthonic animals, if by no means common, are still present in the Hardeberga Sandstone. This speaks either against a high-arctic environment or against an assignment to the intertidal zone of the beds in which the trace fossils occur. A third possibility is that the trace fossils are evidence of an environment below the tidal range, and that the climate was perhaps not high-arctic. In view of the high wave energy suggested by numerous structures, it is unlikely that burrows could at all have existed and been preserved within the intertidal zone. The burrows do not occur on surfaces of undoubtedly intertidal origin, nor are they demonstrably coeval, in a precise and narrow sense, with ice-push structures. This leaves several uncertain factors, including the possibility that the cold conditions were restricted to the very latest phase of sedimentation of the Hardeberga Sandstone (and the early sedimentation of the Norretorp Sandstone – VORTISCH, manuscript).

Overall comparison with Recent arctic beaches is rendered difficult by features that are unique to the Hardeberga Sandstone. One such feature is the availability of enormous quantities of quartz sand in all directions from the area of sedimentation, another may be the high degree of exposure and perhaps the great tidal range. Beaches in cold or arctic environments that have been well studied are either muddy expanses (DIONNE 1968, 1971), or they are exposed to the relatively low energies of the Barents Sea (GREENE 1970, HUME & SCHALK 1964, REX 1964, MOORE 1960). The last-mentioned author is very sceptic about the possibility of finding cold-climate indicators in beach sediments. The chances for the preservation of such structures, particularly at a high-energy tidal beach, are indeed very slight, and one should not be surprised if the inventory of possible glacial structures is not complete. The circumstance that such structures are at all preserved suggests that much more of the kind may originally have been formed and subsequently erased.

If the Hardeberga Sandstone was formed in a cold climate, this has important paleogeographic consequences. As remarked in the chapter on geologic background, the age of the Hardeberga Sandstone within the framework of the Lower Cambrian is less than certain. It is not younger than the *Holmia torelli* zone, but it might be as young as this zone. This makes it a possible equivalent of a wide choice of clastic series in Estonia, farther east on the same margin of the Baltic Shield as the outcrop area of the Hardeberga Sandstone. The Estonian succession, as described by ÕPIK (1956), contains two members that are interesting in the present context. The Lontova Formation, 35–60 m thick, is a mainly argillaceous unit with an unstable clay mineralogy. The overlying Lükati Beds, 8–9 m thick, consist of sandstone with i.a. mud cracks, evidence of slumping, and deep sediment filled fissures. It is followed by a major diastem with large ripple marks. Unfortunately for any comparison with the structures found in the Hardeberga Sandstone, those occurring in the Lükati Beds have apparently not been described and discussed in greater detail, and the stratigraphic correlation is somewhat awkward, the Lontova and Lükati sequences being regarded as very high in the zone of *Holmia torelli*.

Tillites are well known from the so-called Eocambrian of the western margin of the Baltic Shield, i.e., in the foreland and lower nappe zone of the Norwegian and Swedish Caledonides. The Eocambrian glaciation was probably not much older than the oldest sediments assigned to the Cambrian. At Torneträsk in the northern Caledonides a continuous sequence of sandstones and shales contains trace fossils at most levels and Lower Cambrian body fossils in the upper part. The whole succession has been regarded as Lower Cambrian. A breccia occurring in the lower part was regarded as having a glacial origin by KULLING (1965). KULLING, therefore, regarded it as Eocambrian and thus let the boundary between the Eocambrian and Cambrian fall within the succession.

The discoveries in Scania indicate that the cold climate characterizing the later part of the Eocambrian continued into the Early Cambrian.

In northern Europe outside of the Baltic Shield and its immediate surroundings, Lower Cambrian occurs in the Holy Cross Mountains of Poland and farther west in Lusatia, in the foreland of the Sudeten mountains. Both these occurrences are isolated from the Baltic Shiled by thick successions of younger deposits, the older parts of which were deformed by Paleozoic orogenic movements. The Holy Cross Lower

Cambrian is very thick and exclusively clastic (SAMSONOWICZ 1956). Available data speak neither against nor in favour of their having been formed in a cold climate. With the Lusatian Lower Cambrian things are otherwise.

According to SDZUY (1960) dolomitic limestone, at least 100 m thick, is there followed by *Eodiscus* Shale and *Protolenus* Shale, both of Lower Cambrian *Holmia* age. The calcareous unit formed the northermost known part of an extensive Lower Cambrian carbonate shelf that reached through western Europe southward to the western Mediterranean.

