Meddelelser om Grønland

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The Vendian succession of the central East Greenland fjord region is among the best preserved and most extensively exposed in the world and is represented approximately by the Tillite Group, comprising five formations, which from bottom to top are: the Ulvesø Formation (formerly Lower Tillite, dominantly diamictite), the Arena Formation (formerly Inter-Tillite beds, dominantly sandstone and shale), the Storeelv Formation (formerly Upper Tillite, dominantly diamictite, sandstone and conglomerate), the Canyon Formation (dominantly shale and dolostone) and the Spiral Creek Formation (dominantly sandstone, shale and dolostone). The group is underlain by Bed group 20 (limestone) and Bed group 19 (dominantly carbonate, shale and breccia) in different places and in the peripheral areas by older Bed groups of the Eleonore Bay Group. Above, the transgressive Cambrian sandstones of the Kløftelv Formation cap the Vendian sequence, though the exact level of the Precambrian-Cambrian boundary may be slightly lower.

This paper reviews previous work on the succession and presents numerous new stratigraphic sections and an assessment of the sedimentary structures. The stratigraphic and palaeoenvironmental significance of the succession can therefore be assessed.

Both main diamictite horizons contain other facies, which together with sedimentary structural and fabric data indicate that the following sediments have been produced: lodgement tillites, waterlain tillites, proximal and distal glaciomarine sediments (with ice-rafted dropstones), glaciolacustrine sediments, fluvioglacial deposits, subaqueous and sub-aerial mass-flows and periglacial phenomena. The other sediments of the Tillite Group were deposited in a dominantly shallow marine or lacustrine environment. Deeper water turbidites are recorded in part of the Arena Formation, whilst the upper part of the group indicates periodic emergence. Stromatolites, desiccation cracks and halite pseudomorphs are particularly distinctive in this part of the succession. A hiatus preceded deposition of the Kløftelv Formation, a transgressive unit of tidally-influenced sandstones.

Stratigraphic thicknesses vary considerably, and whereas individual formations can be recognised throughout most of the fjord region, intraformational horizons cannot normally be traced for more than several kilometres. The nature of the bottom contact of the Tillite Group remains enigmatic, and transitional sedimentary, unconformable and thrust contacts are all present. It is possible that Bed Group 20 may be the lateral equivalent of the Ulvesø Formation, or of Bed Group 19.

Although local palaeogeography was complex during deposition of the diamictites, these rocks indicate that a low-level ice sheet prevailed at the time. Together with Svalbard and western Scotland they represent the periphery of an ice-sheet which stretched across much of northern Europe to the Urals. However, much of Vendian time was not characterised by glacial conditions, and warm climates prevailed when the upper part of the Tillite Group was deposited.

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Vendian successions throughout the world are often characterised by abundant evidence of glacial conditions (Hambrey & Harland 1981), but only a few systematic studies have been made to assess the nature, extent and duration of glacial events for this period of some 80 Ma that is prior to the faunistic flourish at the start of the Cambrian Period. The North Atlantic-Arctic region, however, has an exceptionally well-preserved Vendian sedimentary record, notably in Scotland (Spencer 1971), northern Norway (Edwards 1984) and Svalbard (Fairchild & Hambrey 1984). In addition, the Caledonides of East Greenland offered the prospect, through having excellent exposure and a lack of deformation, of providing substantial new evidence for the nature of Vendian environments and climates, as well as providing a significant link with other North Atlantic-Arctic areas in determining pre-Caledonian configurations of the land masses, and the role of subsequent tectonism.

Previous work in East Greenland had provided limited evidence of such aspects, but there were conflicting accounts of the nature of glaciation, or even whether it

Table 1. Summary of the Late Proterozoic sedimentary succession of the central East Greenland Caledonides. Thicknesses of individual formations are extremely variable (data from Henriksen & Higgins 1976, Higgins 1981).

Age	Group	"Formation"	Bed Group	Lithology	Representative thicknesses (m)
Cambrian		Kløftelv		Quartzite and sandstone	70–75
Vendian	Kap Oswald	Spiral Creek		Limestone breccia, sandstone, mudstone	25–55
		Canyon		Dolostone, mudstone, marly shale, limestone	250–300
		Storeelv		Diamictite, sandstone, conglomerate	up to 200
		Arena		Sandstone, shale	150
		Ulvesø		Diamictite, sandstone, conglomerate, shale	up to 100
Late Riphean	Upper Eleonore Bay	Limestone Dolomite Series	20	Dark grey limestone	0–80
			19	Thinly bedded dolostone, limestone, silty shale	160–210
			18	Grey, black bituminous, partly oolitic limestone, stromatolitic dolostone	*c.* 400
			17	Dolostone, breccia	60–70
			16	Dark grey-black limestone, bituminous and oolitic	80–200
			15	Greyish limestone with breccia, dolomite	50–80
			14	Dark limestone, breccia	140–300
		Multicoloured "series"	13	Red/green sandstone, arenaceous shale, marl, limestone, dolostone	220–300
			12	Light grey algal dolostone	125–200
			11	Dark grey to black bituminous limestone	100–150
			10	Multicoloured marl, shale, limestone, dolostone, breccia	100–150
			9	Grey limestone	110–150
			8	Arenaceous dolostone	*c.* 50
			7	Red shaly, flaggy laminated mudstone	*c.* 200
		Quartzite "series"	6	Leucocratic quartzitic sandstone	40–140
			3,4,5	Semipelitic, pelitic and psammitic rocks	900–1100
			1,2	Pure quartzite, thin shale bands	1000–1100
	Lower Eleonore Bay	Upper Argillaceous-Arenaceous "series"		Quartzite, slate, shale	1200–1400
		Calc-Argillaceous "series"		Siliceous limestone, shale, thinly bedded quartzite	150
		Lower Arenaceous-Argillaceous "series"		Pure quartzite, fine-grained greywacke	8000
Metamorphic crystalline complex					

had existed at all. The purpose of this paper, therefore, is to present detailed stratigraphic and sedimentological data to establish the nature of Vendian environments and climates of East Greenland. We show that glacial conditions were represented by a wide range of facies, from terrestrial to marine, and occurred during two distinct periods. Non-glacial, possibly warm, climates with marine to shallow-marine sedimentation, however, prevailed for the greater part of Vendian time. We do not begin by assuming a glacial origin for the alleged tillites, but after presenting the data conclude that the evidence for glaciation is unequivocal.

The sedimentary succession in the central East Greenland Caledonides (71°30′–74°N) is characterised by a wide range of multi-coloured carbonate and clastic strata (Table 1). Amongst the most striking of the clastic rocks are diamictites that have variously been interpreted as glaciomarine, terrestrial glacial and mass-flow deposits. These probable glacigenic rocks were first discovered at Kap Weber (Poulsen 1930) and on Ella Ø

(Kulling 1929), and many workers since have described similar rocks in other parts of the region, principally during the regional surveys led by Lauge Koch in the 1950's. The diamictites occur in the so-called Tillite Group (Haller 1971, Henriksen & Higgins 1976) which generally varies from 500 to 800 m in thickness, but in places reaches 1300 m (Higgins 1981). The Tillite Group overlies the many kilometres thick Eleonore Bay Group and is overlain by some 3 km of Cambro-Ordovician strata. The Tillite Group is best known on Ella Ø, where the Ulvesø Formation (formerly Lower Tillite, *c.* 100 m thick), the Arena Formation (formerly Inter-Tillite beds, *c.* 270 m), and the Storeelv Formation (formerly Upper Tillite, *c.* 200 m) are overlain by the Canyon and Spiral Creek formations (*c.* 330 m thick) (Fig. 1). Whereas the two younger formations are relatively uniform in thickness, the other three are extremely variable in thickness.

The rocks were subjected to north–south trending folding and westward-directed thrusting during the Caledonian orogeny. Locally stratal thicknesses have been significantly modified by thrusting, especially in the upper part of the Eleonore Bay Group. However, metamorphism either did not occur or was only slight. Penetrative deformation is generally weak, and only locally has the original sedimentary fabric been totally overprinted.

The Tillite Group was deposited essentially during the Vendian Period (*sensu* Harland et al. 1981, Vidal 1979), and it is the association of alleged glacigenic and other clastic sediments with carbonates that makes the group particularly interesting. The distinctive assemblage of rocks is matched with an almost identical succession in northeastern Svalbard, and with similar successions in other parts of the North Atlantic – Arctic region. In this paper we give an account of the stratigraphy of the group and its adjacent formations and present sedimentological data in order to assess the mode of deposition and especially to determine whether the diamictites formed by mass-flow, glaciomarine or terrestrial glacial processes, or by a combination of these.

The field work for this paper was undertaken in 1968 (by A.M.S.) and 1984 (M.J.H.). In the first season, accompanying the Cambridge University Devonian expedition led by Dr P. F. Friend, fifty days were spent measuring stratal columns at ten localities. In the 1984 season a Cambridge expedition was joined by A. C. M. Moncrieff (sedimentology), Dr. G. Bylund (palaeomagnetism) and Dr. G. Vidal (micro-palaeontology). Four of the earlier localities were revisited, including Ella Ø, and three other sites were also visited. Further areas were investigated in 1985, but are largely outside the scope of this paper.

The 1984–85 project was prompted by a broadening out of work in Svalbard, with a view to assessing the validity of the various hypotheses concerning the Late Proterozoic – Early Phanerozoic evolution of the North Atlantic region, and in particular the timing of the opening of Iapetus Ocean. It was also prompted by an increasing impetus to improve international correlation of Proterozoic rocks through IGCP Project 179, "Stratigraphic methods as applied to the Protorozoic record".

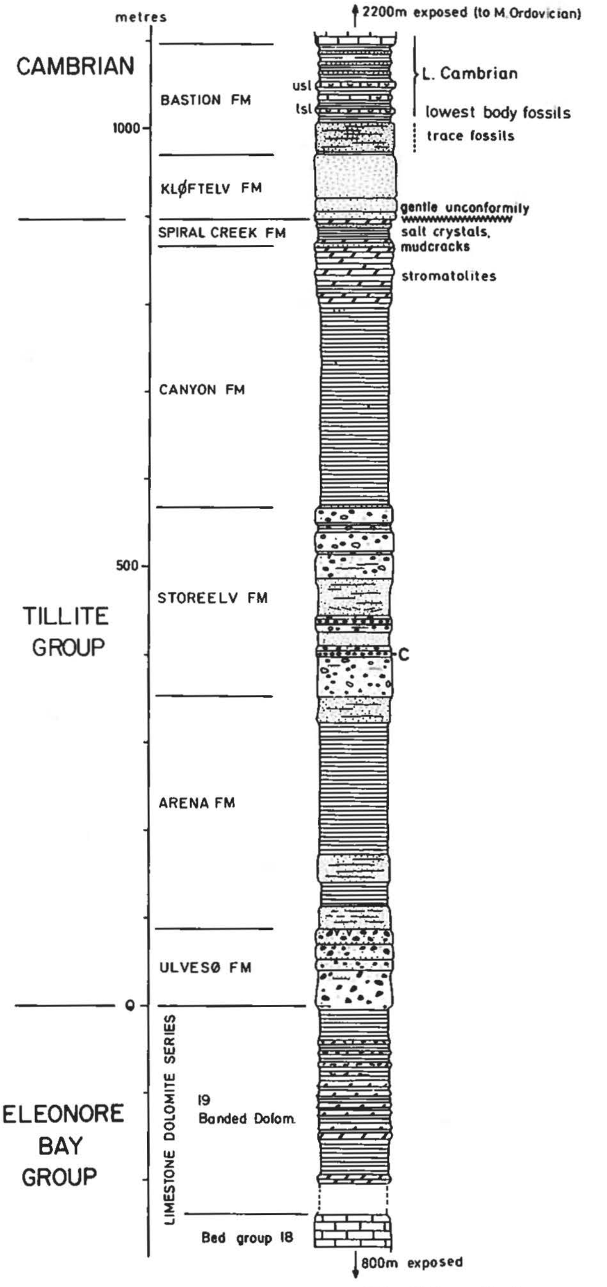


Fig. 1. Outline stratigraphic column on Ella Ø from Bed group 19 to Lower Cambrian strata. lsl – Lower Shell Limestone; usl – Upper Shell Limestone.

<table>
<tr><th>KOCH 1929</th><th>POULSEN 1930</th><th colspan="2">KULLING 1929</th><th colspan="2">SCHAUB 1950</th><th>POULSEN & RASMUSSEN 1951</th><th colspan="2">SCHAUB 1955</th></tr>
<tr><td rowspan="2">BASTION FORMATION</td><td rowspan="2">BASTION FORMATION</td><td colspan="2" rowspan="2">BASTION FORMATION</td><td rowspan="6">TOMMER BAY GROUP</td><td rowspan="2">SANDY SHALE MEMBER
QUARTZITE MEMBER</td><td rowspan="2">BASTION FORMATION</td><td colspan="2">BASTION FORMATION</td></tr>
<tr><td rowspan="4">TILLITE FORMATION</td><td>SANDSTONE SE</td></tr>
<tr><td rowspan="5">ELEONORE BAY FORMATION</td><td>SPIRAL CREEK FORMATION</td><td colspan="2" rowspan="3">TILLITE SERIES</td><td>SALT CAST MEMBER</td><td>SPIRAL CREEK FORMATION</td><td>SPIRAL CREEK SERIE</td></tr>
<tr><td>TILLITE CANYON FORMATION</td><td>SUN CRACKED MEMBER
VARVE MEMBER</td><td>TILLITE CANYON FORMATION</td><td>CANYON SERI</td></tr>
<tr><td>CAPE OSWALD FORMATION</td><td>UPPER TILLITE MEMBER
INTER TILLITE MEMBER
LOWER TILLITE MEMBER</td><td>CAPE OSWALD FORMATION</td><td>TILLITE SERI</td></tr>
<tr><td rowspan="2">ELEONORE BAY FORMATION</td><td rowspan="2">ELEONORE BAY FORMATION (UPPER)</td><td rowspan="2">LIMESTONE-DOLOMITE SERIES</td><td>SILTY SHALE MEMBER
BRECCIA MEMBER
BANDED DOLOMITE MEMBER</td><td rowspan="2">ELEONORE BAY FORMATION</td><td rowspan="2">ELEONORE BAY FORMATION</td><td rowspan="2">LIMESTONE-DOLOMITE SERIES (BED GROUPS 1</td></tr>
<tr><td>LOWER LIMESTONE GROUP</td><td>GREY LIMESTONE MEMBER
BLACK LIMESTONE MEMBER
COLLENIA MEMBER
PISOLITE MEMBER</td></tr>
</table>

Stratigraphic terminology

Various schemes have been proposed for the Late Proterozoic – Early Palaeozoic succession of the East Greenland Caledonides (Table 2). Few, however, are consistent with modern stratigraphic procedure, whereby names should not generally imply any particular genetic interpretation of a rock unit, while the use of geographical names, related to type sections, is preferred. For this reason the term "Tillite Group" and the names of three of its five formations do not accord with modern stratigraphic procedure. Indeed, only a small proportion of the Tillite Group is in fact composed of tillite. However, the group name is so well established that it is retained in this paper, as in fact the International Stratigraphic Guide (Hedberg 1976) allows. On the other hand the formational names have been made consistent with the recommendations of the guide, and have been selected following discussion with geologists of the Geological Survey of Greenland (GGU). The new names are formally proposed in the following discussion according to GGU procedure, and measured type sections have been designated. Brief details of the individual rock units are given in this section. A fuller account is presented later under "Lithostratigraphic description".

Tillite Group (existing name)

History. – The group as now defined (Haller 1971, Henriksen & Higgins 1976) was originally called the Tillite Series (Kulling 1929). With rock units above and/or below it has also received the following names: Tommer Bay Group (Schaub 1950), Tillite Formation (Schaub 1955, Fränkl 1953a,b) and Mørkebjerg Formation (Katz 1954). It was also included as part of the Eleonore Bay "Formation" (Koch 1929).

Name. – After the most distinctive rock type in the group, diamictite, which has been interpreted as tillite *sensu lato*. In fact less than a quarter of the group contains tillite.

Type area. – No one area has been designated, but there are two contenders where the strata were first examined and subdivided: Kap Weber (Poulsen 1930) and Ella Ø (Kulling 1929). The most accessible and reasonably complete is in the Kap Oswald area of Ella Ø. The Kap Weber area is affected by tectonic complications.

Thickness. – In the East Greenland fjord region it ranges from 500–900 m thick, but an incomplete succession in Canning Land is only 60 m thick.

Lithologies. – The group is a major siliciclastic unit sandwiched between the entirely carbonate Limestone-Dolomite "series" of the Eleonore Bay Group below and the mainly carbonate Cambro-Ordovician group. It comprises two main diamictite horizons with associated shales, siltstones, sandstones and conglomerates, a shale-siltstone-sandstone sequence between, and a shale-carbonate-siltstone-sandstone sequence at the top. The clastic units contain a high proportion of carbonate.

Boundaries. – The group generally rests on Bed groups 19 and 20 (Eha 1953) of the Limestone-Dolomite "series", but the exact nature of the contact is variable. Contacts with both Bed groups are sharp or rapidly transitional, or are thrust. In the south the group may rest on an erosion surface of Bed group 18 or lower. The group is overlain by basal Cambrian sandstones of the Kløftelv Formation. This contact is conformable and sharp; it probably represents a long depositional hiatus.

Distribution. – The group occurs throughout the central fjord region of East Greenland from Grantagletscher in the north (74°25'N), through Ole Rømer Land, Hudson Land, Strindberg Land, eastern Andrée Land, Ymer Ø, eastern Suess Land, Ella Ø, eastern Lyell Land, northern Scoresby Land, to Canning Land in the south (71°37'N).

Age. – This is considered to be Vendian (Vidal 1976, 1979), although the Precambrian – Cambrian boundary may occur a short distance below the top of the group.

Ulvesø Formation (new name)

History. – The rock unit with this name is the lowermost of the two diamictite formations. It first formed part of Poulsen's (1930) Cape Oswald Formation (embracing both diamictites), Schaub's (1955), Fränkl's (1953a,b) and Katz's (1954, 1961) Tillite Series and is totally represented by the Lower Tillite of Haller (1971) and Henriksen & Higgins (1976).

Type sections. – A near complete but composite section occurs immediately north of the east end of Ulvesø (top) and down through the gorge of Kløftelv (Fig. 6). A continuous coastal section also occurs 2 km WNW of Ulvesø, at the western end of Tømmerbugt (base) and round into Bastionbugt (72°52'30"N, 25°07'W).

FRÄNKL 1953		KATZ 1954/1961			HALLER 1971, HENRIKSEN & HIGGINS 1976 STANDARD SUBDIVISION		THIS PAPER	
BASTION FORMATION		BASTION FORMATION			BASTION FORMATION		BASTION FORMATION	
:ONORE BAY IMATION JPPER)	SANDSTONE SERIES		MØRKE-BJERG FORMATION	SANDSTONE SERIES	KLØFTELV FORMATION		KLØFTELV FORMATION	
	SPIRAL CREEK SERIES			SPIRAL CREEK SERIES	TILLITE GROUP	SPIRAL CREEK FORMATION	TILLITE GROUP	SPIRAL CREEK FORMATION
	CANYON SERIES			CANYON SERIES		CANYON FORMATION		CANYON FORMATION
	TILLITE SERIES			TILLITE SERIES		UPPER TILLITE		STOREELV FORMATION
						INTER TILLITE		ARENA FORMATION
						LOWER TILLITE		ULVESØ FORMATION
	LIMESTONE-DOLOMITE SERIES	ELEONORE BAY GROUP	NØKKE-FOSSEN FORMATION (BED GROUP 14–20)		ELEONORE BAY GROUP (UPPER)	LIMESTONE-DOLOMITE SERIES (BED GROUP 14–20)	ELEONORE BAY GROUP (UPPER)	LIMESTONE-DOLOMITE SERIES (BED GROUPS 14–20)

Table 2. Summary of the stratigraphic schemes used by various authors for the Late Precambrian succession of central East Greenland.

Thickness. – At Ulvesø-Kløftelv it is 100 m thick and 5 m or so thinner at Tømmerbugt. It attains its greatest thickness (318 m) at Sorteelv Gletscher in northern Scoresby Land, but in the north (except at Albert Heim Bjerge) is only 15 m or so in thickness. In Canning Land it seems to be absent.

Lithologies. – The formation is dominated by massive and bedded diamictites containing almost entirely intrabasinal clasts. Sandstones, conglomerates, shales and rhythmites (sometimes with dropstones) are also present.

Boundaries. – The lower boundary is described under Tillite Group. The upper boundary is conformable but generally sharp, frequently with sandstone wedges and downfolds (Fig. 9).

Distribution. – The formation is present throughout the area, except in Canning Land, and frequently forms crag features.

Age. – This is Vendian on the basis of acritarchs from the formation (Vidal 1979).

Arena Formation (new name)

History. – This formation formed part of the Cape Oswald Formation of Poulsen (1930), Tillite Series of Kulling (1929), Schaub (1953) and Katz (1954, 1961). Schaub (1950) divided his Tommer Bay Group into 11 members of which this was one – the Inter Tillite Member. In the standard subdivision used more recently it has been referred to as the Inter-Tillite (beds) (Haller 1971, Henriksen & Higgins 1976, Higgins 1981).

Name. – After the mountainside named Arenaen overlooking the head of Dusén Fjord in Gunnar Andersson Land, Ymer Ø.

Type and other reference sections. – A practically continuous section was measured in the stream which descends from the ice cap that crowns the mountain at 73°20′N, 24°53′W (Fig. 8). Other accessible and almost complete sections occur at Sorteelv Gletscher in northern Scoresby Land, and between the 1410 and 845 m summits 9 km west of Kap Weber in eastern Andrée Land (Fig. 16).

Thickness. – At the type locality the formation is 223 m thick (Fig. 16, loc. 9), reaching a maximum at Sorteelv Gletscher (loc. 2) of 320 m. It is absent in Canning Land.

Lithologies. – The formation is dominated by dolomitic shales, siltstones and sandstones. Diamictites are absent except in a minor way at Sorteelv Gletscher.

Boundaries. – Both lower and upper boundaries are sharp but conformable. On Ella Ø a boulder pavement with some exotic clasts, set in sandstone and siltstone, defines the top.

Distribution. – The formation occurs throughout the area, except in Canning Land.

Age. – This is Vendian on the basis of acritarchs from the formation (Vidal 1979).

Storeelv Formation (new name)

History. – The formation formed the upper part of the Cape Oswald Formation of Poulsen (1930) and Poulsen & Rasmussen (1951), and of the Tillite Series of Schaub (1953), Fränkl (1953) and Katz (1954, 1961). In Kulling's (1929) Tillite Series it occurred in the middle. In the standard subdivision of Haller (1971), Henriksen & Higgins (1976) and Higgins (1981), it was referred to as the Upper Tillite, a term introduced as a member by Schaub (1950).

Name. – After the stream Storeelv which drains the plateau east of Bastionen and debouches in Solitærbugt on the north coast of Ella Ø (Fig. 5).

Type section. – An almost complete section is exposed where Storeelv cuts perpendicularly through SE-dipping strata of the whole Tillite Group. The section is exposed on and above the east side of the gorge below the point where Storeelv is joined by its major (unnamed) tributary at 72°51′20″N, 25°07′W (Figs 5, 6 and 16 loc. 4).

Thickness. – At the type section it is 223 m thick, and is a similar thickness at Arenaen. Elsewhere it is thinner, declining to *c.* 60 m in Canning Land (Fig. 16).

Lithologies. – The formation is dominated by diamictite, generally massive, with a high proportion of exotic clasts. There are also shales, siltstones, rhythmites (sometimes with dropstones), sandstones (dominant in some sections) and conglomerates.

Boundaries. – Both lower and upper boundaries are generally sharp but conformable. On Ella Ø diamictite rests on a boulder pavement set into the top of the Arena Formation (see above). In Canning Land the formation rests on an *in situ* brecciated surface of Bed group (?) 18 of the Limestone-Dolomite "series".

Distribution. – This formation occurs throughout the area, in all the sections studied.

Age. – No fossils (acritarchs) have been found, but a Vendian age is suggested from the bounding formations.

Canyon Formation (existing name)

History. – This formation was first named the Tillite Canyon Formation (Poulsen 1930) but renamed the Canyon Series by Schaub (1955) and Fränkl (1953) because of the confusion with Tillite Formation. It was adopted as Canyon Formation by Haller (1971) and the term has been used subsequently.

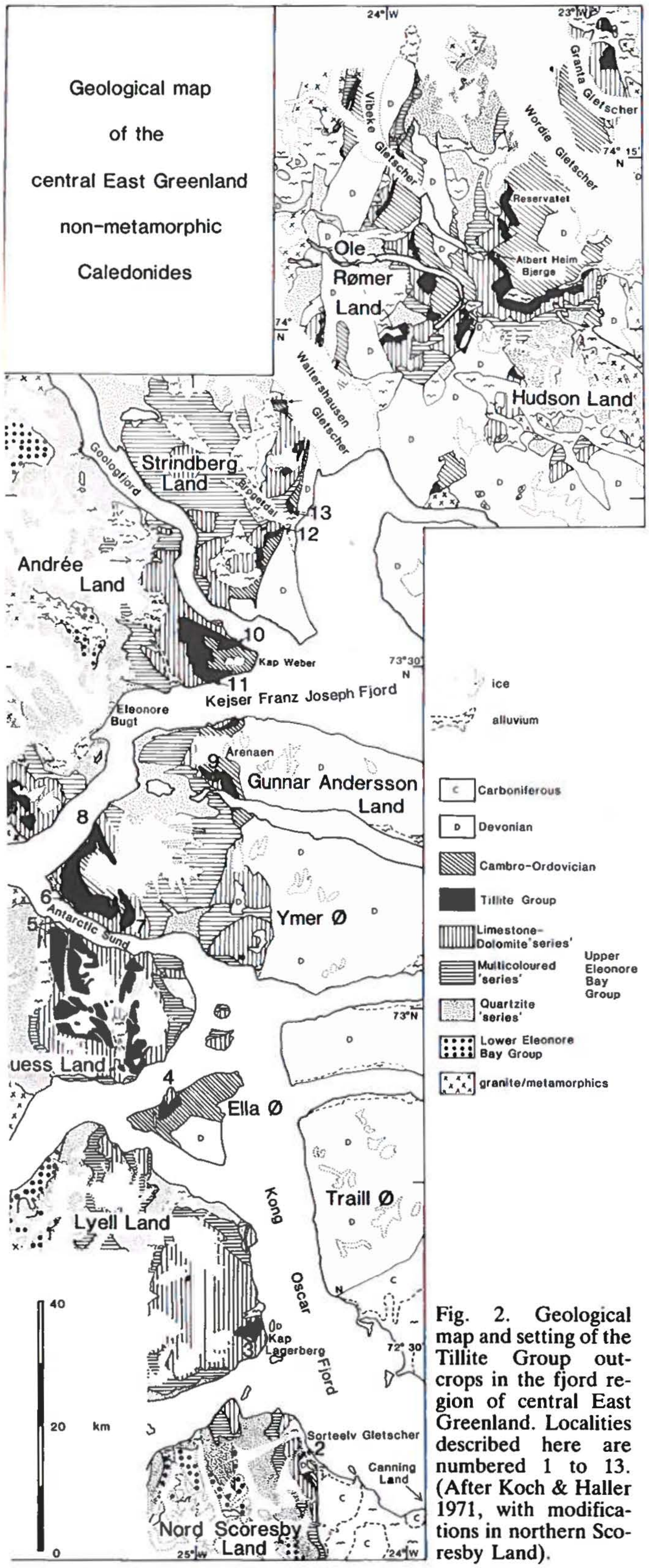


Fig. 2. Geological map and setting of the Tillite Group outcrops in the fjord region of central East Greenland. Localities described here are numbered 1 to 13. (After Koch & Haller 1971, with modifications in northern Scoresby Land).

