

W. B. HARLAND, M. J. HAMBREY & P. WADDAMS

VENDIAN GEOLOGY OF SVALBARD



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Cover: Vendian outcrops in Hornsund. In the foreground are polymict diamictites with stones up to boulder size, interpreted as proximal glaciomarine sediment or subaqueous gravity flows derived from glaciogenic debris. The glacier in the background is Gåsbreen, occupying a valley containing shales of the Gåshamna Formation (?Ediacara). The hypothesised Kongsfjorden-Hansbreen Fault (terrane boundary) runs across the fjord to a point on the coast to the right of Gåsbreen, where it disappears beneath post-Devonian sediments. The above interpretation may be questioned by some and is discussed in the text.

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The Vendian Period is represented in Svalbard by a remarkable range of sedimentary, with some volcanic, rocks that were formed in at least three contrasting environments. The bulk of the record is Early Vendian (i.e. Varanger); however, some evidence obtains for a Late Vendian (Ediacara) record.

The best-preserved succession belongs to the Heela Hoek Geosyncline of northeast Svalbard. It contains a variety of carbonates and clastic rocks, including tillites, deposited in a stable, dominantly marine environment (with periodic emergence). A Varanger (Vendian) age has been established on the basis of an exceptionally well-preserved microflora. Two main glacial stages are recorded: the first producing tillites with only intrabasinal stones, the second with exotic granites, gneisses and volcanics as well as intrabasinal stones. However, the rest of the succession indicates generally warm conditions. Cold climates probably represented only a small part of Vendian time. The eastern succession is less than 1 km thick. The rocks were deformed in the Ny Friesland (Caledonian) Orogeny.

In western Svalbard, from Engelsbukta to outer Hornsund, a very different terrane (the Høltedahl Geosyncline) contains tillites *sensu lato* (predominantly turbidites with a considerable ice-rafted glacial component), carbonates, volcanics (metabasic rocks and tuffs), subaqueous debris-flows and finer-grained facies, possibly related to crustal rifting. The western Svalbard successions were metamorphosed and deformed in Cambrian to Devonian diastrophism, and thrust and folded again in the Eocene West Spitsbergen Orogeny. These variable rocks have been investigated in five distinct areas so that five different nomenclatural schemes have evolved, thereby with the advantage at this stage that correlation between them is not implied. Unlike other workers, we distinguish two glacial stages. On the basis of composition, the lower stage has only intrabasinal stones near the base of a 13 km succession and the upper stage has exotic granitoid as well as intrabasinal stones. With two distinct, widely separated tillite horizons, a relatively simple stratigraphy has been demonstrated throughout the western coastal area. Moreover, the post-glacial sequence in northern Svalbard has been demonstrated to be of Ediacara (Late Vendian) age. Therefore, the areal extent and thickness of Vendian rocks in western Svalbard is much greater than hitherto assumed.

The third terrane of supposed Vendian rocks, in middle Hornsund, also includes two glacially influenced units and a post-glacial succession, the overall sequence having affinities with and differences from each of the above-mentioned terranes. Limited outcrops on Bjørnøya do not match the other three terranes closely and certainly not the western terrane.

The two-fold glacial sequence correlates not only throughout Svalbard but also with North Norway and East Greenland (as well as beyond the Arctic region). The differences between the terranes indicate deposition in separate basins, the glacial imprint being the only significant common factor because it was related to global climatic events rather than to local basin evolution.

Detailed comparison with other North Atlantic successions shows that the northeast Svalbard succession closely matches the Tillite Group of East Greenland. Indeed these two areas must have been juxtaposed in Vendian time. Therefore, to bring the different environment of western Svalbard and middle Hornsund into their present intervening position, major post-Vendian strike-slip movements are necessary. Vendian stratigraphic evidence thus supports that of older and younger rocks in the hypothesis that Svalbard comprised at least three tectonic provinces that were widely separated in Vendian time and were juxtaposed in Late Devonian time.

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1 Introduction

1.1 Distribution and tectonic setting of Vendian strata

The Varanger (i.e. early Vendian) record in Svalbard is among the best preserved and most varied in the world. It is represented by an impressive

range of carbonates and clastic rocks, including tillites (in the original sense, commonly now included with diamictites), in both metamorphosed and unmetamorphosed states. There is substantial evidence for a wide range of depositional environments, and the sedimentary record appears to be unbroken. From this study Varanger rocks are far more extensive than is

apparent from earlier maps. Ediacara (late Vendian) strata though of limited extent also crop out.

Vendian rocks occur within thick Late Proterozoic-Early Palaeozoic sequences in a number of platform and basinal sequences in Svalbard. All are folded, but some are hardly altered by penetrative deformation and metamorphism, whereas others are strongly tectonised.

In northeast Spitsbergen and western Nord-austlandet, Late Proterozoic to Mid-Ordovician sediments form the Hecla Hoek Geosyncline. This may total 18 km in thickness, of which about 1 km of well-dated Vendian strata include well-preserved carbonates and clastic sediments, diamictites being the most distinctive feature of the succession. The earlier rocks of the geosyncline are everywhere strongly tectonised and, in the north, Vendian rocks are also affected. This phase of diastrophism was the Ny Friesland Orogeny (Caledonian). It was post-Llanvirn, and probably began in Ordovician time with a Silurian climax and Devonian completion.

Along the western coast of Spitsbergen and on Prins Karls Forland, a different sequence (the Holtedahl Geosyncline), comprising carbonates, psammites, pelites, volcanics, as well as diamictites, was deformed and metamorphosed in mid-Palaeozoic time, and deformed again in Palaeogene time. This sequence is poorly dated, but is distinguished i.a. by Ediacara as well as Varanger rocks. The part we suggest as Vendian is several kilometres thick.

A third central terrane is best demonstrated in middle Hornsund (southern Spitsbergen), and forms part of the Hornsundian Geosyncline.

A possible fourth terrane of Vendian rocks may also occur on Bjørnøya. These strata have more affinity with the eastern or central terranes than with the western terranes.

These four pre-Carboniferous tectonic terranes or provinces were proposed by Harland & Wright (1979) as having been originally widely separated: the eastern and central terranes being separated by the Billefjorden Fault Zone, and the western and central terranes by the hypothetical West Spitsbergen Fault Zone. The evidence, drawn mainly from pre- and post-Vendian rocks, is not considered in this work.

Whereas the Vendian stratigraphy of northeast Svalbard is now well understood, that of western and southern Svalbard has been in a state of flux. In the 1970s, British, Norwegian, Polish and Soviet geologists proposed different schemes for

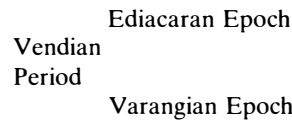
western Svalbard. This reflects not only the difficulty of dating the rocks, but also the differences in the areas studied and the tectonic complications. Cambridge parties over four decades have investigated the Proterozoic rocks of Svalbard, and this monograph is a distillation of the Vendian part of this work (much of it previously unpublished) as well as that published by Norwegian, Polish, Soviet and American groups in recent years.

1.2 Time-scale

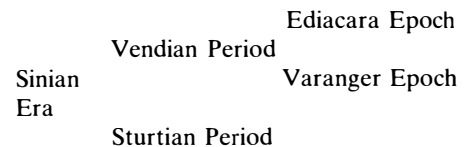
We use the name Vendian for the period immediately preceding the Cambrian Period. Its terminal boundary would thus coincide with the initial Cambrian boundary, as standardised by the I.U.G.S. in 1992 and estimated at about 545 Ma.

We follow the scheme adopted in *A Geologic Time Scale* (Harland et al. 1982) and which is applied with more developed argument in *A Geologic Time Scale* 1989 (Harland et al. 1990) (Table 1). This geologic time scale was an attempt at a classification for global rather than purely regional use. In the present work, we follow this as our standard scale, pending an international decision that would vary it. In the above works, Harland & Herod (1975) was followed in defining the Vendian Period as comprising two epochs: the earlier one characterised by the two widespread Varanger glacial episodes first identified in Finnmark (the Smålfjord and Mortensnes episodes), the later interval (to the initial Cambrian boundary) characterised in part by the Ediacara fauna.

The original scheme on these lines (Harland & Herod 1975) was thus:



and this nomenclature was elaborated in 1982 and then in 1989 (Harland et al. 1990), thus:



The names Varangian and Ediacaran have been changed to Varanger and Ediacara as is argued and applied in Harland et al. (1990).

Table 1. Late Proterozoic time-scale terminologies used by various authors with reference to rocks in the Barents Sea region and the Russian Platform. Ages in Ma.

Regional schemes used in literature on Barents and Russian platforms.		Proposed global scheme. Harland et al. 1982 and 1990.					
Vidal 1981 and Knoll 1982 a,b		Keller & Krasnobaev 1983		(age 1990)			
Chumakov and Semikhalov 1981.				stage epoch period era			
Cambrian (540±10) 570±20	Cambrian Sub-Holmia	Cambrian 590±10	Phanerozoic	Tommotian	Sinian		Riphean
Vendian	Valdaian	Vendian 620±10	Upper with Metazoa	Poundian	Ediacara	Vendian	
	Varangerian		Lower with tillites	Wonokan	Varanger	Sturtian	
	?Early Vendian			Mortensnes			
650-680±20				Smålfjord			
Kudash (R4)							800
	Late Riphean						
Riphean Karatavia (R3)							

Some Soviet writers have defined Vendian similarly, beginning with the glacial episode (e.g. Keller & Krasnobaev 1983). Others (e.g. Chumakov & Semikhatov 1981) allow Vendian to include at least part of the terminal Riphean R4 (Kudashian), as does Vidal (1981) who thus includes three epochs: Early Vendian, Varangerian and Valdaian (Table 1). We convert these regional alternatives to our selected standard for consistency.

Vendian correlation in Svalbard is largely aided by ubiquitous glacial diamicrites (e.g. Harland & Herod 1975; Hambrey 1983), and confirmed by occasional microbotas (e.g. Vidal 1979a, b, 1981; Knoll 1981, 1982a, b; Knoll & Ohta 1988).

The Vendian part of the time scale is proving difficult to calibrate numerically, with chronometric values for the initial Cambrian boundary as widely divergent as 530 and 610 Ma. (Harland 1983, 1987; Cowie & Harland 1989) and now approximating to 540–550. Whole-rock Rb-Sr determinations of argillites give high values and so must be suspect; thus Pringle's (1973) determination for the age of the Nyborg Formation, between the two main tillites in Finnmark, (recalculated at 654 ± 23 Ma) cannot be taken as reliable. Indeed, radiometric data are still too divergent for Vendian correlation and are not referred to further. These data appear in Table 1, suggesting a Vendian duration of around 40 Ma (610 to 570 Ma, Harland et al. 1990) but with uncertainties up to ± 20 Ma at each boundary. A reduction of the initial Cambrian value to 550 or 540 would increase the duration of the Vendian Period to 60 ~ 70 million years.

A practical advantage of the chronostratic scale adopted is that the initial Vendian boundary would approximate to, but not be defined by, the initial Varanger tillite boundary. This is recognisable even in metamorphic facies by the presence in Svalbard of mainly quartzite, limestone and dolomitic stones in a carbonate matrix. In contrast, the later tillite is characterised i.a. by some granitoid stones. The argument for such correlation, even in distinct and originally distant successions, depends on the evidence of low-latitude glacial environments at sea level. It is, therefore, correlation by major climatic events that could not be local (e.g. Harland 1964a, b; Harland & Herod 1975). Such correlation has proved to work very well in relation to other characteristics in this North Atlantic environment (e.g. Hambrey 1983).

1.3 Nomenclature and terminology

The traditional use of the name *Hecla Hoek* for all Proterozoic and Early Paleozoic rocks in Svalbard, we suggest, is no longer justifiable. In the past it has led to unsatisfactory correlations across the archipelago. The evidence for at least three provinces originally widely separated is now overwhelming, though it is often ignored. We therefore use the name *Hecla Hoek Complex* only for the successions of northeast Svalbard (*Eastern Province*), the Hecla Hoek Geosyncline having been deformed in the Caledonian Orogeny sensu stricto. For the pre-Devonian sequence of western Svalbard (*Western Province*) we refer to the *Holte-dahl Geosyncline* or sequence (Harland & Wright 1979) which was deformed in a mid-Palaeozoic orogeny (Caledonian in a broad sense only, and perhaps related more closely to Ellesmerian). For the *Central Province*: the *Hornsund Geosyncline* or sequence is used – it has an intermediate history. However, we do not allow this interpretation to modify our descriptive procedure. We treat the rocks area by area so the data may be used for alternative models. In any case distinct nomenclature facilitates this.

Glacial sediment terminology is controversial and fluid (e.g. Harland, Herod & Krinsley 1966; Boulton & Deynoux 1981; Hambrey & Harland 1981; Lawson 1981).

Several terms have been employed previously with reference to Svalbard: tilloid, tillite, diamicrite, mixtite, tillitic conglomerate, schistose diamicrite. In general *diamicrite* has found the greatest favour with workers in recent years, since it has no genetic connotation and may embrace a wide range of rocks. It is defined as "any lithified non-sorted or poorly sorted terrigenous sediment that consists of sand and/or larger particles in a muddy matrix" (Flint, Sanders & Rogers 1960). *Tilloid*, also a non-genetic term, has been used for a diamicrite that resembles a till as traditionally conceived, i.e. a stone-rich, but still matrix-supported diamicrite, generally lacking in bedding. The term *tillite* has been used generally when a glacial component was intended and, following previous practice in Svalbard and elsewhere, has been applied to a wide range of sediments thought to be glacially influenced, whether continental or marine and even if a minor constituent only is glacially derived. Quaternary geologists, unfamiliar with the immense literature of pre-Pleistocene tillites, have used tillite in a narrower

sense for deposits directly deriving from glacier ice, i.e. for the lithified equivalent of their *till*.

In consideration of specific glacial environments, tillites are discriminated according to Hambrey & Harland (1981). Our use of till/tillite is broader than that used by some Quaternary specialists who restrict “till” to sediment deposited from glacier ice on land without any reworking. *Lodgement tillites* are formed by active “plastering” onto the bed by overriding ice and are normally massive diamictites, perhaps with a synsedimentary shear fabric. *Waterlain tillites* are the result of raining out of debris from a floating glacier through the water column without reworking by currents, and are normally massive diamictites. *Proximal glaciomarine sediments* comprise a marine component and an ice-rafted component of more than about 10%, formed within a few kilometres of a floating glacier tongue. These are weakly to well-bedded, muddy-sandy sediments with dropstones. *Distal glaciomarine sediments* are similar but are muddier, more finely laminated and contain fewer dropstones. The marine component may be turbiditic. We do not accept the narrow definition of till/tillite, simply because it has generally been applied more widely; moreover it is often difficult to discriminate lodgement from waterlain tills/tillites.

Harland & Wright (1979) used the term *Tectonic Province* for unity of tectonic sequence and to contrast with other tectonic sequences thought to have developed at much greater distance than now obtains (i.e. allochthonous). Their ideas required substantial late Devonian strike-slip first proposed for Svalbard (and perhaps anywhere) in 1964 (Harland 1965). Subsequently the familiar concept of suspect terranes developed in North America. We use *terrane* for a tract of rock with certain features in common without palinspastic implications, and *province* for juxtaposed distant terranes. We therefore describe terranes and may interpret provinces. *Suspect terranes* may or may not turn out to be separate provinces on this basis.

1.4 History of Vendian research in Svalbard

Although Thomson (1871, 1877) was the earliest to claim the existence of late Precambrian glacial strata (in Scotland), age of the strata was not easy to establish; it is therefore generally regarded that Reusch's “moraine” and striated pavement at

Bigganjargga, Varangerfjord in northern Norway (Reusch 1891) typifies this late Precambrian episode. The claim that boulder beds at Kapp Lyell at Bellsund in Spitsbergen were glacial (Garwood & Gregory 1898) was only the third such claim, but some hundreds of occurrences of alleged tillites have since been reported throughout the world. It is noteworthy that Nordenskiöld had previously sought evidence of former glacial epochs in Spitsbergen, but without success (1866 p. 53). In 1917 Hoel and Røvig collected from what they thought was a tillite at Gåshamna in Hornsund; but this observation was not published until 1937 (Føyn 1937 p. 144). On the Swedish expedition to Nordaustlandet (North East Land) in 1930, Kulling (1932, 1934) discovered another glacial formation (the Sveanor) and described not only the unequivocal characteristics of that formation, but a Precambrian to Early Paleozoic succession. Having also found similar rocks in East Greenland (Kulling 1930), he reviewed the world-wide evidence then known for an ice age. In 1933 the “Gorge Valley” (Kluftdalen) boulder bed was discovered in northern Ny Friesland and described as a tillite by Fleming & Edmonds (1941), and correlated with the Sveanor Formation. Additional and more extensive outcrops of this formation were then discovered further south in Ny Friesland and Olav V Land (Harland & Wilson 1956; Wilson & Harland 1964; Harland, Wallis & Gayer 1966).

Meanwhile, Kulling (1934, 1951) had proposed the term *Varangeristiden* to describe this widespread glacial epoch, which later became *Varangian Ice Age* in English (Harland 1964a, b), while in Sweden the term *Varegian* was used for latest Precambrian rocks (Asklund 1956). Further studies were undertaken on Nordaustlandet by Edwards (1976), with the presentation of a detailed section through, and a sedimentological description of, the Sveanor Formation in inner Wahlenbergfjorden. In 1968 Chumakov presented additional evidence for glacial conditions in Ny Friesland.

Apart from the isolated report by Garwood & Gregory (1898), diamictites were probably known from western Svalbard but not described until much later. Deformed diamictites described as tillites were noticed in 1958 and 1959 by Cambridge expeditions at Engelskbukta in Oscar II Land (Harland 1960), and Hjelle (1962) described similar rocks, known previously, from Kapp Linné at the mouth of Isfjorden and from

Bellsund. These widespread occurrences in Svalbard were reviewed by Wilson & Harland (1964), Spjeldnaes (1964) and Winsnes (1965).

More recently, much work on the inferred Vendian rocks of western Svalbard has been undertaken, notably by the Norsk Polarinstittutt (Flood, Nagy & Winsnes 1971; Hjelle, Ohta & Winsnes 1979; Hjelle & Lauritzen 1982; Dallmann et al. 1990), by Russian parties from Sevmorego in St. Petersburg (e.g. Krasil'shchikov 1979) and from Academy institutes in Moscow (e.g. Mil'shtein & Golovanov 1979) by Cambridge expeditions (Hjelle 1969; Harland et al. 1979; Hambrey, Harland & Waddams 1981; Hambrey & Waddams 1981; Waddams 1983a, b), by the University of Wisconsin (Kowallis & Craddock 1984; Craddock et al. 1985; Bjørnerud 1990) and by the University of Texas (Kanat & Morris 1988). Much additional information is in the form of unpublished Ph.D. and M.Sci. dissertations in Norway, the U.K. and U.S.A. and are not cited here.

In 1981 and 1982 Cambridge parties returned to Olav V Land and Ny Friesland and undertook detailed logging and sedimentological studies of the Vendian and older rocks, part of this work having already been published (Hambrey 1982; Fairchild 1983; Fairchild & Hambrey 1984; Fairchild & Spiro 1987). The biostratigraphic work of Knoll (e.g. Knoll 1982a, b; Knoll & Butterfield 1989; Knoll, Swett & Burkhardt 1989) has confirmed a Vendian age of the diamictite-bearing succession. We believe the evidence given in this monograph for a glacial origin is decisive.

The glacial nature of the Svalbard diamictites, and many others of Late Precambrian age around the world, has been doubted or even denied (e.g. by Klitin 1960, 1965; Schermerhorn 1974), but since then the sedimentological evidence has been documented in many areas and a glacial origin is now widely accepted.

Until recently, the Svalbard rocks known as Vendian have in fact been almost entirely Early Vendian i.e. belonging to the Varanger Epoch. Knoll & Ohta (1988) recorded microfossils, almost certainly Late Vendian (i.e. of the Ediacara Epoch). By analogy several other successions are now thought to be Ediacara in age.

1.5 Tectonic events

1.5.1 Vendian tectonic events

In northeast Svalbard the Polarisbreen (Varanger) strata appear to be everywhere conformable

both with the preceding Akademikerbreen strata and with the succeeding Oslobreen strata. The underlying rocks have been shown to be pre-Vendian late Riphean or Sturtian. The oldest overlying strata are early Cambrian but not necessarily earliest Cambrian and it would seem that Ediacara rocks are missing in northeast Svalbard. In each case there is a marked disconformity from carbonate to Polarisbreen clastic facies and in turn from these back into carbonate Oslobreen facies. This perhaps led to some earlier interpretation of such sequences as of tectonic rather than glacial origin. Although the glacial origin is now certain we cannot rule out tectonic (epeirogenic) events, although the same facies can be explained as eustatic (i.e. glacioeustatic) changes. In particular, the whole area was positive during and possibly also after Ediacara time, but throughout Vendian time the area was stable.

In western Svalbard the thick mobile sedimentary and occasionally volcanic facies display continuous, often localised tectonic activity, but subsequent deformation makes it difficult to identify tectonic breaks in the various successions. There is, however, a clear angular unconformity in central western Wedel Jarlsberg Land where the lower diamictite formations rest unconformably on truncated folds in the underlying rocks (Bjørnerud et al. 1990). In four other localities the sedimentary contact beneath the lower diamictite is visible. Similarly, the post-Varanger sedimentary contact is generally not observed. Where Ediacara rocks are now part of the established sequence, as in Prins Karls Forland, no obvious break is seen, albeit in a structurally complex area. It may be added that in only one clear locality are early Paleozoic rocks established by fossil evidence and the age is Ordovician and Silurian, so there may be a major hiatus from Ediacara to Ordovician; on the other hand, there is no recorded evidence to constrain such a structural event. However, in both northern Prins Karls Forland at Sutorfjella, and in Oscar II Land (St Jonsfjorden) at Bullbreen, conglomerates containing Vendian – possibly Ediacara – schistose clasts are present; but the age of the conglomerates cannot be constrained sufficiently to argue for a Vendian tectonic episode.

In the Central Province (inner Hornsund) the composite sequence compiled by Birkenmajer 1958, 1960a, b et seq. suggests many distinct (Stille-like) tectonic episodes, but these are not

all related to observed unconformities. In any case our interpretation of the sequence of strata differs from his, as will be discussed below. We do not deny that there were tectonic episodes during Vendian time but we have not located evidence to constrain their timing, except for the pre-Vendian Torellian events.

Throughout the Spitsbergen terranes the stones and matrix of the lower diamictites are of limited variety, a feature consistent with erosion of dolostones, limestones and siliciclastics which can be matched with the immediately underlying strata. The upper diamictite contains in addition exotic stones, typically pink granitoids for which no source has been identified locally. They seem to be far travelled and suggest deeper erosion in the source area or greater distance of transport or both. Nevertheless the consistency in this sedimentary pattern suggests that there were no major disturbances preceding, or at the time of, the early glaciation. It will be noted, however, that the proportion of such exotic stones is much less in the Western Province, suggesting a greater distance from their source.