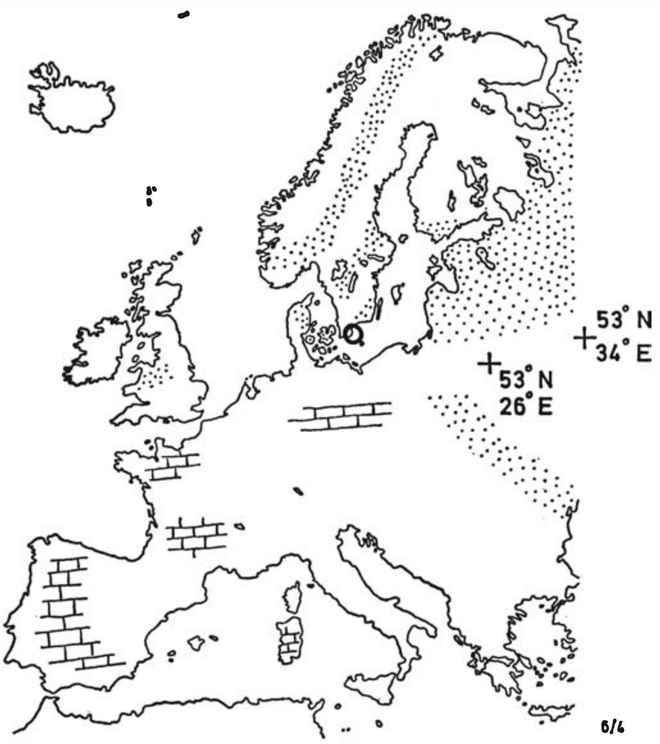

Fig. 4: Situation of investigated area (circlet), extent of Lower Cambrian carbonate shelf (brick signature), extent of Lower Cambrian clastic facies (stippled), and paleomagnetic poles (crosses), neglecting the orogenic distortion of the European-Mediterranean area.

Arguing from the correlation of the Hardeberga and Norretorp Formations with the middle of the three *Holmia* zones, the Zone of *H. torelli*, we may define the following alternatives:

1. The Hardeberga and Norretorp Formations are roughly coeval with the carbonate complex. The geographic distances were the same in the Lower Cambrian as at present. This alternative means that dolomitic limestone could form in a relatively cold climate, a most unlikely supposition even when applied to a period as distant and difficult to visualize as the Cambrian.

2. The formations are coeval as assumed under alternative 1, but the distance between the carbonate shelf and the Baltic Shield was much greater than the present distance between Lusatia and Scania. This is possible since the younger sediments of the North European Lowland might hide a branch of the Caledonian orogen (VON GAERTNER 1960). The amount of crustal shortening that can take place in an orogen is unknown but might theoretically be great. A wider separation in the Early Paleozoic would help to explain the faunal differences between Central and southern Europe, including Lusatia, and the Baltic Shield (SDZUY 1962).

3. The formations are not coeval, and the geographic frame might not have become greatly distorted. The age difference would probably have to be considerable for the climate to change between cold and the warm conditions necessary for dolomite formation. If it is assumed that the carbonate was laid down in the *Holmia* interval, this time interval must have been very long.

Alternatives 2 and 3 have to be regarded as equally possible. The sediment structures of the Hardeberga Sandstone of the Simrishamn area were formed under winds and waves coming from mainly southerly directions. The waves can be shown to have been considerable (p. 15). This speaks for an open coast. The amount of sediment and time available for the shaping of the coast was almost certainly great enough for the coastline to become adapted to the dominant wind regime. The wave and wind generated structures can thus be assumed to give approximately accurate indications about dominant winds. In cold areas the wind regime is determined by the situation relative to the polar front. However, judging from present atmospheric circulation and notwithstanding regional complications, a westerly wind regime is the most likely one in any circumpolar maritime area. If the surprisingly constant direction of push found at different localities approximates the wind direction, the wave-induced structures being more dependent on the orientation of the shore, the Early Cambrian winds of the Baltic area would have come from the southwestern to southern sector according to the geographic coordinates of the present. If the winds came from the west this would place the pole – the South Pole in this case – somewhere to the east of Sweden.

It is interesting in this connection to note that MCELHINNY (1969) lists a Cambrian South Pole (for Morocco) at 53° N 34° E, and that BUCUR (1971) found a Cambro-Ordovician South Pole (for Hassi-Messaoud) at 53° N 26° E. Assuming a moderate orogenic distortion of the European and Mediterranean areas of the order of 500 km or less, this would place a Cambrian South Pole within the area of White Russia or Ukraine. This agrees surprisingly well with the results of the preceding discussion. The question remains, whether this agreement is more than fortuitous. Greater orogenic distortion might place the pole in the Tethys province in southern Europe.