Name. – After Tillitekløft, formerly Tillite Canyon, the gorge debouching into the mouth of Geologfjord 5 km NW of Kap Weber in eastern Andrée Land (Fränkl 1953a, Tafel 1). N.B. on the 1:250 000 topographic map this gorge is named Hyolithusklöft; Poulsen's (1930, fig. 19) "Hyolithus Creek" is a smaller watercourse 3 km SE of this gorge.

Type and reference sections. – The section of Tillitekløft, the type locality, has not been measured, being rather inaccessible. A complete section was, however, measured at Arenaen, and a near complete section recorded in more detail in Storeelv on Ella Ø (Fig. 20).

Thickness. – About 300 m at Arenaen and on Ella Ø.

Lithologies. – In the north a basal dolostone occurs, followed by dolomitic shales which occur everywhere, with stromatolitic dolostones towards the top.

Boundaries. – The lower contact is invariably sharp but conformable. The top is transitional with sandstones and siltstones of the Spiral Creek Formation.

Distribution. – The formation occurs throughout the area, except in the south: in northern Scoresby Land, where it is replaced by pure sandstones that are conformable with the Storeelv Formation, and in Canning Land.

Age. – This is Vendian on the basis of acritarchs extracted from the formation (Vidal 1979).

Spiral Creek Formation (existing name)

History. – This formation was defined by Poulsen (1930) for the unit between basal Cambrian sandstones and the shales and dolostones of the Canyon Formation. Except for being called "series" in the 1950's the name survives to the present day.

Name. – After Spiralkløft, a tributary gully to Tillitekløft.

Type and reference sections. – The type section occurs in Spiralkløft but is rather inaccessible and has not been measured there. Excellent complete sections occur on Ella Ø, notably above the right bank of Kløftelv, and to the east along the shores of Solitærbugt, and also at Arenaen (Fig. 20).

Thickness. – This is about 25 m on Ella Ø, but Fränkl (1953b) recorded 35–45 m in eastern Andrée Land.

Lithologies. – The formation comprises sandstones and siltstones with halite pseudomorphs.

Boundaries. – The lower boundary is transitional with the Canyon Formation. The upper one is sharp, probably representing a hiatus prior to deposition of the sandstones of the Kløftelv Formation, although there is no sign of an angular discordance. On Ella Ø *in situ* brecciation, reddening and silicification has occurred at the contact.

Distribution. – The formation has only been definitely recognised between Ella Ø and Kap Weber. Cowie & Adams (1957) argued for its absence at Albert Heim Bjerge, while at Sorteelv Gletscher it is missing from a conformable succession, and it is also missing in Canning Land.

Age. – No fossils have been recorded in this formation. It lies below the Kløftelv Formation which contains Early Cambrian trace fossils, so it could be Vendian, depending on the significance of the hiatus at the top of the Spiral Creek Formation.

Description of localities

The outcrops visited lie between 71°30' and 74°N over a NNW – SSE distance of about 240 km. Details of the locations of the sections studied are presented below (Fig. 2).

Fig. 3. The 600 m high cliffs on the south side of the Kap Fletcher peninsula, Canning Land (locality 1). The dark horizon of irregular thickness is of diamictite and probably belongs to the Storeelv Formation (SF). It rests on brecciated dolostone of the Limestone-Dolomite "series" (LDS), and is overlain by possibly Cambrian quartzites.

Locality 1, Kap Fletcher, Canning Land (71°37'40"N, 22°10'W)

This represents the southern limit of the Late Proterozoic – Early Palaeozoic sedimentary sequence east of the metamorphic Caledonides. A map by Caby (1972) indicates a narrow belt of tillite in the Kap Fletcher peninsula, but the exact location of the section he described was not given. From aerial photographs we selected a site on a NW-facing hillside, 3 km west of Kap Fletcher, on the north side of the peninsula. However, exposures were limited and although the Tillite Group was clearly visible in the seaward-facing cliffs, these proved to be inaccessible. The tillites are best exposed in steep cliffs on the south side of the peninsula (Fig. 3), but we were unable to visit this area. The sedimentary rocks are disrupted by microgranite intrusions and faults.

Locality 2, Sorteelv Gletscher, northern Scoresby Land (72°21'15"N, 24°30'W)

A small outcrop displaying an almost complete section through the Tillite Group is located on the lower northern slopes of Syltoppene, just outside the moraines SE of the snout of Sorteelv Gletscher. The beds dip moderately steeply to the east, and the upper half of the section is well exposed in the bed of a stream. A section recorded by Fränkl (1953a, pp. 25–26) was remeasured by taping and the thicknesses found to have been grossly underestimated. The new thickness may be a slight overestimate of the true thickness as a result of thrusting which is widespread in the area (Fig. 2).

Locality 3, Kap Lagerberg, Lyell Land (72°31'N, 24°49'W)

Two sections through the Ulvesø Formation and the underlying Limestone-Dolomite "series" were measured in adjacent gullies, above the stream in a small valley that lies south and SE of the 800 m summit (Fig. 4). Another section through poorly exposed Storeelv Formation was measured on the upper east-facing slopes above Kap Lagerberg. This section is capped by a massive white sandstone mapped as Devonian by Koch & Haller (1971, plate 12), but in the absence of visible contacts this cannot be verified. The overall geological column was previously measured by Sommer (1957, pp. 61–64).

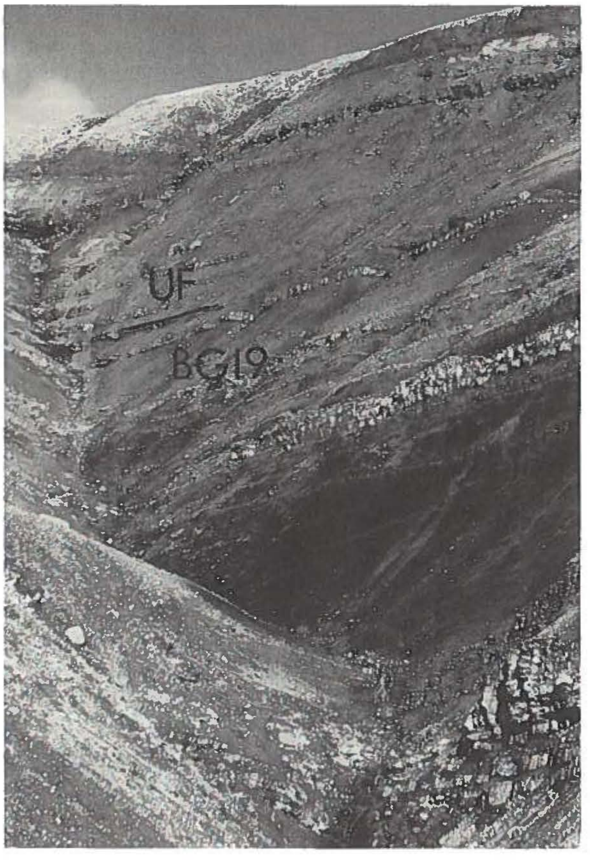


Fig. 4. Section through the upper part of Bed group 19 and the Ulvesø Formation (UF), in a gully above and west of Kap Lagerberg, Lyell Land (locality 3).

Locality 4, Kap Oswald, Ella Ø (72°52′N, 25°07′W)

Extensive exposures of the whole of the Tillite Group occur on Ella Ø in a faulted anticline (Fig. 5). They are the best known of all diamictite-bearing sections in East Greenland, and have previously been mapped at a scale of 1:10 000 (Schaub 1955, plate 1). A minor amount of new mapping was undertaken (Fig. 6) in order to extend the area covered by Schaub's map to show the whole outcrop of the Tillite Group. Sections through Bed group 19 of the Limestone-Dolomite "series" beneath the Ulvesø Formation were measured to give evidence of the nature of the contact beneath the Ulvesø Formation. Three complete sections through the Ulvesø Formation, including that of the type locality, were measured. Only one poorly exposed section through the Arena Formation and only one complete section through the Storeelv Formation (the type locality) were found. Measurement of the latter section was continued up through much of the overlying Canyon Formation, repeating measurements made by Cowie & Adams (1957, pp. 168–169). The uppermost part of the Canyon Formation is best exposed along the coast of Solitærbugt where it is overlain by the Spiral Creek Formation and the lower part of the Kløftelv Formation.

Locality 5, Trugbjerg and Langgletscher Dal, northern Suess Land (73°06′N, 25°40′W)

Trugbjerg is the name given to the northern end of a long ridge running between Nanortalikdal and Langgletscher Dal. The mountain forms the core of a shallow syncline with a practically complete succession from the Limestone-Dolomite "series" to the lower part of the Canyon Formation (Fig. 7), the latter being exposed near the top of the ridge at 1200 m (N.B. the published topographic map is inaccurate at this point). Much of the succession in Trugbjerg is difficult of access. A composite section was measured: by aneroid barometer on the north coast, west limb of the syncline (Limestone-Dolomite "series"); by taping on the north coast, east limb of the syncline (Ulvesø Formation); and by aneroid in three successive gullies moving south on the west face of Trugbjerg (Arena Formation to lower Canyon Formation). A fault runs along the east side of Langgletcher Dal, displacing the succession there downwards.

The rocks in this area are strongly cleaved and slightly metamorphosed. Calcite and quartz veining are common, and there has been small-scale westward thrusting.

Locality 6, north coast of Antarctic Sund, 5 km SE of Kap Mohn, Ymer Ø (73°09′40″N, 25°37′W)

A good section from the top of the Limestone-Dolomite "series" near sea level through the Ulvesø Formation is exposed in the crags facing Antarctic Sund. A section through these units was examined above the right bank of the stream that descends from the plateau via a prominent waterfall. The Arena and Storeelv formations are affected by faulting and thrusting, and the latter forms a precipitous cliff face. The section here occurs in the same syncline as that in Trugbjerg and is similar; the deformation characteristics are also much the same as those across the sound.

Locality 7, north coast of Antarctic Sund, 17 km ESE of Kap Mohn, Ymer Ø (73°07′20″N, 25°20′W)

The section here is in a small valley at the southern extremity of the Tillite Group outcrop. Only the section beneath the Ulvesø Formation was measured. The Ulvesø to Storeelv formations are exposed in a vertical cliff and were not visited; stratal divisions and thicknesses were estimated.

Locality 8, Kiledal, western Ymer Ø (73°16′40″N, 25°30′W)

A section through the steeply dipping Ulvesø Formation was measured at sea level immediately south of Kiledal.

Fig. 5. The Kap Oswald anticline, Ella Ø, viewed from the SW (locality 4). The succession includes part of the Limestone-Dolomite "series" (LDS), the whole of the Tillite Group, and Cambro-Ordovician strata. UF: Ulvesø Formation, AF: Arena Formation, SF: Storeelv Formation, CF: Canyon Formation, SCF: Spiral Creek Formation, KF: Kløftelv Formation, BF: Bastion Formation, f = fault. Arrow indicates position of the Storeelv gorge.

Locality 9, Arenaen, Gunnar Andersson Land, NW Ymer Ø (73°20'N, 24°53'W)

Sections stretching from beneath the Ulvesø Formation to the Kløftelv Formation were measured on the mountainside called Arenaen in south Gunnar Andersson Land, in the two highest fault blocks. The sections were measured from the top downwards, since the Kløftelv Formation is a clear marker bed on the mountainside (altitude *c.* 1000 m) (Fig. 8). In general the higher sections were measured at the eastern end of the mountainside and the lower sections at the western end. The thickness of the lower half of the Canyon Formation was calculated from the measured width of outcrop, ground slope and angle of dip. The section through the Storeelv Formation is a composite of two parts – the upper 60 m and the rest – measured in two places 300 m apart. The section through the Arena Formation down to the base of the 52 m sandstone unit is from the western end of the outcrops; most of the bed thicknesses have been calculated. The remainder of the Arena Formation and the section through the Ulvesø Formation (Fig. 9:9B) were measured in the walls of the main stream which descends from the ice cap above Arenaen. All of these sections were measured in the third highest of the four fault blocks marked on the geological map (Koch & Haller 1971, plate 9). The lowest section (Fig. 9:9A) is from the second highest of the two fault blocks.

Locality 10, Tillitekløft, Kap Weber, eastern Andrée Land (73°32'N, 24°50'W)

Four sections were measured in and near this valley, which drains into Geologfjord opposite the small island of Bjørneø. In the lower part of the canyon, Bed group 19 was measured whilst the thickness of the overlying Bed group 20, exposed in a vertical cliff, was estimated (Fig. 9:10A). The two sections through the Ulvesø Formation were measured immediately NW of the stream in Tillitekløft (Fig. 9:10B) and 300 m further NW (Fig. 9:10C); their relationship with Bed group 20 was not visible. The lower part of the Arena Formation is unexposed and its thickness was estimated. The rest of this formation and the succession up through the Storeelv

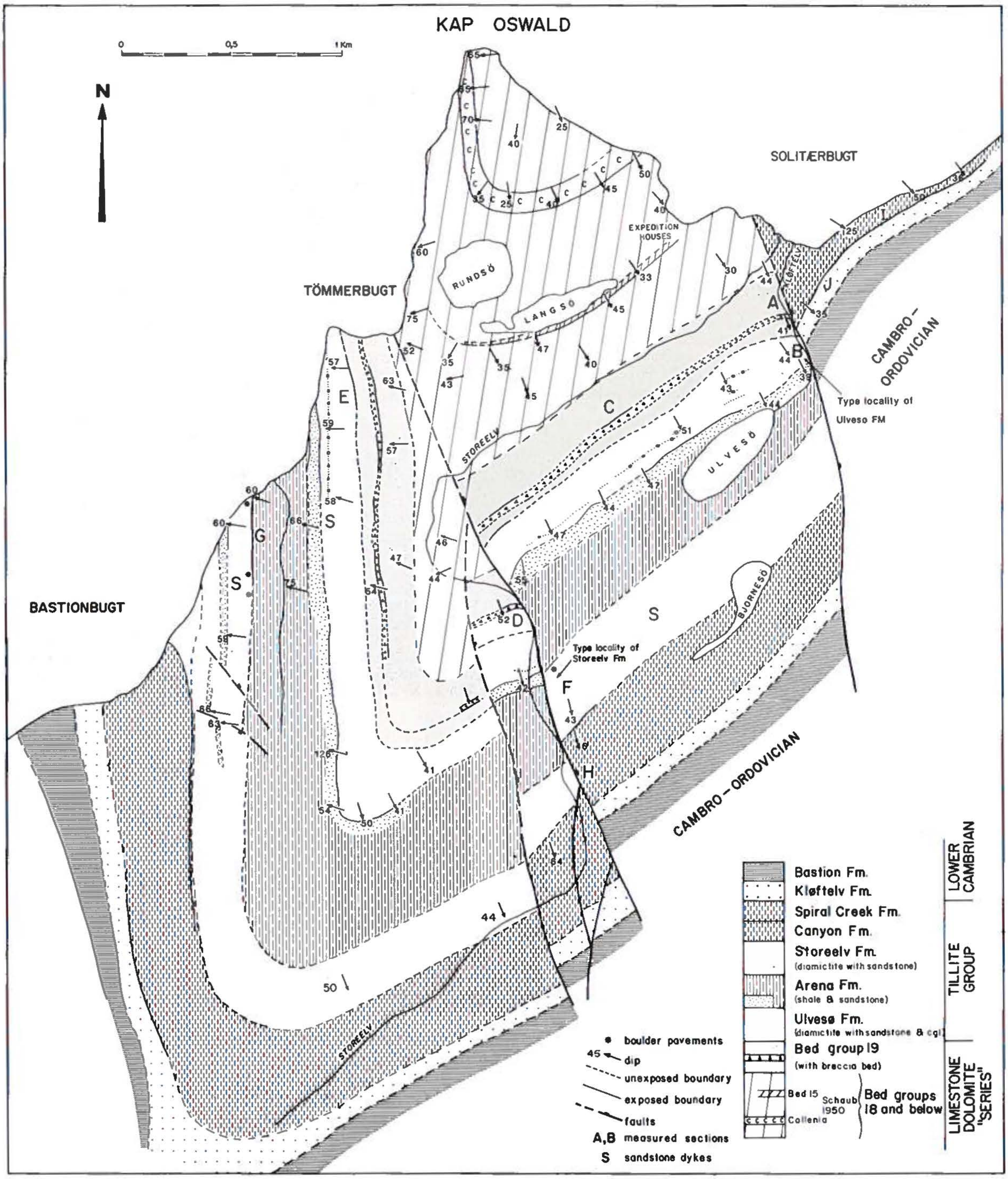


Fig. 6. Outline geological map of the Kap Oswald area of Ella Ø. North and east of the outcrop of the Arena Formation the map is based partly on Schaub (1955, plates I and II). South and west of this formation the map is approximate, sketched from vertical air photographs, no adequate topographical base being available.

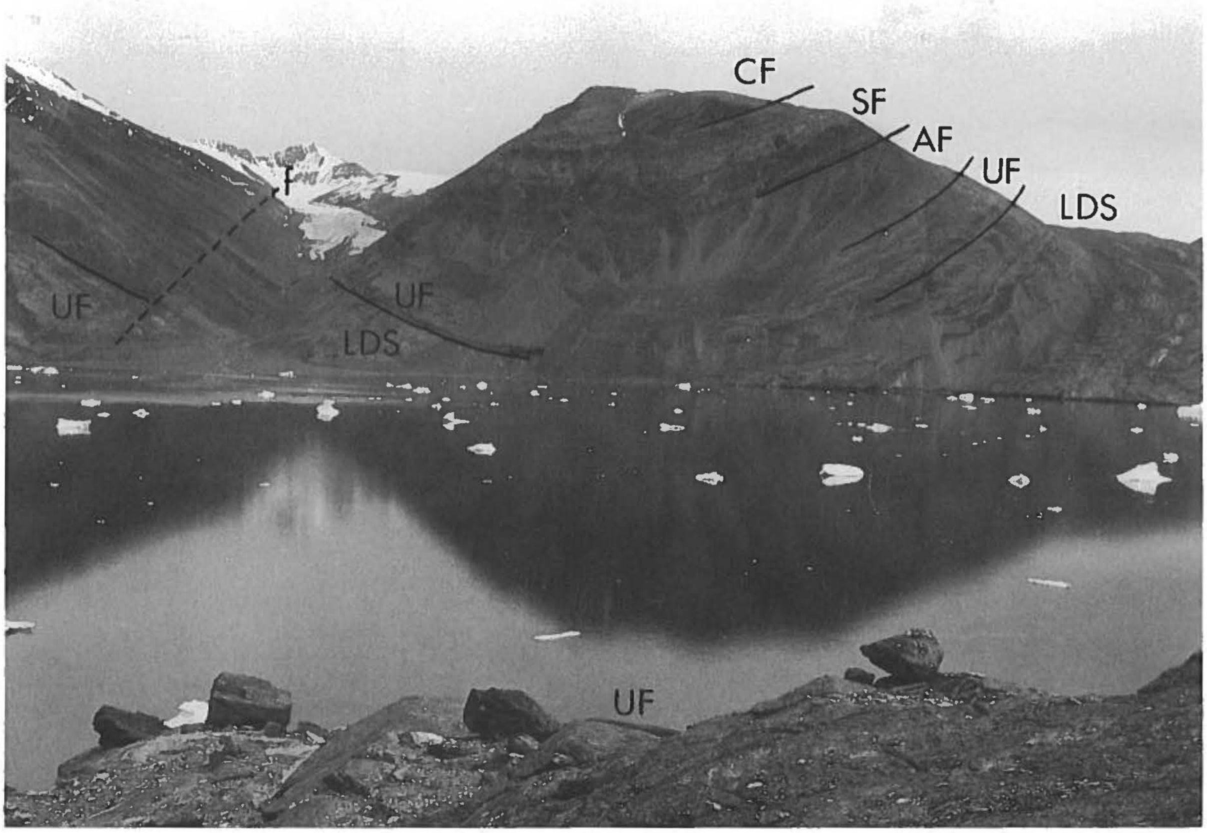


Fig. 7. Langgletscher Dal and Trugbjerg, northern Suess Land, viewed from the SW coast of Ymer Ø, showing the faulted syncline in which the sequence from Bed group 19 up to the lower part of the Canyon Formation is exposed (locality 5). For abbreviations see Figure 5.

Formation was measured in a narrow gully on the south side of Tillitekløft. This overall geological column had previously been measured by Fränkl (1953b, pp. 71–72).

Locality 11, 1410 m summit, Kap Weber (73°30′N, 24°59′W)

One section through Bed group 19, Bed group 20 and the Ulvesø Formation was measured in a small gully just north of the 1410 m summit, 9 km west of Kap Weber. This section probably lies about 500 m north of the section measured by Fränkl (1953b, pp. 69–70).

Localities 12 and 13, Brogetdal, Strindberg Land (73°43′10″N, 24°31′W and 73°44′40″N, 24°29′W respectively)

Two sections were measured on the south side of Brogetdal (locality 12). One shows Bed group 19, Bed group 20 and the Ulvesø Formation (Fig. 9:12A) and continues up into the Arena Formation (Fig. 16). A second section through the Ulvesø Formation (Fig. 9:12B) was measured a few hundred metres away in order to demonstrate the lateral variation. A section through the Storeelv Formation (Fig. 16) was measured on the north side of Brogetdal (locality 13) in the central of three main gullies which dissect the hillside.

Lithostratigraphic description

Bed group 19 (Fig. 9)

On Ella Ø this unit is *c.* 250 m thick. The succession there was measured by Schaub (1950, pp. 11–12) and, according to Eha (1953, pp. 25–26), Bed group 19 corresponds to units 18 to 24 of Schaub's description. Five subdivisions can be distinguished there (Fig. 9, units I–V) which from bottom to top are:

Unit I (? *c.* 44 m) has at its top a 6 m thick yellow argillaceous dolostone with grey shale laminae up to 2 cm thick, spaced at 5–15 cm intervals (Fig. 9:4C). Between Kløftelv and Storeelv, lower strata in the unit are buried beneath the latter's floodplain. Above Tømmerbugt the base is again unexposed (Fig. 9:4E).

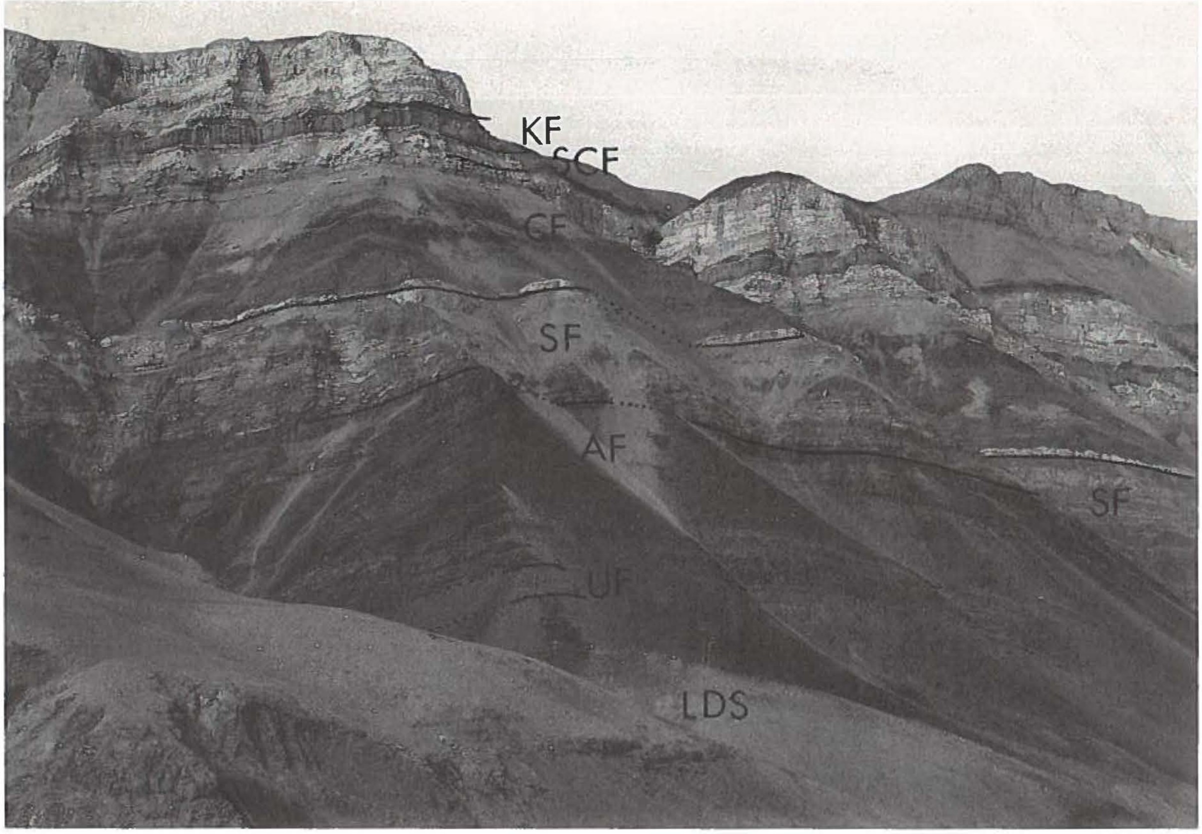


Fig. 8. Section through the whole of the Tillite Group at Arenaen, Gunnar Andersson Land, Ymer Ø. Abbreviations as in Fig. 5. Note the large sandstone bodies in the Storeelv Formation, shown in detail in Fig. 18e.

Unit II (*c.* 40 m) consists of shales and siltstones of interlaminated grey-green and maroon or purple colours, with thin, yellow-weathering dolomitic siltstones. The middle part of this unit shows the best rhythmic colour banding (e.g. green laminae 2–30 mm thick spaced at intervals of 10–30 mm in purple shales). Elsewhere, the siltstones are often green, contain fine ripple cross-lamination and are arranged in non-graded couplets *c.* 25 mm thick with overlying shale.

Unit III (*c.* 45 m) contains five or more prominent dolostone beds, separated by thicker green or maroon-purple siltstones. The dolostones, particularly the lowest bed, are distinctively striped with purple siltstone laminae (up to 20 mm thick) spaced at intervals of 20–150 mm (Fig. 10a). The siltstones are similar in their colour banding and presence of couplets to Unit II.

Unit IV (*c.* 70 m) is more varied lithologically than the underlying units, containing grey siltstones and perhaps six beds of breccia. The last are massive, hard beds of dolomitic siltstone or grey dolomitic limestone, containing only intraformational, mostly angular fragments of grey limestone and siltstone, which are thin and plate-shaped but up to 0.5 m in length (see Schaub 1950, fig. 7). Some fragments are folded and one breccia bed terminates laterally when traced along the outcrop (Fig. 9:4E). The largest fragment of limestone measured 8×3 m in cross section.

Unit V (*c.* 50 m) is a uniform, friable, finely-laminated greenish and bluish-grey shale. The contact with the diamictite of the Ulvesø Formation is sharp and the top 2 m of the shale unit appears to be more highly weathered than the shale below.