In northwest Svalbard the metamorphic (probably pre-Vendian) rocks are overlain by (latest Silurian and/or) earliest Devonian clastics. This terrane belongs to our Central Province. Although isotopic dates are dominantly mid-Paleozoic, with some possibly Grenvillian basement relics, some determinations from Biskayerhuken suggest an intrusive phase at 660–620 Ma and a regional metamorphism 620–540 Ma (Peucat et al. 1989). There is thus an indication of pre-, syn- and post-Vendian mobility.

1.5.2 Pre-Vendian tectonic events

In northeast Svalbard the Polarisbreen (Varanger) sequence is about 1 km thick and rests conformably on about 16 km of strata in which no contemporary tectonic event has yet been demonstrated, in spite of much effort. Higher grade rocks lower in the succession have been tectonically juxtaposed.

In western Svalbard there is a marked metamorphic contrast between the Vendian rocks and adjacent higher-grade metamorphic units, consistent with the evidence to suppose that these are older. In Wedel Jarlsberg Land there is evidence of pre-Vendian late Proterozoic tectonism with nappe formation and metamorphism.

In inner Hornsund the Höferpynten dolostones which we interpret to be pre-Vendian are not

conspicuously discordant but the area is tectonically complex. There are more highly metamorphosed rocks to the east but not in contact with the supposed Vendian strata. They may be presumed to be older, as indeed are the rocks to the west of Hansbreen.

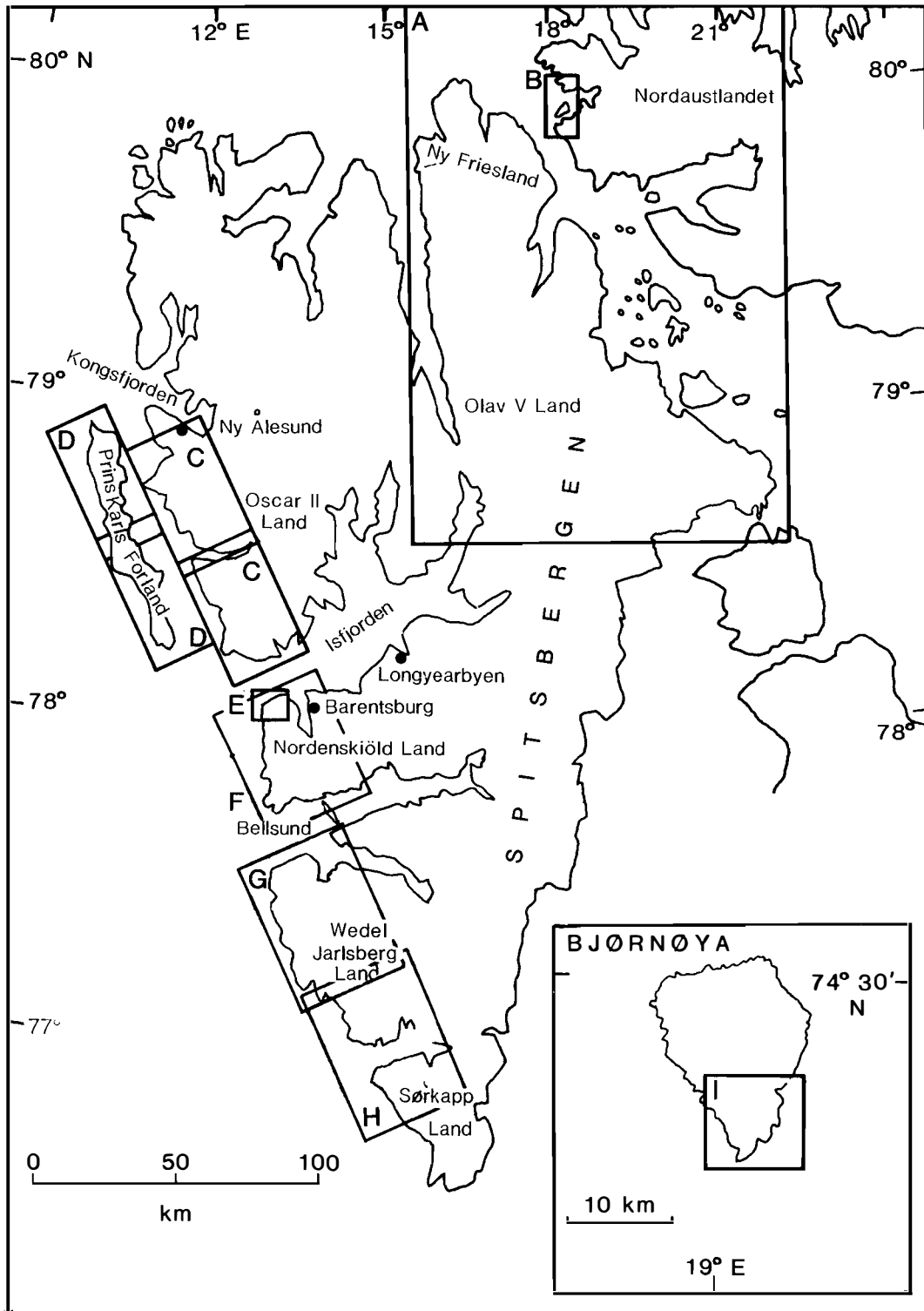
In Bjørnøya the Caledonian tectonic complexities, in part due to the contrasting lower competence of supposed Vendian rocks, may obscure the evidence for any early tectonic break.

1.5.3 Post-Vendian tectonic events

Mid-Paleozoic orogenic events affected the whole Svalbard region. In the west, the mid-Paleogene West Spitsbergen Orogeny was superimposed on earlier structures. This further confuses the stratigraphic interpretation of Vendian strata. It is through these tectonic overprints that Vendian geology must be interpreted and the present state of the Vendian rocks is part of Vendian geology. However, after this introduction we exclude from this work consideration of these structural and metamorphic aspects and of later mineralisation, except where it is necessary to understand Vendian history. Literature concerning the structures includes the following: Harland 1959, 1960, 1985; Harland & Horsfield (1974); Harland & Wright (1979); Hjelle, Ohta & Winsnes (1979); Hambrey & Waddams (1981); Kowallis & Craddock (1984); Craddock et al. (1985); Manby (1986).

In northeast Svalbard the strata are folded about N–S axes and the relatively incompetent Varanger rocks are seen in pinched synclines, with development of cleavage and flattening of stones in the north. These post-Llanvirn folds were penetrated and displaced by Early Devonian granite plutons, all part of the Ny Friesland Orogeny (Harland 1959; Harland et al. 1992). Late Devonian movements of the Svalbardian phase were concentrated in N–S sinistral strike-slip zones of which the best known Billefjorden Fault Zone was several kilometres to the west of the presently exposed Vendian and Early Paleozoic strata. After uplift and erosion this Caledonian Orogen was covered unconformably by Carboniferous and Permian strata which were only warped and faulted during the later movements.

In western Svalbard, on the other hand, the Eocene West Spitsbergen Orogeny, with eastward verging thrusts and folds, was superimposed on the more intense mid-Paleozoic diastrophism (Harland & Horsfield 1974). The mid-Paleozoic



orogeny in the west may have been somewhat later than the Ny Friesland Orogeny. Its vergence seems to have been westwards. It has thus been difficult to establish a stratigraphic sequence for the pre-Carboniferous rocks in this orogen. In general, however, the 7–11 km of Vendian strata appear to be the right way up and the tectonic aftermath has not unduly distorted the successions. The thrusts often follow the bedding and the pre-Carboniferous basement has not been so much affected by the thin-skinned Paleogene tectonics. The basement is thus parautochthonous in structure and, with exceptions, not intensely metamorphosed. However, marked elongation of stones and schistosity of pelites reveal zones of considerable N–S sinistral shear, as do some tight isoclinal folds within major stratigraphic units. These are interpreted as pre-Carboniferous.

Vendian and related rocks in inner Hornsund (our Central Province) were folded and thrust towards the east and covered by relatively undeformed Triassic rocks. The deformation there was clearly Paleozoic with less post-Paleozoic complication. In Bjørnøya Caledonian structures verge westwards.

1.6 Approach in this monograph

The Vendian successions are described by area (Fig. 1). They may be conveniently considered in two sectors: northeast and southwest Svalbard.

In the northeast sector the strata are well displayed, with little tectonic complication or metamorphism so that correlation throughout presents few problems. This sector therefore provides a convenient standard and is described fully in Chapter 2.

In the southwest sector sedimentary and tectonic complexities abound. Different areas were investigated at different times by different groups with different ideas so each has its own nomenclature. This is an advantage as no overall correlation is implied. Each of our chapters 3 to 8 uses the local nomenclature.

The descriptive scheme does not assume the hypothesis of the three or more originally distant

terrane, nor does it assume the particular environments of formation. General conclusions are expressed in Chapter 9. Stratigraphic nomenclature herein follows prior usage whether formal or informal. Our proposed units in the southwest sector are not defined according to the highest standards and we prefer that they be treated as informal; they are useful for discussion. All successions are tabulated, listed or described from the top down. Thicknesses are estimated, except in the northeast sector where they were measured.

1.7 Wider implications

For such a small area, the Vendian, especially the Varanger, record of Svalbard is exceptionally rich and varied. Assessment of this stratigraphy and depositional setting in comparison with sequences in surrounding countries constrains various late Precambrian reconstructions. Evidence from Svalbard has implications for interpreting the tectonic evolution throughout the Caledonides.

The northeast Svalbard successions in particular are among the best preserved of any of this age and can be regarded as a good reference section; were it not for Svalbard's remoteness it might be a strong contender for an initial Vendian boundary stratotype section (GSSP).

The hypothesis of a Varanger ice age has been developed on the basis of evidence in Svalbard and throughout the world (e.g. Kulling 1934, 1951; Harland & Wilson 1956; Harland 1964a, b, 1983; Harland, Herod & Krinsley 1966; Hambrey & Harland 1985). However, part of the argument in support of a glacial origin of some rocks is their possible time-correlation with other rocks possessing unequivocal glacial characters, and a circular argument might be suspected. We therefore do not assume the glacial origin of the diamictites, but in each case present the sedimentological evidence for glacial as well as non-glacial climates. In this way it is intended that the rocks of Svalbard shall contribute to a general understanding of Vendian events and also make a critical case for glaciation.

Fig. 1. Outline map of Svalbard depicting principal areas of work. Boxes indicate areas for which geological maps are given in this work: A = Fig. 2; B = Fig. 21; C = Fig. 24; D = Fig. 35; E = Fig. 38; F = Fig. 37; G = Fig. 42; H = Fig. 48; I = Fig. 52.

Table 2. Pre-Devonian stratigraphy of northeast Svalbard. Northeast Spitsbergen succession based mainly on Harland, Wallis & Gayer (1966), with modification in Polarisbreen Group by Fairchild & Hambrey (1984); west Nordaustlandet succession based mainly on Flood et al. (1969) and modified according to Krasil'shchikov (1973) and Hambrey (1982). Correlation based on lithostratigraphy and biostratigraphy (Knoll 1982a,b).

Age Harland et al 1982 time scale	NY FRIESLAND & OLAV V LAND					W. NORDAUSTLANDET				
	Supergroup	Group	Formation	Lithologies	Thickness (m)	Supergroup	Group	Formation	Lithologies	Thickness (m)
CAMBRO- ORDOVICIAN	Hinlopen- stretet (U. Hecla Hoek)	Oslobreen	Kirtonryggen	Limestone, dolostone	750	(Upper Hecla Hoek)	Gotia	Kap Sparré	Dolostone	110-140
			Tokammane	Dolostone, sandstone	192			Klackberget	Sandstone, shale, dolostone	640
VENDIAN		Polarisbreen	Drakolsen (6 members)	Shale, dolostone	525			Sveanor	Diamictite, shale, sandstone	100-150
			Wilsonbreen (3 members)	Diamictite, shale, sandstone, siltstone, dolostone	160			Baclaerberget	Dolostone, shale	250
STURTIAN			Ellobreen (4 members)	Dolostone, diamictite, sandstone, shale	350-420			Ryssø	Dolostone, limestone	750
			Backlundtoppen (6 members)	Dolostone, limestone, shale	360-700					
LATE RIPHEAN	Lomfjord (M. Hecla Hoek)	Akademiker- breen	Draken	Dolostone	25-300	Murchison - fjorden (M. Hecla Hoek)	Roald - toppen	Hunnberg	Limestone	500
			Svanbergfjellet (4 members)	Limestone, dolostone	100-625			Raudstupp - Salodd	Shale, sandstone	550
			Grusdiebreen (10 divs.)	Limestone	865			Norvik	Sandstone, shale	340
			Oxfordbreen	Shale	550			Flora	Quartzite, sandstone	1,250
			Glasgowbreen	Greywacke, quartzite	540			Kapp Lord	Quartzite, limestone, shale	c. 1,000
		Veteranen	Kingbreen	Quartzite, limestone, volcanics	1500		Franklin - sundet	Westmanbukta	Quartzite, mudstone	625
			Kortbreen	Quartzite, limestone	1200			Persberget	Quartzite	150+
	Stubendorff - breen (L. Hecla Hoek)	3 groups	9 formations	Metamorphic complex	c. 11,500	(Lower Hecla Hoek)	Bornia - halvøya	Metamorphic complex		

2 Northeastern Spitsbergen and western Nordaustlandet

2.1 Distribution

Vendian rocks in the Eastern Province occur in a linear north-south trending belt through east-central Ny Friesland to north-central Olav V Land, and in another north-south trending belt north and south of Murchisonfjorden, and at the head of Wahlenbergfjorden in western Nordaustlandet. The best-preserved exposures occur in northeastern Spitsbergen in a series of nunataks, where large glaciers descend from the highland ice fields towards the east, providing practically complete east-west sections through the stratigraphic succession (Figs. 2 and 3, Table 2), which generally young to the east (Harland et al. 1992).

Outcrops of the similar but opposed Nordaustlandet succession occur on gently sloping terrain close to the coast. Locally exposure is good, especially through diamictites and dolostones, but the intervening shales and other lithologies are poorly exposed.

2.2 Previous research

The essentials of the stratigraphic succession of Nordaustlandet were established by Kulling (1932, 1934). In Murchisonfjorden he discovered extensive "Eocambrian" deposits, including some with unequivocal glacial characteristics. Although by this time many alleged pre-Pleistocene tillites had been recorded, Kulling's was one of the early sedimentological studies of such rocks and stands today as one of the best.

In 1933 a tillite was recognised in Kluftdalen (Gorge Valley) near Sorgfjorden in northern Ny Friesland; the succession there was correlated with that in Murchisonfjorden across the strait (Fleming & Edmonds 1941). Between 1950 and 1962, further extensive outcrops, similar to the Nordaustlandet succession, including diamictites, were mapped and the stratigraphic record of the whole Late Precambrian-Early Palaeozoic Hecla Hoek succession established (Harland & Wilson 1956; Harland 1959; Wilson & Harland 1964; Harland, Wallis & Gayer 1966). Back in Nordaustlandet, Kulling's work was extended with new sections (Flood et al. 1969). Further investigations which supported the glacial origin of the diamictites were undertaken by Chumakov (1968,

1978) in Ny Friesland and by Edwards (1976) at a newly discovered locality in Wahlenbergfjorden in Nordaustlandet. The age of the diamictites was for long considered to be "Eocambrian" by analogy with Finnmark in northern Norway. The first biostratigraphic data were provided by Soviet geologists, notably Golovanov (1967) and Mil'shtein (in Krasil'shchikov 1973) from Nordaustlandet (reviewed by Harland & Wright 1979). The calcareous strata are rich in stromatolites, microphytolites, oncolites and catagraphs, and shales below the diamictites yielded microphytolites. These data permitted broad correlation with Late Precambrian successions in the western U.S.S.R. and established that the diamictite-bearing units were of Vendian age.

Meanwhile it had become fashionable to dismiss almost all alleged Late Proterozoic tilloids as non-glacial. With reference to the Svalbard diamictites three authors refuted the glacial hypothesis. Firstly, Klitin (1960, 1965), without having first-hand experience of the rocks in question, proposed that the Svalbard diamictites (as well as others in the Caledonides) were associated with the zone between continental shields and the Caledonian fold belt, and that they were the product of faulting at the boundaries of the ancient platforms. Secondly, Krasil'shchikov (1967, 1973) came to the same conclusion, having undertaken petrological, petrographical and heavy mineral analyses of the rocks. Neither he nor Klitin offered any explanation for the features characteristic of glacial activity, such as those recorded by Kulling (1930), Harland & Wilson (1956) and Wilson & Harland (1964).

The most closely argued critique of the glacial hypothesis was by Schermerhorn (1974), who rejected the concept of a global glacial period, and offered a tectonic explanation for most of the Late Precambrian diamictites. Specifically he dismissed the glacial explanation for the northeastern Svalbard diamictites, using the evidence presented by Wilson & Harland (1964) and Chumakov (1968). Although many of Schermerhorn's arguments were invalid, his work did prompt careful sedimentological studies of alleged glacial sequences helped by a significant increase in understanding of the nature and mode of deposition of contemporary glacial deposits.

The emphasis, therefore, concerning our recent work on the northeastern Svalbard Late Proterozoic successions has been the documentation

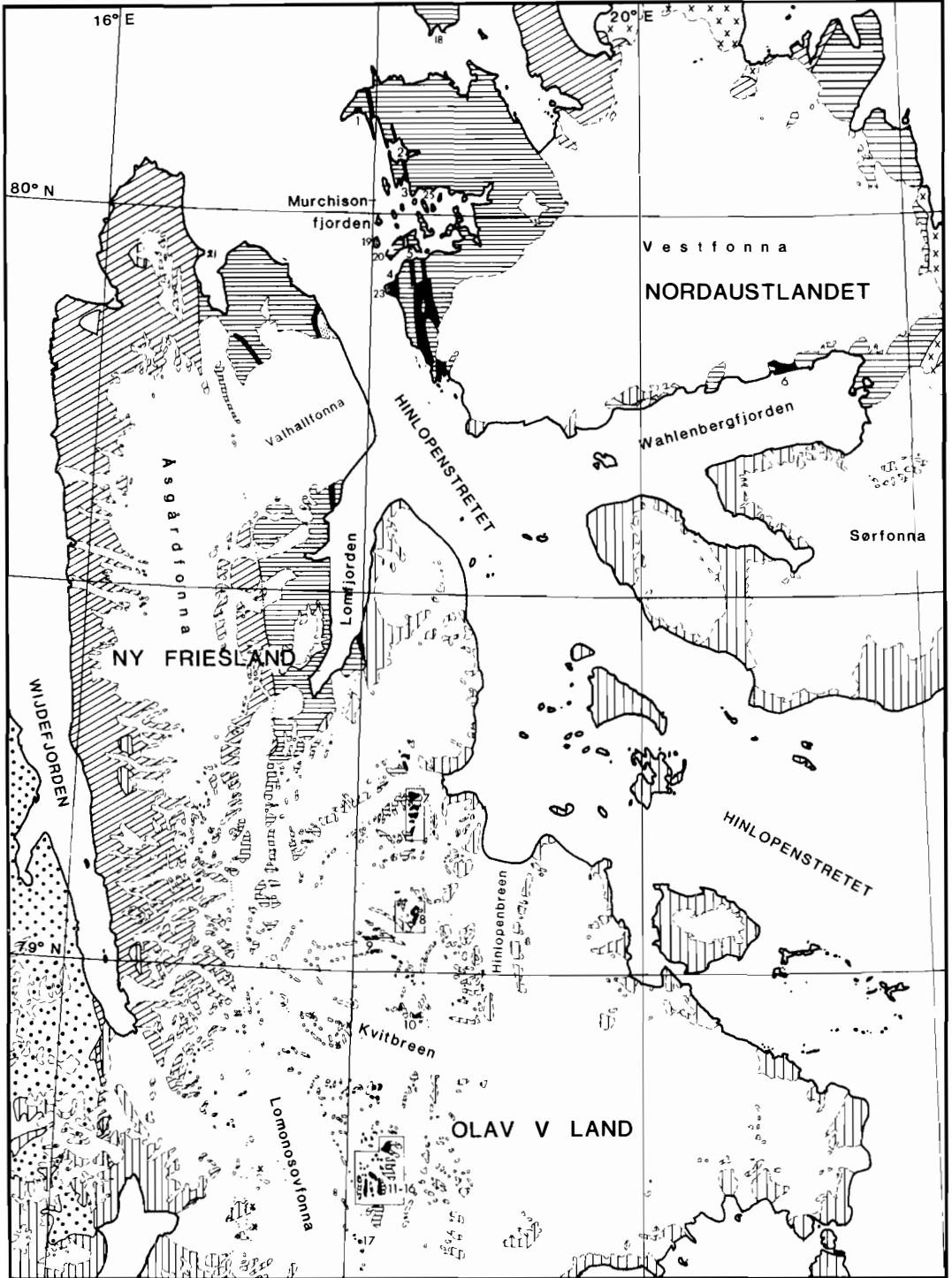
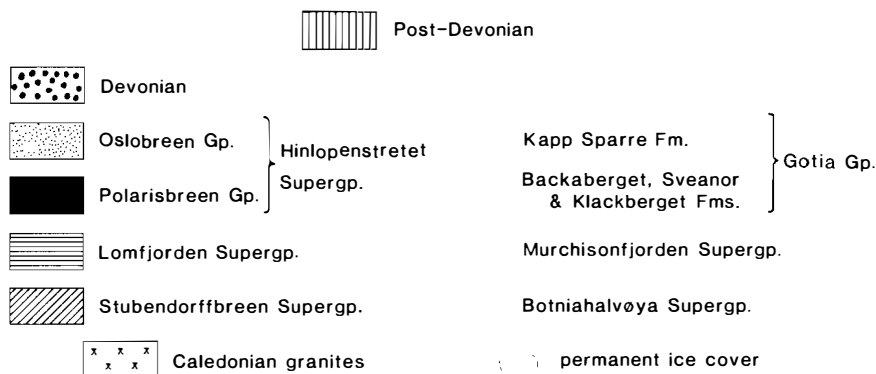


Fig. 2. Summary geological map of northeast Svalbard (modified from Hjelle & Lauritzen 1982 and Lauritzen & Ohta 1984). Locality numbers 1–17 refer to stratigraphic sections in Figs. 4 and 5. Detailed maps of Ny Friesland

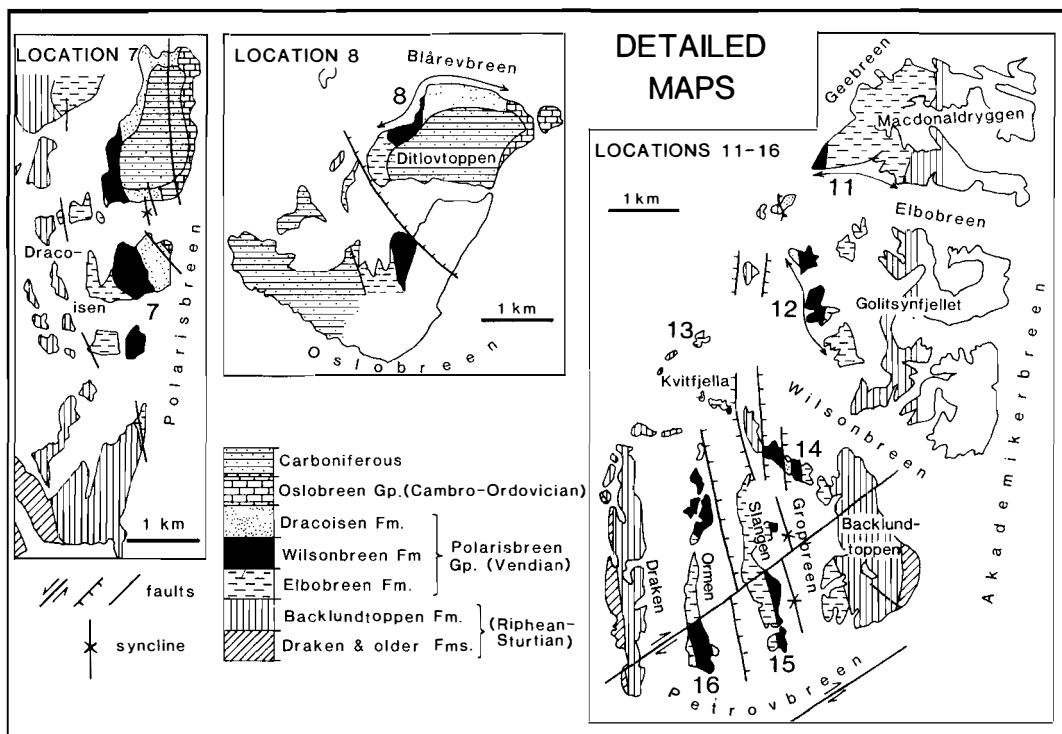
N. & N.E. SPITSBERGEN

NORDAUSTLANDET



Locations of sections

- | | | | |
|------------------|-----------------|---------------------|---|
| 1. Langgrunneset | 5. Sveanor | 9. Oslobreen | 13. Mid-Wilsonbreen |
| 2. Claravågen | 6. Aldousbreen | 10. Ellevepiggane | 14. Kvittjella-
Backlundtoppen ridge |
| 3. Bråvika | 7. Dracoisen | 11. Macdonaldryggen | 15. Slangen |
| 4. Sparreneset | 8. Ditlovtoppen | 12. Golitsynfjellet | 16. Ormen |
| | | | 17. Chansjinfjellet |



and Olav V Land from Fairchild & Hambrey (1984). Further place names: Franklinsundet 18; Krossøya 19; Søre Russøya 20; Sorgfjorden 21.