Summary

The Lower Cambrian Hardeberga Sandstone of the Simrishamn area is a white, medium to thin grained quartzite. It shows pi-type cross-bedding and is characterized by its relative scarcity of trace fossils.

In several places there are wave-type ripples with wavelengths of 40–118 cm and Ripple Indices about 10. Northward dips of observed cross-bedding indicate that the ripples were generated by waves coming from southerly and southeasterly directions. They were probably formed in the shallow subtidal zone, by large waves with a long (oceanic) fetch. Other structures indicate sedimentation within the tidal zone. Such structures are planar laminae with parting lineations and heavy mineral concentrates, indicating swash zone, and pitting interpreted as due to gas bubbles, indicating alternation of drying and submergence.

At three localities there are striations that may be combined with small-scale thrust structures. In analogy with structures found on recent arctic beaches they are believed to be due to

shoreward push of sea-ice. The direction was constantly from about S 20° W.

In the light of this structure, for which no alternative interpretations appear to be possible, the following structures are also regarded as evidence of cold conditions. A small collapse structure in a quarry south of Simrislund is likely to have formed over a buried ice block. Different sediment surfaces south of Brantevik show features that indicate that they had developed resistance to erosion before the deposition of overlying coarse deposits. The implied cementation of these surfaces is likely to have been due to freezing. Occasional thawing gave rise to a characteristic corrosion pattern. Oversize and angular clay pebbles are believed to have been transported and deposited in a frozen condition.

It is suggested that the Hardeberga Sandstone was deposited within the west-wind belt surrounding a paleomagnetically indicated South Pole that was situated in eastern Europe. The wave regime indicates a southwest-northeast local strike of the coast. This might have corresponded to northwest-southeast in terms of Lower Cambrian paleogeography. The cold-age Hardeberga Sandstone was probably not formed contemporaneously with the Lower Cambrian carbonate shelf of central and southwestern Europe. If it was, considerable deformation must have taken place in Paleozoic time within the area of the wider North Sea Basin.

Acknowledgements

This work has profited greatly from discussions with my friends and fellow geologists Jan BERGSTRÖM, Lund, Harald SVENSSON, Lund, and W. VORTISCH, Marburg, who have offered views on the structures in the Simrishamn area, and K.-W. TIETZE and H. ZANKL, both Marburg, with whom projects are being conducted at Roscoff.

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NOTE. – In this context it must be pointed out that erroneous formation names are given in two places in the paper LINDSTRÖM & STAUDE 1971 (see above list of References). The reason for the errors was less than careful proof-reading by the senior author, who was under stress. The errors should be corrected as follows:

p. 5, line 17, left, replace Tobisborg by Hardeberga,
p. 6, explanation pl. 1, fig. 3, replace Brantevik-Sandstein by Hardeberga-Sandstein,
fig. 4, replace Tobisborg-Sandstein by Brantevik-Sandstein,
fig. 5, replace Simrislund-Sandstein by Norretorp-Sandstein.

Plate 1

Fig. 1: Ice-push lineations in Hardeberga Sandstone at Q (text-fig. 3), outcrop 1.2 km S of Simrislund. Looking N. Hammer left of middle for scale.

Fig. 2: Background: Same lineations as in Fig. 1. Foreground: channelfill of pitted foresets, younger than the ice-push lineations.

Fig. 3: Parting (current) lineations at Y (text-fig. 3), same outcrop as in Fig. 1. Looking N.

Fig. 4: Ice-push lineation in Hardeberga Sandstone S of dolerite dyke at Simrislund, looking SE. Photo Vortisch.

Fig. 5: Irregular surface strewn with clay pebbles at C (text-fig 3), same outcrop as in Fig. 1, looking E. Clay-flakes of various sizes appear as molds.

Fig. 6: Same surface as in Fig. 5, looking E at B (text-fig. 3). Angular and partly deformed clay flakes as molds; small-scale thrust-like structure facing N.

Fig. 7: Small stepped faults on sandstone at Brantevik (text-fig. 1, A). Note non-faulted superposed layer of gravel conglomerate lower left. Looking SE.

Fig. 8: Small graben-like structure on sandstone surface at Brantevik, filled by nonfaulted base of next younger bed. Following bedding-plane smooth (see upper right corner).