The units described above correspond to Schaub's units approximately thus: I, 18; II, 19–22; III, 22; IV, 22–23; V, 24. Schaub (1950, pp. 24–28) described the rhythmic colour banding and striping, and suggested a varve-like origin. However, the resemblance to varves is only superficial, and these striped beds are more likely to be distal turbidites. Schaub suggested that the breccia beds were the result of "submarine sliding" and this suggestion is supported by the folded fragments and lateral discontinuity of the beds.

North and south of Ella Ø, Bed group 19 has been recognised by the earlier workers but was reported as being thinner (thicknesses from north to south: Strindberg Land 110 m, eastern Andrée Land 120–130 m, Ymer Ø and Suess Land 140–210 m, Ella Ø 250 m, Lyell Land 120–150 m, and northern Scoresby Land 140–150 m). On the other hand measurements made by I. J. Fairchild & P. Herrington in 1985 (pers. comm.) indicate that in eastern Andrée Land Bed group 19 is as thick as on Ella Ø, but some differences in thickness are due to thrusting. In northern Scoresby Land Bed group 19 appears to us absent and may never have been deposited. It seems possible to correlate units II to IV south to Kap Lagerberg and units III to V north to Tillitekløft. At the latter locality, however, the striping in the lowest 10.5 m thick dolostone in Unit III is faint and the spacing is wide (up to 300 mm), while the overlying siltstones are no longer green/purple banded, but are dark grey.

At locality 5 (Fig. 9) units II and III match quite well with their counterparts on Ella Ø, but above them the shale interval is thin and contains only one breccia bed (unit IV). This comprises a dolomitic siltstone, partly well-laminated with numerous outsize clasts of greyish limestone, that has become brecciated slightly or completely with slump folds developing (Fig. 10b, c, d). At Kap Lagerberg there are several similar polygenetic breccia units, each with a sharply-defined top and base, with slump folds and with matrix-supported clasts around which laminae are deformed (Fig. 10e).

In NW Antarctic Sund, on both sides of the fjord, as well as at Kap Lagerberg, the uppermost breccia is overlain by a shale unit only a few metres thick. If the correlation proposed here (Fig. 9) is correct, then Unit IV as well as Unit V, the uppermost shale unit, are very thin compared with Ella Ø.

The top of Bed group 19, which on Ella Ø is sharp, elsewhere is clearly transitional with the Ulvesø Formation, though usually over a few centimetres only (Fig. 10f). This is well seen at localities 5 and 6, whilst at localities 3 and 6 dispersed clasts (including quartzites) occur near the top of Unit V (Fig. 10g). Most of these clasts are pebble-sized but one 67 cm long oval boulder was observed at locality 6.

At localities 9 to 13 Bed group 19 shales are overlain by the dark grey limestones of Bed group 20.

Bed group 20 (Fig. 9)

This only occurs to the north of Ella Ø and was recognised by the earlier workers on Ymer Ø (up to 70 m thick), eastern Andrée Land (40–80 m), and Strindberg Land (40–50 m). Bed group 20 everywhere consists of hard, cliff-forming, black to dark blue limestone, usually regularly bedded (50–250 mm), with dark, carbonaceous shale partings (Fig. 11a). The original nature of limestone has been obscured by recrystallisation but evidence to suggest a clastic origin is seen in one sample from Arenaen which comprises millimetre-scale black rounded fragments set in a medium grey matrix; another sample shows finely laminated couplets in which the coarser fraction is of sand grain size

The thicknesses of Bed group 20 given by earlier workers may be conservative. The thickest succession through Bed group 20 was found 1 km SW of Ajorpoq in Andrée Land where *c.* 150 m of dark limestone (with dark shales in the middle) are overlain by *c.* 70 m of dark shale; above come sandstones followed by diamictites. In Brogetdal the limestones are overlain by 40 m of green-grey weathering, dark blue siltstones with carbonaceous fragments which here are included in Bed group 20. Observations in 1985 in Andrée Land, at and north of locality 11, indicate that the limestone is folded (Fig. 11a), thrusted and heavily calcite-veined (Fig. 11b). It is possible, therefore, that the measured thicknesses may be too great because of deformation.

The relationship of Bed groups 19 and 20 has been problematical. Eha (1953, p. 26) wrote that "the upper beds of group 19 and group 20 are not horizons following upon one another in time, but facies equivalents, for there are nowhere indications that, to the south, group 19 was followed by erosion." Later authors have specifically referred to the breccia beds of Ella Ø (herein included in Unit IV of Bed group 19) as the lateral equivalents of Bed group 20 (Katz 1961, p. 317; Haller 1971, p. 104). This suggestion of lateral facies change is not supported by the new observation of breccia beds in the correct stratigraphic position, within Unit IV of Bed group 19 at Tillitekløft and again within Bed group 19 at Brogetdal (Fig. 9).

The base of the Ulvesø Formation

The examination of the stratigraphy of the beds beneath the Ulvesø Formation was conducted with a view to deciding whether or not the base of that formation was an unconformity. The subject has important genetic implications: tills deposited by continental ice sheets are likely to rest on erosional unconformities, whilst tills formed by deposition from floating ice are likely to have conformable or gradational contacts.

Previous observations. – Few detailed observations were made by previous workers, but inferences about the nature of the Ulvesø Formation were frequent. Poulsen (1930, p. 304) noted that "At Cape Oswald the shale series below the Cape Oswald Formation [i.e. Tillite Group] is about 215 m thick, while at Tillite Canyon it is more than 500 m, and the minor beds of this complex are different in the two localities; these facts are suggestive of a considerable break between the Cape Oswald Formation and the Eleonore Bay Formation." Schaub (1950, p. 28) observed on Ella Ø that "a gradual transition apparently connects the Silty Shale member with the over- [i.e. the Ulvesø Formation] and underlying formations." This character was used (p. 30) to infer that, although land ice caps must have existed nearby, "deposition of the glacial till did not probably take place on the land area but in a shallow sea extending in front of it. This is made probable by the absence of a break in sedimentation and of a striated surface at

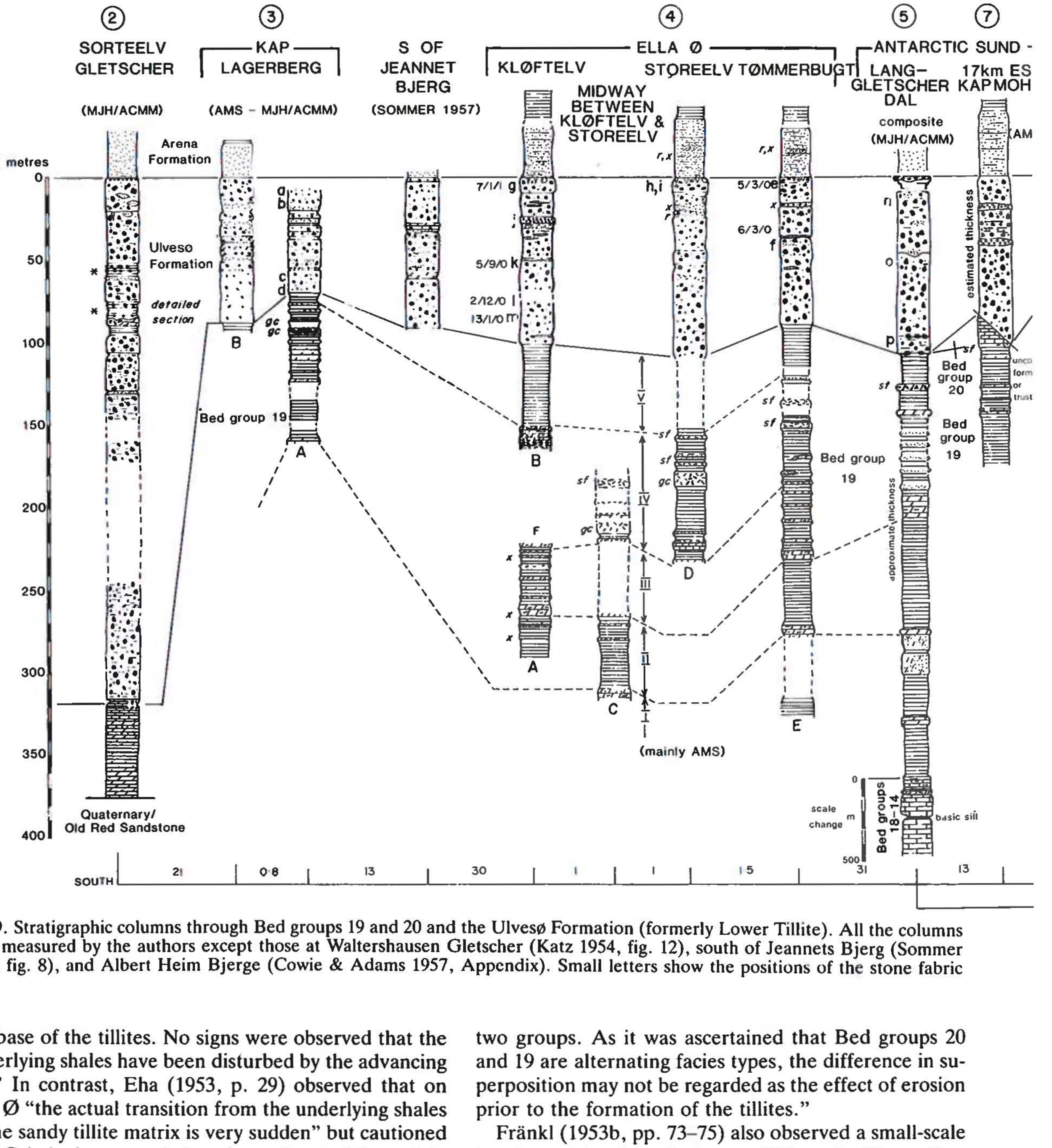
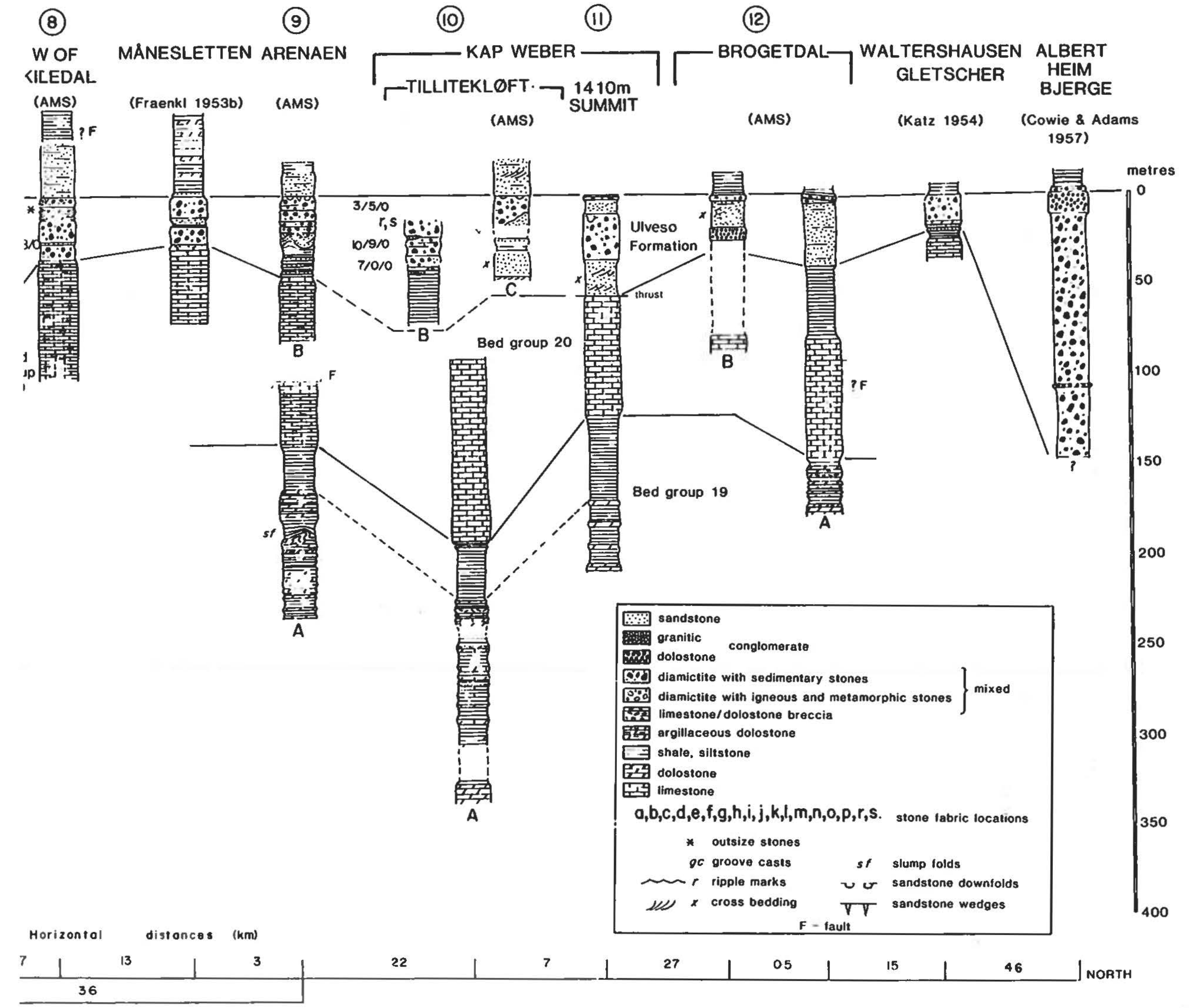


Fig. 9. Stratigraphic columns through Bed groups 19 and 20 and the Ulvesø Formation (formerly Lower Tillite). All the columns were measured by the authors except those at Waltershausen Gletscher (Katz 1954, fig. 12), south of Jeannets Bjerg (Sommer 1957, fig. 8), and Albert Heim Bjerge (Cowie & Adams 1957, Appendix). Small letters show the positions of the stone fabric

the base of the tillites. No signs were observed that the underlying shales have been disturbed by the advancing ice." In contrast, Eha (1953, p. 29) observed that on Ella Ø "the actual transition from the underlying shales to the sandy tillite matrix is very sudden" but cautioned that Caledonian tectonic intraformational sliding might have been responsible. At four localities in Suess Land, Eha (1953, pp. 27–28) observed that where the Ulvesø Formation overlies Bed group 19, dolomite "balls" up to 60 cm in diameter occur within 0.5 and 1 m beneath the base of the formation. His general inference on the nature of the contact was as follows: "The Lower Tillite does not rest on the same substratum everywhere. To the north the substratum is formed by Bed group 20, to the south by Bed group 19 or a facial variation of the two groups. As it was ascertained that Bed groups 20 and 19 are alternating facies types, the difference in superposition may not be regarded as the effect of erosion prior to the formation of the tillites."

Fränkl (1953b, pp. 73–75) also observed a small-scale basal transition from Bed group 20 into the Ulvesø Formation on Månesletten and around Kap Weber in Andrée Land: "This change can be seen, for example in zone C [i.e. Månesletten] in a layer of *c.* 0.5 m thickness. First occur small limestone pebbles (2–5 mm) in the shaly horizons of Bed group 20, then the limestone becomes more compact, contains yellow dolomite splinters, weathered brown, and finally we have a somewhat shaly tillite with a strongly calcareous, grey-black matrix." (free translation from the German). Fränkl went



measurements of Fig. 27. Figures quoted thus (6/3/0) give the numbers of stones with diameters larger than 1 cm in 0.094 m^2 (1 ft^2), in the order pale dolostone/dark limestone/metamorphic and igneous types. Sources of data: AMS – A. M. Spencer 1968; MJH/ACMM – M. J. Hambrey & A. C. M. Moncrieff 1984.

on to conclude that the Ulvesø Formation in the western part of the area, i.e. NW Antarctic Sund, was deposited at the same time as Bed group 20 and the immediately overlying clastic rocks (including diamictites) in the east (i.e. at Kap Weber). Therefore, according to this reasoning, the lowermost diamictite in the western area is a lateral equivalent of Bed group 20 in the east.

Katz (1954, p. 14) observed that in Strindberg Land a weathered and limonitised surface with slight signs of erosion occurs at the base of the Ulvesø Formation. Finally Haller's summary (1971, p. 105) was: "At both the base and top [of the Kap Oswald Group] there are distinct stratigraphic breaks. No angular discordances of bedding are to be seen, but both breaks indicate important regional unconformities. No traces of Precambrian glacial abrasion were found at the base of these formations anywhere in East Greenland. Thus these boulder beds were interpreted as glaciomarine tillites."

In Canning Land, some 160 km SE of Ella Ø, Caby (1972) reported that the Tillite Group was represented by 60 m of structureless and varved pebbly siltstone and mudstone, coloured red, dark green or black, and containing unsorted erratic blocks. A 15 m sandstone divides the succession. The blocks include limestone, dolostone and quartzite of the Eleonore Bay Group, as well as rare red granite stones in the higher parts of the unit. The top of the Eleonore Bay Group comprises 10–20 m of black shales and grey dolostone of (?) Bed group 19, and 250 m of massive white limestone of (?) Bed group 18. Conformably above the tillite lies 80 m of

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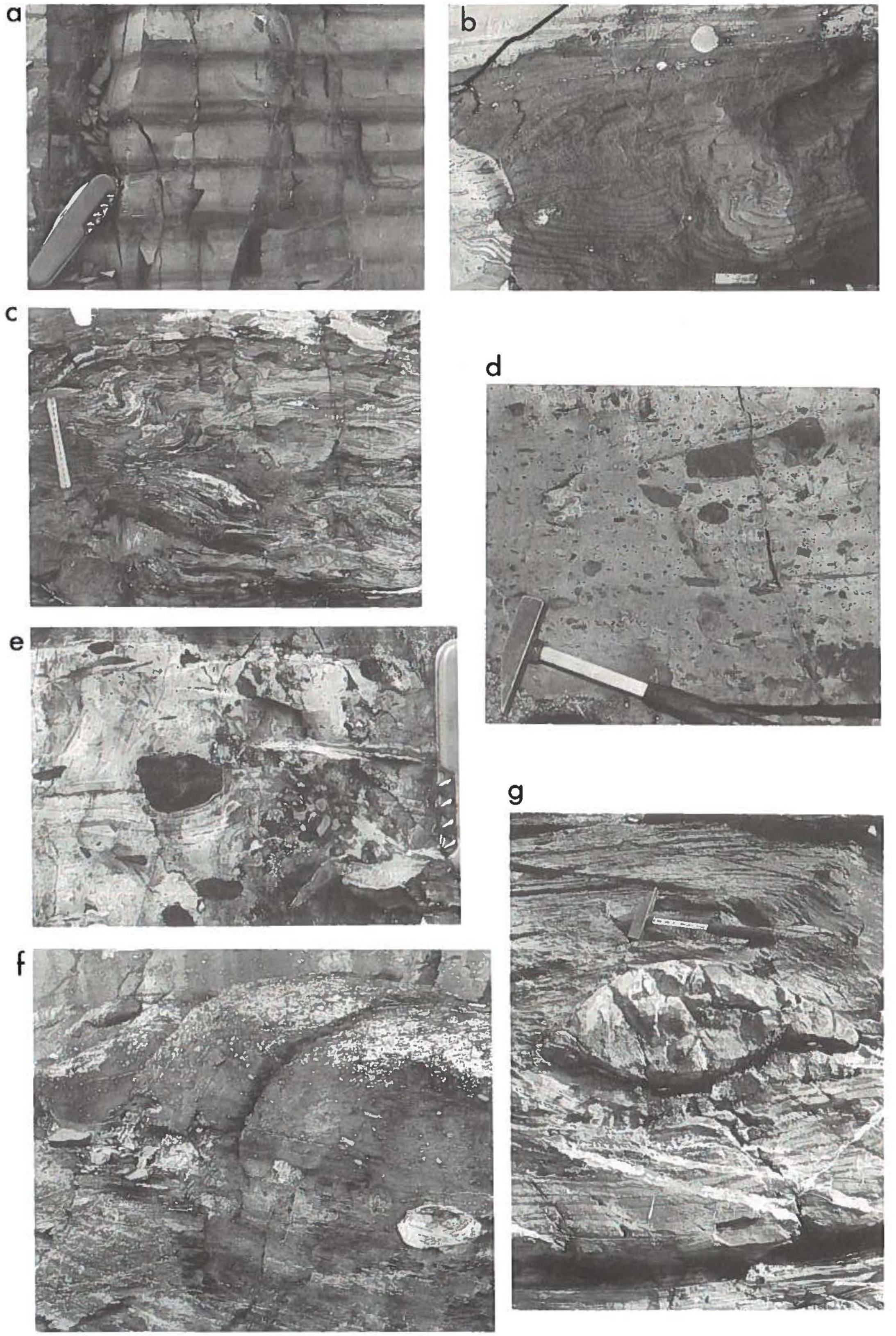
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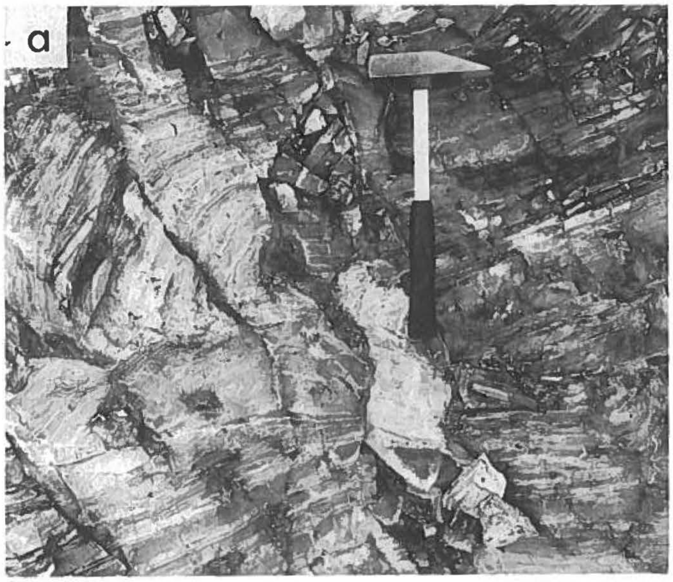


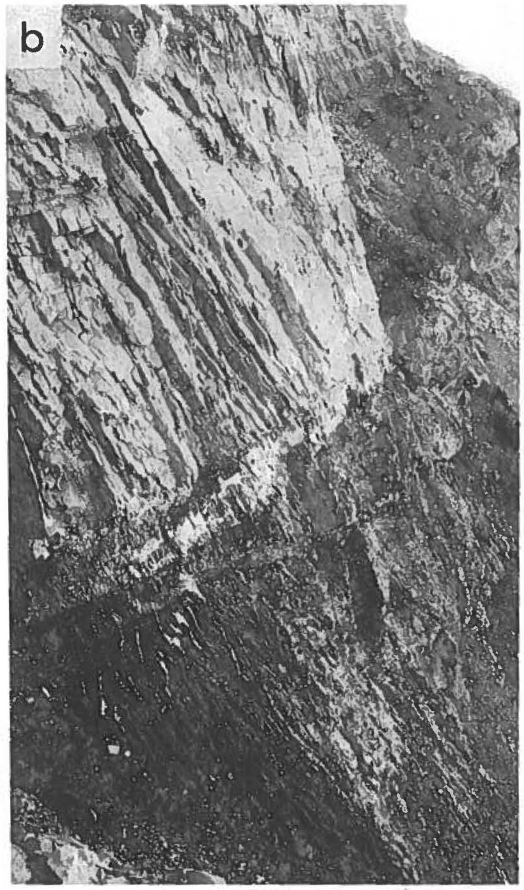


Fig. 11. (a) Blue-black limestones near the top of Bed group 20, tectonically folded in proximity to a thrust, below pt. 1410 m, west of Kap Weber. (b) Bedding parallel thrust contact between limestones of Bed group 20 and cross-bedded sandstones of the Ulvesø Formation, below pt. 1410 m, west of Kap Weber. Sigmoidal and other types of calcite veining are present near the contact. Height of section about 6 m.

massive white quartzite, followed by 40 m of siltstone with shelly limestone containing small brachiopods, fragments of (?) Ollenellidae and the trilobite *Obella congesta*. The latter unit is equivalent to the Lower Cambrian Bastion Formation. Caby did not specify which part of the Tillite Group was represented, but his description suggests the absence of all formations except the Storeelv Formation with its red granite clasts. The nature of the lower contact was not described.

Observations in 1968 (AMS). – The principal observation from the outcrops visited was that the Ulvesø Formation mostly appeared stratigraphically *conformable:* no mappable or clearly visible large-scale angular unconformity could be distinguished. Lithologically, however, the Ulvesø Formation is very distinct; it is the first *sandy* unit seen for over 1000 m, the underlying Limestone-Dolomite "series" being composed exclusively of shale and carbonate.

In detail, where the lowest bed of the Ulvesø Formation is diamictite and it overlies limestone (e.g. at Kiledal) or the shales of Bed group 19 (e.g. on Ella Ø and at Kap Lagerberg), the contact was found to be knife-sharp, there being no transition.

At locality 7 the Ulvesø Formation rests on Bed group 20 in the lowest outcrops (Fig. 12a, b), but on Bed group 19 in the headwaters of the stream, and bedding in the limestone is truncated by the sharp base of

Fig. 10. Facies and sedimentary structures of Bed group 19. (a) Banded dolostone, Kløftelv section, Ella Ø. (b) Slump-folded laminated dolostone with dispersed carbonate clasts, interpreted as a mass-flow, in scree boulder, north flank of Trugbjerg, northern Suess Land. (c) Slump-folded dolomitic shale, north flank of Trugbjerg. (d) Typical breccia near the top of Bed group 19: limestone clasts in a dolostone matrix; Kap Lagerberg, Lyell Land. (e) Outsize limestone clasts in laminated dolostone. The stone in the centre of the picture suggests deposition from an ice raft, although the lamination in the surrounding dolostone may be a flow lamination when the sediment underwent subaqueous mass-flow; Kap Lagerberg, Lyell Land. (f) Contact between Bed group 19 and the Ulvesø Formation, immediately east of Langgletscher Dal, on the coast. The contact, which is transitional over a few centimetres from strongly cleaved shale to diamictite, is marked by a concentration of boulders (mainly dolostone), which are interpreted as dropstones. (g) Outsize quartzite boulder in shale, 2 m below the top of the Bed group 19; north coast of Antarctic Sund opposite Langgletscher Dal; this also is interpreted as a dropstone.

a

Fig. 12. (a) Stratigraphic succession at locality 7, Antarctic Sund, showing shales and dolostones of Bed group 19, overlain by black, massive limestone of Bed group 20, and diamictites of the Ulvesø Formation. The black limestone appears light coloured here and trends from just above bottom right corner. (b) Close-up of the sharp contact at the base of the Ulvesø Formation (at hammer head) on limestone of Bed group 20, locality 7, Antarctic Sund.

b

the diamictite. In SE Andrée Land thickness variations within Bed group 20 are pronounced. Bed group 20 is *c.* 220 m thick (see preceding section) about 1 km SW of the Ajorpoq, whereas 1 km NE it is the same thickness as the Ulvesø Formation (less than 50 m thick). At the above localities Bed group 20 appears simply to overlie Bed group 19, but from Kap Lagerberg to Ella Ø the former is missing.