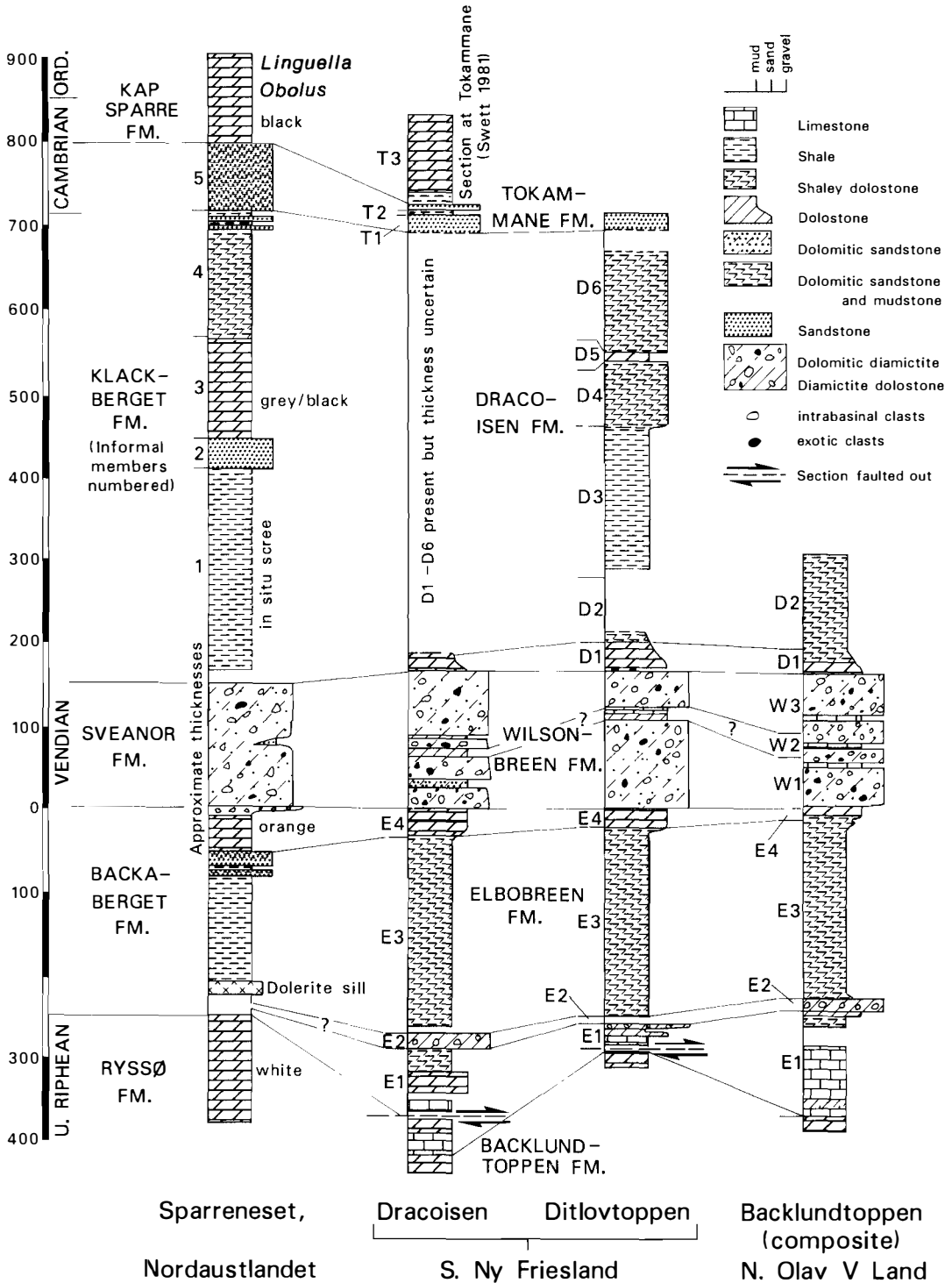


Fig. 3. Summary stratigraphic sections through the Vendian strata of Nordaustlandet and northeast Spitsbergen. The three right-hand sections are from Fairchild & Hambrey (1984).

and reinterpretation of sedimentary structures. In Nordaustlandet this has been associated with the biostratigraphical investigations of A. H. Knoll (Harvard University) and pre- and post-Vendian sedimentological studies by K. Swett (Iowa State University), prompted by a preliminary study of the Cambridge collections. Field work in 1979 and thereafter then led to the discovery of one of the best preserved and varied Late Precambrian biotas in the world, and to the establishment of the biostratigraphical framework for the whole succession (Knoll 1982a,b, 1984; Knoll & Calder 1983). Additional evidence in support of a glacial origin for the diamictites, and the status of these and other diamictites in Svalbard were reported by Hambrey, Harland & Waddams (1981).

The 1981 season began with a renewed programme by Cambridge parties to investigate the Hecla Hoek succession of Olav V Land and Ny Friesland. The major objective proposed by Harland was the reconstruction of the pre-Caledonian geology in Spitsbergen as a key to the tectonic evolution of the Arctic-North Atlantic region. The plan was to test the Vendian origins of the Iapetus Ocean (Harland & Gayer 1972) from the study of continental tillites and their provenance, and also the nature of strike-slip tectonics at its closure. Concurrently, K. Swett and A. H. Knoll, investigated the succession palaeontologically and sedimentologically, thus providing biostratigraphic constraints for assessing the Vendian history of the area. The Vendian stratigraphic succession was revised, the sedimentological record determined and the glacial character of the diamictites confirmed beyond doubt (Hambrey 1982; Fairchild 1983; Fairchild & Hambrey 1984; Dowdeswell, Hambrey & Wu 1985). The north-eastern Spitsbergen rocks, like those in Nordaustlandet, have yielded a beautifully preserved microflora. Few details have yet emerged from the Vendian rocks, but results from the middle and early Cambrian parts of the Hecla Hoek succession have been published (Knoll & Swett 1985, 1987; Swett & Knoll 1985). The regional North Atlantic-Arctic framework of the diamictites has been discussed by Hambrey (1983).

2.3 Structural and stratigraphic setting

The 19-km-thick Hecla Hoek Geosyncline was tectonised in the Ny Friesland (Caledonian) Orogen which now lies to the east of the Billefjorden Fault Zone. This major tectonic lineament runs

the length of Wijdefjorden and into Billefjorden (Harland 1959; Harland et al. 1992). Strike-slip displacements, perhaps of the order of several hundred kilometres, have been proposed for this fault zone (Harland et al. 1974; Harland & Wright 1979; Harland 1985), thereby separating the eastern province from the rest of Svalbard. The uppermost strata in northeastern Spitsbergen (the Hinlopenstretet Supergroup), (Harland, Wallis & Gayer 1966; Valence & Fortey 1968) form the Cambrian-Ordovician Oslobreen Group and the Vendian Polarisbreen Group (with diamictites). The underlying Akademikerbreen Group (in the Lomfjorden Supergroup) (Table 2) in most places is unmetamorphosed. The same is true of the equivalent Gotia and Roaldtoppen groups in Nordaustlandet. The rocks have been deformed into open or tight folds with vertical limbs and north-south trending axes. Parasitic minor folds are occasionally developed in incompetent units, but penetrative deformation fabrics occur only in northern Ny Friesland. Faults of north-south and east-west trend are common, and a number of eastward-directed thrusts have been observed.

Deformation was post-Llanvirn (Fortey & Bruton 1973) and pre-Tournaisian. Radiometric determinations have given Late Silurian metamorphic ages and Early Devonian cooling ages for the granites which include the Hecla Hoek Complex (Gayer et al. 1966).

2.4 Olav V Land and Ny Friesland successions

The Vendian Period as defined here is represented essentially by the Polarisbreen Group. Early Vendian would include part of the Backlundtoppen Formation immediately below the Polarisbreen Group. (The succession is described from top to bottom below and is illustrated in a series of logs in Figs. 4 and 5.) The Polarisbreen Group has been described by Wilson & Harland (1964), Hambrey, Harland & Waddams (1981), Hambrey (1982) and Fairchild & Hambrey (1984).

2.4.1 Tokammane Formation (Oslobreen Group)

This is the oldest Paleozoic formation in northeastern Spitsbergen (Harland, Wallis & Gayer 1966). It has been divided into three members by Swett (1981).

(T3) *Ditloutoppen Dolomite Member (264 m)*: medium to finely crystalline dolostones with some

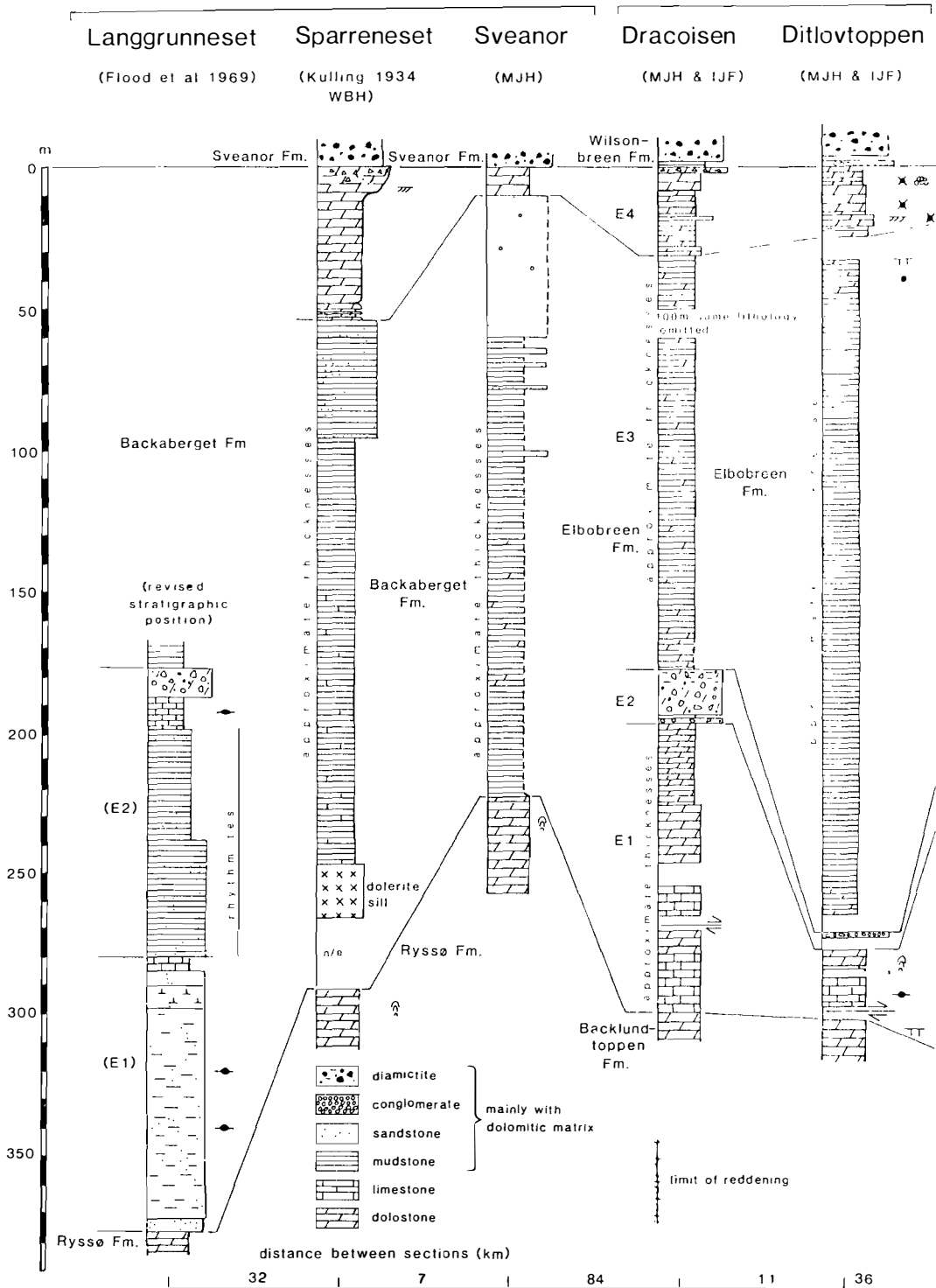
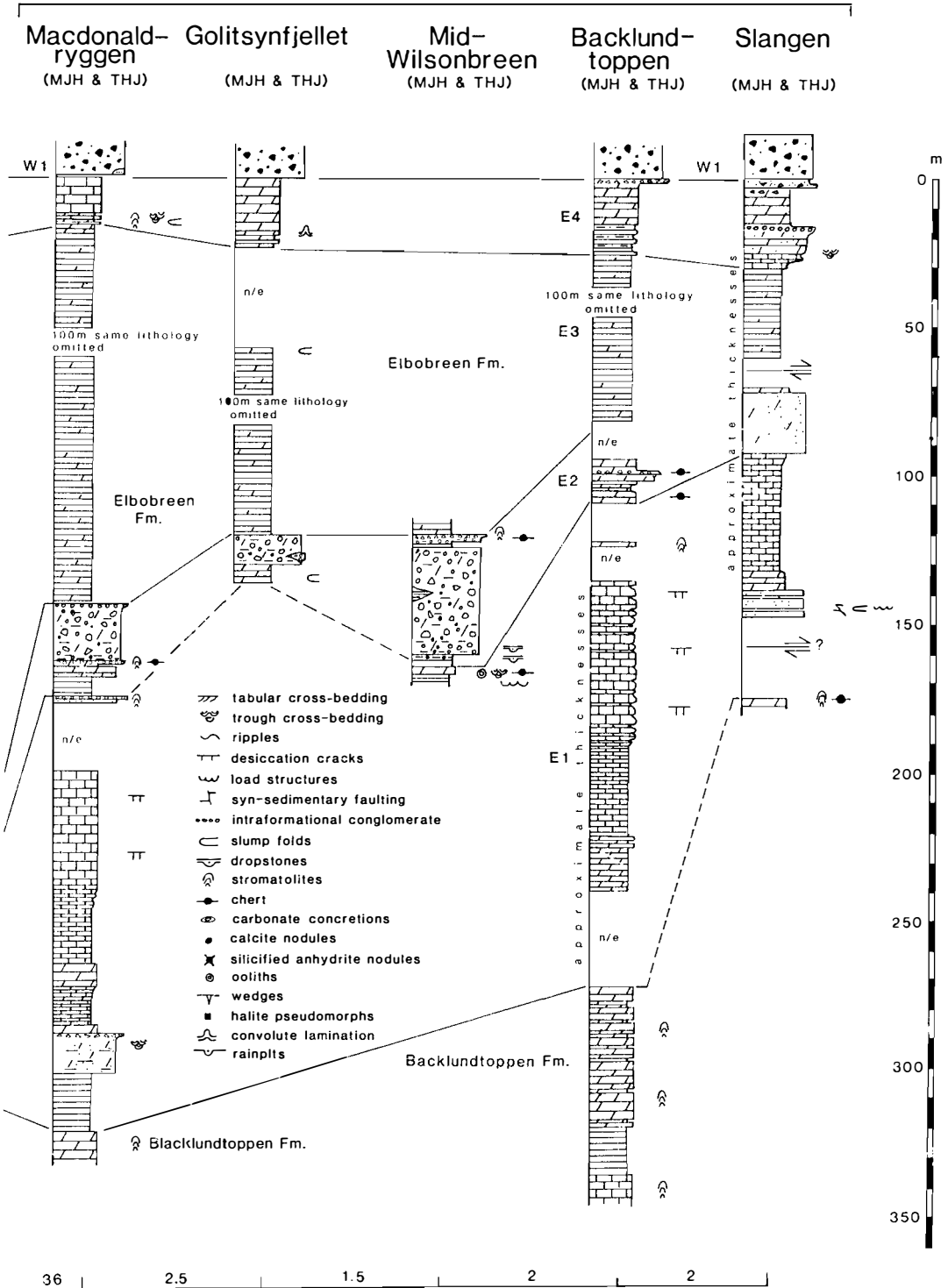


Fig. 5. Stratigraphic logs and correlations through the Backaberget Formation of Nordaustlandet and the Elbobreen Formation of Ny Friesland and Olav V Land. Sedimentary structures are also shown. IJF = I. J. Fairchild; THJ =



T. H. Jefferson. For locations see Fig. 2.

stromatolitic horizons and chert nodules. On the basis of a prominent *Salterella* horizon and other fossils, (*Obolus* sp., *Lingulella* sp. and *Planolites* trace fossils) an Early Cambrian age is indicated.

(T2) *Topiggane Shale Member* (22 m): green to grey shales, interbedded with thin glauconitic, phosphatic and dolomitic sandstones. The shales are anomalously rich in potassium, occurring as authigenic K-feldspar. Various microfossils indicate that the higher shales are of *Holmia*-A age; other microfossils permit correlation with the Lontova beds of the Early Cambrian Sub-Holmia stage of Eastern Europe (Knoll & Swett 1987).

(T1) *Blårevbreen Sandstone Member* (25–33 m): principally quartz-arenites. An Early Cambrian age is suggested by the presence of abundant trace fossils: *Diplocraterion*, *Monocraterion*, *Scolithus*, *Planolites* and *Cruziana* (Knoll & Swett 1987).

The Tokammane Formation probably represents an early Cambrian transgression, with the Blårevbreen Sandstone Member having formed in a littoral/tidal environment, with progressively deeper water conditions following.

2.4.2 *Dracoisen Formation (Polarisbreen Group)* (525 m)

2.4.2.1 *The strata*. – Although no disconformity has been noted at the top of this group, micropaleontological studies suggest a depositional hiatus spanning the time interval equivalent to the Valdai (Ediacara) and Rovno (Earliest Cambrian) beds of Eastern Europe (Knoll & Swett 1987). *Polarisbreen Group* microfossils include *Bavinella faveolata*, *Protosphaeridium* sp., thin-walled leiosphaerids and rare large acritarchs, which collectively indicate a Vendian age (Knoll & Swett 1987).

The Dracoisen Formation was described by Wilson & Harland (1964) under the name of Upper *Polarisbreen Shales*. It received its present name soon afterwards (Harland, Wallis & Gayer 1966). Superficially a rather monotonous succession, it received little attention until 1981/

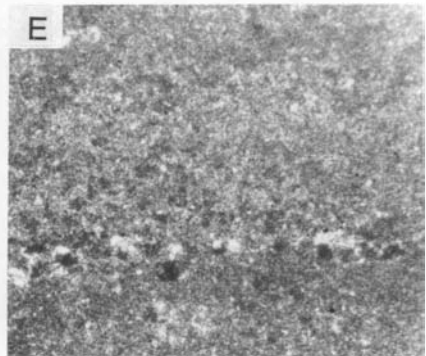
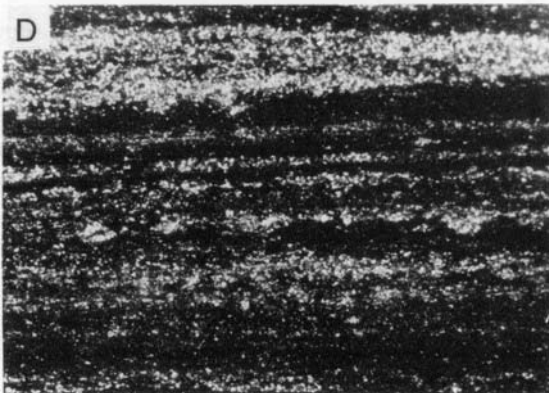
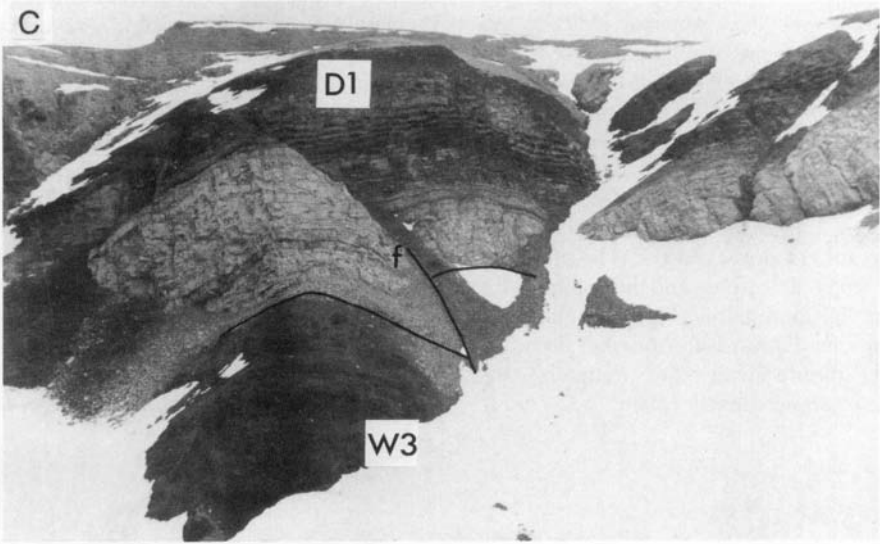
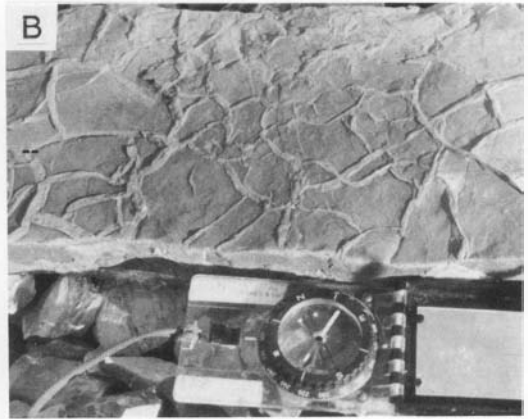
82. Most sections are incomplete owing to faulting, and as far as we can ascertain the only complete section occurs at Ditlovtoppen in southeastern Ny Friesland. The earlier quoted thickness of 280 m (Harland & Wilson 1956; Wilson & Harland 1964) is a considerable underestimate because of miscorrelation of dolostone marker horizons (Fairchild & Hambrey 1984).