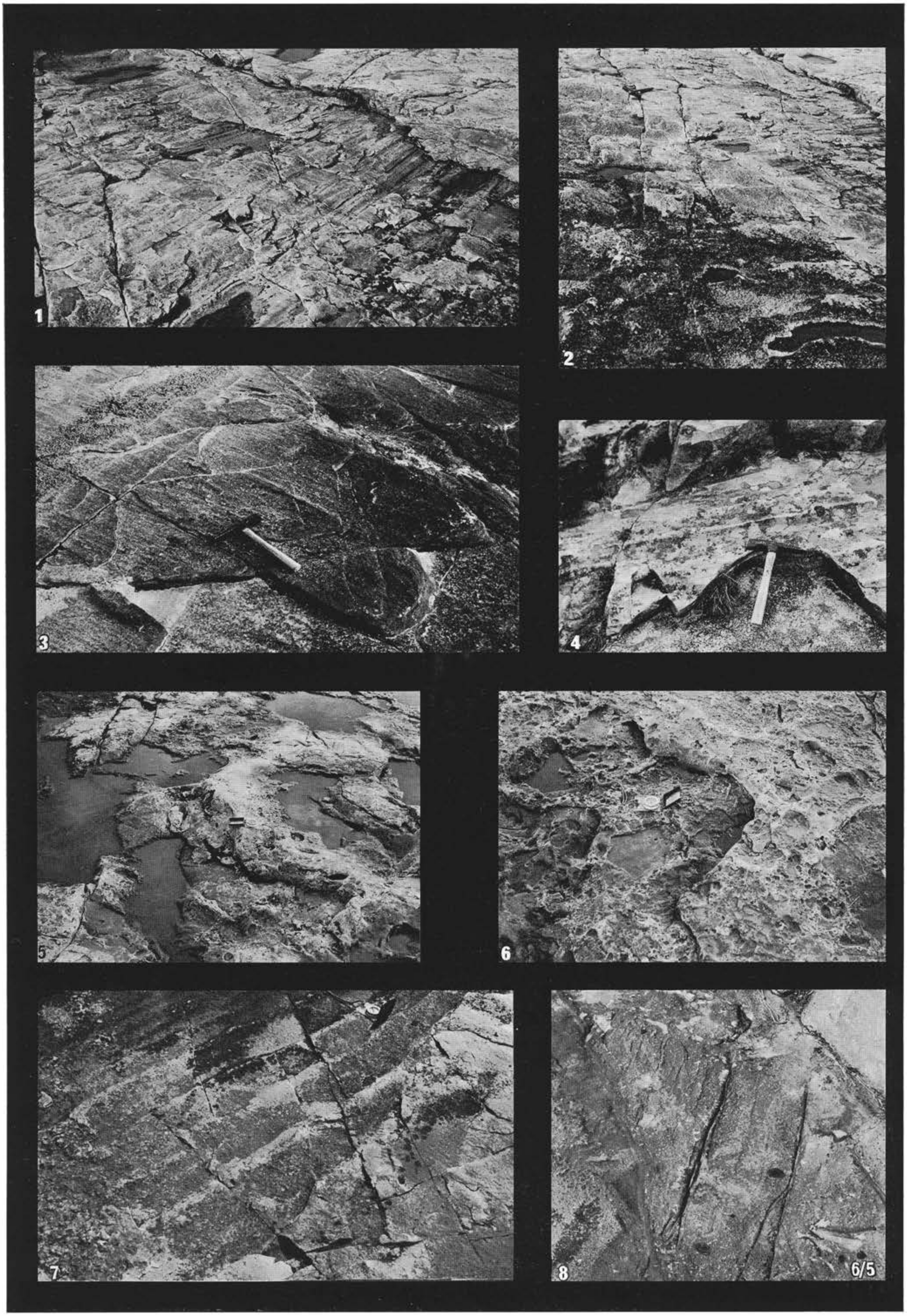
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Plate 2

Fig. 1: Small collapse structure in northern part of Jurgård quarry at Simrislund (text-fig. 1, C). The man leans his hand on the same bed as he stands on. The structure was originally filled with rock belonging to the next younger sandstone bed. This was removed by Mr. Jurgård.

Fig. 2: Original aspect of the same structure, from the east side, before the layers filling the central parts were removed.

Fig. 3: Cross-bedded Hardeberga Sandstone S of Brantevik (text-fig. 1, A). Looking S.