Observations in 1984/85 (MJH). – At Kap Lagerberg, in northern Suess Land (both on Trugbjerg and on the east side of Langgletscher Dal; locality 5) and in SW Ymer Ø facing Antarctic Sund (locality 6), the contact between the lowest diamictite and Bed group 19 is transitional over one to several centimetres (Figs. 10f, g; 13). The dolomite balls of Eha (1953), which occur at the contact at localities 5 and 6 (Fig. 10f), are concen-

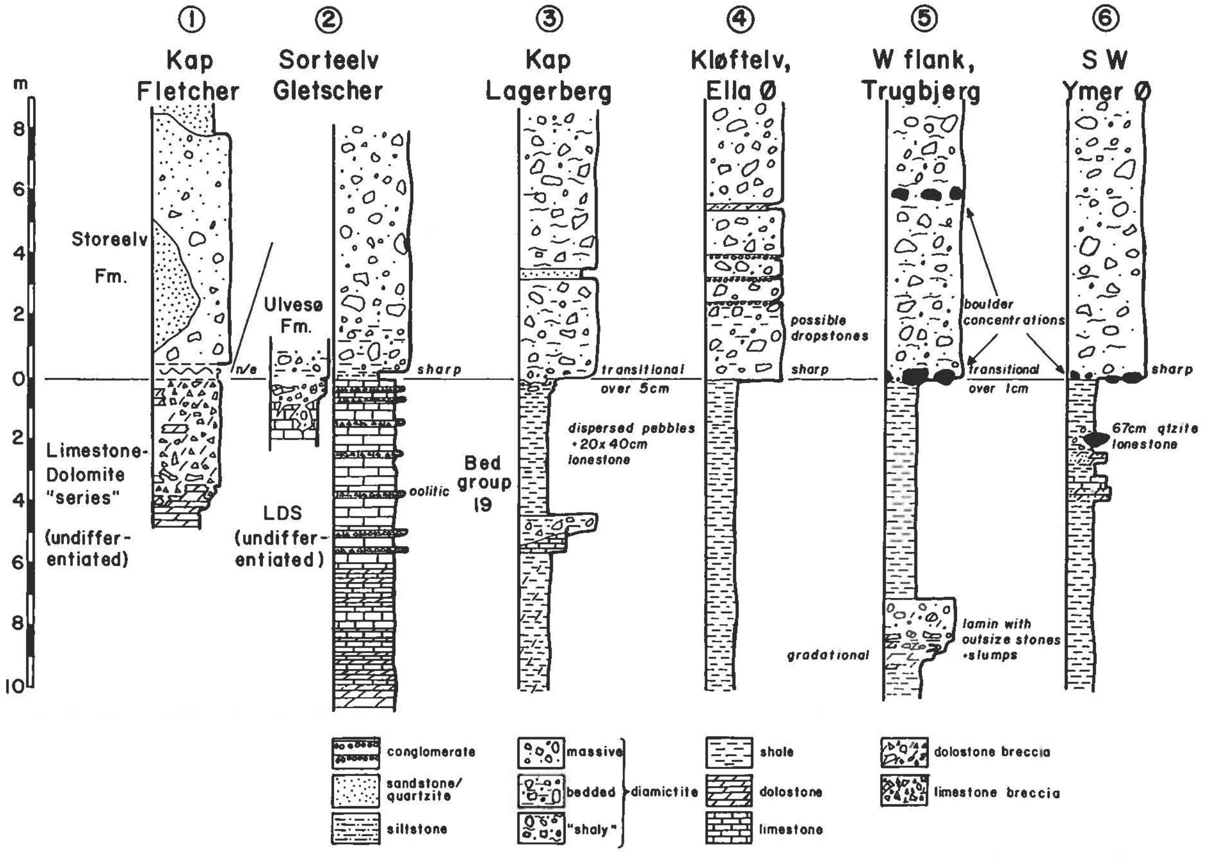


Fig. 13. Detailed measured sections across the boundary between the Limestone-Dolomite series and the Ulvesø Formation.

trations of what appear to be dropstones. They match lithologies of the Limestone-Dolomite "series" (pisolitic and stromatolitic carbonates), though a few quartzite boulders also were observed. At locality 6 only, layers and patches of coarse clastic material, including a quartzite boulder, occur about 2 m below the contact. On Ella Ø, the contact was again observed as being sharp: there is no concentration of dropstones and no obvious angular discordance between the diamictites, which are weakly bedded, and the underlying shales. There is no indication of deformation at the contact.

At Kap Weber, high up on the west flanks of the plateau of point 1410 m (locality 11), several tens of metres of dark grey limestones occur directly below a basal sandstone unit of the Ulvesø Formation. The contact is sharp and clearly tectonic (Fig. 11b): thrusting approximately parallel to bedding, local thickening and mylonitisation are all in evidence, while the limestones themselves are isoclinally folded and heavily veined with calcite near the contact. Other lithological contacts above are also thrust, with occasional tectonic repetition of some units locally. The direction of tectonic transport was approximately westwards.

Tectonic contacts between the Arena and Storeelv formations were observed elsewhere, notably in SW Ymer Ø facing Antarctic Sund.

At Sorteelv Gletscher in northern Scoresby Land (locality 2) diamictite rests on several metres of dark grey limestones (with some intraformational brecciation, minor trough cross-lamination and oolitic horizons) which in turn rest on interbedded pale dolostones and limestones (Fig. 13). None of these carbonates resemble those in either Bed groups 19 or 20, but are more akin to lower units in the Limestone-Dolomite "series", although Devonian conglomerates obscure much of the sequence in the critical locality. The precise nature of the contact was observed in two places 300 m apart (Fig. 13). At one place, a knife-sharp contact occurs between dark grey limestones and a 30 cm thick siltstone, grading thence rapidly into weakly bedded diamictite. In the other place, the contact is heavily silicified, but the top of the original limestone is irregularly brecciated to a depth of 1.5 m.

In Canning Land our observations indicate that diamictite rests directly on pale dolostones that were brecciated *in situ* to a depth of 4 m (Fig. 13). The dolostone resembles Bed group 18, but at the locality investigated there was no evidence of the presence of Bed group 19

(Caby 1972). There clearly is a major stratigraphic break here. The diamictite closely resembles the Storeelv Formation, so it appears that the Ulvesø and Arena formations are missing. Also, the Canyon and Spiral Creek formations seem to be absent.

Interpretation of nature of contact. – As well as containing its distinctive diamicites, the Ulvesø Formation is the first sandy formation after the long episode of Limestone-Dolomite "series" deposition, and clearly represents a major new sedimentation phase. In the outcrops visited between Kap Lagerberg and Brogetdal there is, however, no clearly visible angular unconformity beneath the formation. An unconformity can be *inferred* from rapid field observations at locality 7 (AMS) and from possible erosional stripping off of Bed group 20 south of about locality 7. However, none of these observations is conclusive, and more recent observations of the extent of thrusting in SE Andrée Land (MJH) suggest that the contact relations there and at locality 7 may alternatively be tectonic.

In detail, the contact beneath the lowest diamictite is knife-sharp at Ella Ø and Kiledal (locality 8). At Kap Lagerberg, northern Suess Land and SW Ymer Ø, however, the contact between the lowest diamictite and Bed group 19 – transitional over one to several centimetres – suggests continuous deposition, which in turn would imply that Bed group 20 must be the lateral equivalent of part of Bed group 19 or part of the Ulvesø Formation, or both. But again this reasoning is not conclusive: the transitions can alternatively be explained by soft sediment reworking.

The clearest evidence for continuity of deposition between the Limestone-Dolomite "series" and the Ulvesø Formation comes from the presence of inferred dropstones at localities 5 and 6, especially the latter where one possible dropstone occurs 2 m below the contact.

To the south of Kap Lagerberg, in northern Scoresby Land and certainly in Canning Land, Bed groups 19 and 20 do appear to be missing: the lowest diamictites rest unconformably on older rocks.

In summary, over most of the area studied the evidence on the nature of the lower contact of the Ulvesø Formation is inconclusive: in places it is sharp, in others it is transitional, in others it is thrust. Only in the very south of the area studied is it demonstrably unconformable. Nevertheless, in view of the presence in the Ulvesø Formation of abundant clasts matching the lithologies of the carbonates of the Limestone-Dolomite "series", the latter must have been deeply eroded somewhere.

Ulvesø Formation (formerly Lower Tillite) (Fig. 9)

The bulk of this distinctive formation consists of diamictite. A good section from the top of Bed group 19 to the Arena Formation occurs in the gorge of Kløftelv up to Ulvesø on Ella Ø (Fig. 9, 4B). This is the type locality. Another good, continuous section, 110 m thick, is exposed around the point between Tømmerbugt and Bastionbugt on Ella Ø (Fig. 9, 4E). Northwards it thins to 20–50 m, but in the far north it reaches nearly 160 m at Albert Heim Bjerge in Ole Rømer Land (Cowie & Adams 1957, Appendix). To the south, in northern Scoresby Land, the formation attains its maximum thickness of almost 170 m, but is absent altogether in Canning Land.

On Ella Ø the formation can be divided as follows: (i) lower half, massive or weakly bedded diamictite with shaly, friable matrix (Fig. 14a) and a few persistent conglomerate layers with erosional bases (Fig. 14b), (ii) upper half (except the top), massive diamictite with similar matrix (Fig. 14c, d), together with several sandstone and conglomerate beds or lens-shaped bodies, and (iii) at the top a hard, dark 4 to 9 m thick, bedded to massive diamictite with smaller stones than the more friable diamictites below (Fig. 14e, f). The diamictites, other than the topmost unit, are yellow-weathering, greenish-grey dolomitic siltstones with abundant stones of all shapes and sizes up to 3 m in diameter. At Kap Lagerberg and Sorteelv Gletscher local reddening appears to be related to jointing and Devonian weathering. The sandstones are medium- to coarse-grained, dolomitic and occasionally cross-bedded and pebbly. The conglomerates are composed of closely-packed, subrounded to rounded pebbles and cobbles of the same composition as the pebbles in the diamictites (Fig. 15a). Some thin sandstone and gravel interbeds have transitional bases and sharp tops, and are laterally extensive. Other such units are lens-shaped on a scale of a few to hundreds of metres, and have sharp upper and lower contacts, the latter often showing signs of erosion.

The three main subdivisions on Ella Ø cannot be distinguished outside the island. At Antarctic Sund the formation is more homogeneous, with few sandstone and conglomerate bodies except near the top. In general, despite a strong cleavage (Fig. 15b), the Antarctic Sund diamictites are better bedded than on Ella Ø and contain stones much bigger than the scale of the bedding (Fig. 15c).

In the thick northern Scoresby Land succession a wide variety of facies occurs. Particularly distinctive are two units of varve-like laminated siltstone and thin

Fig. 14. Facies in the Ulvesø Formation, Ella Ø. (a) Typical weakly bedded and slightly cleaved diamictite interpreted as a lodgement or waterlain tillite, middle of the formation. (b) Slightly boudinaged, partly matrix-supported mass-flow conglomerate, surrounded by diamictite which has a strong cleavage approximately parallel to bedding, which here is vertical and parallel to hammer shaft; Tømmerbugt section. (c) Massive diamictite in the middle of the formation, Storeelv. (d) Conglomeratic diamictite *c.* 15 m beneath the top of the formation, 400 m west of Ulvesø. (e) Well-bedded diamictite with wispy sandstone interbed and outsize stone, interpreted as a waterlain tillite; base of uppermost hard unit. (f) Hard, weakly bedded diamictite at the top of the formation; Tømmerbugt-Bastionbugt section (waterlain tillite).


a
b
c
d
e
f

dolostone horizons (Fig. 15d), 8.2 and 9.1 m thick (individual beds 0.1 to 3 m thick), which contain many outsize stones, often of algal dolostone (the largest measuring 125×55×40 cm) (Fig. 15e). The much thinner succession at Kiledal contains a varve-like siltstone horizon. This is 7.7 m thick and has laminae 4–10 mm thick and outsize stones (i.e. stones much bigger than the thickness of the laminae) of up to 9×5 cm. At Kiledal there are also thin dolostone beds and two massive diamictites, and the base of the 7.7 m unit is a gradation through 0.2 m from massive diamictite into laminated siltstones.

To the north of Kiledal sandstones occur beneath the lowest diamictite but are included within the Ulvesø Formation. They are dark and thinly laminated, and are interbedded with grey shales at Arenaen and Tillitekløft (Fig. 9, upper part of section 10C), but are white to yellow, and very coarse grained to pebbly at Tillitekløft (Fig. 9, lower part of section 10C), at the 1410 m summit above Kap Weber (locality 11), and in Brogetdal (loc. 12). The diamictite in the Kap Weber 1410 m summit area is distinctively hard, weakly bedded and reminiscent of the hard uppermost diamictite on Ella Ø. Locally, it contains rhythmites with dispersed outsize stones that have produced dropstone structures (Fig. 15f).

North of Antarctic Sund the thickness of the diamictite is much reduced. In Brogetdal the Ulvesø Formation is represented only by a small amount of diamictite with 35 m of yellow medium grained, planar-bedded sandstone in one section (Fig. 9, loc. 12A), whilst in another section a few hundred metres away there is a 7 m thick conglomerate composed dominantly of dolostone pebbles with some silicified oolite pebbles (average size 3 cm; largest stone 20×11 cm). At Waltershausen Gletscher, the formation is also thin (Katz 1954, fig. 12), but to the NE, at Albert Heim Bjerge, it reaches close to its maximum thickness (Cowie & Adams 1957, Appendix).

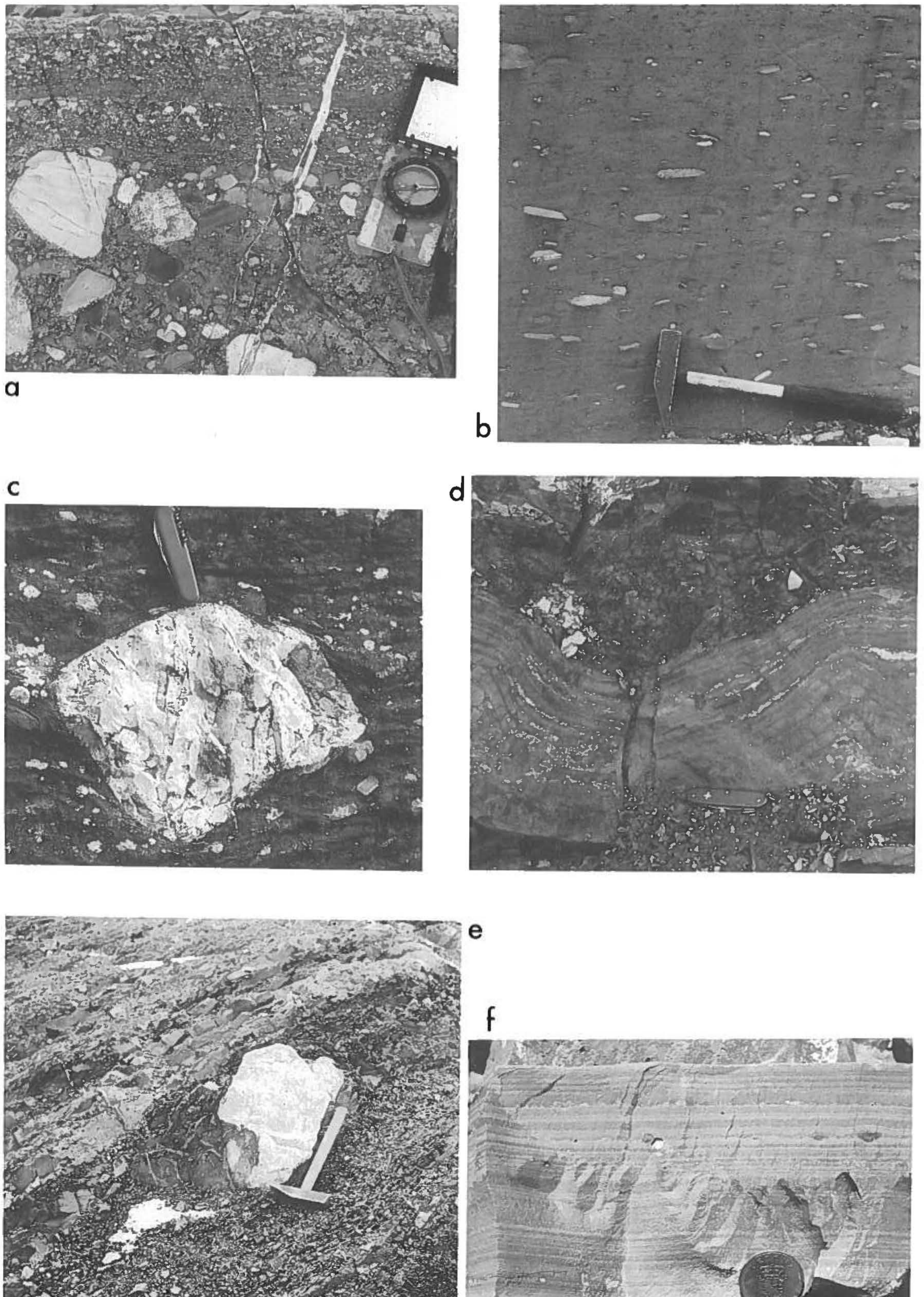
No internal correlation of the Ulvesø Formation can be carried all the way from Sorteelv Gletscher to Brogetdal (Fig. 9). One of the stratified beds appears to correlate for over 3 km between the three measured sections on Ella Ø, but even this is illusory. A 2.5 m thick pebbly sandstone can be traced continuously for several hundred metres in the outcrops above Tømmerbugt but the equivalent sandstone/conglomerate bed in the Kløftelv section varies in thickness and level and is often absent in the well exposed outcrops south of Ulvesø. This phenomenon – that stratified horizons within diamictites die out laterally – is observed at other stratigraphic levels within the formation on Ella Ø. In its extreme form, many sandstone bodies within the diamictites are sharp-edged lenticular pods. The one horizon which can be traced for a substantial distance is the distinctive, hard, bedded diamictite at the top of the formation: it occurs throughout Ella Ø, is visible in the cliffs in southern Suess Land, and near the 1410 m summit at Kap Weber, although it is not obviously present in northern Suess Land or on Ymer Ø.

Arena Formation (formerly Inter Tillite Beds) (Fig. 16)

Between the two diamictite formations occurs a sequence dominated by shales and sandstones, which at the type locality, Arenaen, is 223 m thick, with a monotonous succession of sandstone at the base, then shale, more sandstone, shale and sandy shale interbeds. In the south it is well exposed near the snout of Sorteelv Gletscher (*c.* 360 m thick) (Fig. 16, loc. 2). The lower two-thirds of the formation there consists of massive, poorly bedded, reddish sandstone with minor gravel lenses. It is interrupted by two distinctive diamictite units, each a few metres thick. One of these is a complex of massive to weakly bedded diamictite, sandstone, siltstone laminite and dolostone breccia. Compositionally, they resemble the diamictite of the Ulvesø Formation. The sandstone is overlain sharply by grey shale, in part dolomitic, with thin beds (5–20 cm) of pale brown dolarenite. The coarser units sometimes are trough cross-laminated. At the top, clasts of dolostone a few millimetres in size occur in the laminated shale, and a few trough cross-laminae and slumps (1 cm) occur. The contact with the overlying formation is channelled and a dolostone boulder occurs in the uppermost part of the shale unit.

On Ella Ø the formation is *c.* 250 m thick but is incompletely exposed, even in the best outcrops along the coast of Bastionbugt. There the same lithologies are present as at Sorteelv Gletscher except for the thin diamictite units. The lowest sandstone on Ella Ø is yellow and thin; wave ripples are present on some bedding surfaces near the base (Fig. 17a). A second sandstone unit (grey) shows graded bedding and slump structures. A sandstone at the top of the formation contains large interference ripples (probably shallow marine), minor convolute bedding and mudflakes (the largest meas-

Fig. 15. Facies and sedimentary structures in the Ulvesø Formation. (a) Clast-supported conglomerate with clasts primarily of dolostone and limestone, inferred to have been fluvially deposited. Inverse grading is evident towards the top of each of the two beds shown here. Lower half of the formation at locality 2, Sorteelv Gletscher. (b) Deformed, weakly bedded diamictite (interpreted as a waterlain tillite) at the base of the formation, Antarctic Sund, SW coast of Ymer Ø. Stones are flattened in the plane of a bedding-parallel cleavage. (c) Outsize stone of dolostone in the weakly bedded but strongly cleaved diamictite of the lower part of the formation, northern flank of Trugbjerg, northern Suess Land. (d) Dolostone rhythmite, slump folded and partially brecciated, in between two diamictite beds, middle of formation at locality 2. (e) Dolostone dropstone in bedded shales at locality 2 (shown in Fig. 26a). (f) Rhythmite with dispersed dropstones (interpreted as a glaciolacustrine varvite), below the 1410 m summit, west of Kap Weber.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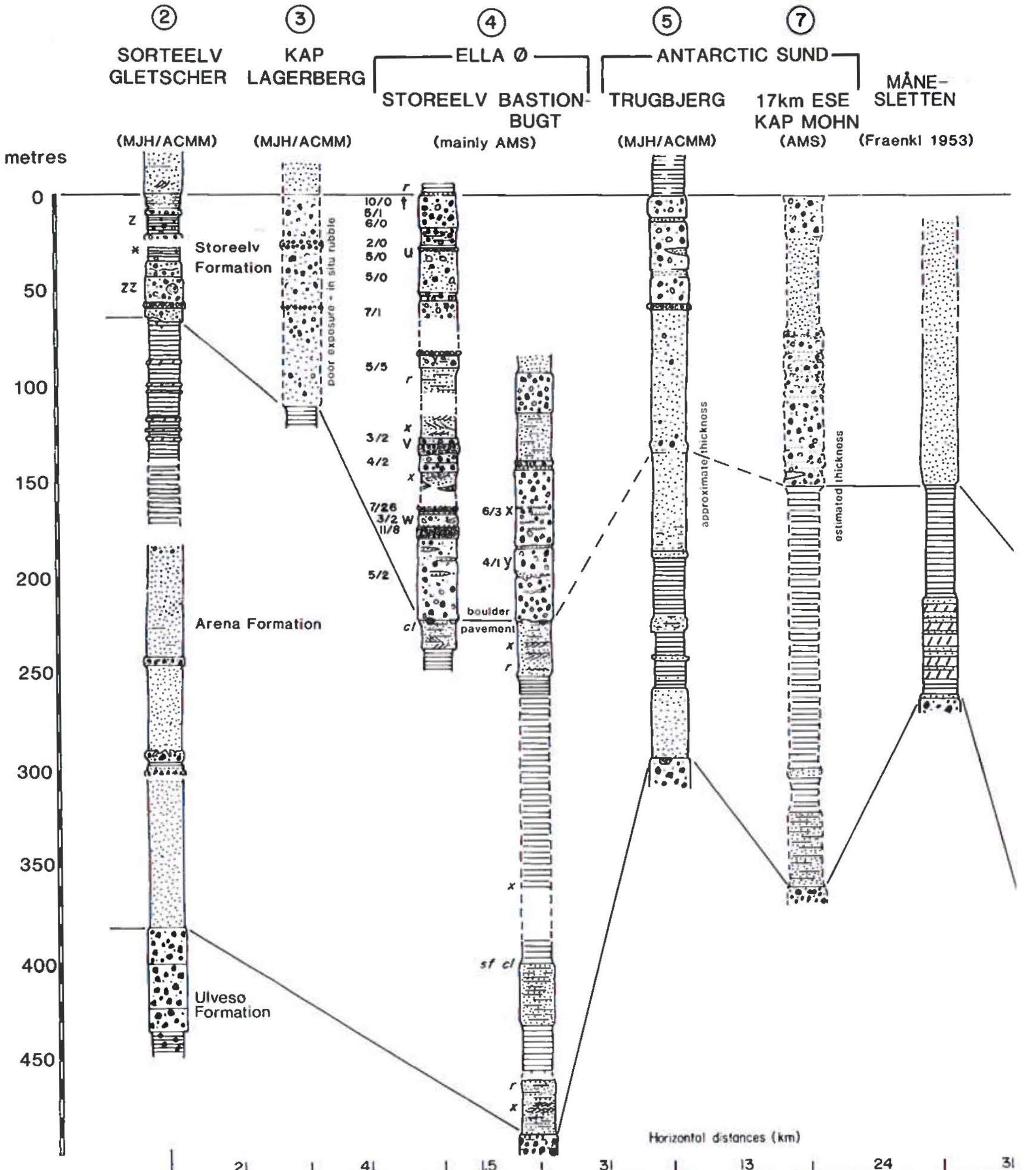


uring 70×9×1 cm). Its top surface contains a concentration of cobbles and boulders. largely granitoids, which appear to be planed off (Fig. 17d) beneath the massive diamictite of the overlying formation.

In the Kap Weber area the formation is composed mainly of dark blue or dark green shale, with thin, rare limestone and dolostone beds, but with sandstone units at the base, in the middle and at the top. The latter have cross-lamination (Fig. 17b) and load structures (Fig. 17c). At Brogetdal and Waltershausen Gletscher the formation is only of the order of 100 m thick, but increases to 220 m again at Albert Heim Bjerge where it consists of argillaceous siltstone with a calcareous sandstone in the middle (Cowie & Adams 1957).