The 525-m-thick, near-complete succession at Ditlovtoppen, directly underlies the basal Cambrian sandstones (Blårevbreen Sandstone Member of the Tokammane Formation) described from Topiggane by Swett (1981). Thicknesses have been estimated from a 1:50,000 aerial photograph and from bedding dips. Six members have been distinguished (Fig. 3) (Fairchild & Hambrey 1984).

(D6) *Upper Dolomitic Shale-Sandstone Member* (150 m): the contact with the Blårevbreen Sandstone Member is obscured. D6 consists of fine-grained dolomitic sandstone interbedded with highly dolomitic mudstone. Colour differences reflect the lithology: pale green rocks are sandstones, whereas maroon rocks are mudstones. Individual beds range from several millimetres to 15 cm in thickness and tend to occur in horizons with minor mudstone up to several metres thick. Sandstone layers show various components of an ideal vertical sequence from a basal portion with intraclasts, through parallel laminated sands to sands with gently undulating or wave-rippled laminations, capped by a mud layer. Wave ripples have wavelengths of 1.5–12 cm. Mudstone layers are desiccated and rain-pitted. Some sandstones exhibit groups of nodules of centimetre-scale diameter, comprising ferroan-dolomite cements or a mixture of barite, calcite and ferroan-dolomite cements. The nodules appear to have been originally anhydrite or gypsum. A single occurrence of sand-filled hopper halite pseudomorphs was also found.

(D5) *Middle Dolostone Member* (10 m): the upper contact of this member is fairly sharp. The member consists of pure, cream-weathering, grey, laminated dolostone and minor limestone, the laminations reflecting crystal size, impurities

Fig. 6. Dracoisen Formation facies at Ditlovtoppen, Ny Friesland. A. Middle dolostone unit (D5): limestone matrix with dolostone clasts interbedded with dolostone, intersected by Caledonian calcite veins. B. Variegated sandstone-mudstone-dolostone unit (D4) with sand-filled desiccation cracks. C. Lowest member of the formation: D1 interbedded maroon and greenish grey dolomitic shales grading down into pale yellow dolostone capping the dark diamictite of the Wilsonbreen Formation, and uncomformably overlain by Carboniferous strata. D. Thin section of compacted peloidal dolostone. E. Dolostone of member D1, representing clastic accumulations of dolopeloids. (Photographs D and E taken by I. J. Fairchild.)



or low relief stylolites. The member exhibits desiccation cracks, horizons of tabular intraclasts (Fig. 6A) and evaporite pseudomorphs. The latter are composed of quartzite and quartz with anhydrite inclusions, with cores of ferroan dolomite cement, and are thought to be replaced anhydrite or gypsum nodules.

(D4) *Middle Dolomitic Shale-Sandstone Member (80 m)*: this member has a fairly sharp contact with D5. It consists of a fine-grained dolomitic sandstone, interbedded with highly dolomitic mudstone, varying from maroon (mudstone) to pale green (sandstone). Pale yellow-weathering dolostone and dark grey weathering dolostone occur at the base. This member is similar to D6 with the same range of sedimentary structures: wave ripples and undulatory lamination, desiccation cracks (Fig. 6B) calcite nodules and halite pseudomorphs.

(D3) *Black Paper Shale Member (150 m)*: the lower contact of this member is unexposed, and the member itself is not well exposed. It comprises a finely laminated, extremely fissile, black-, dark-grey- and brown-weathering shale. It is not apparently dolomitic and apart from the lamination has no sedimentary structures.

(D2) *Impure Carbonate Member (105 m)*: the top of this unit is not exposed. The member consists of shaly dolostone and limestone with uniform parallel lamination (Fig. 6D) and low-angle truncations. Upwards the member becomes increasingly impure with clay minerals, siliclastic silt and microspiral calcite.

(D1) *Basal Dolostone Member (20 m)*: this distinctive member (Fig. 6C) was referred to as the "third pale band" of Wilson & Harland's (1964) Wilsonbreen Formation, but transferred to the Dracoisen Formation by Hambrey (1982). The top is gradational with D2 over several metres. The member consists of centimetre to sub-millimetre laminated dolostones, becoming purer downwards. The laminations are defined by variation of organic matter or cement content or the presence of subordinate medium to coarse silt, or both. This unit is maroon and highly fissile at the top and yellow or orange and relatively resistant to weathering at the base, making it a useful marker horizon that can be traced throughout Olav V Land and Ny Friesland. The dolostones represent clastic accumulations of dolopeloids (Fig. 6E) and dolintraclasts compacted together except where separated by early dolomite cement. The basal contact of D1 is visible at several localities in Olav V Land, where the underlying diamictite in some places has a reworked, channelled top, overlain sharply by dolostone.

2.4.2.2 Interpretation. – The Dracoisen Formation reflects a dominantly marine or lacustrine environment that followed abruptly from full glacial conditions of the underlying Wilsonbreen Formation. The first post-glacial sediments are pale clastic dolostones with subordinate silt of the basal members of the Dracoisen Formation (D1). Their well-sorted nature, together with their scoured surfaces and truncations, are consistent

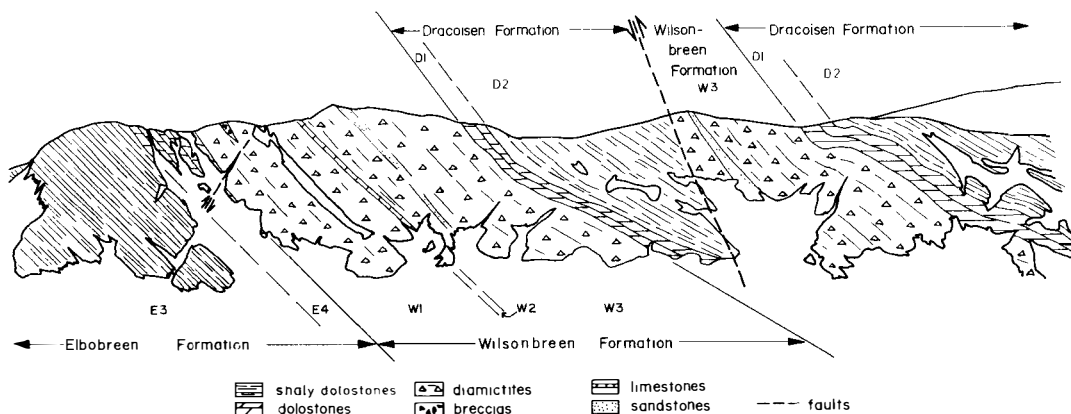


Fig. 7. Sketch from photographs of the Kvitfjella-Backlundtoppen ridge, viewed from the northeast on Wilsonbreen. Note the repetition of part of the succession by a thrust.

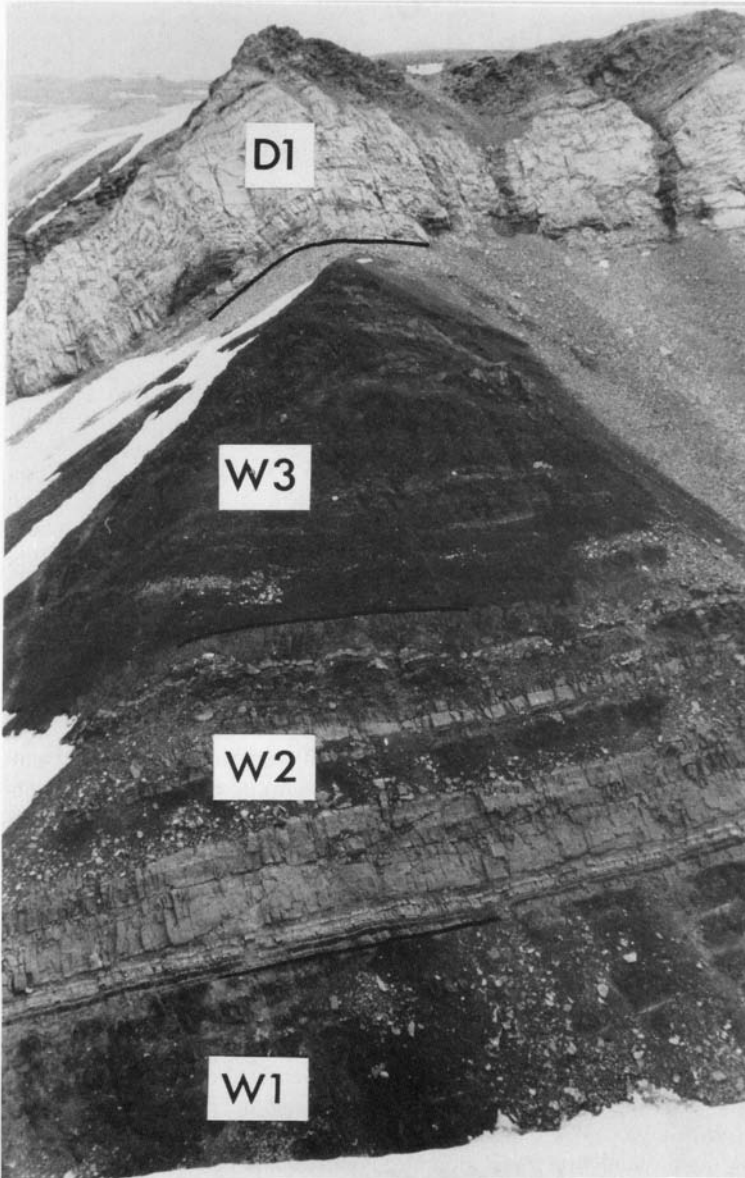


Fig. 8. Wilsonbreen Formation exposed on northwest flank of Ditlovtoppen with cap dolostone (D1) of Dracosen Formation. W3 is massive diamictite with lenses and beds of sandstone; W2 comprises dolomitic sandstones, mudstones, conglomerates and rhythmites; and W1 consists of predominantly weakly bedded diamictite with lenses and beds of sandstone.

with rapid deposition under strong wave action (rather than unidirectional currents), such as in the beach or upper shoreface zone with erosion surfaces cut by storms.

Upwards, through D1, D2 and D3, deepening water sedimentation, though still under wave influence, is suggested by the decline in the size of the erosion surfaces. Dolomite was supplied by a nearby intertidal area which was no longer

exposed, but was progressively diluted by siliciclastic detritus, eventually giving “offshore” shales in D3. The intensity of wave action suggested in the basal part of the formation, is compatible with deposition in a large lake or the sea.

Emergence once again is recorded in members D4 to D6. Fine-grained dolostone with evaporite minerals, associated with desiccation-cracked and wave-rippled sands is commonly associated with

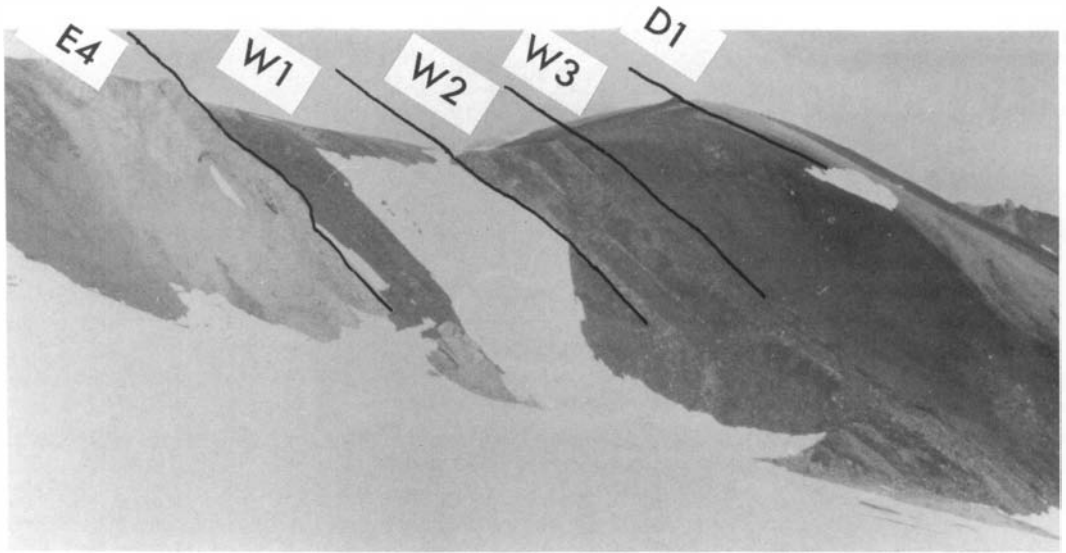


Fig. 9. Wilsonbreen Formation exposed on the east flank of Dracoisen above Polarisbreen; bounded by pale dolostone above (D1) and beneath (E4).

lakes which periodically dry out, although a marginal marine (e.g. lagoonal) environment cannot be discounted. The relatively low quantities of the more soluble evaporites suggests a non-arid climate. In general, therefore, the upper part of the Dracoisen Formation is representative of waning oscillatory flow.

2.4.3 Wilsonbreen Formation (160 m)

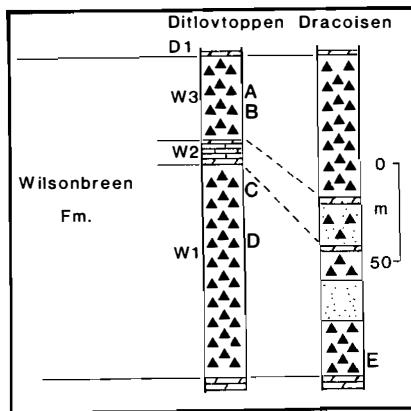
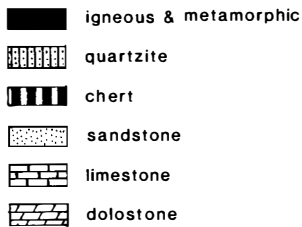
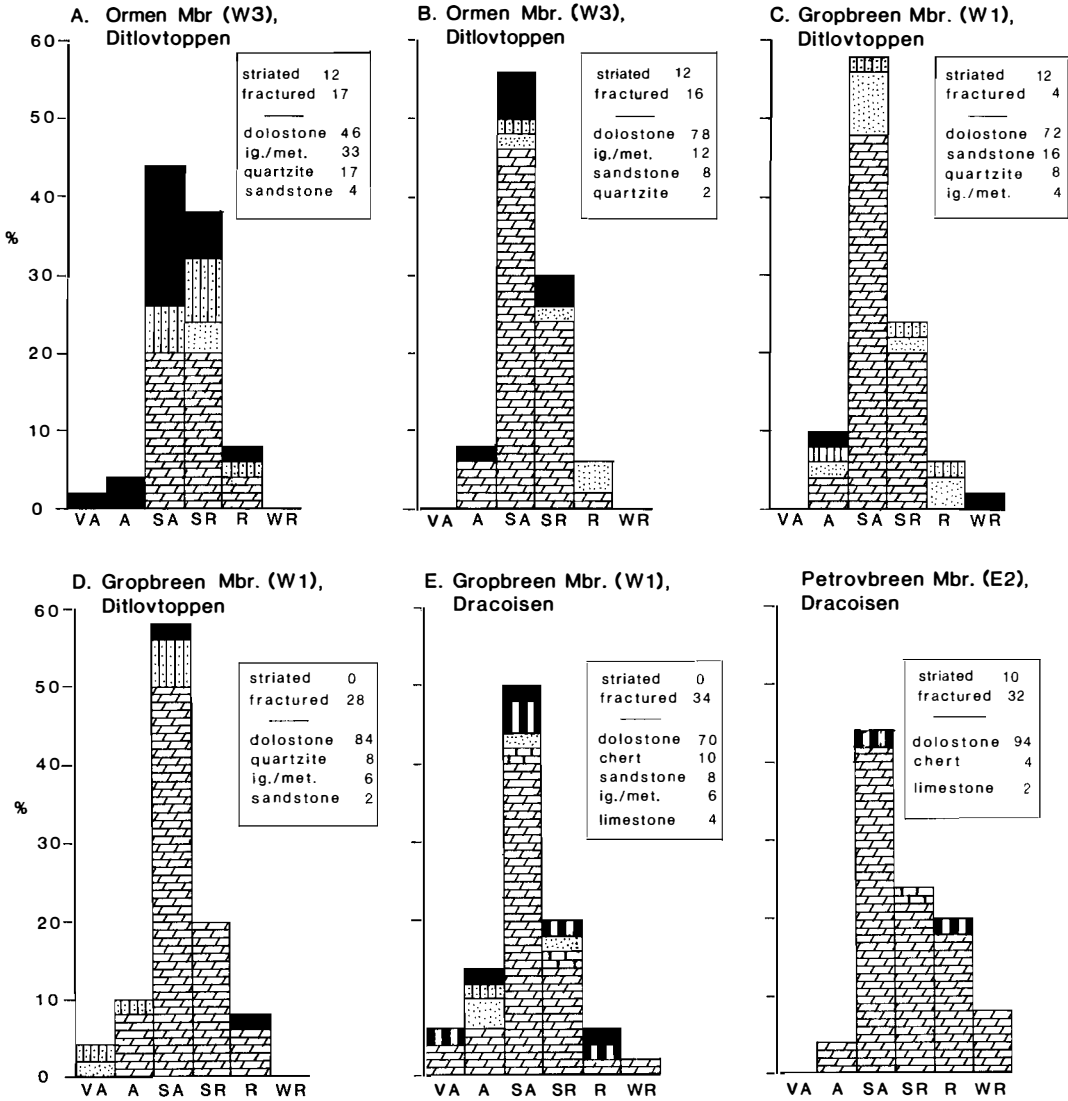
2.4.3.1 The strata. – This formation, named after the glacier that bears the name of C. B. Wilson who died in 1959 after making several outstanding journeys through Ny Friesland (Harland, Wallis & Gayer 1966), was formerly known as the Polarisbreen Tillite (Harland & Wilson 1956; Wilson & Harland 1964). It is the main diamictite-bearing unit in the Polarisbreen Group, although a wide range of other facies are present. The type section follows the Kvitfjella-Backlundtoppen ridge (Fig. 7) where it is almost completely exposed. Good sections also occur at Ditlovtoppen (Fig. 8) and Dracoisen (Fig. 9). Formerly, the formation was defined at top and

bottom by persistent pale carbonate layers (Wilson & Harland 1964), the lower one was excluded by Chumakov (1978) and both of them by Hambrey (1982) as they have sharp contacts with the diamictite but are gradational with their other adjacent units. The overall stratigraphy at the type locality was not recorded correctly by Wilson & Harland (1964) and Hambrey (1982) owing to the failure to recognise a thrust which repeated part of the formation (Fig. 7, cf. plate 1a in Hambrey 1982). The succession presented below is therefore that of Fairchild & Hambrey (1984).

Three members were defined at the type locality, a distinctive carbonate unit separating two dominantly diamictite units. These can be recognised in neighbouring nunataks, but correlation into Ny Friesland is less certain. Indeed, individual beds are often lenticular over only a few hundred metres, and detailed correlations are not possible (Fig. 4). Therefore, after summarising three defined members, the composition of the sediments and nature of the various facies are described.

(W3) *Gropbreen Member (73 m)*: this consists

Fig. 10. Histograms of stone shape and lithology from diamictite of the Wilsonbreen Formation (A–E) and the Petrovbreen Member. VA = very angular; A = angular; SA = subangular; SR = subrounded; R = rounded; WR = well rounded. Total proportions of different lithologies and the percentages of striated and of probable subglacially fractured stones are given. The inset indicates the stratigraphic position of the sampled sites.



of diamictite with minor sandstone and siltstone, and lies with sharp, channelled contact below the dolostone of D1.

(W2) *Middle Carbonate Member (3–10 m)*: this is limestone-bearing, present in all complete sections, and was described in detail by Fairchild et al. (1989). Typically, ungraded rhythmites display alternating sand and carbonate laminae with stromatolite occurrences. Some distortion and brecciation suggest collapse from evaporite dissolution, supported by evidences of former anhydrite and gypsum. Detailed isotopic data were presented, and their bearing on the environment of formation considered.

(W1) *Ormen Member (85 m)*: this is similar to W3 but has minor breccia. The top is sharp with sandstone wedges penetrating the diamictite. The base also is sharp with basal conglomerate on brecciated dolostone of the Elbobreen Formation.

The Wilsonbreen Formation has a uniform thickness of 160–170 m along strike (Fig. 4), over a distance of 55 km. Each of the northeastern Spitsbergen localities has a Middle Carbonate Member of variable thickness. If these are correlated, the thickness variations of the constituent members of the formation are considerable (Fig. 4).

2.4.3.2 Composition and diagenesis. – Most of the sediments of the Wilsonbreen Formation are texturally and mineralogically immature. The gravel fraction in diamictites and rare conglomerates is extremely varied, with both intrabasinal and extrabasinal clasts present.

Intrabasinal clasts can be matched with some of the underlying strata, especially the Elbobreen and Backlundtoppen formations. Stromatolitic and oolitic dolostones, black limestones and black chert are particularly distinctive. Other lithologies may have come from older formations or their lateral equivalents, but precise matching is not possible. For example, some quartzite stones may have come from the Veteranen Group.

Extrabasinal clasts comprise igneous and metamorphic rocks from an unknown source area. No rocks of these types are currently exposed in Svalbard, yet they sometimes make up one-third of the stones. Red granites and pink grey gneisses are the most common. Wilson & Harland (1964) recorded the following rock types: coarse-grained pink alkali granite (most common), biotite alkali granite, quartz orthoclase granophyre, albite and

oligoclase syenite, weathered porphyritic and amygdaloidal felsites, andesites, possibly basalts, banded granitic gneiss, granulite, mica schist and quartzite. Although many clasts are fresh, some are weathered to a varying degree, e.g. chlorite has replaced ferro-magnesian minerals. Such lithologies are probably reworked material that had already been weathered.

The stone composition of the diamictite varies a great deal stratigraphically, but analysis of the main lithological groupings shows a crude trend towards an increasing proportion of igneous/metamorphic clasts towards the top of the formation, at the expense of dolostones (Fig. 10). However, lateral changes have not been examined and this requires more systematic study.

Analysis of clast shape in the diamictites (Fig. 10) shows a preponderance of subangular, followed by subrounded clasts. Well-rounded and very angular clasts are rare. Shape data have been compared with data from modern glacial sediments (Dowdeswell, Hambrey & Wu 1985). Plots of Krumbein roundness against sphericity indicate that the diamictites are similar to modern basally derived glacial sediments. Comparisons of different lithologies did not reveal any significant difference between igneous/metamorphic and carbonate clasts. None of the diamictites sampled resembled supraglacial rock-fall debris.