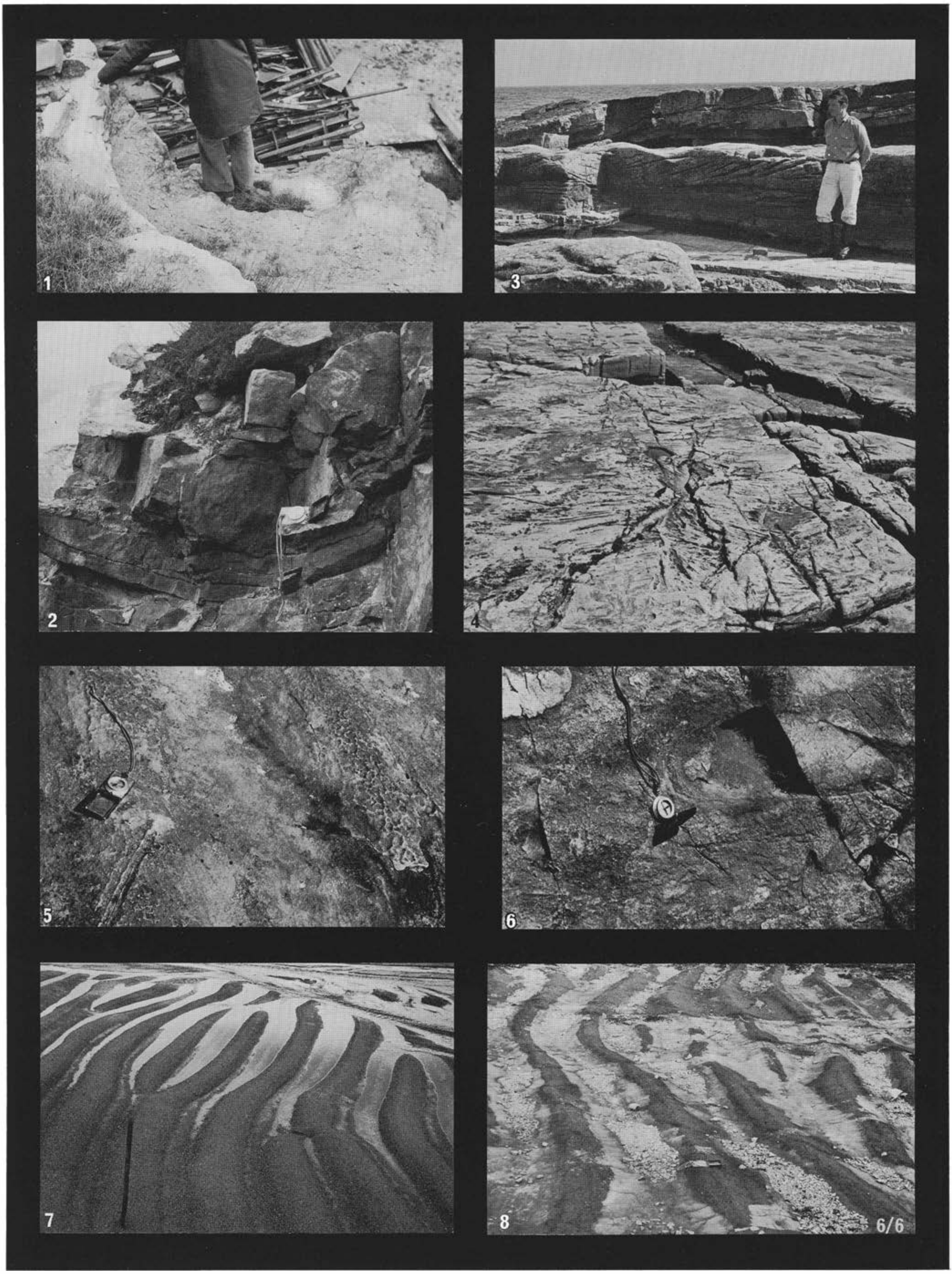
Fig. 4: Cross-bedded Hardeberga Sandstone S of Brantevik, looking E. The compass near the middle indicates the scale.

Fig. 5: Wave-ripples with corroded crests. Hardeberga Sandstone S of Brantevik (text-fig. 1, A).

Fig. 6: Oblong pit in Hardeberga Sandstone, filled with coarse sandstone to fine gravel. End of another pit at upper left corner. The sandstone surface surrounding the pits is rough from corrosion of same type as in fig. 5. Just S of structures shown in fig. 5.

Fig. 7: Large wave-ripples exposed by low tide, Anse de Kernic, Bretagne. Runoff is going on; the sea is towards the right.

Fig. 8: Large wave-ripples exposed by quarrying, Hardeberga Sandstone Sw of Tobisborg quarry. Northern part of text-fig. 2, looking E. Ripple crests covered by lichens.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