Storeelv Formation (formerly Upper Tillite) (Fig. 16)

The formation is thickly developed (*c.* 200 m) in the region from Ella Ø to Arenaen. North of there it thins to 60 m in Strindberg Land, while at Albert Heim Bjerge,

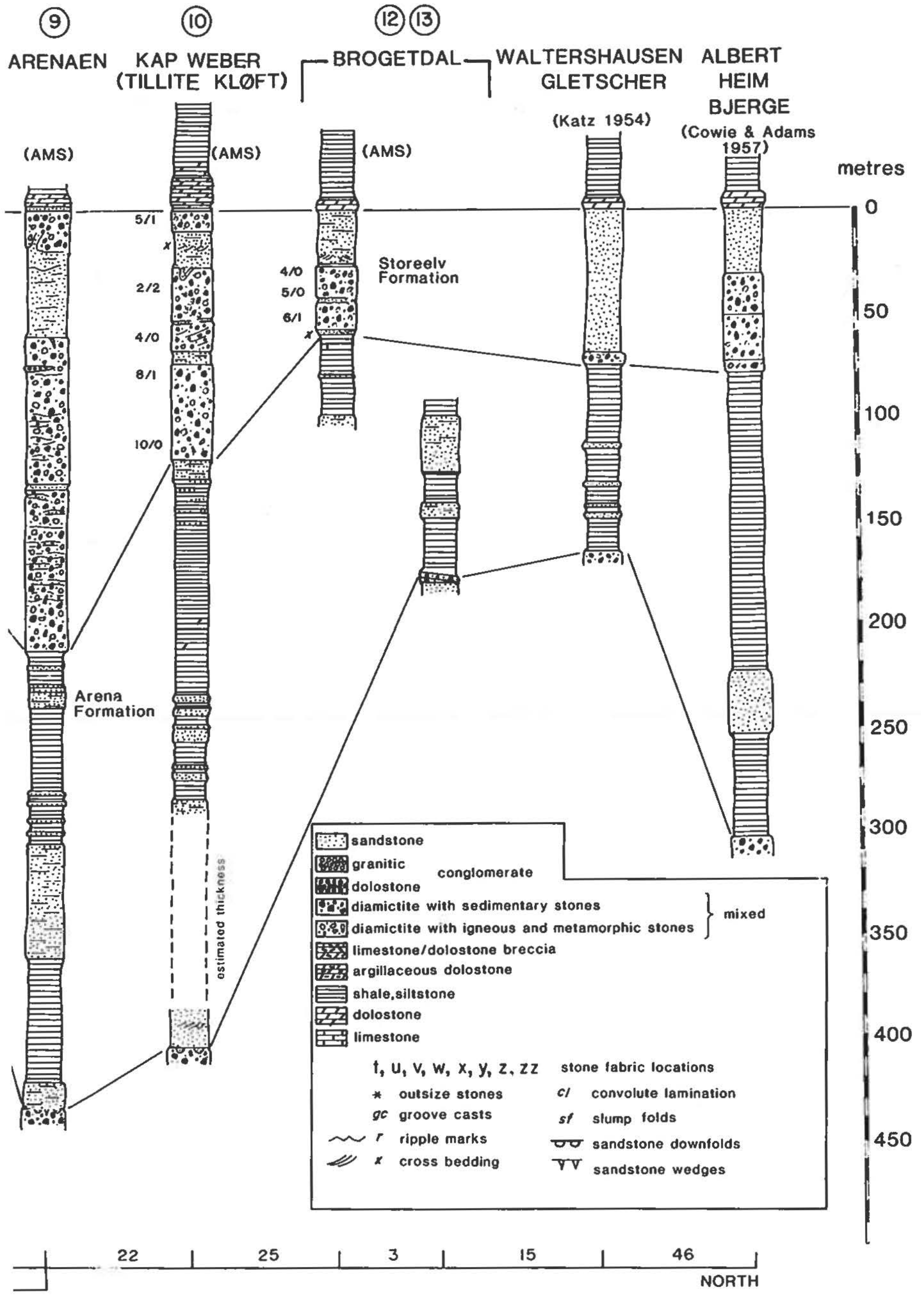


Fig. 16. Stratigraphic columns through the Arena Formation (formerly Inter Tillite Beds) and the Storeelv Formation (formerly Upper Tillite). The column at Waltershausen Gletscher is from Katz (1954, fig. 12), Månesletten from Fränkl (1953b), and that at Albert Heim Bjerge from Cowie & Adams (1957, Appendix). Small letters show the positions of the stone fabric measurements of Fig. 28. Figures quoted thus (6/3) give the numbers of stones with diameters larger than 1 cm in 1 ft^2, in the order pale dolostone/metamorphic and igneous types. Data source abbreviations as for fig. 9.

Cowie & Adams (1957) recorded a thickness of 80 m, of which some 30 m was sandstone. The formation also thins to the south of Ella Ø. No subdivisions can be correlated between the separate outcrops, but in general the lower part of the formation is most often composed of thick diamictite beds, whilst the upper part is often dominated by lenticular sandstones.

The base of the formation everywhere is drawn beneath the lowest diamictite bed where it overlies shale or sandstone of the Arena Formation. The contact normally is knife-sharp, massive diamictite resting on sandstone or shale. At and above Bastionbugt and above the right bank of Storeelv on Ella Ø, however, the contact is marked by a planed-off boulder-cobble pavement (Fig. 17d) (described in the previous section). About 300 m inland from Bastionbugt, a 1 m thick, poorly bedded sandstone with scattered cobbles separates the massive sandstone from the unbedded diamictite. In Brogetdal the 2 m cross-bedded sandstone at the base of the formation is lenticular and is replaced laterally by con-

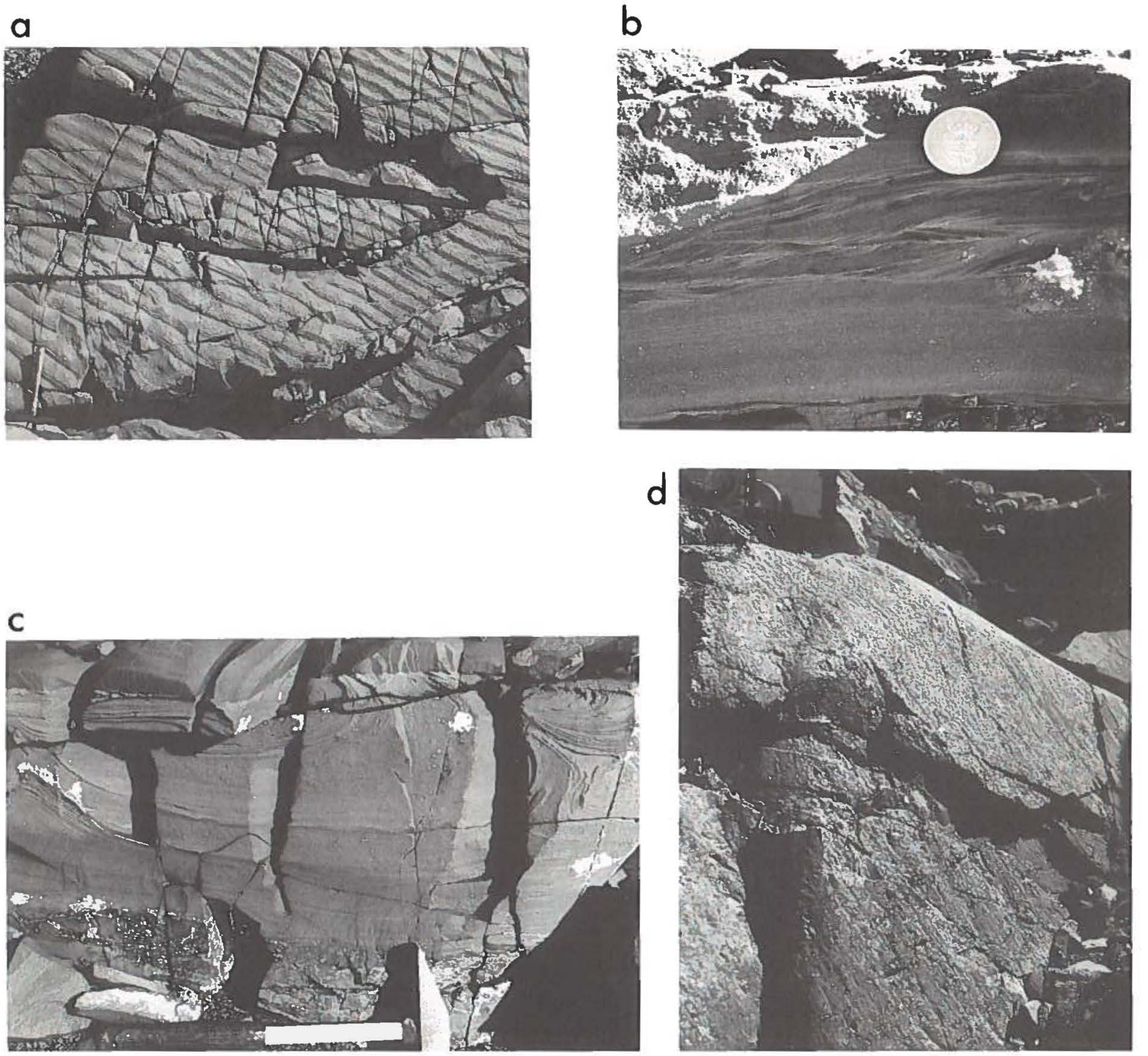
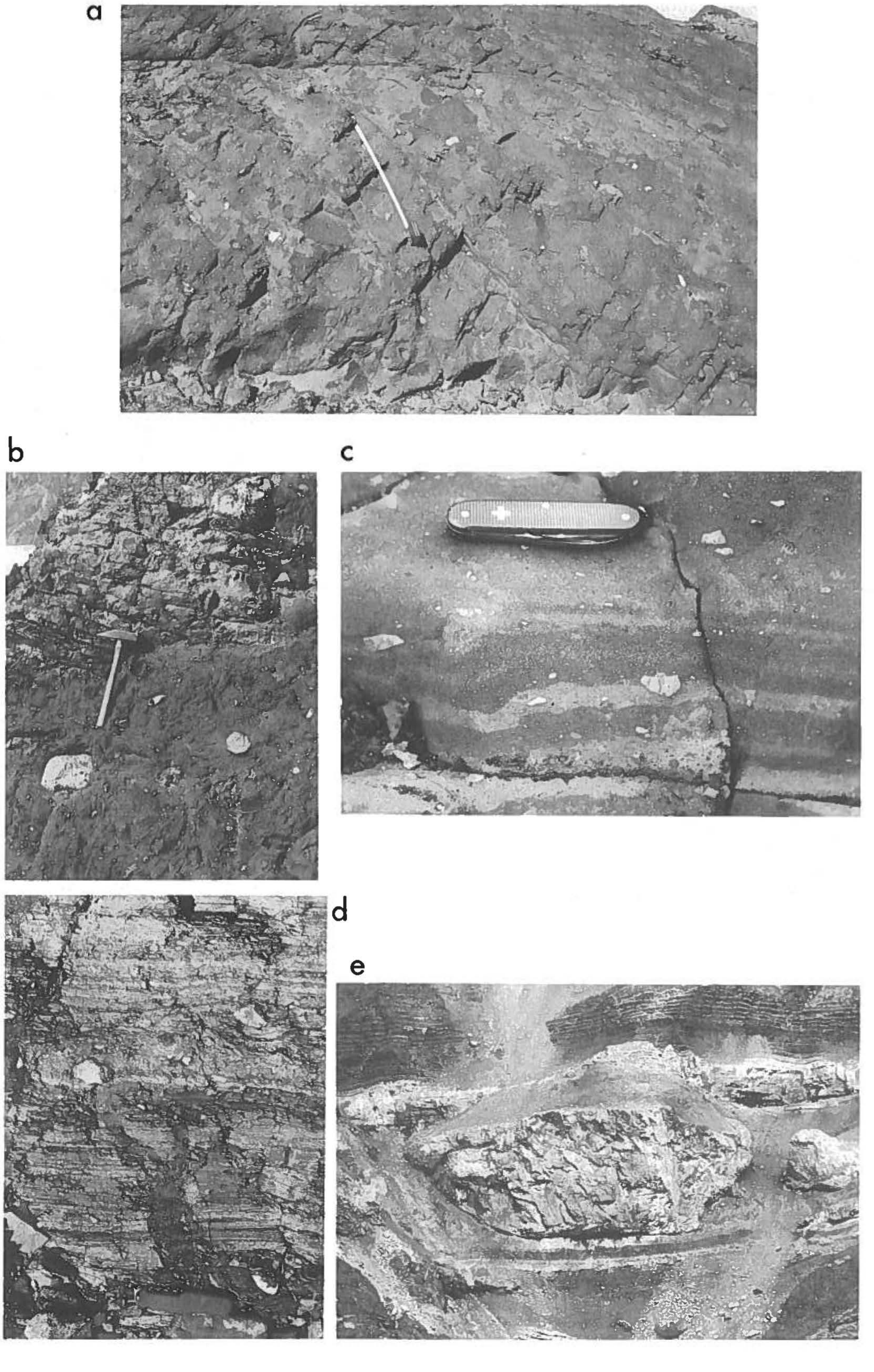


Fig. 17. Facies and sedimentary structures in the Arena Formation. (a) Wave-rippled sandstone near the base of the formation, Bastionbugt shore section, Ella Ø. (b) Cross-lamination and scouring in sandstone in the middle of the formation, 845–1410 m ridge, west of Kap Weber. (c) Convolute laminated sandstone due to loading, upper part of formation, 945–1410 m ridge, west of Kap Weber. (d) Contact with Storeelv Formation, with a large striated and planed-off granite boulder embedded in laminated siltstone, and overlain by massive diamictite, at Bastionbugt. This is the top, abraded surface of the boulder, looking directly down on to it. (Moncrieff & Hambrey in prep.).

glomeratic diamictite. At Sorteelv Gletscher the contact shows a rapid transition. Finally, at Kap Fletcher in Canning Land, a diamictite inferred to represent the Storeelv Formation rests directly on shattered dolostone of the Limestone-Dolomite "series", and the Arena and Ulvesø formations, plus Bed groups 19 and 20, are apparently missing (Fig. 3), although Caby (1972) does report the possible occurrence of a few metres of Bed group 19.

The Storeelv Formation contains a wider range of fac-

Fig. 18. Facies and sedimentary structures of the Storeelv Formation. (a) Massive diamictite in the middle of the formation, Storeelv, lower section, Ella Ø. (b) Massive maroon diamictite (lodgement tillite) in diffuse contact with less matrix-rich diamictite with signs of reworking by water (lighter colour); note the variably developed cleavage; Storeelv section, Ella Ø. (c) Bedded maroon and greenish-grey diamictite with dispersed outsize stones, interpreted as a waterlain tillite; Storeelv, upper gorge section. (d) Rhythmite with dispersed stones interpreted as a varvite with ice-rafted material; Sorteelv Gletscher section, northern Scoresby Land. (e) Approximately 15–20 m high sandstone lens in maroon diamictite, interpreted as a braided stream channel fill in tillite, Arenaen, Gunnar Andersson Land. Above lies the basal dolostone and striped dolomitic shales of the Canyon Formation.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ies than the Ulvesø Formation. Diamictites are generally massive (Fig. 18a, b) but there are also units with weak to prominent bedding on a scale of a few metres, or rarely diamictites with an irregular lamination on a scale of a few centimetres (Fig. 18c). The most obvious difference with the Ulvesø Formation is in the colour of the matrix: maroon, chocolate brown, light brown, green, dark grey and (where somewhat tectonised, as in northern Suess Land) purple. The matrix of both massive and weakly bedded diamictites has a grain size ranging from clay to sand and both contain stones up to 1 m in diameter. These stones include an abundance of crystalline components as well as lithologies represented in the Limestone-Dolomite "series" (see section "Description of stones"). Well-bedded diamictite grading into rhythmite with numercus dispersed stones has been observed at a number of localities. For example, in the type locality at Storeelv, a 3 m unit lying 50 m below the top of the formation consists of (from top to bottom): maroon, massive but friable diamictite with green streaks; siltstone with dispersed clasts; a lens of maroon shaly diamictite; maroon silty diamictite; laminite with numerous clasts; slump-folded silty sandstone with streaky lamination; all resting on massive maroon, greenish-grey mottled diamictite. At Sorteelv Gletscher a 20 m unit at the top of the formation comprises a sandy laminite grading into rhythmite with numerous dispersed stones up to 6 cm in diameter, and includes a few centimetres of millimetre-scale couplets (Fig. 18d).

Sandstones are common and are medium- to coarse-grained, sometimes cross-bedded and pebbly, though bedding generally is not well defined. Poorly sorted polymict conglomerates are also common; they contain dolostone and crystalline pebbles in a sandy matrix. Both the sandstone and the conglomerate beds are lenticular. To illustrate this, the well-exposed outcrops lying just NE of Storeelv were measured in the form of a horizontal section chart (Fig. 19): some sandstone and conglomerate beds there die out laterally and are equivalent to homogeneous, massive diamictite. At Arenaen numerous lens-shaped bodies are well-exposed, illustrating clearly that they represent channel fills within massive diamictite (Fig. 18e).

Other facies in the Storeelv Formation include conglomerate lag deposits a few centimetres thick at the top of (and gradational with) diamictite units, minor shale horizons and wedge-shaped bodies of pebbly sandstone extending down from bedding surfaces. No carbonates have been observed.

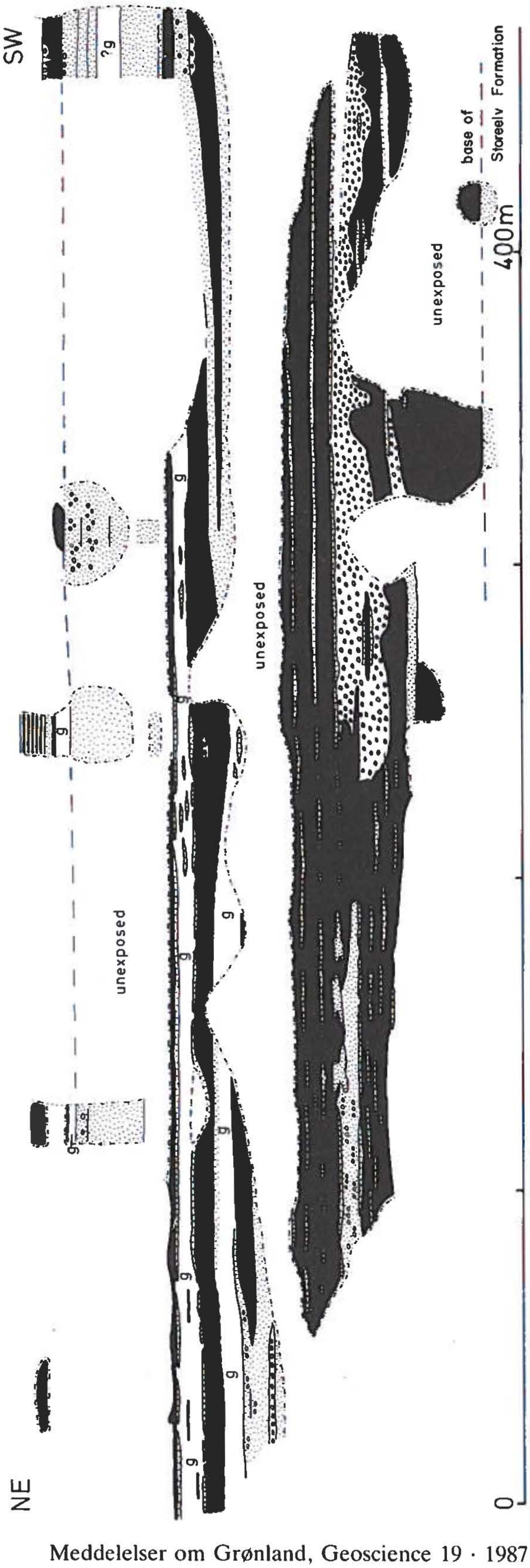


Fig. 19. Horizontal section chart showing the lateral stratigraphic changes in the lower two-thirds of the Storeelv Formation 450 m eastwards from Storeelv, Ella Ø. Solid black is diamictite with maroon matrix; g is diamictite with greenish-grey matrix. The succession depicted at the south-western end of the diagram is close to the location of the measured column given in Fig. 16.

The variation in matrix colour of the diamictites, maroon or greenish grey, has been noted previously. Fränkl (1953a, Tafel 3; fig. 19) observed that the diamictite was red from Ella Ø to Kap Weber but greenish grey to the north and south. This is an over-generalisation. On Ella Ø, perhaps through 10% of its total thickness, the Storeelv Formation consists of green or greenish grey diamictite. At Arenaen two massive diamictite units are maroon (the basal 25 m bed; the central 20 m bed), another contains intercalated maroon and greenish grey horizons (the lower 36 m bed) and the rest are greenish grey. The diamictite beds in Brogetdal show interbedded brown/green and red/green colouring throughout. Often the colouring is not confined to a particular bed exactly, but gives a mottled effect.

The top of the Storeelv Formation is most clearly seen in the stream after which it is named. There the top maroon diamictite assumes a green colour in its uppermost 0.5 m, and then is overlain sharply by a 0.5 m thick ripple-marked and desiccation-cracked sandstone, above which come the maroon and green dolomitic shales of the Canyon Formation. Northwards from Ella Ø a prominent dolostone horizon intervenes between the uppermost diamictite and the maroon-green dolomitic shales and is considered to be the basal unit of the Canyon Formation (Fig. 16). At Sorteelv Gletscher the top of the Storeelv Formation is conformably overlain by maroon sandy shale, sandstone and then a thick unit (>95 m) of white quartzite, all of which are cross-bedded. Fränkl (1953a) considered these to belong to the Kløftelv Formation, but the conformable contacts belie this interpretation. At Canning Land the diamictite in one exposure is capped and incised to a depth of several metres by a channel-like fill of white quartzite. At Kap Lagerberg, the succession is poorly exposed, but a massive white sandstone overlies the diamictite; Sommer (1957) inferred this sandstone to be an unconformable Devonian outlier, but it could be equivalent to the conformably overlying quartzites of Sorteelv Gletscher.

Canyon Formation (Fig. 20)

The approximately 300 m thick Canyon Formation is present on and to the north of Ella Ø. Schaub (1950) described the Ella Ø succession, identifying a "Varve member" and an overlying "Suncracked member". Katz (1961) proposed a tri-partite subdivision, reflecting more closely the succession at Kap Weber and in Strindberg Land, namely a "Yellow-red Dolomite Member", "Black Shale Member" and "Limestone Member". Two sections are described here: a composite section measured in Storeelv and in Solitærbugt on Ella Ø, which repeats the observations of Schaub and Cowie & Adams (1957, pp. 168–169), and a new section at Arenaen in Gunnar Andersson Land (Fig. 20). No new "members" will be erected here: four informal units will be employed, the lowest two of which correspond to Schaub's "Varve Member" and Katz's "Yellow-red Dolomite Member".

The lowest unit in the formation is an orange or yellow, laminated dolostone, 6 to 13 m thick, which at Arenaen and Tillitekløft rests almost directly on diamictite or a thin horizon of silty shales of the Storeelv Formation (Fig. 16). At Arenaen the dolostone is a trough cross-bedded dolarenite (Fig. 21a) with some autobrecciation at the bottom and top. The base is knife-sharp, but the top is transitional over 2 m with green/maroon dolomitic shales.

In Tillitekløft and Brogetdal the dolostone is succeeded by green/maroon dolomitic shales in which the green laminae become thicker upwards until the strata are entirely green or greenish grey. The thickness of this second unit in the formation (to the level of the highest maroon shale) is 25 m at Arenaen, 36+ m at Tillitekløft and 28 m at Brogetdal. In Tillitekløft the yellow laminated dolostone is transitional upwards into the maroon dolomitic shales through 9 m of colour-banded dolostone similar to the dolostones in Unit IV of Bed group 19 of the Limestone-Dolomite "series". On Ella Ø the yellow, laminated dolostone is absent and maroon shales with green and white laminae (Fig. 21b) rest almost directly on the highest diamictite of the Storeelv Formation, less than 1 m of ripple-marked sandstones and greenish-grey shale intervening. The unit with maroon/green colour banding has been suggested to be of varve origin (Poulsen 1930), an idea which was supported by the detailed descriptions and study of Schaub (1950). However, the colouring is not exactly coincident with individual laminae or beds and appears to be post-depositional.

The third unit consists of argillaceous beds 160–190 m thick. Mostly these are dark grey, sometimes greenish shales and siltstones. In Storeelv the central 17 m and 9.2 m beds are predominantly maroon and a 6 m maroon siltstone bed at Arenaen may be the equivalent. Sparse dolostone nodules are often developed in several parts of the unit. The top 30 m of the unit consists mainly of cross-laminated sandstones with load-casted ripples (Fig. 22). No mudcracks were observed.

The fourth unit is a 50 m thick succession of yellow dolostones, dark grey shales, flake breccia beds and rare oolite horizons (Fig. 22). On Ella Ø units 1–3 were measured in Storeelv and unit 4 along the coast of Solitærbugt (Fig. 20): the two columns were correlated using the lowest 2.5 m dolostone bed, which has a distinctive tri-partite sequence (Fig. 21c). It was from this fourth unit that Schaub (1950) described the "Suncracked laminae", here interpreted as desiccation flake breccias (Fig. 21g) which are commonly associated with algal stromatolites. Several beds of algal structures are present. They vary from ovoid stromatolitic masses (Fig. 21d) to laterally continuous beds. Some beds are thin (Fig. 21f) but the thickest is a massive 2 m dolostone with a well-developed lamination arranged in stromatolitic growth structures (Fig. 21e). Occasionally,