A varying proportion of the clasts are striated (Figs. 10 and 11) (Dowdeswell, Hambrey & Wu 1985), though this may, to some degree, reflect the ease in which stones can be extracted from the matrix or the degree to which they are weathered. The highest percentage recorded was 18%, but values of 10–13% are more typical. Striations tend to occur randomly or in subparallel sets; they are clearly not tectonic. Usually only fine-grained lithologies, notably black-limestones, are striated and none of the coarse igneous and metamorphic rocks examined had striations. Other characteristics of stones include fractured and faceted surfaces, and flat-iron shapes are common.

The sand and silt fractions (Fig. 11C) are predominantly angular to subrounded quartz grains (often strained) with subordinate dolostone and other rock-fragments, feldspar (including microcline, perthite and plagioclase) and minor muscovite. Heavy minerals include zircon, tourmaline, pyrite, haematite and magnetite, often as quite large grains; these probably come from the same source as the igneous and metamorphic rocks. The composition of the sand is

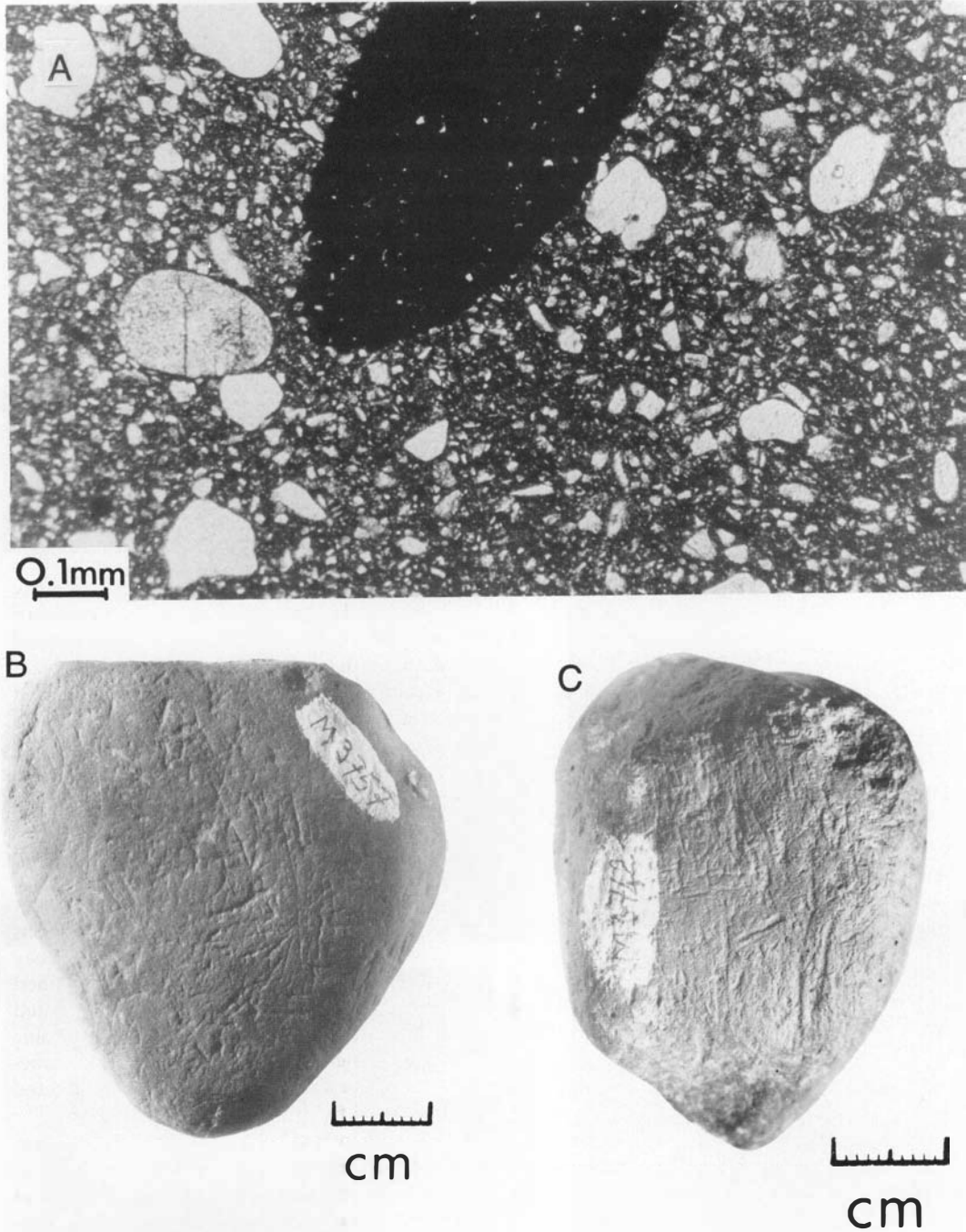
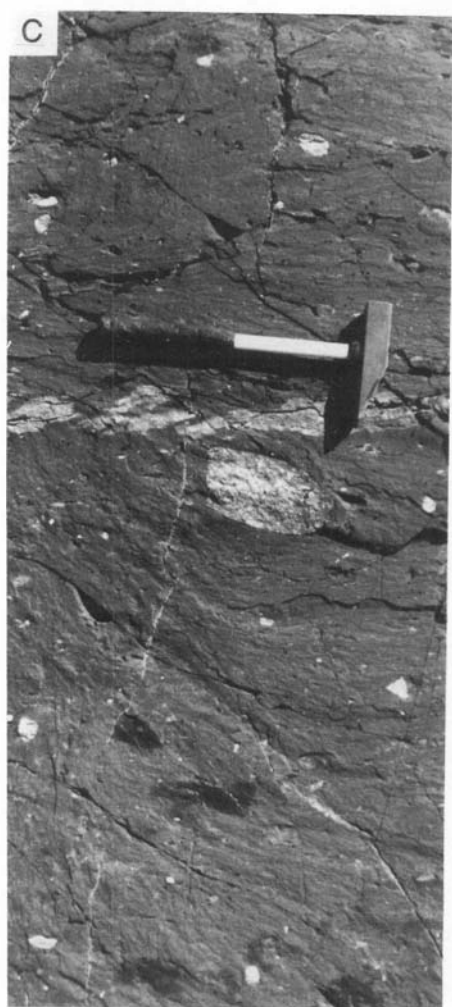


Fig. 11. A. Thin section of massive diamictite from the Wilsonbreen Formation. Note variable grain shape, dark matrix, rich in carbonate and haematite. Most grains are of plagioclase and quartz; the large black fragment is a weathered gneiss clast. B and C. Striated and partly faceted stones from the Ormen Member of the Wilsonbreen Formation (W1) on the Kvitfjella-Backlundtoppen ridge: B. Randomly orientated striations on dolostone, due to rotation at glacier bed; C. Striations with preferred orientations of two sets on a fine-grained basic igneous rocks.



variable: quartz arenite, feldspathic sandstone, lithic and feldspathic greywackes are all present (Pettijohn 1975 terminology).

The silt fraction grades into a dark opaque groundmass of dolomitic with varying proportions of quartz, clay minerals and haematite. This fine fraction is interpreted as rock flour (Wilson & Harland 1964; Fairchild 1983; Fairchild & Hambrey 1984).

Rhythmites contain microsparry calcite and calcitic and dolomitic stromatolites, which are chemical, replaced or biochemical precipitates.

Diagenesis involved compaction, cementation, veining and partial replacement by ferroan dolomite, zoned or ferroan calcite and quartz, and probable chloritisation of volcanic fragments. Some grains of quartz show carbonate overgrowths, slight etching and thin altered rims. It was suggested that surface oxidation may have led to the characteristic reddening in this formation (Harland & Herod 1975; Hambrey 1982), but subsequent work has favoured a climatically unrelated burial diagenetic origin of the haematite (Fairchild & Hambrey 1984).

2.4.3.3 Description of facies. – The facies present in the Wilsonbreen Formation have been described by Fairchild & Hambrey (1984) and are summarised below.

Diamictite: This facies makes up the bulk of the Wilsonbreen Formation. It is a mottled, greenish-grey and maroon, matrix-supported rudite with stones up to 1 m in diameter. Both massive and bedded diamictites are present with gradations between. The sand and finer fractions are lithic or feldspathic greywackes.

Massive diamictite (Fig. 12A) weathers into irregular blocks and is generally maroon. Sedimentary structures are absent except for a striated cobble pavement at Ditlovtoppen that was first described by Chumakov (1968) (Fig. 12B). It consists of planed-off cobbles, each bearing striations of the nailhead type, all with approximately the same orientation. Bedded diamictite is grey or maroon. Bedding is generally weak, irregular

and subtle, picked out by colour differences which reflect variations of grain size, i.e. sandy beds are generally grey, but boundaries are gradational. Where the stone content is low the diamictite takes on a shaly appearance owing to the ease with which weathering takes place along the irregular bedding surfaces. Outsized stones, disturbing the bedding, and interpreted as dropstones, occur locally. Bedding shows evidence of soft-sediment deformation with weak load and flame structures present.

Stone fabrics were measured at several levels within the Wilsonbreen Formation, plotted on stereographic projections and analysed by the Eigenvalue method (Dowdeswell, Hambrey & Wu 1985). Massive diamictites show weak preferred orientations of the girdle type with one or more maxima within the girdle (Dowdeswell, Hambrey & Wu 1985; Fig. 10). Normalised Eigenvalues S1 and S3 compared with the limited data from present-day glacial sediments suggest that most of them fall within the glacial sediment flow (flow till) field. One weakly bedded diamictite plotted in the same broad field. However, even statistical analysis of fabric data does not provide an unequivocal distinction between glacial sediment flows and lodgement tills (see later discussion). The weak preferred orientations reflect flow directions. Trends of SE–NW and SW–NE are apparent. Together with the nailhead striations on the Ditlovtoppen boulder pavement, ice flow towards the NW was the most likely. All fabrics measured in northeastern Spitsbergen are regarded as primary because tectonic lineaments trend north-south, and, except for major axes, are only observable in incompetent (shale) units.

Conglomerate: Layers and lenses of pebble conglomerate and sandstone up to a metre or so in thickness occur sporadically within the diamictite units. Layers of conglomerate are up to 20 cm thick, having a gradational boundary with underlying diamictite, and a sharp (occasionally wave-rippled) top. The clasts are a representative selection from the diamictite and typically are sup-

Fig. 12. Facies and structures in the Wilsonbreen Formation. A. Massive diamictites, with calcite-coated faceted and striated limestone clast at top, Gropbreen Member (W1), southwest flank of Golitsynfjellet, Olav V Land. B. Planed-off cobble with striations (some of the nail-head type), on a boulder pavement in the section at Ditlovtoppen, Ny Friesland. C. Weakly bedded diamictite with diffuse pale sandy layer in predominantly maroon unit; note granite clast below the hammer; Macdonaldryggen, Olav V Land. D. Shaly diamictite, reflecting weak bedding and intersection cleavage, Slangen, Olav V Land. E. Well-bedded, clast-poor diamictite. The steeply dipping beds show alternations of paler sandier and maroon muddier units, MacDonaldryggen, Olav V Land.

ported by a sandy matrix. Some poorly sorted conglomerate layers form more discrete beds, often contorted, and with evidence of loading or slumping.

Lens-shaped conglomerates, where contacts are visible, are sharply defined, channel forms commonly being recognisable. The best exposed channel forms were observed on the summit plateau of Golitsynfjellet, ranging from 0.2 to c. 7 m deep, having a broadly WSW–ENE preferred orientation (Fig. 13). Grain-size characteristics range from well-sorted, clast-supported gravels (rare) through the more common poorly sorted gravels with a sandy matrix supporting the clasts, and into poorly sorted sandstones. Poorly developed trough cross-stratification is sometimes present.

Breccia: Lens-shaped breccia horizons with diffuse boundaries occur locally within massive or weakly bedded diamictite in the Wilsonbreen and Dracosen sections. In the type locality, on the ridge crest, 20 m above the base of the formation, a dolostone breccia forms an irregular lens up to 1 m thick. It varies laterally from clast- to matrix-supported, and clasts are composed entirely of a distinctive cemented dolostone from the top of the Elbobreen Formation (E4). The matrix is maroon, resembling that of the adjacent diamictite. At other localities breccias consist of the same variety of lithologies as do the diamictites.

Sandstone and massive siltstone: Well-cemented dolomitic sandstone and rarer siltstone

units up to a few metres (and locally > 10 m) thick occur in sharply defined, laterally persistent layers or lenses between diamictite units. They vary in colour from maroon to pale yellowish or greenish grey. A weak planar stratification is characteristic, but exceptionally sandstone units exhibit either parallel or undulatory lamination, wave ripples, trough cross-stratification, slump folds, convolute laminations intraformational brecciation. On the SW spur of MacDonaldryggen above Elbobreen one 9-m-thick orange sandstone has lenticular bedding, a possible loaded base (sharp but uneven contact), a slump-fold overturned to the NW and dropstone-like structures (from small pebbles). Irregularly branching, symmetrical wave ripples are well developed on the upper surface (wavelength 19 cm, ripple index = 10), which also has faint lineations, a small groove subparallel to the lineations and is noticeably pitted. Diamictite overlies this unit directly. The lineations and grooves could be the result of glacial abrasion, but this conflicts with the rippled nature of the surface. Alternatively, an iceberg in the intertidal zone may have created the groove. On the Geebreen flank of MacDonaldryggen the same unit divides into a series of wedge-shaped bodies, interbedded with diamictite. Large symmetrical straight-crested wave ripples with smaller ripples in their troughs occur on these bedding surfaces. Eight major ripple pairs showed a wavelength ranging from 35–79 cm (mean 61 cm) and a ripple index ranging from 6–20. Here also lineations

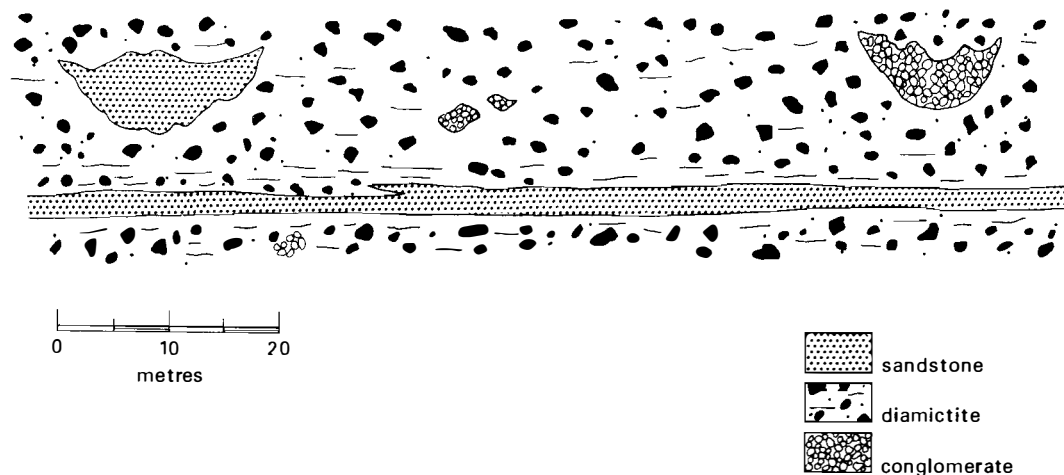


Fig. 13. Schematic sketch showing geometry of fluviglacial channel fills in Ormen Member (W3) of Wilsonbreen Formation on summit plateau of Golitsynfjellet.

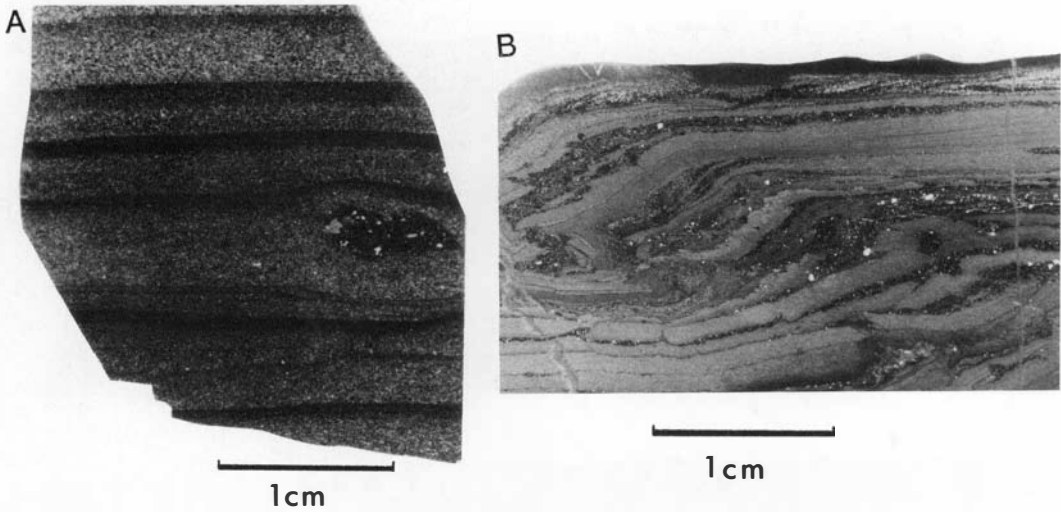


Fig. 14. Rhythmite facies in Wilsonbreen Formation. A. Silty rhythmite defined by grain-size variation and a pellet of diamictite, Dracoisen. The matrix consists of quartz grains in dolomicrite and ferroan calcite. B. Slump folded silt/sand-carbonate rhythmites, Middle Sandstone – Carbonate Member, Ditlovtoppen. (From Fairchild & Hambrey 1984.)

were observed on several rippled bedding surfaces, all consistently orientated at a moderate angle to the ripples. The origin of the lineations is not known; it does not coincide with structural trends in the area, but one could speculate on their being the result of drift ice abrading tidal flats.

The sandstones comprise lithic and feldspathic greywackes, sublitharenite, arkose and quartz arenite. They are moderately sorted, very fine- to medium-grained, and contain minor silt and sparse rock flour. The siltstones are grain-supported but contain 10–25% matrix.

Rhythmite: Two types of rhythmite have been observed: (i) silty rhythmites defined by grain-size variations, and (ii) silt/sand-carbonate rhythmites defined mainly on the basis of composition. Silty rhythmites comprise pairs of layers of poorly sorted sand-sized grains in a matrix of dolomicrite and ferroan calcite passing up into coarse silt-sized grains in a rather more abundant but similar matrix. Both types of lamina are feldspathic-lithic greywackes. Maroon silty rhythmites (lithic greywackes) occur in the Ormen Member at Dracoisen (Fig. 14A). They consist of laminated siltstone couplets 1–6 mm thick with mainly angular grains in an opaque, haematite-rich matrix. There is a sharp contrast between haematite- and

quartz-dominated laminae in each couplet. A crude lamination is defined by alignment of grains, particularly by the minor amounts of muscovite present. The coarse layer forms the lower part of each couplet and is substantially thicker than the haematite clay layer. No outsize clasts have been observed, but a diamictite pellet occurs in one sample. The silt/sand-carbonate rhythmites are more abundant and are particularly prominent in the Middle Carbonate Member (W2). Maroon-brownish pink, maroon-yellow and maroon-greenish grey rhythmites are all present. Each rhythm is a couplet comprising:

- *At the top:* micrite, dolomicrite or ferroan calcite, neomorphic sparite, with rare angular silt or sand grains (about 10%).
- *At the bottom:* below an irregular, but generally sharp contact, is a thick lamina up to 4 mm thick of mainly angular silt and sand in a haematite clay-micrite/dolomicrite matrix (when maroon) or dolomicrite (if pale-coloured). One sample had the following composition: quartz 45%, feldspar 10%, matrix 40%, rock fragments 5% (lithic greywacke). Some grains puncture the lamination within couplets, and there is evidence of loading.

Both types of rhythmite have invariably under-

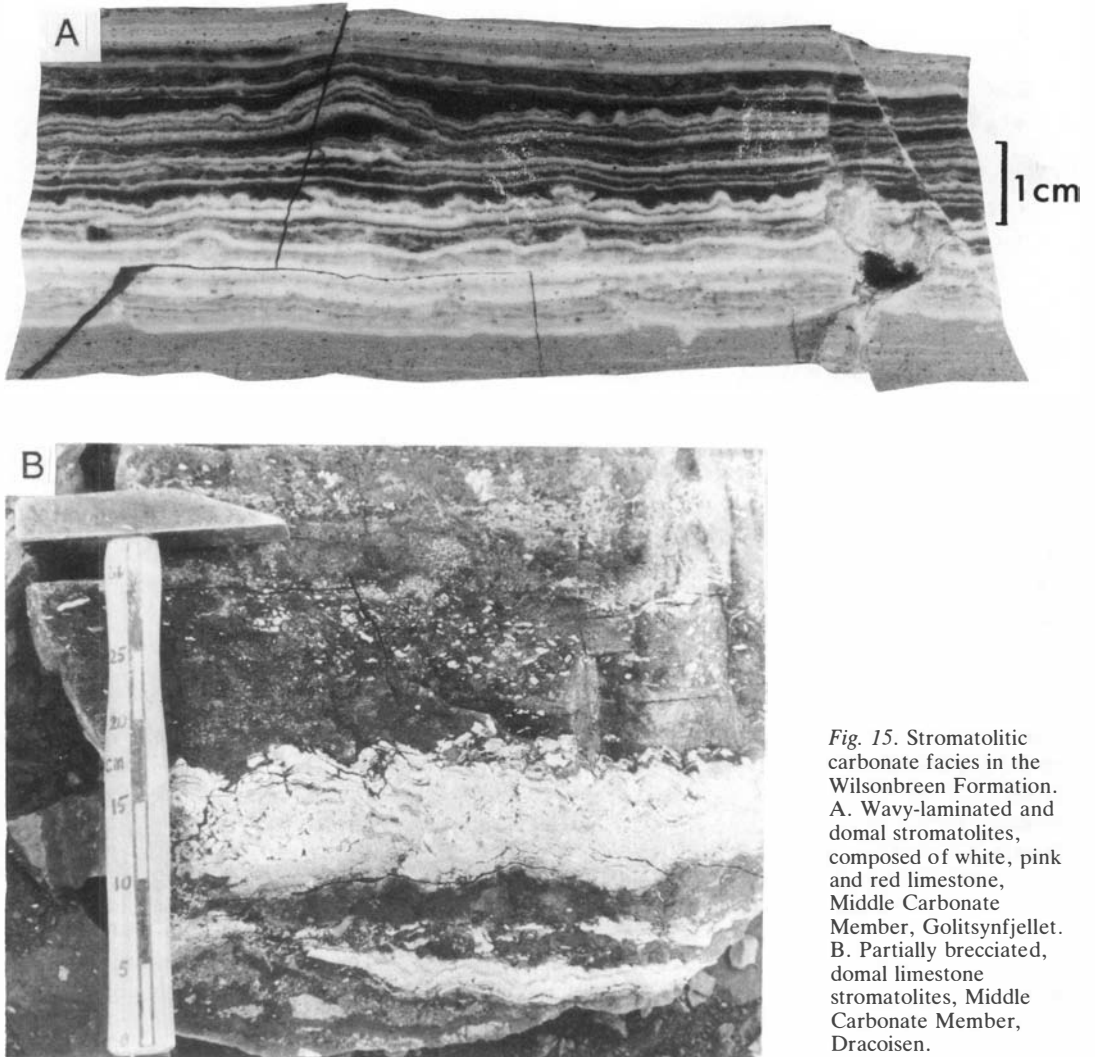


Fig. 15. Stromatolitic carbonate facies in the Wilsonbreen Formation. A. Wavy-laminated and domal stromatolites, composed of white, pink and red limestone, Middle Carbonate Member, Golitsynfjellet. B. Partially brecciated, domal limestone stromatolites, Middle Carbonate Member, Dracoisen.

gone syn-sedimentary deformation and disruption. In addition to contorted and broken or boudinaged laminae (the carbonates behaving more competently), there are slump folds (sometimes isoclinal) and microfaults with grains having fallen into the fault zone. Micrograben with partial brecciation are also common.