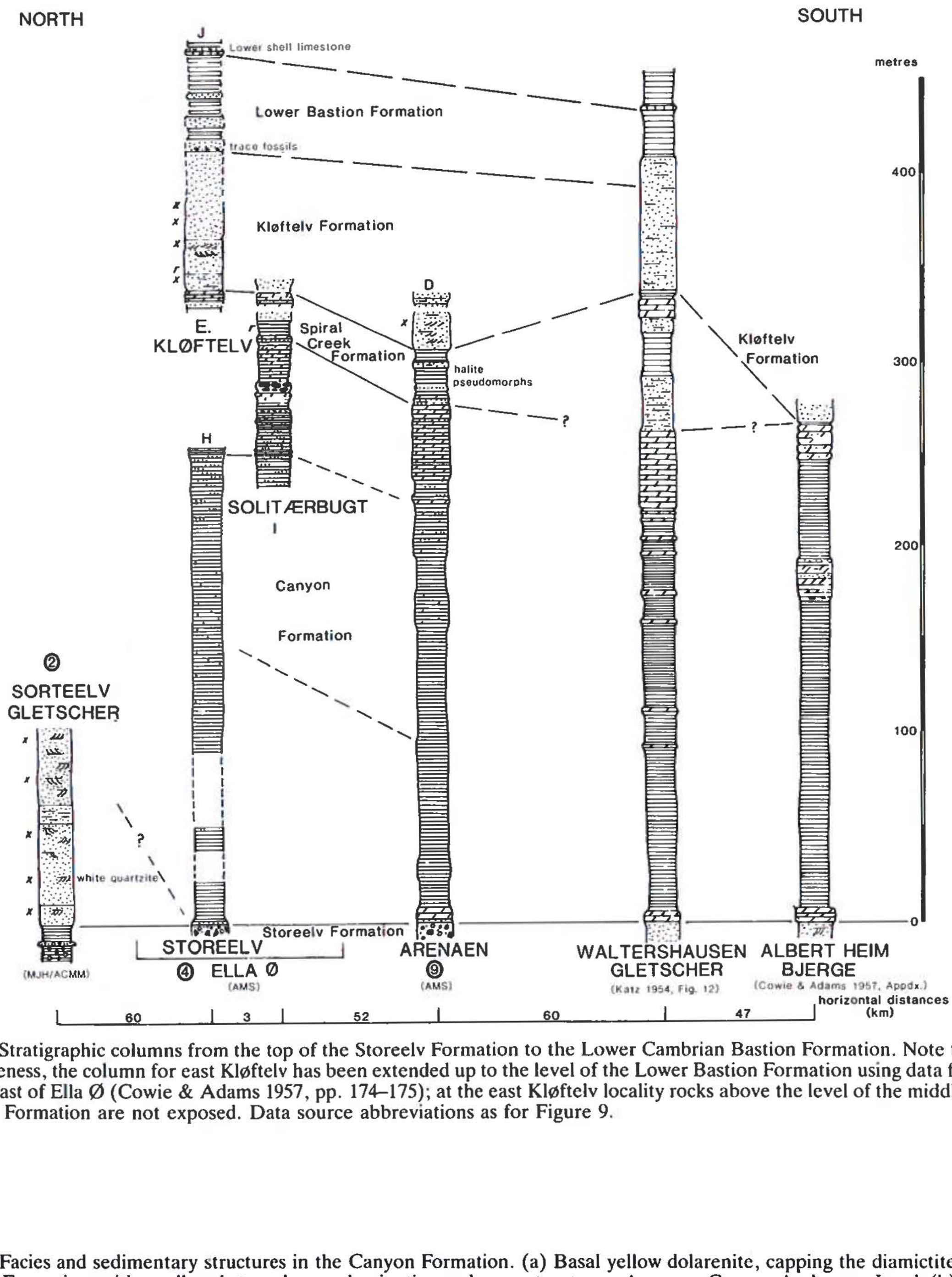
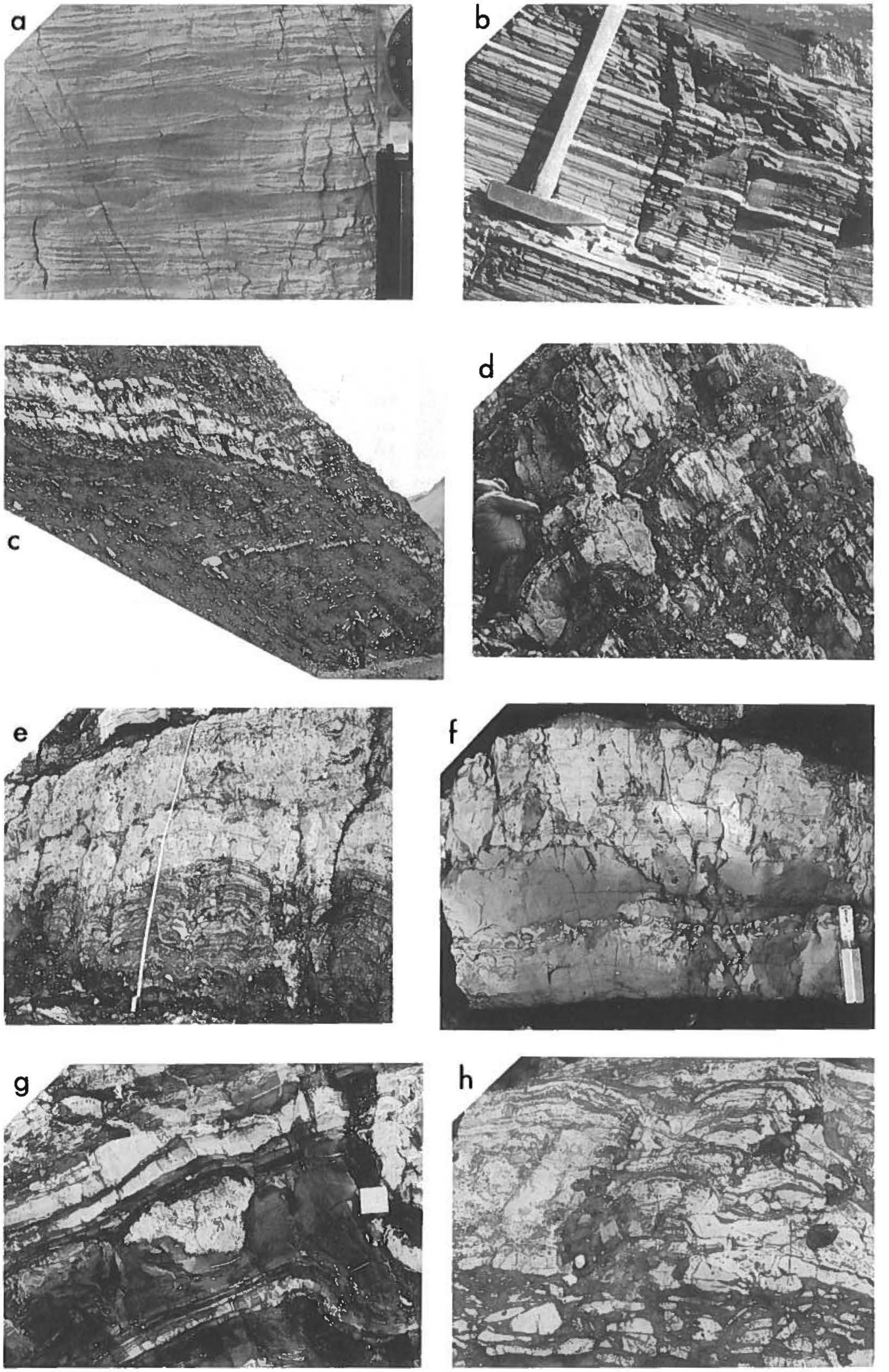


Fig. 20. Stratigraphic columns from the top of the Storeelv Formation to the Lower Cambrian Bastion Formation. Note that, for completeness, the column for east Kløftelv has been extended up to the level of the Lower Bastion Formation using data from the south coast of Ella Ø (Cowie & Adams 1957, pp. 174–175); at the east Kløftelv locality rocks above the level of the middle of the Kløftelv Formation are not exposed. Data source abbreviations as for Figure 9.

Fig. 21. Facies and sedimentary structures in the Canyon Formation. (a) Basal yellow dolarenite, capping the diamictites of the Storeelv Formation, with small-scale trough cross-lamination and scour structures; Arenaen, Gunnar Andersson Land. (b) Rhythmically laminated maroon and pale green dolomitic siltstones near the base of the formation in the Storeelv section, Ella Ø; this is the so-called "varve member" of Schaub (1950) but there is no evidence to suggest an annual cyclicity of deposition, and the colour banding is a secondary phenomenon with the greenish colour resulting from reduction. (c) Sequence at Solitærbugt, Ella Ø, at and below the lowest dolostone bed. (This is the 2.5 m thick tri-partite bed of Fig. 22). (d) Horizon of ovoid stromatolites (below geologist's arm), overlain by massive stromatolitic dolostone, Solitærbugt (the 1 m and 2 m beds of Fig. 22). (e) Massive stromatolitic dolostone at Solitærbugt (the 1.2 m bed of Fig. 22). (f) Stromatolitic dolostone with the lower bed showing 2 cm high algal growth heads, Solitærbugt (immediately above the 1.2 m bed of Fig. 22). (g) Channel filled with stromatolitic flake breccia, Solitærbugt (the 4 m bed below the lowest stromatolitic horizon of Fig. 22). (h) Dolostone stromatolites developed on a dolostone breccia that probably resulted from a storm event in relatively shallow water; from near the top of the formation, waterfall section east of upper Storeelv, Ella Ø.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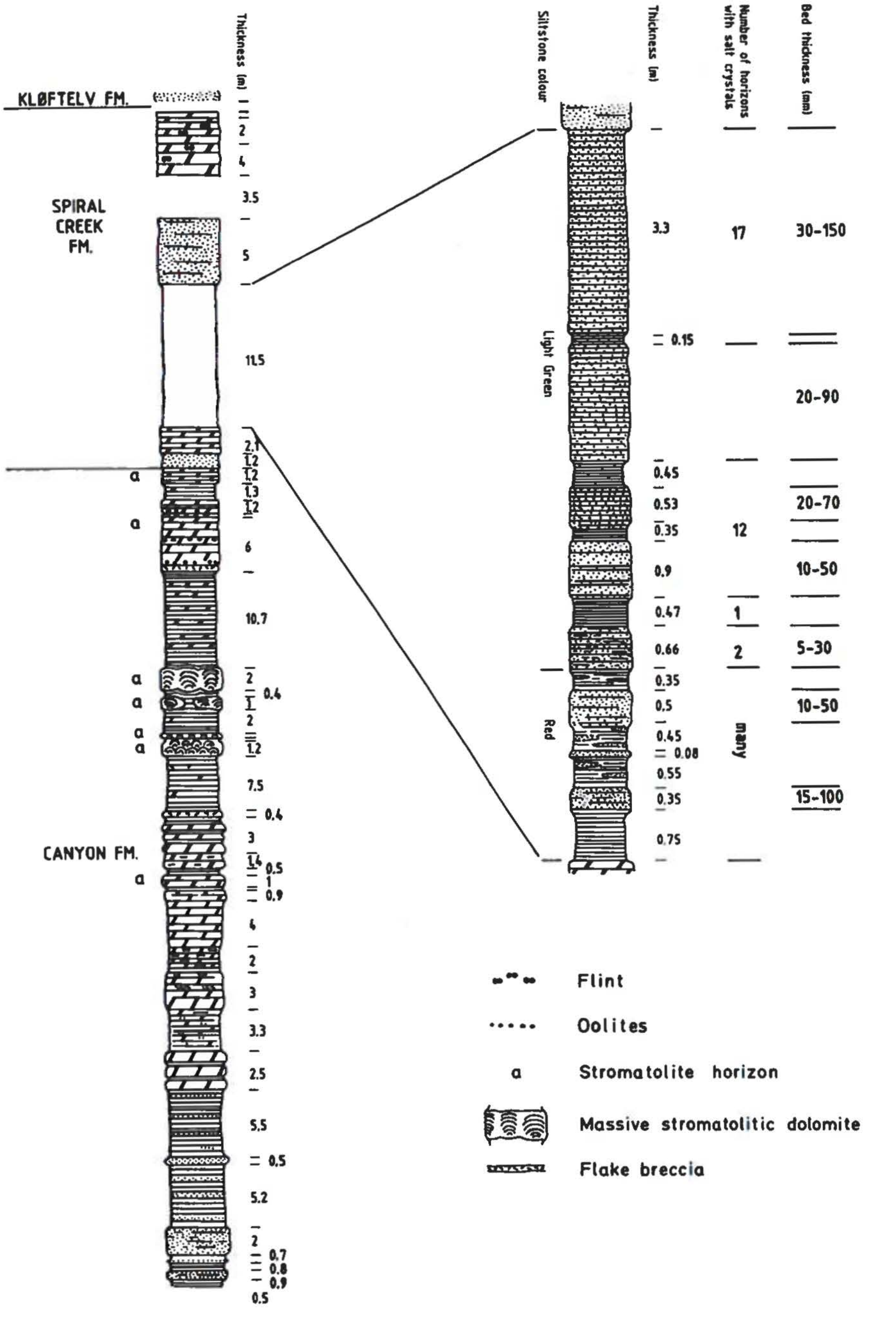

Fig. 22. Stratigraphic column through the upper Canyon Formation and Spiral Creek Formation at Solitærbugt, Ella Ø. It is an enlargement of that shown in Fig. 20 (I).

the stromatolites are observed to have grown on intraformational (rip-up) dolostone breccias (Fig. 21h).

Spiral Creek Formation (Figs 20, 22)

This 25 m thick formation consists of sandstones, siltstones and dolostones. One 11.5 m unit of thinly laminated sandstones (Fig. 20), interbedded with siltstones (Fig. 23a), contains abundant halite pseudomorphs on the base of the sandstone beds (Fig. 23b), which are also ripple-marked (Fig. 23c), mud-cracked and have occasional trough cross-lamination (Fig. 23d) and silicified pebbles. Full descriptions have previously been given by Schaub (1950) and Cowie & Adams (1957) and no description is presented here. However, it is worth noting that there is little evidence for the unconformity at the base of the formation that Poulsen (1930) and Schaub (1950) proposed; the succession on Ella Ø and at Arenaen are identical (Fig. 20).

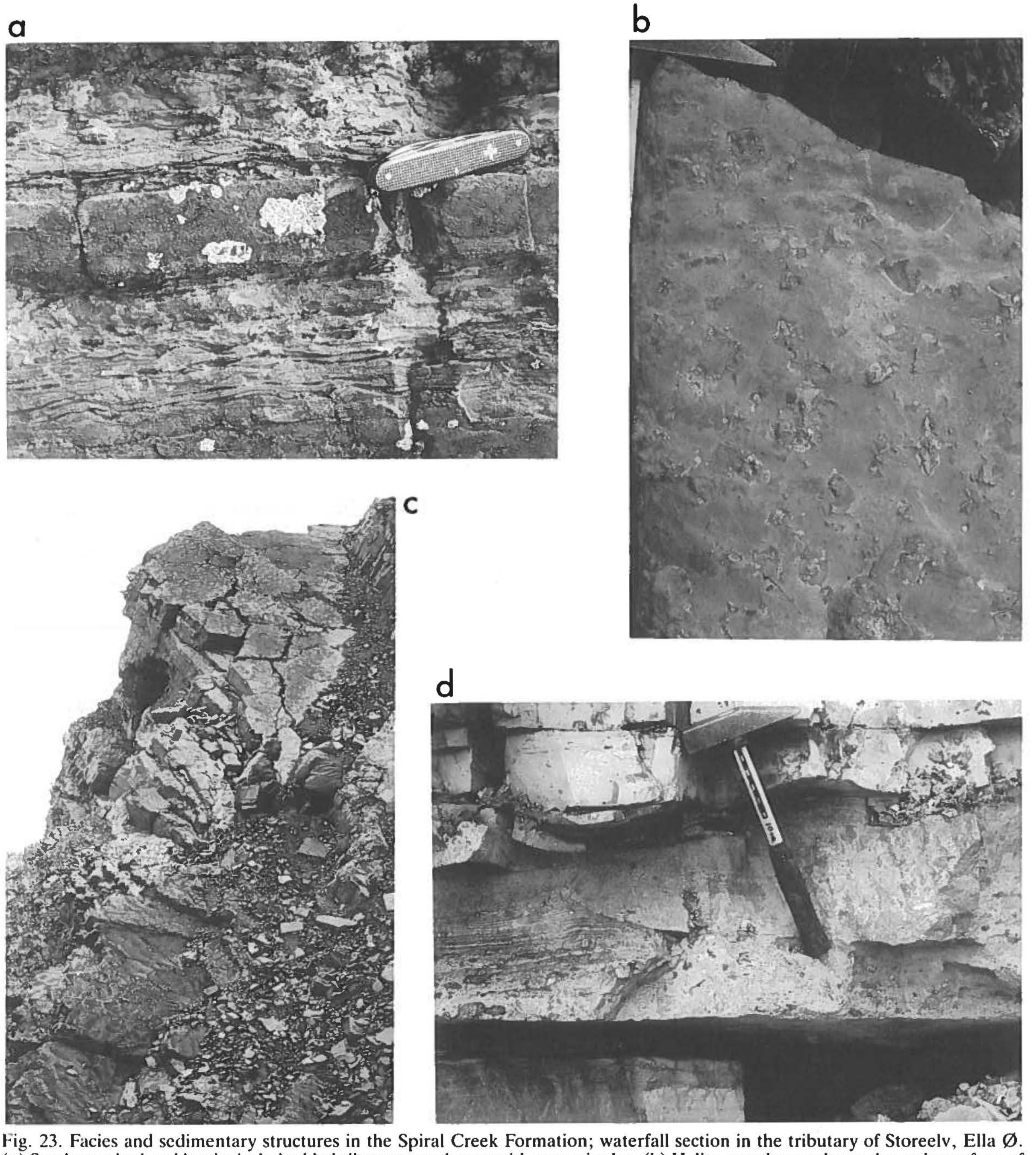

Fig. 23. Facies and sedimentary structures in the Spiral Creek Formation; waterfall section in the tributary of Storeelv, Ella Ø. (a) Sandstone bed and lenticularly-bedded siltstone-sandstone with wave ripples. (b) Halite pseudomorphs on the undersurface of a siltstone bed. (c) Wave ripples and interference ripples on bedding planes of sandstone and siltstone. (d) Trough cross-bedding in laminated sandstone-pebbly sandstone.

Kløftelv Formation (Figs 20, 24)

From Ella Ø to Kap Weber the halite pseudomorph beds are succeeded by *c.* 70 m of cross-bedded quartzites and sandstones which Cowie & Adams (1957) placed in the Kløftelv Formation. Their measured succession (*op. cit.* fig. 40) was from the south coast of Ella Ø. An incomplete succession was measured above Solitærbugt (Fig. 24). There, possible trace fossils were found as bottom structures on thin sandstone beds and irregular and sometimes polygonal, possibly desiccation cracks occur on the bottom of small basin-like depressions on some bedding planes.

Haller (1971, p. 124) noted the uniformity of thick-

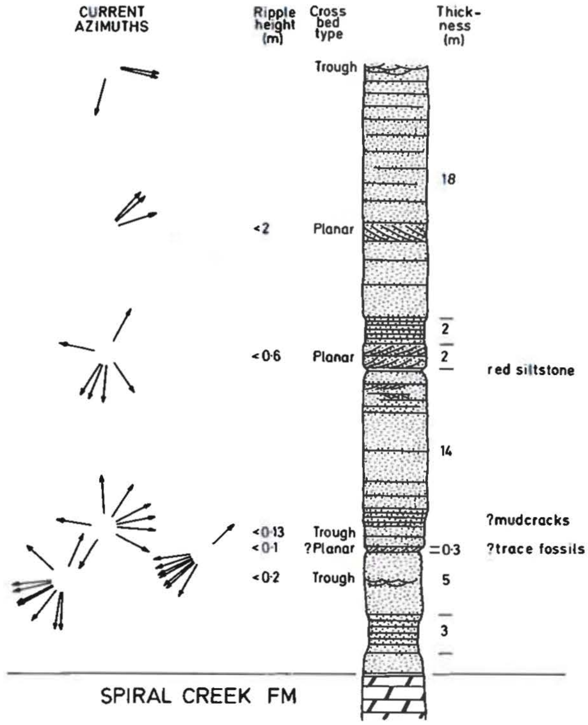

Fig. 24. Stratigraphic column through the Kløftelv Formation about 200 m east of Kløftelv, Ella Ø. The top of the formation is not exposed here, but the succession probably corresponds to only the Lower and Middle Quartzites of the succession measured by Cowie & Adams (1957, fig. 40) on the south coast of the island (see Fig. 20(J)).

ness and development of the Kløftelv Formation over the whole region. The base of the formation, however, is interpreted as a regional unconformity. At Albert Heim Bjerge, 60 km NE of Brogetdal, the formation rests directly on the Canyon Formation (Cowie & Adams 1957). In northern Scoresby Land the formation was believed to rest directly on the Storeelv Formation (Fränkl 1953a, pp. 28–29), though we have argued that the contact with the quartzites there is conformable, and that these do not belong to this formation. The base of the formation was observed in the lowest waterfall of the main tributary of Storeelv. There the top of the Spiral Creek Formation, represented by laminated dolostone, was fissured, brecciated and reddened beneath an irregular erosion surface overlain by a silicified basal breccia-conglomerate several centimetres thick (Fig. 25). Then follow, all within 4 m, dark red sandstone, green and maroon shale, finally interfingering with rusty weathering quartzite before the latter become dominant.

By comparing the Kløftelv Formation with equivalent units in Newfoundland and Scotland, Swett & Smit (1972) suggested deposition in a tidal environment, the basal unconformity reflecting erosion during initial transgression.

Bastion Formation (Figs 1, 20)

The first Lower Cambrian body fossils occur in a 60 cm shelly limestone at the base of the Upper Bastion Formation. This horizon was visited on the north face of Bastionen and above Solitærbugt on Ella Ø, and at both localities trace fossil markings were found in the lowest *c.* 10 m of the glauconitic sandstones above the Kløftelv Formation (Cowie & Spencer 1971).

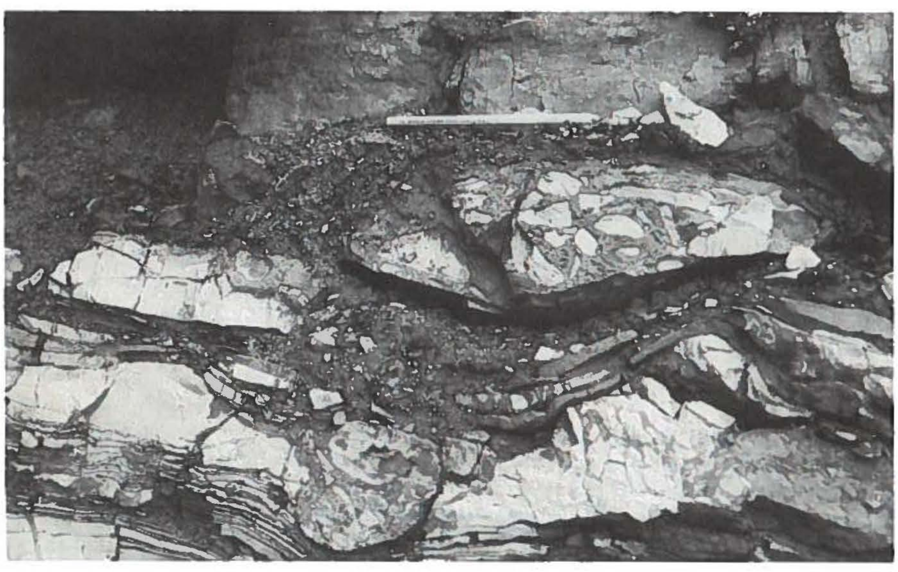

Fig. 25. Contact between the Spiral Creek Formation and the Kløftelv Formation, waterfall section east of upper Storeelv, Ella Ø. The top of the Spiral Creek Formation is brecciated and reddened, and the contact zone affected by silicification.

Sedimentary structures and interpretation

Internal bedding in the diamictites

The diamictites are mostly homogeneous, massive or weakly bedded, but horizons of sandstone and conglomerate do occur within them and provide direct evidence of the mode of deposition.

This is the same as in the Port Askaig Formation of Scotland, where Spencer (1971, p. 12) stated that "The criterion which shows that bedded horizons lie within mixtites [syn: diamictites] (and do not just separate mixtites formed by two successive events) is that the horizons *thin laterally to zero and where they are absent the mixtite is completely homogeneous and undivided......* the bedded horizons formed whilst the mixtite material around them was also being deposited...... they provide the only direct evidence of the mode of deposition of the mixtites". The Wilsonbreen Formation of NE Svalbard contains similar lenticular bedded horizons. Both the Port Askaig and Wilsonbreen formations have been interpreted as having been deposited primarily from grounded ice, though with periodic flotation in a marine environment (Spencer 1971; and Hambrey 1982, Fairchild & Hambrey 1984 respectively). The bedded horizons that are enclosed by the massive diamictite units within the Ulvesø Formation, and especially the Storeelv Formation, exhibit the same characters as do those in the Port Askaig Formation and the Wilsonbreen Formation. The sandstone and conglomerate beds mostly lie parallel to the overall stratification and show internal planar and cross-bedding but are frequently lenticular (Fig. 19) or lens-shaped (Fig. 18e). In one case, a large-scale cross-bed arrangement was observed (Fig. 16, Kap Weber, middle diamictite bed). The difficulty of correlating even some of the thicker bedded horizons from one measured column to the next is probably due to the lenticularity of the horizons. We therefore consider these massive diamictites to be the result of deposition from grounded ice, possibly as a lodgement till, accompanied by deposition of fluvioglacial material in subglacial or proglacial channels.

The weakly bedded diamictites generally occur without lenticular bodies of conglomerate or sandstone. They form only a small part of the Storeelv Formation, but make up a considerable proportion of the lower Ulvesø Formation around Antarctic Sund and at Sorteelv Gletscher. This type of diamictite (Fig. 18c) is inferred to be the result of deposition of basal debris from a floating glacier tongue ("waterlain till"; Dreimanis 1979). Better bedded diamictites, especially towards the base of the Ulvesø Formation in northern Suess Land, show disruption of bedding by outsize stones, and these are inferred to be proximal glaciomarine sediments formed just beyond the glacier tongue were ice-rafting is vigorous. Bedded diamictites sometimes form transitional contacts over a few centimetres with underlying clast-free sediments (Fig. 13, columns 3 & 5). Some thick units of weakly bedded diamictite have pebble or conglomerate concentrations on top; these are interpreted as lag deposits formed as a result of winnowing by current action.

The above-mentioned bedding characteristics preclude deposition from subaqueous mass-flow. Nevertheless, there are units of less matrix-rich diamictite from a few tens of centimetres to a few metres in thickness, but accounting for only a small volume of the total diamictite, which may be the result of resedimentation of unconsolidated diamicton by subaqueous mass flowage. Such units are laterally persistent in individual outcrops and have sharp, irregular, erosional bases and sharp planar tops. Examples occur in the Ulvesø Formation at three levels in the lower half of the formation at the type locality (Fig. 14b) and in the upper part of the formation at Langgletscher Dal (locality 5). Subaqueous mass-flows are to be expected in the glaciomarine environment, since diamicton deposited on even gentle slopes is unstable; such deposits have been reported from contemporary glaciomarine environments around Antarctica and Alaska (Kurtz & Anderson 1979). Subaqueous mass-flows do not appear to be present to any significant degree in the Storeelv Formation, except in association with rhythmites (see below).

Rhythmites with outsize stones

Within both diamictite formations there are stratified horizons with outsize stones that have dropstone structures. They are distinct from normal diamictites (though sometimes gradational with them) in that they consist of finely laminated siltstones and sandstones (with laminae commonly 1–10 mm thick), punctured by stones with diameters that exceed the thickness of the laminae (Figs 15e, 18d); the largest stone observed was 125×55×40 cm. The laminae are frequently graded, and some are sand-silt couplets reminiscent of varves. Two examples of such rhythmite successions from the Ulvesø Formation are illustrated in Fig. 26. Slump folds occur sporadically and unsorted gravel horizons a few centimetres thick occasionally interrupt the rhythmic sequence.

These rhythmites indicate deposition in quiet waters, possibly from turbid underflows (Ashley 1975, Church & Gilbert 1975), whilst the abundant dropstones indicate the presence of floating ice. The unsorted gravel horizons suggest small-scale mass-flows. The rhythmites appear to be of limited lateral extent, which together with the varve-like laminations, suggests deposition in glaciolacustrine or restricted glaciomarine environments, rather than in the open sea.

Lamination, described as varve-like by Schaub (1950) had previously been noted both in the Canyon Formation and in Bed group 19. In both cases the laminated rocks are of dolomitic siltstones, but outsize stones are absent, and there is no reason to infer glacial conditions.

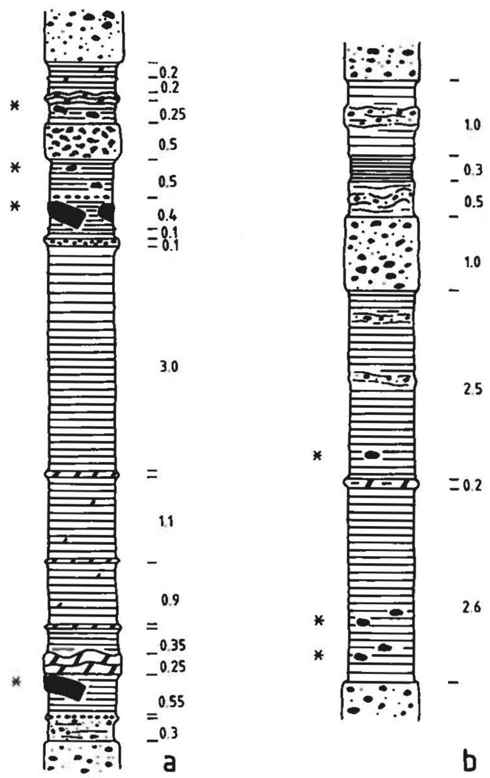

Fig. 26. Detailed sections through rhythmite (varvite) sequences with outsize stones in the Ulvesø Formation. (a) Sequence in the 9.1 m unit at Sorteelv Gletscher (see Fig. 15d for photograph). (b) Sequence in the 7.7 m unit west of Kiledal (see Fig. 9 for location). Levels with outsize stones are shown with an asterisk. The presence of dolostone beds, some with low amplitude folds resulting from soft-sedimentary deformation, is somewhat analogous to the "Disrupted Beds" in the Port Askaig Formation of Scotland (Spencer 1971, p. 77). Bed thicknesses in metres are shown.

Stone fabric in the diamictites

Based on bedding characteristics alone, it is often difficult to distinguish the mode of deposition of a diamictite and other criteria must be employed, of which three-dimensional stone fabrics statistically analysed are often helpful (Dowdeswell *et al.* 1985; Dowdeswell & Sharp 1986). This aspect is currently under investigation but here we present two-dimensional data which were collected to determine palaeo-ice flow directions and to distinguish waterlain tills (which have a generally random fabric) and basally deposited tills (which generally have a preferred orientation fabric).