Stromatolites and associated lithologies: The Middle Carbonate Member (W2) also contains stromatolites, forming beds up to 1 m thick within sandy lithologies. Their relief generally is only a few millimetres to several centimetres, normally

with wavy lamination but occasionally domal or bulbous (Fig. 15A). They are often partly brecciated and incorporated into sandstones as intraclasts or form flake breccias a few centimetres thick (Fig. 15B). They are dominantly calcitic, occasionally dolomitic. Microstructurally there is, differentiation of (dolo-)micritic parts and sparry (cemented) parts. A detailed study of the stromatolite-diamictite association has been published (Fairchild et al. 1989).

Wedge-fillings: Wedge-shaped fillings of sand and breccia occur at several localities. Sandy

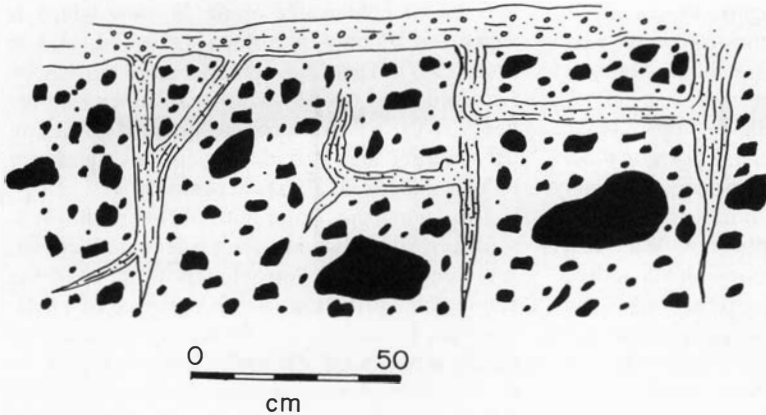


Fig. 16. Sketch of sand-filled wedges, penetrating massive diamictite near the top of the Gropbreen Member (W1) of the Wilsonbreen Formation, south flank of Golitsynfjellet.

breccia-filled wedges occur only at the base of the Wilsonbreen Formation but occur everywhere where it is underlain by the pale dolostone (oolitic) of the Slangen Member (E4) of the Elbobreen Formation. Dolostone breccias grade down into brecciated dolostone which displays narrow fractures extending 0.5 m below the top. In plan these cracks are either randomly orientated or (less commonly) occur in parallel groups. Fracturing postdates lithification of the dolostones. Particularly good examples occur in the Kvitfjella-Backlundtoppen and Dracoisen sections.

Sand-filled wedges penetrate diamictite up to 3.5 m below sandstone horizons in the Ormen Member at Ormen, Golitsynfjellet, Ditlovtoppen and Dracoisen. The largest and best examples were described by Chumakov (1968, 1978). There, the well-defined sandstone wedges taper downwards from 0.6 m at the top. The layering in the wedges sag downwards at the top, whereas lower down the layering is parallel to the walls of the wedges. Sandstone wedges at Golitsynfjellet are rather complex in form, more like inter-connecting veins (Fig. 16) which extend below a sandy conglomerate layer and comprise the finer fraction of that horizon. This wedge comprises poorly sorted, subrounded to subangular sand, cemented by calcite. At Dracoisen, light-coloured sandstone wedges were observed in a maroon, poorly sorted sandstone; these have been folded by compaction.

2.4.3.4 Interpretation. – The Wilsonbreen Formation is a diamictite-dominated unit of the order of 160 m thick, and of remarkably uniform thick-

ness throughout northeastern Spitsbergen. It represents the second glacial epoch recorded in the Late Proterozoic successions of Svalbard, and one that resulted in a thicker sequence of glacial sediment than the first.

Diamictite invariably rests with sharp contact on the underlying pale dolostones. Prior to glaciation this must have been a subaerial surface in northeastern Spitsbergen, because of the presence of wedges in what apparently was already lithified material topped by in situ dolostone breccia, suggestive of periglacial activity and frost shattering. Lowering of sea level at the onset of glaciation, with the emergence of a lithified supratidal plain, would have led to the development of periglacial features. However, the first glacial material appears to have been waterlain. Evidence for terrestrial glacial conditions is also clear at many levels within the Wilsonbreen Formation. The striated cobble pavement at Ditlovtoppen, with nailhead striae, suggests ice movement from the southeast (Chumakov 1968, 1978; Fairchild & Hambrey 1984); it is overlain by massive diamictite with a preferred orientation of stones indicating approximately the same direction. Lens-shaped bodies of sandstone and conglomerate in massive diamictites indicate fluvio-glacial braided stream deposition. At a few levels in the Wilsonbreen Formation, sandy wedge fillings are present; they seem to be analogous to periglacial ice-wedge casts or less likely cold-arid sand wedges, rather than to be the result of soft-sediment loading. There is, however, little evidence of debris being subaerially derived and transported at the surface of a glacier, so ice-sheet

conditions are again envisaged. Practically all debris suggests that it was transported in the basal zone of a glacier, but one patch of monomict breccia does point to at least one local nunatak supplying supraglacial material.

Evidence for waterlain glacial deposition is also strong, though in massive but fractured to weakly bedded diamictites the distinction is often difficult to make (Dowdeswell, Hambrey & Wu 1985). Weakly bedded diamictites contain hints of dropstones where wispy sandy segregations occur. Local rhythmite beds are better indicators of aqueous deposition, as are diamictite beds with tops containing rippled lag deposits. Such diamictites are probably proximal glaciomarine sediments or waterlain tills. Some sandstone and siltstone sheets, the former with large wavelength ripples, are also more likely to be of marine rather than terrestrial or even lacustrine deposition.

A unique horizon of interbedded limestone with stromatolites, rhythmite, diamictite and sandstone in the middle Wilsonbreen Formation (W2) is interpreted as having formed in a marginal marine environment, during a minor retreat phase in the glaciation. In this case the stromatolites

may be of cold water origin, a view which is supported by oxygen isotope data (Fairchild & Spiro 1987). The data were discussed further by Fairchild et al. (1989) who found unexpectedly heavy oxygen isotope compositions if glaciation occurred at a high latitude (e.g. as for Quaternary or Late Paleozoic glacial deposits).

The significant difference between the Wilsonbreen Formation and the earlier glacial epoch, represented by the Petrovbreen Member of the Elbobreen Formation, is the presence of exotic material. Although the sedimentary clasts can be matched only with lithologies in the 500 m or so of underlying strata, igneous and metamorphic stones have no obvious source in any exposed older strata in Svalbard today. They are therefore probably far-travelled from a terrane in the south.

2.4.4 Elbobreen Formation (320 m)

2.4.4.1 *Distribution.* – Formerly known as the Lower Polarisbreen Shales (Wilson & Harland 1964), the Elbobreen Formation (Harland, Wallis & Gayer 1966) has been redefined and divided



Fig. 17. Type locality of the Petrovbreen Member, south flank of Backlundtoppen. In the foreground is the lateral moraine of Petrovbreen. The Petrovbreen Member forms the prominent rib of rock between the two snow gullies, and the succession youngs to the left.

into four members, including a dolomitic diamictite (Hambrey 1982; Fairchild & Hambrey 1984). The most complete section occurs in MacDonaldryggen, on the northern flank of Elbreen, although the members were defined at Backlundtoppen. Other sections have been studied at Dracoisen (faulted), Ditlovtoppen and Slangen (faulted), with observations at further localities on the diamictite member. The members are laterally continuous (Fig. 5) except where faulted out, but thicknesses are variable.

The four members from top to bottom are as follows:

2.4.4.2 (E4) Slangen Member (14–28 m). – Beneath the sharply defined base of the Wilsonbreen Formation occurs this horizon of cream- or white-weathering dolostone, the “first pale band” of Wilson & Harland (1964). The member consists of three distinct units (Fairchild & Hambrey 1984). The upper one (unit C) at Ditlovtoppen consists of sub-millimetre laminae of silt and dolomicrite; locally it is peloidal, oolitic or intraclastic. The lamination typically is contorted, and there are stylolites defined by shaly dolomite. Below occur oolitic dolostones with abundant fenestral and fibrous dolomite cement. Ooids and early cements are cut by irregular fractures, also cemented, a form of brecciation distinct from that associated with basal Wilsonbreen deposits. The lowest of the three units comprises well-sorted dolarenites of variable grain-size, crudely parallel- or cross-laminated. Grains are composed of dolomicrite of which some appear to be intraclasts (e.g. badly preserved ooids). White chert occurs as bedding-parallel trains of centimetre-sized equant nodules, containing chalcedony and quartz with anhydrite inclusions, and which may originally have been all calcium sulphate. E4 is transitional over several metres with E3, by interbedding of dolomitic siltstones with fine- to very-fine-grained dolarenites.

2.4.4.3 (E3) MacDonaldryggen Member (145 m faulted to 180 m). – This consists of grey, laminated, shaly-muddy dolostones with siltstones and pure dolostones. Coarser and finer units alternate on a scale of 0.2–1 mm, and lamination is defined by variation of the abundance or size of quartz and feldspar grains, and in the amount of dolomicrite or silt-size dolomite crystals. Minor amounts of phyllosilicate minerals also occur. In the top 20 m of this member coarser horizons

contain cross-lamination, low-angle erosion surfaces and thin finer layers with silt-filled desiccation cracks. Fluidisation of such silt has produced upwardly branching sheet-like structures or “pillars”, within which lamination has been destroyed, and which could be confused with animal burrows. The basal E3 beds are pure to slightly silty carbonates, with fine, generally anastomosing lamination of dolomicrospar and dolomicrite, which locally (e.g. at Backlundtoppen) shows centimetre-scale slump folds. The base of this member was seen to be sharp at one locality. In a few places, in areas of greater than usual tectonic deformation, E4 has behaved in a somewhat incompetent fashion, and become chevron folded.

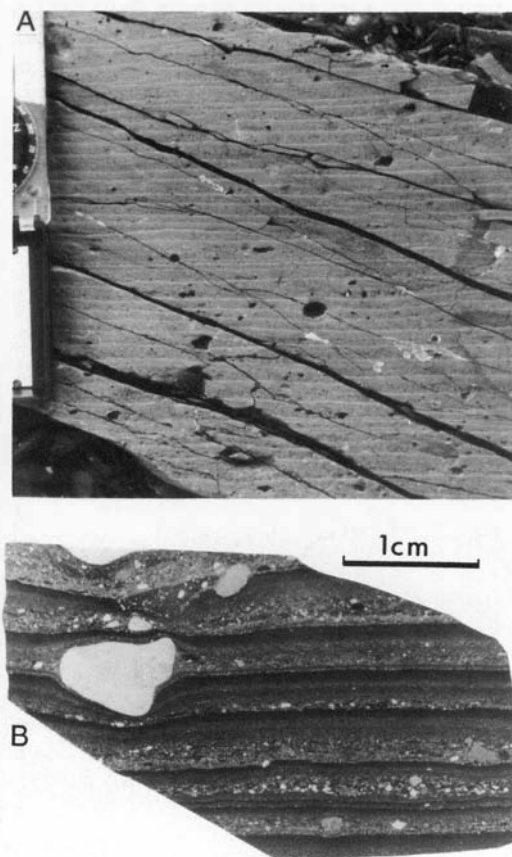


Fig. 18. Outcrop (A) and thin section (B) of dropstone-bearing rhythmite facies near the top of Petrovbreen Member, type locality. Note in (A) spaced cleavage cutting across bedding at a low angle, and in (B) the silty/sandy carbonate couplets, suggestive of varves.

2.4.4.4 (E2) *Petrovbreen Member (>2 to 42 m)*. – This member consists of diamictite, wacke and mudrock and is highly dolomitic. It is extremely variable in thickness, and has a sharp base, although there is no evidence of an erosional unconformity. The type locality and best outcrops occur on the south flank of Backlundtoppen above the lateral moraine of Petrovbreen (Figs. 17 and 18).

Composition of sediments and diagenesis: The gravel to coarse sand fraction consists principally of pale-weathering dolostone (often pisolitic and stromatolitic), with a few per cent each of chert, cherty dolostone, sandstone and clayey siltstone, all of which can be matched with the underlying member of the Elbobreen Formation (Fig. 3). In addition there are rare altered volcanic fragments and black limestones in Olav V Land, neither of which match with E1. Unlike the Wilsonbreen Formation there are no granite and gneiss stones.

In the diamictites the maximum clast size ranges

from about 5 to 90 cm and analysis of Powers' roundness illustrates that subangular stones form the biggest percentage, though all shapes are present (Fig. 10). Around a tenth of the stones are striated (Fig. 19A) or have flat-iron shapes; a few were faceted and a large number fractured after rounding. These characteristics are similar to those in the Wilsonbreen Formation.

Silt- to medium-sand-sized grains consist of quartz and rock fragments of the same composition as the gravel fraction, as well as minor fresh to slightly weathered plagioclase (Fig. 19B). This fraction grades into a dolomitic groundmass interpreted as rock flour (Fairchild 1983) and varying proportions of muscovite, quartz and pyrite.

Compaction has produced a bedding-parallel orientation of phyllosilicate minerals which is difficult to distinguish from primary bedding. Calcite and dolomite veining, as well as secondary chert, quartz, pyrite and chlorite, occur locally. Neo-

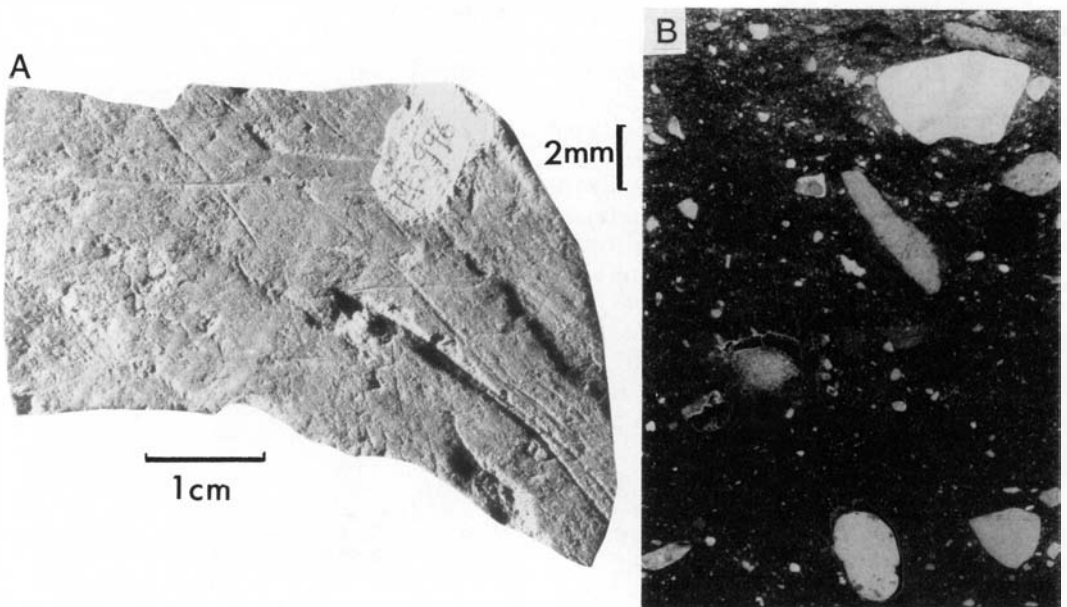


Fig. 19. Lithologies and structures of the Petrovbreen Member. A. Heavily striated and grooved dolostone clast from shaly (weakly bedded) diamictite, type section. B. Thin section of weakly bedded diamictite, Macdonaldryggen section. Note variably shaped clasts (mainly carbonate and quartz) with alteration rims. C. Flame structures of massive diamictite matrix, penetrating gravelly conglomerate bed, Dracoisen. D. Massive diamictite with predominance of subrounded black limestone (some chert) and dolostone clasts, mid-Wilsonbreen. E. Massive to weakly bedded diamictite with variable distribution of somewhat more angular, largely dolostone, clasts, Dracoisen.

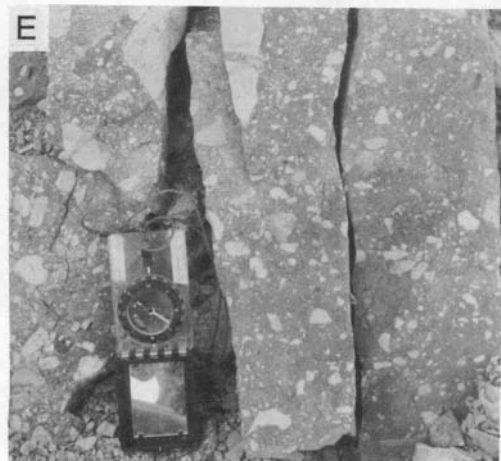
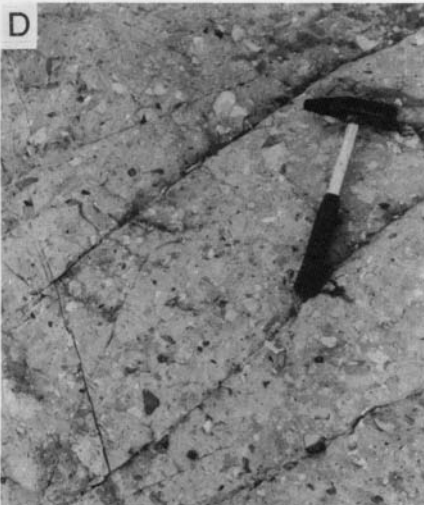
morphism of the very fine-grained dolomite matrix (rock flour) has given rise to fine-grained ferroan dolomite in places (Fairchild 1983). Egg-shell-like coatings of quartz, ferroan calcite, ferroan dolomite and chlorite are developed around dolostone or quartz clasts, and may either be the result of reactions during diagenesis or during freeze-thaw at the base of a glacier.

According to Fairchild et al. (1989) this fine matrix is depleted in ^{13}C and is enriched in Fe (in authigenic pyrite), Mn and Na. Iron enrichment is shown by the weathering colour. Values of $\delta^{18}\text{O}$ are much heavier than recorded for non-

glacial Precambrian or Lower Paleozoic carbonates.

Description of facies (from Fairchild & Hambrey 1984): There is a wide range as in the Wilsonbreen Formation.

Diamictite occurs as yellowish grey-weathering, massive or bedded units, with similar stone shape and size. The gravel fraction makes up 5–40% of the rock, uniform in massive, but variable in bedded units (Fig. 19C, D). Massive diamictites sometimes show pseudobedding due to orientation of phyllosilicates parallel to gross bedding on compaction. Stone fabric analyses (Dow-



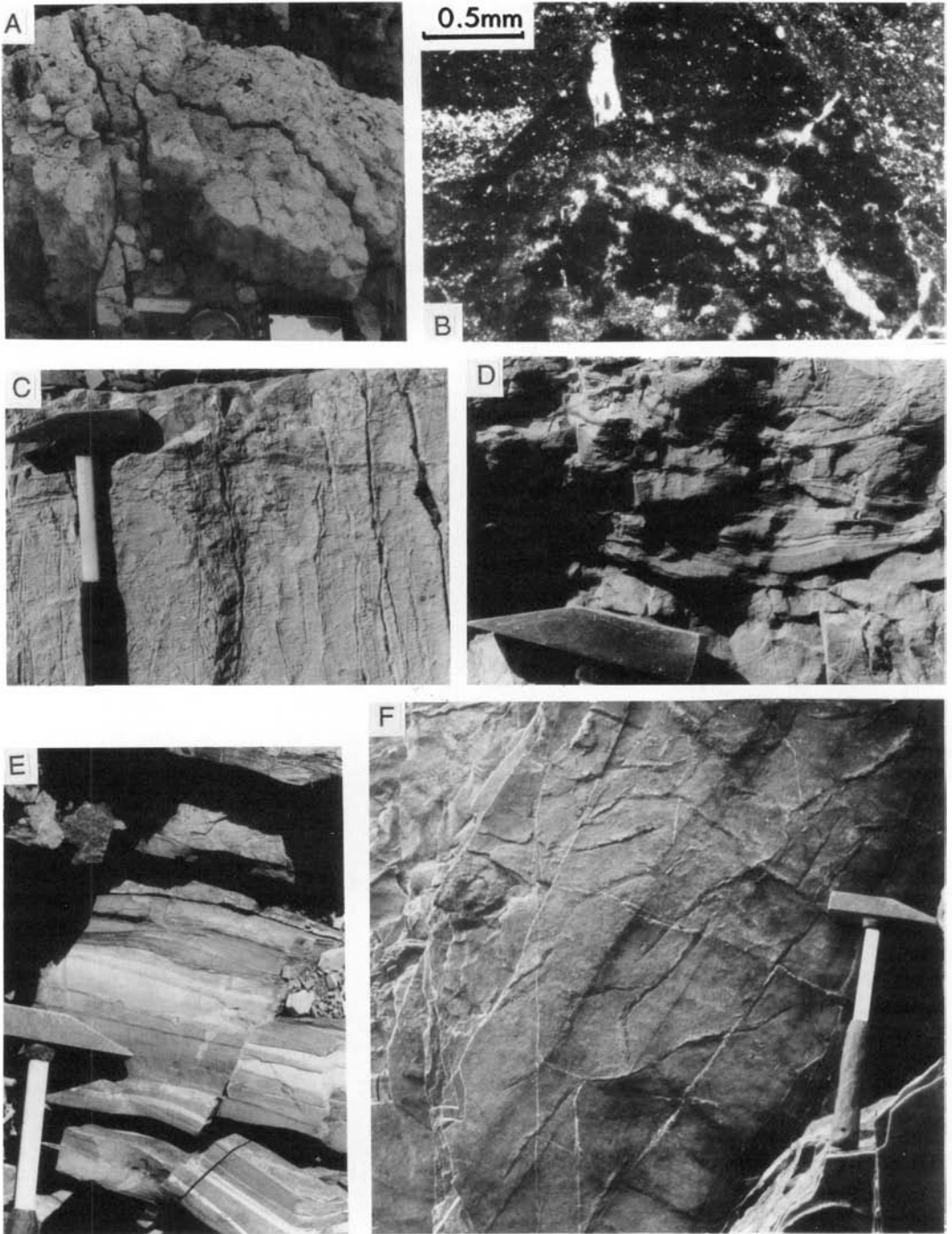


Fig. 20. Facies in the Lowest Carbonate Member (E1). A. Columnar stromatolite in dolostone, top of E1. B. Thin section through top of stromatolite column, showing micritic and microsparry dolomite. C. Laminated and well-jointed dolostone with darker bedding-parallel chert layer left of hammer-head near top of E1. D. Trough and cross-laminated dolarenite near top of E1. E. Flaggy dolarenite with small scale scour structures near top of E1. F. Synaeresis cracks in the typical black basal limestone of E1. Photo (A) was taken at Ditlovtoppen, the remainder are at or near the type locality.

deswell, Hambrey & Wu 1985) showed a random fabric at one site and a preferred orientation at another, which by comparison with contemporary sediments suggests respectively waterlain or lodgement glacial deposition. Bedded diamictites are characterised by decimetre-scale variations of gravel content, gravelly pockets, marked fissility, and weak, irregular lamination defined by grain-size or compositional variations. These grade into more discretely layered lithologies with gravel-rich and gravel-free layers. Dropstones are common and a climbing ripple horizon has been noted. In general, contacts between massive and bedded diamictite and homogeneous dolostone and shale are gradational. A coarsening-upwards sequence from dolostone to bedded diamictite to massive diamictite is typical.