The method of measurement on Ella Ø and at Kap Weber was the same as that used on the Port Askaig Formation in Scotland (Spencer 1971, p. 23), i.e. apparent long axes of elongate stones were measured systematically in a small area of outcrop surface lying approximately parallel to the regional bedding. In the other areas actual long axes of extractable clasts bigger than 1 cm in length were measured in 3-D as in Svalbard (Dowdeswell *et al.* 1985), but the data here is plotted in 2-D form after correction for tectonic dip of the beds to facilitate comparison with the other measurements. The data are plotted as rose diagrams (Figs 27, 28).

In Scotland the pebbles were preferentially orientated in the plane of the main cleavage; the orientation was therefore probably of tectonic origin. In Svalbard most of the diamictites studied had no tectonic fabric, and the measured fabrics were considered to be primary. The East Greenland diamictites have a variety of penetrative and non-penetrative tectonic structures, so it is important to distinguish tectonic from non-tectonic fabrics. On Ella Ø the Tillite Group has only a weakly developed cleavage, and then only locally. Thin sections reveal little more than diagenetic textures such as minor pressure solution where sand and larger grains are in contact. Even where cleavage is developed there does not appear to have been rotation into that plane. The clasts themselves preserve their original shapes. Furthermore, systematic fabric measurements through the Ulvesø Formation reveal both random fabrics where the diamictite was suspected from other evidence of being a waterlain tillite, and preferred orientation fabrics where the evidence suggested deposition from grounded ice. We therefore conclude that these fabrics are primary. The same pattern is seen at Kap Lagerberg and Kap Weber. However, on both sides of Antarctic Sund the Ulvesø Formation is strongly cleaved, and even visually the stones seem to lie preferentially in the plane of cleavage rather than the bedding, which forms a small angle with it. The resulting pebble fabric clearly is tectonic, with a strong preferred orientation parallel to the bedding/cleavage intersection; this is equivalent to a prominent lineation in the shales of Bed group 19 immediately beneath the diamictites (Fig. 27, n, o, p. q).

The preferred orientations shown by the undeformed diamictites are variable in the Ulvesø Formation. At Kap Lagerberg, the formation shows (from bottom to top) approximately random fabric, two bimodal fabrics and one strong NE–SW alignment (Fig. 27, d, c, b, a, respectively). The bimodal fabrics are difficult to interpret, but perhaps indicate slight flowage after deposition. The strong preferred orientation fabric is probably a reflection of ice-flow direction. On Ella Ø the lowest unit of the formation has a random fabric where of waterlain appearance (Fig. 27m) but has strong preferred orientations above (Fig. 27, l, k, f), not coinciding with cleavage, interpreted as reflecting ice-flow directions in lodgement till. At the top of the formation fabrics tend to be random, these rocks showing clear evidence of deposition in water (Fig. 27, e, g, h, i). At Kap Weber the upper part of a massive diamictite in Tillitekløft has a strong NNE–SSW and NE–SW fabric (Fig. 27, r, s), suggesting grounded ice deposition, while above and south of the gorge at *c.* 1000 m, a different bedded diamictite, with clear indications of waterlain deposition, has a random fabric (Fig. 27, last column).

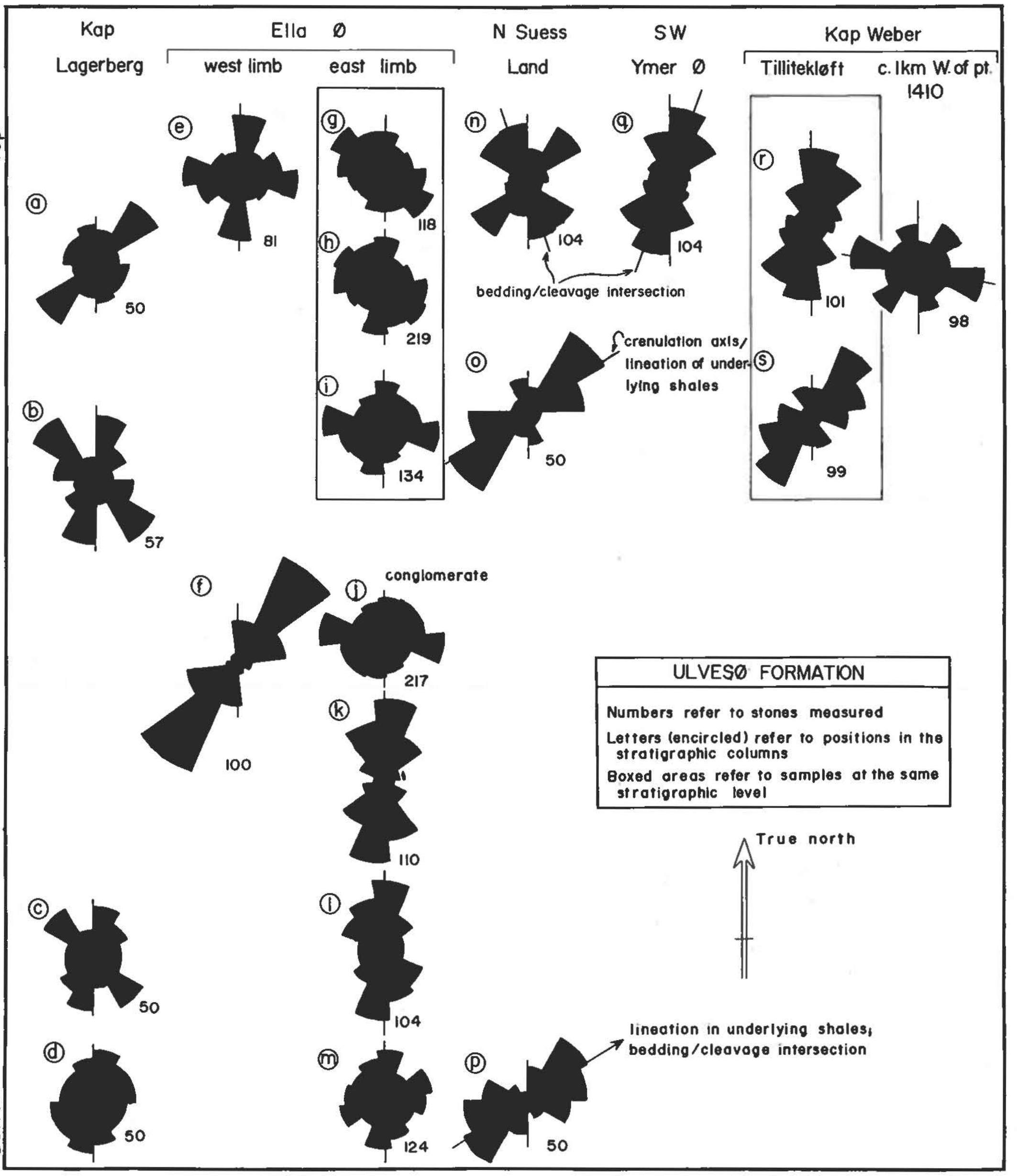

Fig. 27. Rose diagrams of stone fabrics from the Ulvesø Formation. Stratigraphic position of the measurements are shown in Fig. 9, and the geographical locations of the Ella Ø measurements are shown on Fig. 6.

Fabrics in the Storeelv Formation have been examined only at Sorteelv Gletscher and on Ella Ø (Fig. 28). At the former locality massive diamictite is not well developed, but a sandy, clast-poor unit revealed no definite preferred orientation (Fig. 28, z). In contrast a rhythmite with dispersed clasts at the same locality has a distinct SSE–NNW alignment (Fig. 28, zz) whereas one would have expected random orientation, so perhaps there is a tectonic overprint here. On Ella Ø, sedimentological evidence in massive diamictites suggests that the bulk of the formation was deposited from grounded ice, and this is reflected in the preferred orientation fabrics. These are variable in orientation, ranging from north–south, to nearly east–west (Fig. 28, t, u, v), though one locality has a random fabric (Fig. 28, x), and two localities (w, y) have weak preferred orientations to which little significance can be attatched.

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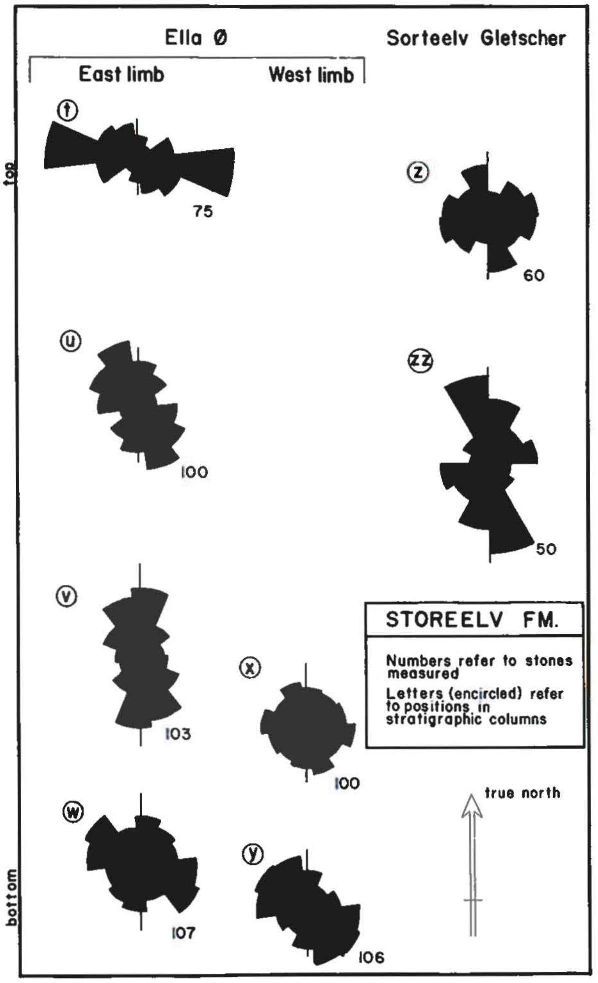

Fig. 28. Rose diagrams of stone fabrics from the Storeelv Formation. Stratigraphic position of the measurements are shown in Fig. 14, and the geographical locations of the Ella Ø measurements on Fig. 6.

Boulder pavements

The base of the Storeelv Formation on Ella Ø is characterised by the presence of dispersed planed-off boulders with striated upper surfaces at several localities over a distance of 4 km, set into the topmost siltstones of the Arena Formation (Fig. 17d). The boulders are matrix-supported and include both intrabasinal and exotic varieties. Some are up to half a metre across and seem to have lost several centimetres on their upper surfaces as a result of glacial abrasion. The boulders were probably dropstones which were projecting above the sediment when grounded ice advanced over the area and abraded them. A boulder pavement also occurs in the middle of the formation at Storeelv. This also is interpreted as a glacial erosional pavement (Moncrieff & Hambrey, in prep.).

Palaeocurrents

Cross-bedding and ripple marks occur at many horizons (Figs 9, 16, 20). Numerous orientations were measured and, after reorientation of the cross-bed dips to remove the structural dip, the resulting azimuths of current structures show great variability (Fig. 29). The majority of the measurements were made on Ella Ø, although those in Fig. 29b are from Kap Weber.

In Bed group 19, Unit IV, slump folds occur in the intraformational carbonate breccias, indicative of slope deposition. Cross-bedding occurs in the basal sandstones and within the Ulvesø Formation (Fig 29b, c); set thicknesses are mostly less than 0.5 m. The basal sandstone of the Arena Formation contains many ripple marks and some larger scale cross-bed sets (up to 2 m thick), probably formed in shallow water offshore. Higher sandstone beds in this formation have similar structures with slump folds in addition. Some trough cross-bedding is present in the sandstones of the Storeelv Formation, with set heights of up to 0.5 m; these are suggestive of fluvial channel deposition. Ripple marks are common at the base of the Canyon Formation and in the Spiral Creek Formation, which along with desiccation cracks, indicate shallow water conditions and periodic emergence. Finally, much of the Kløftelv For-

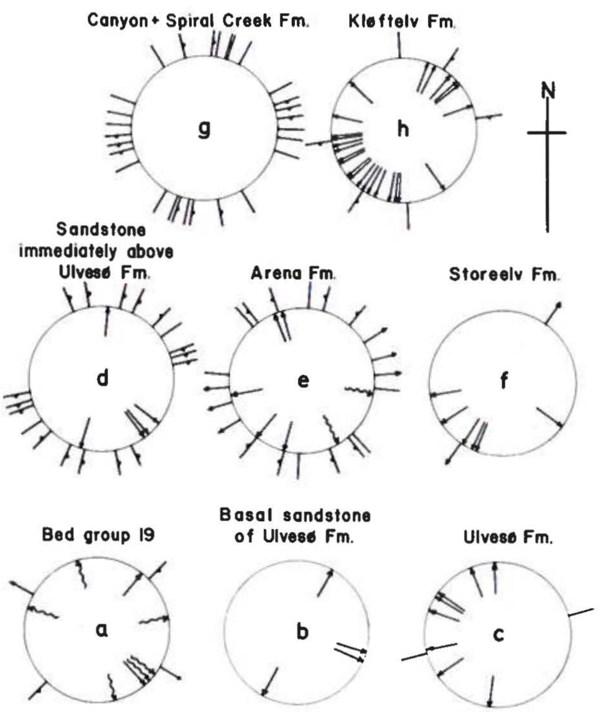

Fig. 29. Azimuths of current structures for the succession from the banded dolostone unit of Bed group 19 to the Kløftelv Formation. All measurements are from Ella Ø, except those plotted in (b) which are from Kap Weber. Stratigraphic and geographical locations of measurements are shown in Figs 9, 16 and 20.

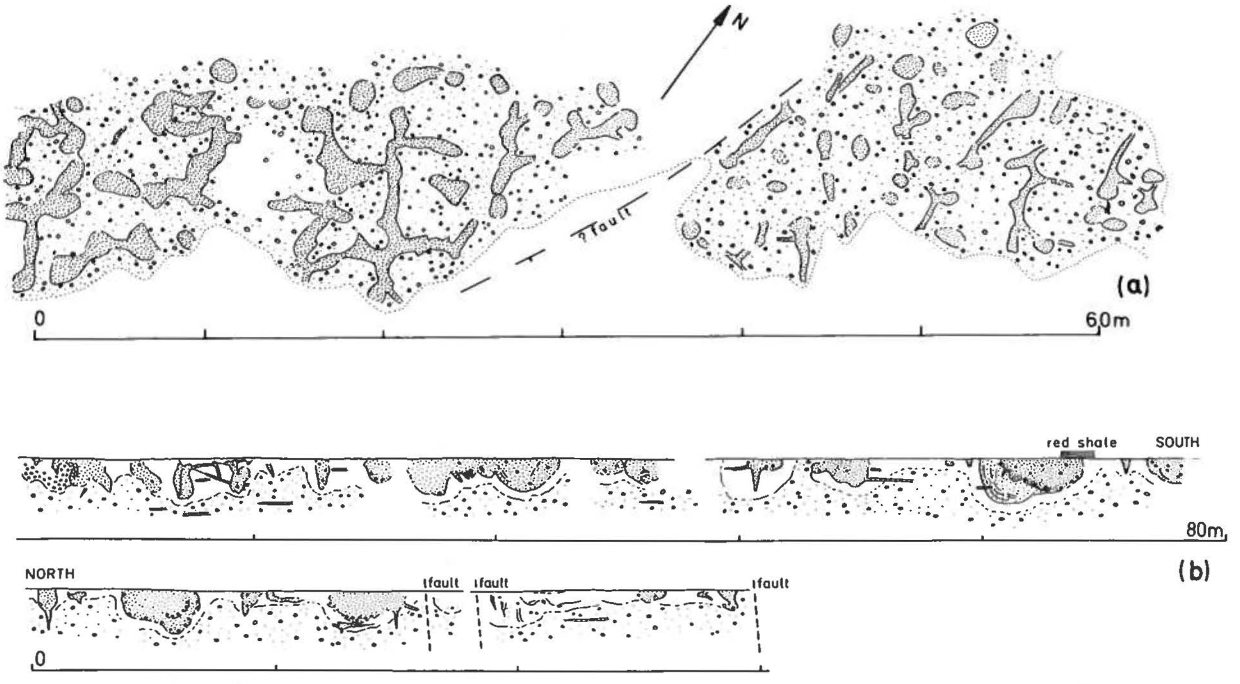

Fig. 30. Field sketches of sandstone wedges and downfolds in plan view and in profile. (a) Plan view of polygonal pattern of sandstone downfolds in the top of the Ulvesø Formation, south of Ulvesø, Ella Ø. (b) View in profile of sandstone wedges/downfolds at top of 15 m diamictite bed within the Ulvesø Formation at Sorteelv Gletscher (see Fig. 9 for location).

mation is cross-bedded, with sets varying in thickness from a few to about 30 cm (Figs 29h and 24), probably formed in a tidal regime.

Despite the abundance and variety of palaeocurrent indicators, few conclusions can be drawn and no single palaeocurrent direction appears to have been dominant (Fig. 29).

Sandstone wedges and sandstone downfolds

Both of these structures are present in the Port Askaig Formation in Scotland (Spencer 1971, pp. 18, 40, Eyles & Clark 1985). Spencer considered the two types to have had different origins: the sandstone wedges to be subaerial periglacial contraction-crack infillings, whilst the downfolds were thought to be quicksand or load-cast structures (but perhaps of periglacial, cryoturbation origin). Eyles & Clark (1985), however, considered these features to be soft-sediment deformation features, formed in a glaciomarine setting. In the Tillite Group, numerous examples of both types of structures were observed, often in association.

The horizon at which sandstone downfolds are best developed is at the top of the Ulvesø Formation, where they have been seen on Ella Ø, at Kiledal, Arenaen and Kap Weber. In the best exposure, a large bedding plane south of Ulvesø on Ella Ø, the structures form polygons with diameters of 3–5 m (Fig. 30a). In cross-section they are mostly rounded basins of pebbly sandstone penetrating *c.* 1.5 m into the diamictite; few wedges are present. At the other outcrops of this horizon only a few individual structures were seen, but again most were rounded basins, not V-shaped wedges. The next best example is from the middle of the Ulvesø Formation at Sorteelv Gletscher. There, in a cross-sectional view, rounded sandstone downfolds are associated with narrow, clearly-defined, V-shaped wedges (Fig. 30b). The structures are penecontemporaneous since they lie at the top of a diamictite bed, but are truncated by overlying bedded strata (Fig. 31b).

Within the Ulvesø Formation the clearest sandstone wedges were observed at Brogetdal, where a dolostone conglomerate bed is cut by three wedges (Fig. 31d). The wedges are up to 0.3 m wide and penetrate 3 m stratigraphically. The wedges do not connect with the overlying sandstone but are truncated beneath its sharp planar base. Only 50 m away however, the base of the sandstone is arranged in downfolds (Fig. 31c). At Sorteelv Gletscher, near the top of the formation, other sandstone wedges have been observed penetrating a massive diamictite to a depth of 1.5 m (Fig. 32); weak bedding parallels the walls of the wedge, but the contact with the diamictite is not clear because of silicification.

In the Storeelv Formation sandstone wedges and downfolds are less common; there is no one horizon where they have been frequently seen. At the top of the formation a few sandstone wedges were found on Ella Ø at the type locality, penetrating diamictite. These are

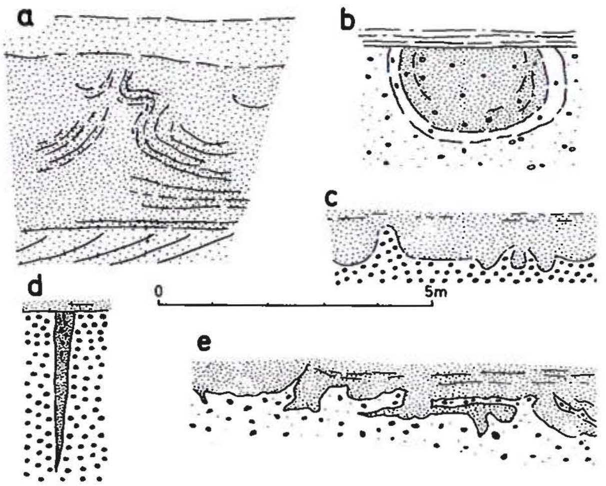

Fig. 31. Field sketches of sandstone downfold structures and sandstone wedges. (a) At the top of the sandstone above the Ulvesø Formation in Kløftelv, Ella Ø. (b) In the top of the 15 m diamictite bed in the Ulvesø Formation at Sorteelv Gletscher: red shale overlies folded sandstone, the bottom 25 cm of which consists of pebbly dolomitic limestone (Fig. 30b shows further sketches of these sandstone downfolds). (c) At the top of the 7 m dolostone conglomerate in the Ulvesø Formation on the west side of Brogetdal. (d) Diagrammatic sketch of a narrow wedge 50 m from locality of sketch (c) and at the same stratigraphic level; vertically aligned pebbles are present at the top of the wedge, which cuts the dolostone conglomerate but does not connect with the overlying sandstone. (e) At the top of the Ulvesø Formation, Storeelv, Ella Ø.

5 mm wide, penetrate 25 cm stratigraphically, connect with each other and with the overlying sandstone (in which mudcracks occur). Similarly, a few wedges were found penetrating diamictites within the Storeelv Formation at Storeelv, Bastionbugt and Arenaen. The best are seen in the west bank of Storeelv, where four wedges occur in 40 m of outcrop, are up to 0.5 m wide and penetrate 3 m stratigraphically.

The origins of the sandstone wedge and downfold structures must be linked. Both are often demonstrably penecontemporaneous, frequently lie at the tops of diamictite beds but occasionally penetrate bedded sediments, there being no evidence of soft-sediment deformation. Narrow V-shaped sandstone wedges are much less frequent here than in the Port Askaig Formation, but are very similar in character; they may therefore be periglacial contraction crack infillings. The origin of the sandstone downfolds could not be decided earlier in the Port Askaig Formation (Spencer 1971), but Eyles & Clark (1985) proposed a soft-sediment depositional mechanism, one which we believe is not applicable to all such downfolds. Here they are arranged in polygons and are associated with wedges, and they are penecontemporaneous. They are thus likely to be glacial involution structures produced by cryoturbation.

Sandstone dykes

On Ella Ø sandstone dykes have been observed at three localities. The largest swarm cross-cuts the thick diamictites of the lowest part of the Storeelv Formation on the west limb of the anticline about 300 m from the coast. The swarm is about 100 m wide and consists of 23 dykes which trend between east and NE and dip at angles from 50° to 90° towards the south (Fig. 33). Individual dykes are mostly a few centimetres wide (widest 15 cm), are parallel-sided, are often traceable for several metres (longest 7 m) and are mostly planar. A few dykes are gently curved and some fork or divide.

A second swarm, comprising 14 dykes, occurs in the diamictites of the Storeelv Formation on the east limb of the anticline SW of Ulvesø. The dykes trend from east to NE and dip south at angles from 30° to 60°. A single sandstone dyke was seen in the Ulvesø Formation on the west limb of the anticline; it is 15 m long and up to 6 cm wide and cuts the 2.5 m pebbly sandstone, trending SE and dipping 60° to the NE.

Fig. 32. Oblique section through irregular sandstone wedge penetrating dolomitised diamictite, top of Ulvesø Formation, Sorteelv Gletscher section.

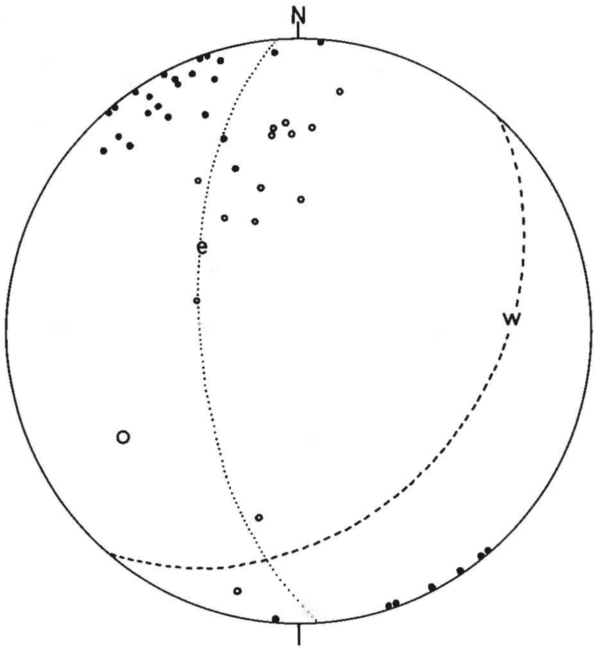

Fig. 33. Equal area, lower hemisphere stereographic projection of the poles to the planes of present-day orientation of 38 sandstone dykes on Ella Ø (solid dots: Storeelv Formation, western limb of anticline; small open circles: Storeelv Formation, eastern limb; large open circle: Ulvesø Formation, western limb). Dashed line: average bedding plane on the east limb of the anticline (pole to this plane indicated by 'e'). Dotted line: average bedding plane on the western limb (pole 'W').

These sandstone dykes much resemble those described from the Port Askaig Formation in Scotland (Spencer 1971, pp. 45–49). These also cut thick diamictite units, were not obviously connected with the sandstone beds in the sequence, and occur in swarms. The orientations of the dykes in the swarms cutting the east and west limbs of the Kap Oswald anticline are similar; in this they seem to be uninfluenced by the very different dips of the two limbs of the anticline. This would be similar to the dykes of the Port Askaig Formation, which perhaps post-date the regional tilting there. Thus, as in the Port Askaig Formation, these sandstone dykes are probably a later structural phenomenon, unconnected with the mode of deposition of the diamictites.

Description of stones

Stones are present in vast numbers in the diamictites. Sedimentary fragments are predominant, granitic and other igneous fragments next in abundance, and metamorphic types less common. The types and origin of the stones have been studied previously. Backlund (1932) described the petrography of certain stones. Huber (1950) estimated the relative abundances of the different types, concluding that many stones resembled rocks in the underlying succession, and that an "unroofing" sequence could be seen, with the higher diamictites containing stones from deep levels in the Eleonore Bay Group.

The abundance of stones was recorded at some localities by counting the number of stones with one axis larger than 1 cm present in an area of 0.094 m^2 (i.e. 1 sq. ft.) (Figs 9, 16). A more comprehensive lithological analysis is underway from collections of 50–100 stones made at the various localities where 3-D fabrics were measured.

In the Ulvesø Formation a pale yellow dolostone suite, a dark grey or black limestone suite and quartzite stones are all abundant; other metamorphic and igneous stones (schists and grey granite pebbles) have been found only in the hard, dark diamictite at the top of the formation on Ella Ø, and there they probably form less than 5% of the total. The grey and black limestone suite resembles lithologies in Bed group 20 (black to dark blue limestone), in Bed groups 16–18 (grey and black limestones) and in Bed group 14 (black pisolitic, partially silicified limestones) of the Limestone-Dolomite "series". The yellow dolostone suite (comprising oolitic, pisolitic, stromatolitic varieties, as well as structureless dolostone and dolarenite) resembles lithologies represented in Bed groups 15 (stromatolitic dolostone) and 19 (cf. Schaub 1955). However, no stones of the colour-banded dolostone of Bed group 19 have been seen, nor have lithologies derived from lower down in the Eleonore Bay Group, e.g. from the Multicoloured "series", been seen except possibly the quartzitic stones. The largest boulder observed was a block of dark grey limestone, 25×5×2 m in size, occurring on Ella Ø on the west limb of the anticline, about 30 m from the base of the formation. Most other large boulders in the Ulvesø Formation are of stromatolitic dolostone with well developed algal growth heads.