Conglomerate occurs as tabular sheets or as lens-shaped channel-fills. Tabular conglomerates form beds up to 0.2 m thick and are clast-supported; they normally rest on top of diamictite. They are poorly sorted in the silt to pebble range and contain little dolomicrite matrix, and appear to represent in situ reworking of diamictite. Some are penetrated by flame structures of diamictite matrix from below (Fig. 19E). Lens-shaped conglomerates occur in beds up to 2 m thick; they have erosional bases and sharp, flattish tops. Compositionally they are similar to diamictites within which they often occur, with variable grain-size characteristics (gravel or sand grade or pebbly sand). They have crude parallel or trough cross-bedding.

Rhythmite units up to a few metres thick at Backlundtoppen are graded couplets or in places triplets with laminae of variable thickness and no obvious cyclicity (Hambrey 1982). Thicker layers contain unequivocal dropstones (Fig. 18A, B). Minor slump folds, microfaults and minor intraformational brecciation also occur. At Dracoisen two varieties of rhythmite occur. One consists of millimetre-sized graded dolomite couplets with an upper quartz-sand-free layer overlying a silt- and very-fine-sand-bearing layer with thin, sharply defined parallel laminae. Scattered quartz and dolomite grains (up to 1 cm) and centimetre-scale lenses of sandy diamictite occur. The other consists of pure dolostone with 3 mm couplets each comprising pure dolomicrite at the top grading into dolomicrite with minor silt or occasionally sand. The lower part of this couplet also has sharply defined internal laminae.

Shale units are highly dolomitic and grade up

into rhythmite by thickening of the laminae, or are gradational with weakly bedded diamictite. They are present in the Backlundtoppen area.

Dolostone beds up to a metre or so thick are homogeneous and composed of dolomicrite with scattered grains of silt. One such bed contains relics of rock flour (Fairchild 1983). Some dolostones contain rather more scattered sand and silt. They are irregularly laminated, with diffuse variations of silt and sand content, as well as relic dolomite rock flour.

Wedge-fillings at Dracoisen penetrating at least 50 cm into pure dolostones at different horizons consist of pebble-rich (30–40%) diamictite with a sandy mudstone matrix. The wedges flare to 30 cm at the top, with margins that vary from straight to irregular, sometimes having been folded by compaction. In plan they persist laterally for at least 0.5 m. No internal bedding has been noted.

2.4.4.5 (E1) Lower Carbonate Member (22 m, partly faulted out, 180 m). – This basal member of the Elbobreen Formation was redefined and renamed by Fairchild & Hambrey (1984) from the Lower Limestone Member (Hambrey 1982), by including the dolostones and sandstones directly beneath the Petrovbreen Member. The member is dominated by a bluish black or grey limestone.

The top of E1 at Backlundtoppen is represented by a pale yellow-weathering stromatolitic dolostone with bioherms up to 3 m high. Grey dolomitic shales assigned to E2 pass gradationally up into dropstone-bearing strata. Stromatolitic layers and bioherms are also prominent near the top of E1 at other localities; for example, at Ditlovtoppen, bioherms 10–50 m in diameter, up to 6 m high and with a spacing of 30–60 m are present. They consist of crudely laminated 1–3 m wide columns which pass into cryptalgal laminates on the steep margins of the bioherms (Fig. 20A). These dolostones are composed of micritic and microsparry dolomite (Fig. 20B), though these original textures have been locally overprinted by dolomicrospars rhombs. Some dolostones are finely laminated (Fig. 20C); others are more flaggy with erosion surfaces (Fig. 20E) or trough cross-bedding (Fig. 20D). Rare chert beds up to 2 m thick occur in these dolostones, but partial silicification of the dolostones is more widespread. Abundant anhydrite inclusions derived from calcium sulphate nodules and crystals are present in some silicified dolostone.

At Dracoisen the top of E1 is represented by a dark grey dolomitic shale up to 27 m thick. It contains at least 10% of dolostone beds in which intraclasts and anhydrite inclusions have been found. This differs in origin from the basal shale of E2 at Backlundtoppen, though it lies in a stratigraphically similar position.

Below the stromatolite horizon at Backlundtoppen are quartz arenites in beds up to 5 m thick. They contain silty laminae and intraclasts and there is evidence of syn-sedimentary faulting. Subordinate shale and shaly limestone also occur.

Beneath these varied units occurs the bulk of E1 – a uniform bluish grey to black limestone. It is microsparry and pure, partially interlaminated with dolomicrites or partially replaced by dolomite rhombohedra. Calcite veining, associated with Caledonian deformation is common. The lower part of the member is characterised by synaeresis cracks a few millimetres wide and 5–30 cm long in plan and up to 5 cm deep (Fig. 20F). Compaction has resulted in pygmatic folding of the crack-fills, accompanied by doming of the adjacent laminae. The crack-fills consist of slightly finer calcite than the host rock.

2.4.4.6 Depositional environments of the Elbobreen Formation. – This formation shows a wide range of environments from preglacial shallow marine to glacial and interglacial, predominantly marine conditions.

Preglacial sedimentation: The basal member of the Elbobreen Formation (E1), mainly comprising chemically precipitated limestones, formed in a lagoonal environment where periodic salinity changes induced synaeresis cracking. The associated dolostones contain anhydrite relics and primary dolomicrite intraclasts, suggesting deposition in a shallow, intermittently hypersaline environment. A minimum depth of a few metres of water is suggested by the dolomitic stromatolite bioherms. Sandstones with intraclasts in the same member may have been deposited subtidally or intertidally. Shales just below the Petrovbreen Member were probably sub-tidal, though interbedded intraclastic dolostones with anhydrite relics could indicate periodic emergence. Isotopic studies suggest a warm water environment of formation (Fairchild et al. 1989).

Glacial sedimentation: This is represented by the carbonate-rich diamictites and rhythmites of the Petrovbreen Member (E2) which occurs

throughout northeastern Spitsbergen. This member, with its wide range of facies, indicates a varied depositional regime, comparable with the later glacial epoch represented by the Wilsovbreen Formation, but with less evidence of terrestrial deposition. There appears to have been no significant depositional break before the onset of glacial conditions, transitional relationships between non-glacial and glacial sediments being apparent in several localities. Glacial influence is indicated in particular by abundant dropstones, especially in rhythmite (possibly varvite) units, the massive to weakly bedded diamictites with striated stones, and stones with a wide range of shapes and sizes, including boulders up to 1 m across. Chumakov (1978) argued for subaqueous mass-flow in the Dracoisen area, but although this may have been significant locally, the material was probably originally deposited as till. Deposition of glacial sediment took place mainly in water (weakly bedded diamictite) beneath a glacier tongue, or by ice-rafting in a more distal glaciomarine setting (well-bedded diamictite with dropstones), but lodgement processes beneath grounded ice could explain stone fabrics and massive appearance in some diamictites.

The presence of rhythmites, interpreted as varvites could be considered as indicative of lacustrine conditions, though as the bulk of the sediment is dolomite, a marine setting is also possible. The thin rhythmites could also be interpreted as the product of turbidity currents derived from glacial meltwaters input subaqueously. Tabular conglomerate facies indicate periods of non-glacial deposition and winnowing or reworking of diamictite to produce lag deposits, and lens-shaped conglomerates, though not common, suggest fluvial deposition either subglacially or proglacially.

Periods of emergence are indicated by wedge-fillings in diamictites, interpreted as periglacial, which occur at Ditlovtoppen and Dracoisen. However, these wedges are typically capped by laminated sediments with dropstones, indicating an abrupt transition to subaqueous conditions.

The Petrovbreen Member represents the first major glacial advance of an ice-sheet into a marine-shoreface-terrestrial environment. No pronounced relief in the hinterland is suspected as no subaerially derived debris (angular debris) occurs in the diamictite units, but somewhere, probably to the south, the underlying lower

Elbreen and Backberget formations, and the Upper Backlundtoppen and Ryssø formations were already lithified and being subject to glacial erosion. Erosion was not particularly deep and no far-travelled exotic clasts were incorporated. Slight fluctuations in the ice-sheet margin are indicated in various places by massive-bedded diamictite transitions, lag deposits and inter-dia-

micrite rhythmites and shales, but there is no consistent pattern from place-to-place. Fairchild & Spiro (1987) had suggested that oxygen isotope studies might constrain paleolatitude estimates of Late Proterozoic glaciation. Fairchild et al. (1989), from Petrovbreen Member data, argued against formation at a high latitude.

Interglacial sedimentation: The change from

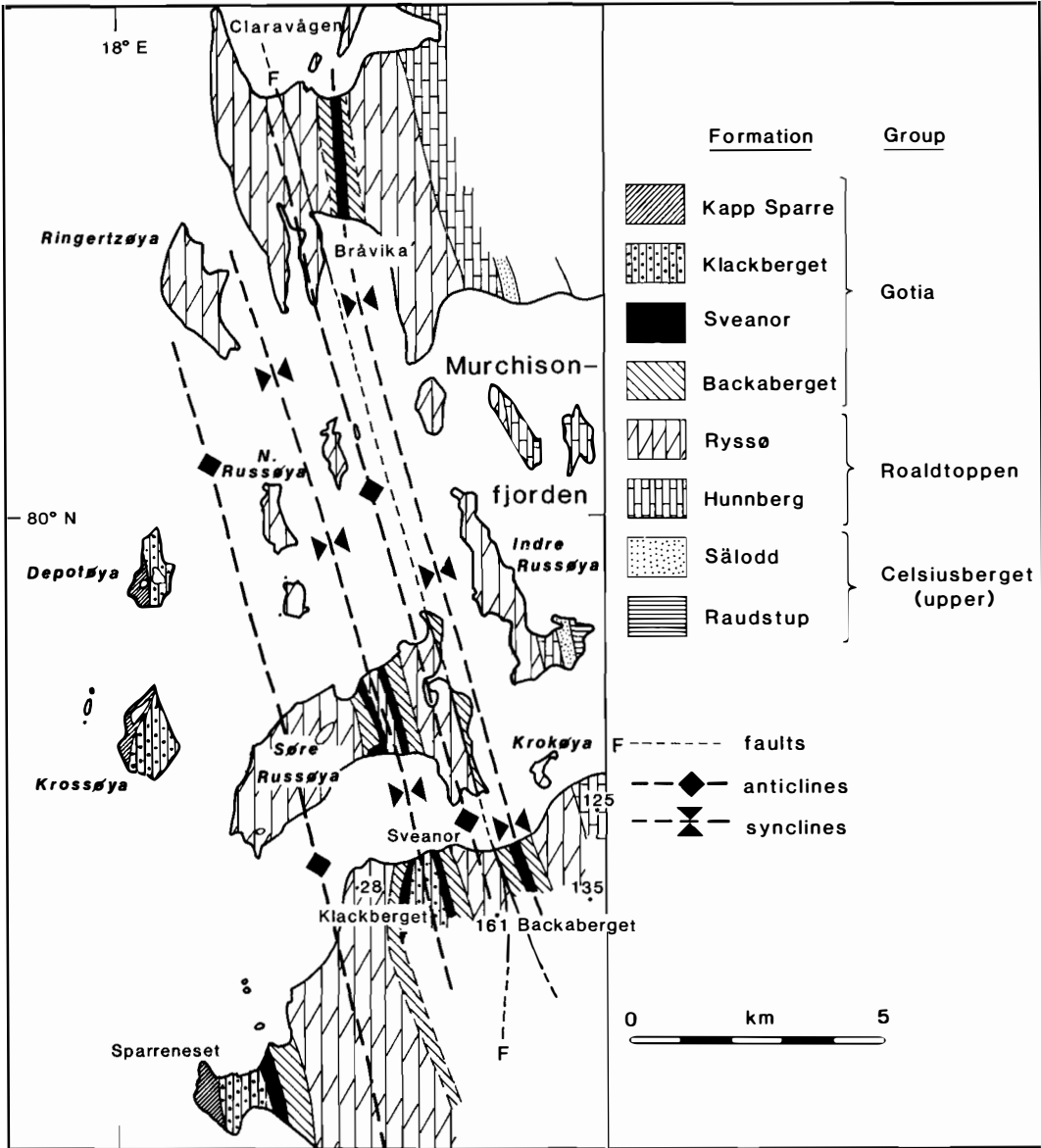
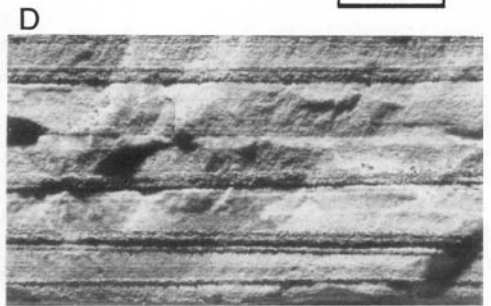
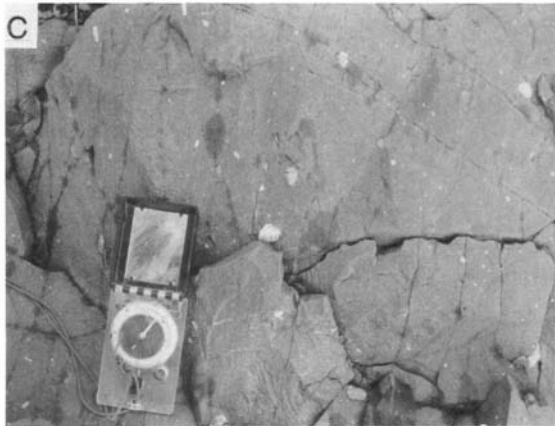
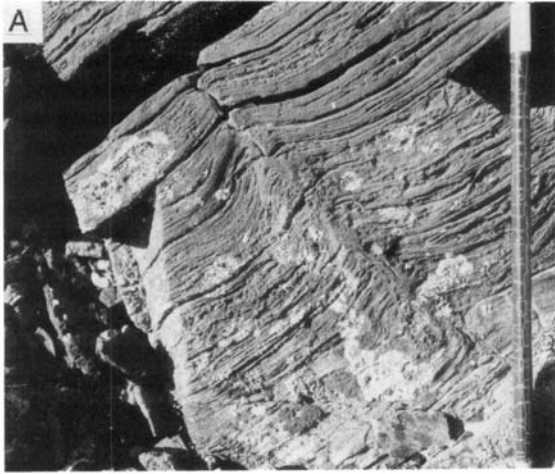


Fig. 21. Geological map of outer Murchisonfjorden, Nordaustlandet (modified from Kulling 1934; faults after Flood et al. 1969).



glacial conditions to the non-glacial conditions of the overlying MacDonaldryggen Member (E3) is illustrated by gradational contacts in some places, and sharp contacts in others, the former suggesting a gradual though rapid retreat of ice. The absence of shallow-water structures in basal E3 carbonates suggests a concomitant rapid rise in sea or water level. The basal carbonates are probably largely chemical precipitates, but a continuing detrital carbonate input cannot be ruled out. Above the shales are uniform carbonate mudrocks with thin intraclastic pure dolostone horizons near the top. The shales show no features of shallow-water origin and may therefore be deeper lagoonal deposits, whereas the intraclastic dolostones do indicate shallower or more marginal settings.

The transition to the overlying pale dolostone of the Slangen Member (E4), with desiccation cracks and cross-laminated silty dolostones, suggests shallowing to tidal-flat deposition. The cross-stratified and parallel-laminated dolarenites would have been deposited in a shallow sub-tidal to low inter-tidal sandflat. Anhydrite relics, and especially abundant precipitated carbonate, indicate high salinities and a warm climate. Although high salinities are possible in lakes in frigid climates (e.g. those of the Dry Valleys of Antarctica) such areas do not show active carbonate precipitation leading to ooid growth and the formation of cements as here. Overlying oolitic beds indicate a more complex environment, the ooids representing a shoal, but fenestrae, inclined bedding and fractures filled by fibrous cement indicate periodic emergence of the shoal, or more likely periodic transport of ooids from a shoal to a supratidal flat. The topmost bed of the Slangen Member, only observed at Ditlovtoppen, may represent less-emergent conditions as there is no evidence of early cementation of the intraclastic sediments. Also, the amount of terrigenous material, increasing upwards, implies a closer proximity to land, e.g. in a back-barrier situation. Emergence is, however, apparent at the top where breccia wedges suggest periglacial action immediately prior to the next glaciation.

2.4.5 Upper Backlundtoppen Formation

This forms part of the Akademikerbreen Group, but is described briefly as Vendian could be redefined and therefore span at least part of it. The Backlundtoppen Formation comprises six divisions (Wilson 1961; Harland, Wallis & Gayer 1966) totalling 360–700 m, of which the uppermost three concern us here. These were grouped under the name Backlundtoppen Dolomite by Wilson (1961), the three divisions being as follows (see also Fairchild & Hambrey 1984).

(3) Massive, pale grey, stromatolitic dolostone (6–25 m). This is the “Dartboard dolomite” of Wilson (1961), and consists of partly silicified cream-weathering stromatolitic dolostone, exhibiting convex-downwards domes up to 0.6 m wide, separated by upward-pointing cusps or flake breccia. Unsilicified stromatolites consist of alternating laminae of dolomicrite and dolospar. Breccia fragments are dolomite-cemented, the cement having a greyish appearance. This distinctive unit permits easy identification of the Backlundtoppen-Elbobreen Formation boundary.

(2) Dark, multicoloured, sandy shales (50 m). This unit shows a sequence from quartz arenite (with parallel- and cross-lamination, and mud laminae with desiccation cracks) to laminated siltstone with fine sandstone interbeds 10 cm thick (also parallel and cross-laminated). Rare grains of glauconite occur.

(1) Massive, pale grey stromatolitic dolostone (150–250 m). It contains both columnar and laterally linked stromatolites, with flake breccias and ooids.

The Upper Backlundtoppen Formation is interpreted as having formed in a shallow marine to inter-tidal (occasionally storm-influenced) environment.

2.5 Nordaustlandet successions

The classic area for studies of Late Precambrian glacial sediments and bounding lithologies in Svalbard is on the south side of Murchisonfjorden. It is from here that Kulling (1934), and most subsequent workers have described the

Fig. 22. Facies of the Gotia Group, Nordaustlandet. A. Water-escape structure in sandstone of the Klackberget Formation, Sparreneset. B. Striated, faceted, flat-iron dolostone clast from mudstone of Sveanor Formation, Sveanor. C. Typical massive diamictite of Sveanor Formation. D. Silt and sand-bearing dolostone rhythmites from the Backaberget Formation at Langgrunneset. E. Massive diamictite overlying rhythmites in the Backaberget formation at Langgrunneset. Facies in D and E are equivalent to the Petrovbreen Member of Spitsbergen.

upper part of the Hecla Hoek sequence, notably Flood et al. (1969). Most outcrops occur in tight synclines and several sections as far north as Franklinsundet were measured by Flood et al. (1969). The most detailed section through the diamictite and succeeding units was presented by Edwards (1976) from near the head of Wahlenbergfjorden (Fig. 2). Further work is recorded by Krasil'shchikov (1967, 1973) and Hambrey, Harland & Waddams (1981).

Exposure is much poorer than in northeastern Spitsbergen, although the presence of in situ frost-shattered debris on flat ground permits the general stratigraphic successions to be worked out; nevertheless, loss of strata by faulting may not have been identified.

The original stratigraphic terminology of Kulling (1934) was modified by Winsnes (in Flood et al. 1969). The further modifications of Krasil'shchikov (1967) were adopted by Hambrey (1982) because they facilitated comparison with northeastern Spitsbergen. The succession from the south shore of Murchisonfjorden east of Sparreneset is summarised in Fig. 3. Detailed sections are presented in Figs. 4 and 5 for correlation with mainland Spitsbergen. The similarities with the mainland are clear, even though we have undertaken much less petrographic work in Nordaustlandet. The following formations belong to the Gotia Group which is equivalent to the Polarisbreen and lower Oslobreen groups. Their distribution in the Murchisonfjorden area is shown in Fig. 21.

2.5.1 Kapp Sparre Formation (>110 m)

This formation represents the youngest exposed Hecla Hoek rocks on Nordaustlandet and is limited to the uppermost three members of Kulling's (1934) Cape Sparre Formation. It is exposed only in a syncline on the southwest shore of Sparreneset (Cape Sparre). The members as noted by Kulling (1934, p. 191) are

- (3) 40 m: black-grey dolomitic mudstone trail marks and brachiopods;
- (2) 70–100 m: grey dolostone;
- (1) 3 m: black-grey, laminated dolostone.

The brachiopods are mainly of the *Lingulella* and *Obolus* types and some of the trail marks were identified as *Helminthoidichnites* (Kulling 1934, pp. 188–189). The brachiopods indicate only a broad Cambro-Ordovician age, though

Kulling took them to be earliest Cambrian. Harland (1974) showed this limit to be faulted and so not in stratigraphic contact with the Klackberget Formation. The nearest analogue in Ny Friesland is the Nordporten Member of the Valhallfonna Formation, which is of Arenig age in Ny Friesland (see Fortey & Bruton 1973).

2.5.2 Klackberget Formation (about 650 m)

2.5.2.1 *The strata.* (Fig 22) – This name was suggested for the lower part of Kulling's Cape Sparre Formation by Krasil'shchikov (1967). It crops out east of Sparreneset, on the two islands to the north (Krossøya and Depotøyå), and north of Bråvika. It probably also occurs on Søre Rus-søya and west of Sveanor on the south shore of Murchisonfjorden (Flood et al. 1969; Kapp Sparre Formation). The lower 40 m of the formation also occurs at Aldousbreen in Wahlenbergfjorden (Edwards 1976; Kapp Sparre Formation).

Five members were recognised by Kulling (1934, p. 191) east of Sparreneset in what we regard as the Klackberget Formation: this section was visited by Hambrey in 1979.

(5) 110 m: "quartzite-sandstone series". Variably coloured (red, grey-green, grey and white) sandstone, slaty in part. Small-scale cross-bedding, convolute lamination, ripple marks, desiccation cracks and water escape structures (Fig. 22A) are all present.

(4) 130–140 m: shale and laminated dolomitic slate with chert streaks.

(3) 120 m: dark grey to black-grey dolostone, tectonically disturbed.

(2) 30–40 m: white sandstone.

(1) 250 m: grey-green and red-brown dolomitic shale, and calcareous mudstone, mostly as in situ frost-shattered debris. Laminae are defined by colour variations and are wavy. Small-scale syn-sedimentary faults are present.