In the Storeelv Formation a similar range of sedimentary stones is present, except that the dark grey and black limestones are uncommon. The main contrast with the Ulvesø Formation is the presence of igneous and metamorphic clasts in large numbers. Particularly common are red granite and granite-gneiss stones, but altered basic igneous rocks are also present. The largest granitoid stone measured was 65×37×20+ cm. The red granites are predominant, as Huber (1950) observed. Igneous and metamorphic stones make up about 40% of the total in some horizons in the middle of the formation, but they are much rarer at the bottom and especially the top. The overall sequence of stone lithologies upwards through the Tillite Group supports the idea of an "unroofing" sequence, although within the diamictite formations there is no detectable clear trend from the data available (numbers in Figs 9, 16).

The shape of stones in the diamictites has not yet been systematically studied, but from general observations most units contain a range from angular to rounded, with a preponderance of subangular and subrounded clasts. In the diamictites that are not cleaved and which have a friable matrix, stones can be extracted which still bear their original striations, often with intersecting sets. These most often are black limestones, but other fine-grained lithologies also sometimes bear striations (see photographs in Poulsen 1930, fig. 17, Schaub 1955, fig. 2). As is common with other stone suites in tills and tillites, the coarse-grained igneous rocks do not have striations, except those with planed-off tops at the base of the Storeelv Formation.

Age

The Tillite Group lies above the *c.* 13 km thick Eleonore Bay Group and beneath the 2–3 km thick Cambro-Ordovician succession. Lower Cambrian body fossils are first recorded in the shelly limestones of the Upper Bastion Formation (Fig. 1) (Cowie & Adams 1957). The sandstones in the Lower Bastion Formation have yielded trace fossils (Cowie & Spencer 1970), including probable arthropod scratch marks. The base of the Cambrian System has conventionally been taken as the base of the Kløftelv Formation (Haller 1971) but, on the basis of regional correlation (Cowie & Spencer 1970), could be lower and lie within the Spiral Creek or Canyon formations.

Acritarchs have been found in the Canyon Formation, the Arena Formation and the Storeelv Formation (Vidal 1976, 1977, 1979) and indicate a Vendian age. In the underlying Limestone-Dolomite "series", acritarchs suggest a Late Riphean age (Vidal 1979). Ealier studies of stromatolites from the Limestone-Dolomite "series" had, however, suggested a Vendian age (Bertrand-Sarfati & Caby 1974). Identical biostratigraphic results using acritarchs have been described from NE Svalbard, that is a Vendian age for the tillite-bearing units and a Riphean age for the underlying strata (Knoll 1982). Further detailed studies of the microflora of the East Greenland succession are currently being undertaken by A. H. Knoll and G. Vidal.

Another imprecise and indirect indication of the maximum age of the whole Eleonore Bay Group-Tillite Group succession comes from an Rb-Sr whole rock isochron determination by P. J. Leggo (Spencer 1975, p. 233) on samples of red granite clasts from the Storeelv Formation. The data obtained, 1830 Ma, reflects the age of the basement which provided the stones to this formation, but which is not represented *in situ* in the area under investigation.

Interpretation of origin and palaeoenvironment

The probable glacigenic nature of the Tillite Group was first recognised by Poulsen (1930) who illustrated striated pebbles and commented thus on the possible nature of glaciation (*op. cit.*, p. 305): "The upper sediments of the Eleonore Bay formation do not furnish evidence of highlands and mountains in the neighbourhood of the glaciated area; the writer is therefore of the opinion that the glaciation was not local, but had the character of an ice age". At the same time Kulling (1929, p. 329) was impressed by the lack of an angular unconformity beneath the Ulvesø Formation in view of the derivation of the stones almost exclusively from the underlying Limestone-Dolomite "series". He therefore suggested that the ice may have descended into the sea as in the Antarctic and "that the névé region of the glaciation was not necessarily much elevated above the base of the erosion".

Schaub (1950, p. 30) suggested that a land area of considerable extent was required on which the glaciers could form: "The deposition of glacial till did not probably take place on this land area but in a shallow sea extending in front of it, i.e. under conditions similar to those which must have reigned outside the coast of New England (the northeastern United States) during the Pleistocene glaciation......... This is made probable by the absence of a break of sedimentation and of a striated surface at the base of the tillites. No signs were observed that the underlying shales have been disturbed by the advancing ice".

In contrast to Schaub, Huber (1950) envisaged for the Storeelv Formation a landscape of terrestrial tills in a desert environment. This was based on the presence of alleged dreikanter pebbles (which we have not observed) and polished sand-silt quartz grains in the matrix of the diamictites, both suggestive of aeolian transport.

Doubts on the glacial nature of the Tillite Group were expressed by Fränkl (1953a, b) which led Schaub (1955) to summarise the evidence in favour of glaciation. He concluded that nine out of eleven characters typical of till were present and that the deposits must be the deposits of several large-scale glaciations.

Eha (1953), summarising and confirming earlier views by Huber (1950), suggested that the Ulvesø Formation was deposited below the level of the sea, either by icebergs or by floating glaciers. Huber's suggested modern analogues were the Humboldt Gletscher in North Greenland and the Ross Ice Shelf in Antarctica.

Katz (1954) considered the Tillite Group as a whole to have been deposited in a shallow marine environment, the debris having been glacier transported. He also stressed that a large amount of tuffaceous material appears to be intermingled with the diamictites. This is a matrix said to consist partly or entirely of volcanic glass, sometimes showing a kind of fluidal texture; very small laths of indeterminable crystals in a somewhat ophitic texture, in part, however, seen to be plagioclase; comparatively large flakes of primary chlorite and sericite, bigger quartz grains, corroded and resorbed along the edges by the surrounding glassy material. The presence of this tuffaceous material, as well as tuffs and greenstones intermingled with the Tillite Group in the nunataks to the west, led Katz to suggest contemporaneous volcanic and orogenic activity. We have certainly observed tuffaceous material in thin sections, some of it at least having been subjected to sedimentary reworking, but have failed to find matrix that is dominated by volcanic glass.

Most recently, Haller (1971, p. 105) has given this summary of the earlier suggestions: "Thus the boulder beds were interpreted as *glaciomarine tillites;* that is, the clastic material was dropped by floating ice in the same way as the present-day marine sedimentation around Greenland."

The previous suggestions for the mode of glacial deposition agree on major, ice sheet glaciation, but have the ice sheets floating, either as ice shelves or glaciers, in the area where the Tillite Group is preserved today. This question of whether the tillites represent deposits from ice sheets on land (terrestrial tillite), or from ice sheets entering the sea (waterlain tillite) where they may be either grounded or floating, or deposits from icebergs (ice-rafted sediments), was discussed for the Port Askaig Formation in Scotland (Spencer 1971, p. 67) and the Wilsonbreen and Elbobreen formations of NE Svalbard (Hambrey 1982, Fairchild & Hambrey 1984).

The diamictites and associated sediments of the Tillite Group indicate a wide range of glacial conditions from terrestrial to marine (Table 3). Deposition from grounded ice was the dominant process in Storeelv Formation times, and significant in Ulvesø Formation times. This is best indicated by the presence of lenticular beds and lenses of conglomerate and sandstone within diamictite units, which are most likely to have formed in subglacial or englacial settings. Together with a preferred orientation of stones in the diamictites, inferred to be parallel to ice flow, the evidence suggests deposition by lodgement (see extended INQUA classification, Hambrey & Harland 1981, p. 25) (Fig. 34). Sandstone wedges are further indication of periodic terrestrial conditions.

Deposition from floating ice, e.g. active glacier tongues or ice streams, is best indicated by weakly bedded units with gradational contacts and stones having a random orientation. Such waterlain tillites (extended INQUA classification) make up only a small part of the Storeelv Formation, but a substantial part of the lower Ulvesø Formation, not so much on Ella Ø as around Antarctic Sund and Sorteelv Gletscher. More distal glaciomarine or glaciolacustrine sediments are indicated by rhythmites with dispersed ice-rafted dropstones. Such units occur at a number of horizons in the Ulvesø Formation, notably at Kiledal and Sorteelv Gletscher. Thin horizons of rhythmites with dropstones occur locally in the Storeelv Formation. More persistent sandstone beds could either be the result of fluvial (braided stream) or marine deposition, whilst the thin but distinct diamictite units or poorly sorted conglomerates with sharply-defined top and bottom, are probably the result of subaqueous mass-flows (Fig. 14b), i.e. material which has been deposited by one of the above mechanisms but which has been resedimented.

In the remainder of the Tillite Group there is much evidence of deposition in shallow water, with even periodic emergence above sea level (Fig. 34). Stromatolites, oolites, halite pseudomorphs and desiccation cracks are common in the Canyon and Spiral Creek formations. After a hiatus, the early Cambrian transgression is represented by the tidally deposited quartzites of the Kløftelv Formation.

The main characteristic of the Vendian successions in East Greenland and the rest of the Arctic-North Atlantic region is that they record two main glacial epochs (Hambrey 1983). This study confirms the remarkable similarity between the East Greenland and NE Svalbard successions, particularly with regard to the distinctive nature of the upper and lower diamictite formations, supporting the hypothesis that the two areas were juxtaposed in Late Proterozoic time (Harland & Wright 1979, Harland 1985, Hambrey 1983) but were later separated by major strike-slip faulting, perhaps in Late Devonian time. Western Svalbard also has two glacigenic formations, but they are much thicker, are of deeper water origin, and must have been separated by a considerable distance from the rest of Svalbard when they were deposited. The well-known Late Proterozoic succession of Finnmark, Norway also has a record of two main glacial epochs (Edwards 1984), though the rest of Scandinavia and North Greenland only has one. In Scotland there are seventeen major glacial units, and it is not known how these can be correlated precisely with the above mentioned diamictite formations.

In general terms, an extensive ice sheet can be envisaged centred over the Russian Platform with ice streams or individual glacier tongues entering the sea in the region of NE Svalbard, Greenland and Scotland (and also in the Urals on the other side of the ice sheet). The absence of angular material in glacigenic successions which can be interpreted as supraglacial debris implies that nunataks were little in evidence. The western Svalbard glaciomarine sediments represent more distal deeper water deposits. This general picture is discussed in more detail elsewhere (Hambrey 1983).

The carbonates below the Ulvesø Formation and above the Storeelv Formation do not on their own indicate warm water conditions since many of them are of clastic origin. The only definite indicators of warm conditions are the halite pseudomorphs in the Spiral Creek Formation. However, just as in the NE Svalbard succes-

Table 3. Summary of criteria for establishing a glacial origin of the diamictites of the Ulvesø and Storeelv formations of central East Greenland, classified according to environment of deposition.

Criteria	Storeelv Fm.	Ulvesø Fm.
(A) Evidence for terrestrial glaciation		
Abraded surfaces:		
Sharp base	Yes, in places	Yes
Polished bedrock, Striated bedrock	No	No
Boulder pavement	Yes	No
Chattermarks	No	No
Diamictite units with:		
Irregular thickness	Yes	Yes
Local slump structures (flow tillite)	Yes	Yes
Lenses of sands/gravel (fluvioglacial)	Yes	Yes
Bedding weak or absent	Yes	Yes
Depositional fossil landforms	No	No
Preferred orientation stone fabrics	Yes	Yes
(B) Evidence of glaciomarine and glaciolacustrine deposition		
Dropstones	Yes, occasionally	Yes, common
Weakly bedded (proximal)	Yes	Yes
Finely laminated with outsize stones (distal)	Yes, but rare	Yes
Slight sorting locally	Yes	Yes
Rhythmites (varvites)	Yes	Yes
Considerable thickness and extent	Yes	Yes
Association with resedimented deposits	Rare	Yes
Random orientation stone fabrics	Yes	Yes
(C) Evidence common to both above environments		
Variable lithologies of stones	Many types	Several types
Unsorted	Yes	Yes
Wide range of grain sizes (clay to boulder)	Yes	Yes
Exotic varieties of stones	Yes, common	Rare
Undecomposed minerals, generally unresistant to weathering	Yes	Yes
Constant mix of stones over wide area	Yes	Yes
Stone characteristics		
Angular (if high proportion of supraglacial debris)	Rare	Rare
Subangular	Common	Common
Subrounded if subglacially transported	Dominant	Dominant
Rounded	Some	Some
Well rounded (if high proportion of fluvioglacial)	Rare except in lenses	Rare
Striated	Rare	Common
Faceted	Common	Common
Flat-iron shapes	Common	Common
Clay-sized particles	Yes	Yes
Calcareous shells	Rare	Common
Fragile stones	None observed	None observed
Quartz grain textures	No data	No data
Chattermarks on garnets	No data	No data
(D) Other evidence of cold climate		
Sandstone wedges (periglacial)	Fairly common	Common
Fossil sorted stone circles, polygons and stripes	No	No
Solifluction lobes	No	No
Loessite	No	No

sion (Fairchild 1983, Fairchild & Hambrey 1984), we suggest that although the two glacial epochs in East Greenland were intense, glacial climates prevailed for probably only a small proportion of Vendian time (Fig. 34). Assuming a constant rate of deposition, and if the 80 Ma of Vendian time (Harland et al. 1982) is represented by *c.* 900 m of strata in the whole Tillite Group, then the Ulvesø and Storeelv formations together (*c.* 300 m) perhaps represent *c.* 27 Ma, which is of the same order of magnitude as the present Late Cenozoic glaciation.

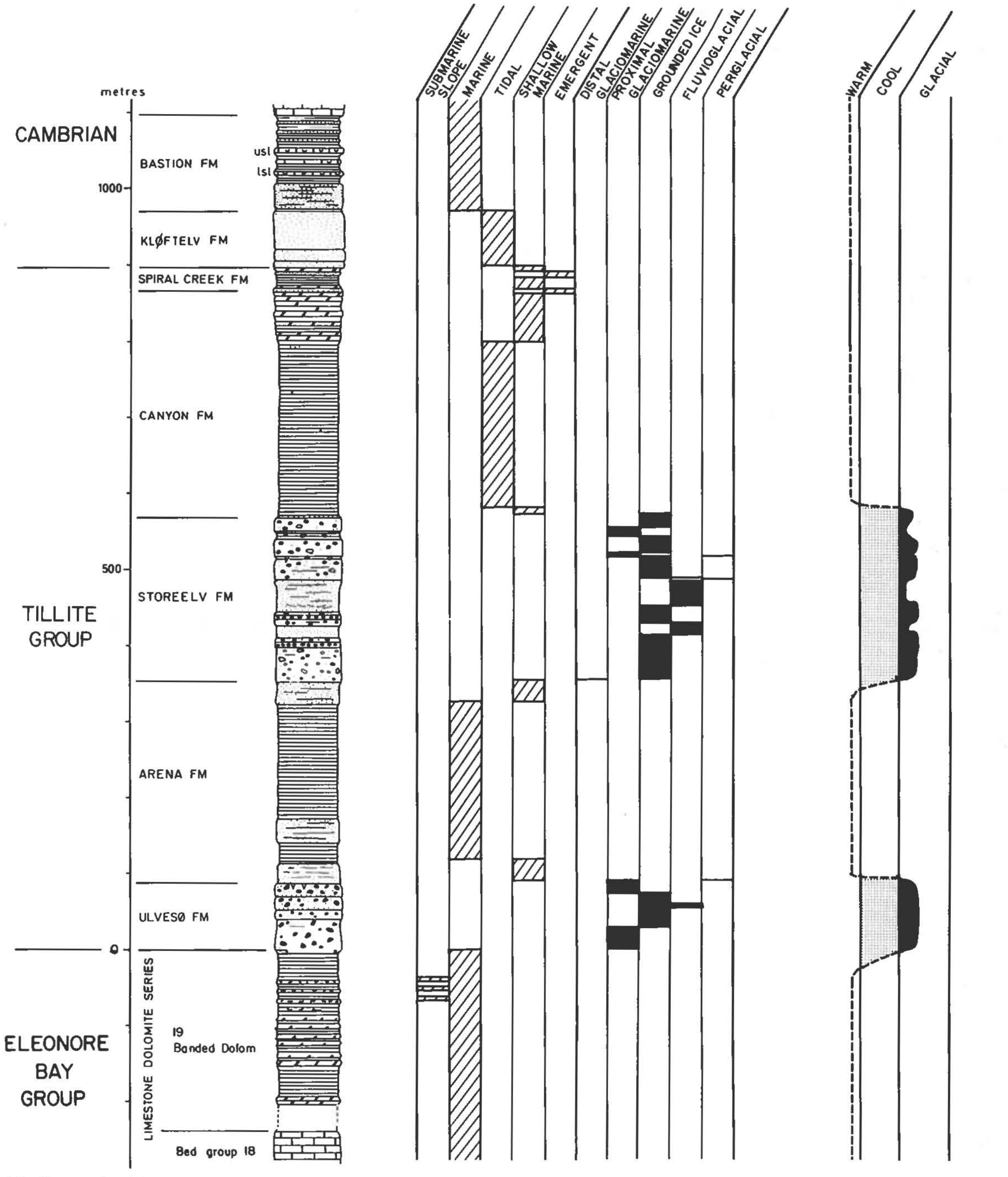

Fig. 34. Generalised interpretation of the depositional environments and climate recorded in the Ella Ø sections. Little positive climatic data are yet available for the non-glacial formations; the inference is based on the equivalent succession in NE Spitsbergen (Fairchild & Hambrey 1984) where petrographic work on the carbonates has yielded abundant information relating to climate.

Palaeolatitude and palaeoclimate

Low palaeolatitudes have been determined palaeomagnetically from a sample of the Tillite Group on Ella Ø (Bidgood & Harland 1961a, b) which is comparable with the results from Norway and Scotland (Tarling 1974), although evidence for the latter has been questioned (Stupavsky et al. 1982). A comprehensive palaeomagnetic investigation of the whole Late Proterozoic succession in East Greenland is currently being undertaken by G. Bylund and N. Abrahamsen.

Summary and conclusions

(1) The Tillite Group is a 500–800 m thick succession of five formations (from bottom to top): the Ulvesø Formation (formerly the Lower Tillite), the Arena Formation (formerly the Inter-Tillite Beds), the Storeelv Formation (formerly the Upper Tillite), the Canyon Formation and the Spiral Creek Formation. The group overlies the Limestone-Dolomite "series" at the top of the *c.* 13 km thick Eleonore Bay Group and is overlain by the *c.* 3 km thick Cambro-Ordovician sequence. The Tillite Group is described at 13 localities (numbered from 1 in the south to 13 in the north) stretching 250 km through the fjord zone of central East Greenland. The rocks are folded but in most places are little metamorphosed. We have studied the stratigraphy and sedimentary structures so as to determine the nature of the glaciations recorded by the two diamictite-bearing formations.

(2) The highest units in the Limestone-Dolomite "series" are Bed group 19 (*c.* 250 m of shale, colour-banded dolostone and limestone breccia) and Bed group 20 (up to *c.* 200 m of dark blue to black limestone and shale). In the north (localities 7 to 13) Bed group 20 overlies Bed group 19, but to the south Bed group 20 is absent.

(3) The Ulvesø Formation is the first sandy formation after the 1000 m sequence of carbonates and shales of the Limestone-Dolomite "series". Where diamictites overlie shales or limestones, the basal contact of the formation varies from knife-sharp to narrowly gradational. No striated pavements at the base have been seen. Where the formation overlies Bed groups 19 or 20 there is no clear unconformity. In the south a basal unconformity is developed, however, since the Ulvesø Formation overlies older units at locality 2 and at locality 1 the lowest unit of the Tillite Group appears to be the Storeelv Formation.

(4) The Ulvesø Formation (100 m thick at the type locality) contains yellow-weathering dolomitic diamictites, rhythmically laminated siltstones with dropstones and lenses of mudstone and conglomerate. The Arena Formation (223 m thick at the type locality) contains shales, siltstones and sandstones and is lacking in dropstones or diamictites except for two thin horizons at Sorteelv Gletscher. The Storeelv Formation (*c.* 200 m thick) consists of maroon, red and green sandy diamictites with sandstone and conglomerate interbeds. The red and green colours of the matrix of the diamictites produce a mottled effect and colour variations are not arranged in a simple geographical pattern. The Canyon Formation (*c.* 300 m) comprises a thin yellow-weathering basal dolostone (in the north), followed by maroon and green dolomitic shales, grey shales and, at the top, yellow-weathering stromatolitic dolostones. The Spiral Creek Formation (25 m thick) comprises sandstones and siltstones with halite pseudomorphs. Above comes the 70 m quartzite of the, inferred Cambrian, Kløftelv Formation and the established Lower Cambrian Bastion Formation.

(5) The following sedimentary features are significant in deciding the modes of deposition of the succession:
Internal bedding in the diamictites: Discontinuous lenses of sandstone and conglomerate are common in the diamictites, particularly in the Storeelv Formation. They are interpreted as having been deposited in subglacial or proglacial channels in grounded ice.
Rhythmites with outsize stones are present at five horizons and record the former presence of floating ice, the sediments reflecting ice-rafting processes.
Stone fabrics have been measured in the diamictites. Random stone orientations occur in the lower Ulvesø Formation (reflecting deposition as waterlain till). Strong preferred orientations occur at several other levels trend approximately north–south to NW–SE, and are interpreted as lodgement till fabrics.
Boulder pavements occur at the base and in the middle of the Storeelv Formation on Ella Ø, and indicate subglacial erosion by grounded ice.
Palaeocurrents from measurements of cross-bedding show great variability in flow directions.
Sandstone wedges and *sandstone downfolds* are present at about five horizons. Sandstone downfolds are well developed at the top of the Ulvesø Formation where they are polygonal in plan view. They are penecontemporaneous, being truncated by overlying erosion surfaces. The sandstone wedges are periglacial contraction crack infillings. The sandstone downfolds are interpreted as periglacial involutions of cryoturbation origin.
Sandstone dykes occur in two swarms on Ella Ø. They are late, 'tectonic' features not connected with the deposition.

(6) The stones in the Ulvesø Formation diamictites consist of dark grey and black limestones dolostones, quartzites, with rare igneous and metamorphic rocks near the top. The Storeelv Formation contains the same dolostones, only rare black limestones, but a significant proportion (up to 50%) of igneous and metamorphic stones. The dark limestone stones are frequently glacially striated, other types rarely so. The sedimentary stones are derived from the Eleonore Bay Group, mainly the Limestone-Dolomite "series". The source of the igneous and metamorphic stones has not yet been identified, but they do not completely match the metamorphic complex beneath the Eleonore Bay Group. The exotic component in the Storeelv Formation indicates significant erosion of an unknown area of crystalline rocks, probably far distant, whereas the composition of the Ulvesø Formation indicates that the material was of relatively local derivation (i.e. intrabasinal). This contrast in composition can be thought of as an unroofing sequence.

(7) *Interpretation of origin and palaeoenvironment:* We agree with many previous authors that the diamictites are of glacial origin. Further, we can show that deposition from grounded ice was the dominant process in the Storeelv Formation and was important in the Ulvesø Formation. The lower Ulvesø Formation was deposited from floating glacier tongues close to the grounding line. Many other features of the sequence suggest that the environment (geographical conditions) of deposition was often that of a shallow shelf (stromatolites, oolites, halite pseudomorphs, desiccation cracks), and that warm climatic conditions may have prevailed for at least part of the time, on the basis of matching with the very similar succession in NE Spitsbergen (Fairchild & Hambrey 1984). The two main glacial epochs therefore appear to have occupied only a small proportion of Vendian time (Fig. 34).

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The mineral occurrences of central East Greenland

OLE HARPØTH, JOHN L. PEDERSEN, HANS KRISTIAN SCHØNWANDT and BJØRN THOMASSEN

Harpøth, O., Pedersen, J.L., Schønwandt, H.K. & Thomassen, B. The mineral occurrences of central East Greenland. Meddr Grønland, Geosci. 17: 139 pp. Copenhagen 1986-12-31.

The present monograph on the mineral occurrences of central East Greenland is the result of an agreement between Nordisk Mineselskab A/S and the Mineral Resources Administration of Greenland (Råstofforvaltningen for Grønland) on compilation of the mineral-exploration activity carried out in central East Greenland by Nordisk Mineselskab A/S during the period 1952–1984. The main aim is to present geological descriptions of all known mineral occurrences and to compile most of the existing geochemical data in a manner applicable to future exploration in the area. More than 200 individual mineral occurrences are described and many in great detail. Geochemical data are presented for scheelite and for 16 elements relevant to the evaluation of the mineral potential of the area. The data are presented as single-element anomaly maps for both rock samples and panned heavy-mineral concentrates and include data from a file consisting of more than 10 000 rock samples and close to 4000 panned heavy-mineral samples.

Mineralization in central East Greenland occurs in rocks of Archaean to Oligocene age and has tentatively been grouped into several periods when mineralization took place.

Mineralization hosted in Archaean-Lower Proterozoic rocks includes magnetite and chromite accumulations and iron-sulphide segregations associated with ultramafic and mafic igneous assemblages, volcanogenic massive-sulphide occurrences, titaniferous magnetite and ilmenite occurrences associated with original plutonic anorthositic massifs, banded iron-formations, gold-bearing quartz veins, a complex copper-skarn occurrence, and uranium and gold-uranium occurrences of unknown origin.

Mineralization hosted in Middle and Upper Proterozoic rocks is restricted to lead-zinc and tungsten skarns and stratiform copper occurrences.

Mineralization hosted in Lower Palaeozoic rocks is in general believed to be associated with Caledonian orogenic activity. It comprises tungsten skarn occurrences mainly associated with granodiorite intrusions, base-metal and tungsten mineralization associated with late-kinematic probably calc-alkaline granite, tin-tungsten-arsenic quartz veins associated with late-kinematic probably mildly alkaline granites, gold-bearing quartz veins associated with late-kinematic granite, uraniferous veins in probably Devonian alkaline granite, tungsten-antimony-gold and silver-bearing base-metal veins in low-grade metamorphic sediments, uranium-fluorite veins in Devonian felsic volcanic rocks and strata-bound uranium occurrences hosted in Devonian clastic rocks.

Mineralization hosted in Upper Palaeozoic sediments (Carboniferous – Permian) includes base-metal quartz-baryte veins locally enriched in precious metals, gold-bearing quartz veins, uraniferous veins, carbonate-hosted strata-bound baryte base-metal occurrences, carbonate-hosted strata-bound celestite occurrences, stratiform base-metal showings of Kupferschiefer type and strata-bound red-bed copper occurrences.

Mineralization hosted in Mesozoic sediments is represented by Triassic stratiform and strata-bound base-metal occurrences of red-bed type and Jurassic placers rich in zirconium and rare-earth elements.

Tertiary mineralization includes a major porphyry-molybdenum occurrence, granite roof-zone molybdenum mineralization, niobium mineralization associated with alkaline intrusive rocks, lead-zinc skarn occurrences, a minor magnetite-skarn showing, lead-zinc-bearing quartz veins and precious-metal, base-metal, molybdenum and fluorite mineralization associated with fumarolic volcanic activity.

The location of all mineral occurrences is shown on a separate map: Mineral Occurrences in Central East Greenland.

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