The contact with the underlying Sveanor Formation is not observed. The formation is better exposed north of Bråvika where it is steeply dipping to the west, and a detailed section was measured here (Flood et al. 1969) (Fig. 4). It is difficult to match this with the Sparreneset section.

Edwards (1976) made detailed observations of the lower part of the formation in Wahlen-

bergfjorden (summarised in Fig. 4). Two distinct members were identified:

(2) >45 m: purple shale with red-brown to purple sandstone beds in the upper 30 m and dolostone and dolostone conglomerate in the lower 5 m. Edgewise conglomerates are up to 15 cm thick, lenticular, and often have erosional bases. Clasts are of angular to rounded dolostone flakes, set in a sandy matrix. Several beds are imbricated, suggesting current flow to the NNW. Conglomerates pass upwards into cross-laminated dolosiltites. The sandstone beds decrease in number downwards, and are graded. They are up to 30 cm thick, laterally continuous and have erosive bases. They show characteristic Bouma sequences of sedimentary structures. Cross-laminations dip to the north and northwest. The sandstones are poorly to moderately sorted, the grains consisting of sparry calcite, recrystallised dolomite and altered felsites (some porphyritic). Quartz grains form a minor component.

(1) 4.5 m: buff-weathering grey dolostone, resistant to weathering. The upper 2 m is thinly parallel-bedded with intercalated purple shale, and a single edgewise conglomerate. The underlying 2 m of dolostone is thinly to medium-bedded with purple shale partings, and the basal dolostone of 1 m thickness is locally parallel-laminated. Bornite and malachite occur in joints in the dolostone.

The contact with the underlying Sveanor Formation is sharp. The basal dolostone matches with the cap dolostone at Sveanor, but the overlying dolomitic shaly lithologies with carbonate concretions cannot be precisely correlated with other areas.

The age of the Klackberget Formation is considered to be Vendian on the basis of poorly preserved fossils obtained from this and the Backaberget Formation (Knoll 1982a) (see section 2.5.4).

2.5.2.2 Depositional environments of the Klackberget Formation. – These are similar to those recorded in the Dracoisen Formation. The first post-glacial sediments suggest beach to upper shoreface conditions, influenced by storms. At Aldousbreen dolostone conglomerates indicate storms or at least (isostatic) uplift of the basin (Edwards 1976).

The lower part of the Klackberget Formation at Aldousbreen (Edwards 1976) otherwise indicates quiet water deposition, with periodic traction currents giving the edgewise conglomerates, and turbidity underflows producing the sandstones derived from an uplifting basin margin. Poor exposure has discouraged investigations of the sedimentology of the rest of the formation, but the bulk probably indicates deeper-water conditions.

The uppermost sandstones of the Klackberget Formation are probably equivalent to the Tokammane Formation, Blårevbreen Sandstone Member and probably of littoral-tidal origin.

2.5.3 Sveanor Formation (100–168 m)

2.5.3.1 The strata. – This distinctive formation, characterised by diamictite, was first defined by Kulling (1934), the type locality being approximately 1 km south of the south shore of Murchisonfjorden at Sveanor. Pale dolostone horizons occur immediately above and below the formation. However, Flood et al. (1969) included part of Kulling's underlying Ryssø Formation in the Sveanor. Krasil'shchikov (1967) followed Kulling's usage of the term Sveanor Formation, as we do here. There is no direct evidence available as to the age of the formation, but the bounding formations are both Vendian (Knoll 1982a).

The Sveanor Formation is exposed in several places north and south of Murchisonfjorden, as well as further north (Flood et al. 1969) and in Wahlenbergfjorden (Edwards 1976). It is concluded that the locality described by Kulling (1934, p. 193) and Flood et al. (1969, p. 26) at Langgrunneset as the northernmost outcrop does not belong to the Sveanor Formation but, by analogy with the Petrovbreen member of northeast Spitsbergen, lies some distance below in the Backaberget Formation.

The Sveanor Formation is lithologically varied, facies changes are marked and individual beds more than a few hundred metres apart cannot be correlated (Fig. 4). In many respects, such as facies and composition, it bears a close resemblance to the Wilsonbreen Formation of Ny Friesland. The several sections that have been measured are summarised in Fig. 4, the most detailed and complete being at Sveanor in Murchisonfjorden (Kulling 1934; Hambrey 1982) and Aldousbreen in Wahlenbergfjorden (Edwards 1976).

2.5.3.2 *Composition*. – The proportion of diamictite in the Sveanor Formation is extremely variable, but at Sparreneset, Sveanor (type section) and Aldousbreen it forms the bulk of the formation. Elsewhere, sandstones, shales (sometimes with rare pebbles) and carbonates are prominent. Most diamictites are greyish green, but diffuse maroon horizons also occur. From observation at Aldousbreen (Edwards 1976), the matrix of the greyish green diamictite consists of a clay-mica-carbonate mixture with abundant sand-and-silt-sized grains of quartz, plagioclase and K-feldspar. Silt grains are generally angular, whereas sand grains tend to be rounded. The carbonate content appears to increase downwards through the section. Maroon diamictite has a haematite matrix with a low carbonate and clay-mica content.

The gravel fraction comprises primarily dolostone (c. 50%) and limestone (about 20%), though proportions vary substantially. The remainder include sandstone, siltstone, granite, granite porphyry, aplite, quartz porphyry, syenite, keratophyre, amygdaloidal basalt, tuff, siliceous sericitic schist, ("slate"), garnet schist ("slate"), gneiss, phyllite, quartzite, basic volcanic rocks and jasperised chert (Kulling 1934; Krasil'shchikov 1967; Flood et al. 1969; Edwards 1976; Hambrey et al. 1981). The igneous and metamorphic stones together make up to 20% of the total and are mainly exotic. Generally, the proportion of clasts in the rock as a whole is only 5–10%; systematic studies of shape have not been made but in diamictites all classes from angular to rounded occur, with a predominance in the subangular and subrounded classes. Faceted stones and some "flat-irons" form a significant percentage of clasts. Kulling (1934) reported numerous striated stones from the type locality and we have noted that some 10% of the stones in the shaly diamictites are striated (Fig. 22B).

Petrographic descriptions of these stones by Krasil'shchikov (1967) are summarised below as they may eventually be useful in comparisons with elsewhere or to identify the source rocks.

Dolostones include about 50% which have oncolites and catagraphs; banded and stromatolitic dolostones are rarer. Some dolostones contain terrigenous silt and organic matter. Both Riphean and Vendian assemblages have been recorded.

Reef dolostones consist of oncolitic concretions,

composed of clayey carbonate. Concretions containing catagraphs amount to 40–50%; authigenic quartz occurs in them. These rocks resemble those of the Backaberget and Ryssø Formations.

The *limestones* are dark grey, micritic and with a secondary layering, organic matter and aggregations of sparry calcite. They resemble limestones in the Hunnberg and Ryssø Formations.

Sandstones and siltstones are of quartz with a calcite cement. Grains are angular though increasing in roundness with size. Minor feldspar, mica, and isolated grains of zircon, tourmaline, limonitised pyrite and fragments of carbonaceous and cherty rocks also occur. Pebbly sandstones and grits have a metamorphic and igneous clast component. These stones bear most resemblance to the lower parts of the Sveanor Formation itself, but the comparison is not very clear.

Tuffaceous sandstones and siltstone clasts occur in the upper part of the formation. They are mainly greenish massive and weakly banded. Up to 70% of the fragments are composed of rounded but corroded quartz grains; and 10% of fresh angular plagioclase fragments. 12–15% of the fragments are carbonates and basic extrusive rocks, and 5–8% of chloritised glass. The groundmass is mainly of mud-silt grains which is said to be predominantly volcanogenic (ashy particles, plagioclase microlites). Extensive carbonisation and chloritisation suggests an original basic composition. Some specimens are vitreous-crystalline-clastic tuffs with 90% chloritised ashy ground mass, and clastic material comprising quartz, plagioclase and some glass.

Amygdaloidal basalts have a porphyritic texture with a micro-doleritic, hyalo-ophitic groundmass consisting of prismatic, albitised plagioclase, carbonised chloritised glass, dendritic segregations of ilmenite, and chalcopyrite. Amygdales (1–2 mm) of calcite, chlorite and sometimes zoisite make up 20–25% of the tuffaceous sandstone. Phenocrysts 0.5–1.5 mm in diameter, occupying 10–20% of the rock, are composed of tabular crystals of frequently carbonised plagioclase and lesser amounts of pseudomorphs of carbonate after pyroxene and plagioclase, and also of serpentine after possibly olivine.

Carbonatised dolerites usually occur as large pebbles. They are dark, greenish-grey massive rocks consisting of andesine-labradorite (60%), carbonate (15–20%), chlorite (10–15%), leucoxene (up to 5%) and rare chalcopyrite. Plagioclase forms long prismatic crystals with carbonate-

filled fractures. Carbonate is also present as large crystals between plagioclases or as tabular pseudomorphs after pyroxene and possibly after plagioclase. Large flakes of greenish chlorite are generally associated with the carbonate and with leucoxene, developing on ilmenite.

Plagioclases occur only as small pebbles. They have subhedral grains, pegmatitic in places and sometimes cataclastic or cemented. 65–80% is of oligoclase andesine forming 1–4 mm tabular or irregular grains that are often crossed with microfractures, along which muscovite, epidote, carbonate, chlorite and quartz have developed. 10–15% consists of brown-chloritised biotite or muscovite. Chain-like segregations of leucoxene are sometimes associated with the mineralised microfractures. Solitary grains of apatite, zircon and magnetite altered to martite also occur.

Leucocratic syenites occur in the middle of the formation. They are coarse-grained rocks with a cataclastic, pseudoporphyratic structure composed of microcline-perthite (45–90%), plagioclase (10–25%), quartz (0–30%), brownish-green biotite with chlorite (5–15%), carbonate (up to 5%) and variously 5% titanomagnetite. Accessory minerals consist of zircon, sphere, leucoxene, rutile, apatite and chalcopryrite. Plagioclase composition varies from acid zoned oligoclase to andesine. The groundmass has crystals measuring 0.1–0.5 mm, but phenocrysts (“catablasts”) of microcline-perthite up to 3 mm occur. The rock as a whole and individual grains are crossed by fractures containing quartz, carbonate, epidote, chlorite and magnetite.

Granite-gneisses are coarsely crystalline bimicropagiogranites. Isometric or tabular crystalloblasts (1–2 mm) of sericitised oligoclase-andesine, and more rarely K-feldspar or quartz, are subrounded by a fine, flaky biotite-muscovite aggregate, the proportion of mica amounting to 10–15%.

Garnetiferous schists (“crystalline slates”) have a granular structure and consist of oligoclase-andesine (up to 30%), quartz (up to 30%), carbonated garnet (up to 15%), secondary carbonate (up to 15%) and chlorite (up to 15%). Minor amounts of leucoxene and chalcopryrite are developed mainly along cracks. Garnet porphyroblasts of 1–2 mm diameter are prominent in a groundmass of finer grained (0.1–0.5 mm) quartz and feldspar.

Siliceous-sericite slates are characterised by slaty cleavage. Layers enriched with thin flakes

of sericite and a microgranular siliceous aggregate alternate every 1–3 mm with recrystallised siliceous layers in which quartz grains up to 0.05 mm occur.

Silicites are microgranular siliceous rocks, sometimes comprising radiating or fibrous spherulites and aggregates of crystalline quartz, as well as pyrite crystals. Ferruginous siliceous-carbonaceous nodules up to 1–3 mm make up some pebbles. The nodules are overgrown by fibrous calcite, whereas the pores between the nodules contain calcite with authigenic quartz or thin flakes of a clay-chlorite aggregate.

The petrographic analysis indicates the dominance of carbonate and lesser amounts of terrigenous rocks, a reflection of the underlying sedimentary strata, e.g. stromatolites from the Ryssø Formation, jasperised chert from an horizon at the base of the same formation, and distinctive black limestone from the upper Hunnberg Formation. On the basis of lithology, and of catagraphs and oncolites in dolostones, the depth of erosion necessary to supply the sedimentary stones in the Sveanor Formation is no more than 500 m. The origin of the volcanic, intrusive and metamorphic rocks is more problematic. The basic volcanics show no signs of metamorphism so the interval of time to when they were incorporated in the Sveanor Formation was probably not great, but no area with rocks that could have been the source has yet been identified. In addition, a red granite clast from Aldousbreen (Edwards & Taylor 1976) yielded a Rb-Sr whole-rock isochron age of 1248 ± 4 Ma (1976 constants). Furthermore none of the metamorphic rocks appear to match with lower formations in the Murchisonfjorden Group, the underlying Kapp Hansteen Formation, the gneisses and schists of the Stubendorffbreen Supergroup of northeastern Spitsbergen, nor does the crystalline basement of eastern Nordaustlandet match these stones. This fits the view that the lower part of the Hecla Hoek geosyncline which was tectonised in post-Vendian time was not exposed to erosion until Devonian time. The source of these stones was therefore likely to have been a distant one. Ultimately, an assessment of paleoenvironments and comparison with the almost identical sequence in East Greenland may permit the location of this source region to be determined.

The composition of the sandstones and siltstones as a whole is 75–90% quartz, 10–15% rock

fragments and 2–8% feldspar for grains, with 20–25% of the matrix in sandy facies, and 40–50% in silty facies being a clay-carbonate cement, thus they have the composition of wackes. Most of the sand grains are angular, but some large (0.5 mm) grains are well rounded. Feldspars tend to be angular, with slightly sericitised plagioclase predominating. In general the feldspars are fresh. Rock fragments have a similar composition to the stones in the diamictites. Solitary grains of zircon, hornblende, chloritised garnet, tourmaline, authigenic pyrite and possibly glauconite have been noted. In addition the heavy fraction has yielded pyroxene, epidote, apatite and magnetite. The cement is a clayey carbonate with flakes of sericite, chlorite, biotite and earthy titanium minerals. The carbonate has corroded the grains, especially the quartz. In some siltstones the cement is chlorite-rich and is saturated with ferric hydroxide (Krasil'shchikov 1967).

Purer sandstones (quartz arenites) occur near the top of the formation at Claravågen and Kinnvika. Quartz makes up more than 95% of the fragmental material, and there is a wide range of other lithologies in the remainder. Up to 5% of the rock is calcite cement.

2.5.3.3 Facies of the Sveanor Formation. – The Sveanor Formation contains a varied range of facies, but few can be traced from one section to another over distances of more than a few tens of metres, partly because of inadequate exposure, but also because lateral persistence is limited. Several of the facies resemble those of their north-eastern Spitsbergen counterparts, but they have only been studied superficially in comparison, and no systematic investigations have been made except at Aldousbreen (Edwards 1976).

Massive diamictite dominates the formation (Fig. 22c), at Sparreneset practically the whole of the formation is composed of this facies. Matrix generally forms at least 90% of the rock. Often the rocks shows two or more intersecting irregular planar surfaces which could be joints and/or weakly developed cleavage, rather than primary features. Near Sparreneset soft-sediment deformation is indicated by irregular veins of sandy silt and a slump fold in the diamictite. Massive diamictites grade into massive sandstones which have the appearance of diamictite matrix, with only dispersed clasts. However, according to Krasil'shchikov (1967) some sandstones comprise 5–6% (or rarely 10–15%) plagioclase, the bulk of the

remainder being of quartz, though carbonate cement is common.

Weakly bedded diamictite usually is gradational with the massive variety, the beds being wispy and defined by subtle variations of sand content in the matrix. Weakly bedded diamictites grade into better bedded units with fewer stones, laminated mudstones (or rarely bedded sandstones) with dropstones up to 20 cm in diameter, and mudstones without stones – or such facies occur as individual beds. These mudstones are variable in texture (Edwards 1976). They have silty-clayey laminae with haematite in the fine laminae of the purple units.

Conglomerates occur as minor lenses or as lag deposits on top of diamictite units. They also occur at the base of sandstone lenses, or as poorly-sorted, thin beds with sharp base and top in dropstone-bearing mudstones. Sandstone lenses up to 10 cm thick and 1 m long also occur in mudstones at Aldousbreen; these have a sharp pebbly base and a gradational top. Sandstone lenses also occur in massive diamictites, the most prominent being 3–4 m thick and several tens of metres in length near Sparreneset. Some are trough cross-bedded. At Aldousbreen some siltstone units consist mainly of angular quartz grains, with some carbonate-clay matrix, or with good sorting.

Carbonates within the Sveanor Formation are limited to a poor section at Claravågen (Fig. 4). No breccias, wedge-fillings or rhythmites have been reported from the Sveanor Formation.

2.5.3.4 Depositional environments of the Sveanor Formation. – The Sveanor Formation has the same range of facies as the Wilsonbreen Formation, with evidence of both lodgement and waterlain till deposition. More distal glaciomarine facies are represented by mudstones with rather dispersed ice-rafted stones, especially at Sveanor and Aldousbreen, but the proximity of land at other times is indicated by angular silt deposits, reminiscent of loess, at Aldousbreen (Edwards 1976, 1979).

Together the Sveanor and Wilsonbreen Formations demonstrate a complex interplay of sub-aerial, subglacial, glaciomarine/glaciolacustrine and fluvial processes, operating over the whole region of northeastern Svalbard. Far-travelled material was brought into the basin of deposition with the first ice, and continued to be supplied along with more local material. Cessation of gla-

cial activity was abrupt, indicated by the sharp contact with the Dracoisen and Klackberget Formations.

2.5.4 Backaberget Formation (about 220–290 m)

2.5.4.1 The strata. – Originally the dolostone at the base of the Sveanor Formation, the underlying shales and the distinctive stromatolitic dolostones were named the Ryssø series (Kulling 1934). Flood et al. (1969) included the uppermost dolostone and the shales within the Sveanor Formation. Krasil'shchikov (1967), however, designated these rocks as a separate formation – the Backaberget – which was adopted by us (Hambrey 1982) and is used here.

Backaberget lies behind and south east of Sveanor, but the formation of this name is poorly exposed here as elsewhere. The thicknesses of this unit (Fig. 5) must therefore be treated with circumspection, and unrecognised faults may have affected these sections.

The succession east of Sparreneset, described by Kulling (1934) and visited by us, is mainly of nearly in situ scree. It consists from top to bottom of the following:

(6) 50 m (cf. 10 m at Sveanor): laminated, cream-weathering, grey, partly cross-laminated dolostone, grading into more massive dolostone. At the contact with sandstones of the Sveanor Formation Krasil'shchikov (1967) described a structure indicative of instability of weakly lithified dolostone when loaded by the sand. Locally a subsidence of about 1 cm occurred, bending and breaking the partially lithified dolostone layers, and incorporating the sand. On a bedding surface the areas of subsidence appear as regular polygons the central part having been filled with sand. Hambrey has noted a rip-up conglomerate at the top of the dolostone. The dolostones generally are often flaggy with impermanent layering with 0.5–4 mm thick layers of silty-clayey dolostone alternating with dolomitic siltstone. Fragmental terrigenous material is most abundant near the contact with the Sveanor Formation. In the section east of Sparreneset, the dolostone grades down into dark grey dolomitic shales. Then follow (Kulling 1934):

- (5) 40 m: dark-grey quartzose slate.
- (4) 50 m: grey-black shale
- (3) 100 m: grey-black shale

- (2) [15–20 m: dolerite sill]
- (1) 25 m: no exposure

The succession is underlain by the Ryssø Formation with its characteristic stromatolites.

A broadly similar succession occurs southeast of Sveanor, as far as can be ascertained from the poor exposure.

Previous authors (Kulling 1934, p. 192) and Flood et al. (1969, p. 26) had described a diamictite-rhythmite-limestone-sandstone sequence from Langgrunneset to the north as belonging to the Sveanor Formation, but exposure is mostly limited to in situ scree. However, the diamictite is compositionally different from the Sveanor Formation, and similar to the Petrovbreen Member of the Elbobreen Formation; so the Langgrunneset diamictite was placed in the Backaberget Formation (Hambrey 1982). The succession is illustrated in Fig. 5. The diamictite (10 m) is grey, brownish weathering, highly dolomitic, dominated by stones up to $20 \times 5 \times 6$ cm characteristic of the Ryssø Formation, and none of exotic nature. The stones are of all shapes, but are predominantly subangular or subrounded. The following proportions were estimated:

dolostone (especially oolitic and stromatolitic)	65%
limestone (light and dark grey)	15%
quartzite	10%
others (including chert and vein quartz)	10%

Directly below the diamictite is a dark, cherty, shaly limestone (10 m), then several tens of metres of marls, sandy towards the base. Many of them are distinct rhythmites 4–10 mm thick comprising couplets or triplets of clayey dolomite with minor silt sized grains of dolostone at the top, and silt-sized dolostone grains, rare quartz grains and little clay at the base (Fig. 22D). No dropstones were observed. Sandstones, generally calcareous, dominate the remaining part of the sequence down to the Ryssø dolostone.

The shales are generally richly carbonaceous, but contain only sparse well-presented acritarchs (Knoll 1982a). The organisms identified are *Protosphaeridium* sp., *Trachysphaeridium* spp., cf. *Stictosphaeridium* sp. and *Bavinella faveolata* (Shepeleva). The last indicates a Vendian, perhaps mid-Vendian (sensu Vidal 1979a) i.e. Varanger age for this part of the Gotia Group. Oncolite species *Osagia svalbardica* and the catagraph *Vermiculites irregularis* (Harland &

Wright 1979, summarised from Soviet literature) also suggest a Vendian age.

2.5.4.2 Depositional environments of the Backaberget formation. – Because of poor exposure, indicators of sedimentation are few, but the general similarity to facies in the Elbobreen Formation suggests a similar range of depositional environments. These include glacial and glaciolacustrine sedimentation, as represented by the small outcrop of diamictite and rhythmite at Langgrunneset, preceded and followed by shallow marine sedimentation.

2.5.5 Ryssø Formation (Roaldtoppen Group)

The top of the Ryssø Formation, as now defined (Flood et al. 1969), consists of 30 m of light-grey, cream-weathering dolostone, with poor stratification but magnificent partly silicified pisolites and stromatolites. This overlies several hundred metres of limestone, carbonate shale and dolostone.

The Ryssø and Hunnberg formations have yielded species of the stromatolites *Conophyton*, *Kusiella*, *Inseria*, *Gymnosolen* and *Tungussia*, which are characteristic of “Late Riphean” (or “Sturtian”, (sensu Harland et al. 1982, 1990) rocks of the southern Urals (Golovanov 1967). Abundant microfossils have also been found in the Ryssø Formation, particularly in silicified limestones and black pyritic shales. Acritarchs include *Chuarina circularis*, *Kildinella hyperborica*, *K. sinica*, *Trachysphaeridium* spp. and others, and a latest Riphean age or “Sturtian”, (sensu Harland et al. 1982, 1989) is indicated (Knoll 1982a; Knoll & Calder 1983).

The Ryssø Formation is a shallow marine deposit, influenced in part by tidal currents.

2.6 Palaeomagnetic studies of the northeastern Spitsbergen succession

Samples were collected from throughout the Vendian sequence in Ny Friesland and Olav V Land in 1958 and again in 1981–82, to determine paleopole positions through time. Samples were analysed on an astatic magnetometer by D. E. T. Bidgood in Cambridge and on a cryogenic magnetometer by Dr D. Watts at the University of Leeds, but it was concluded that no interpretable record exists. Carbonates are weakly magnetised in random orientations, treatment reducing these rocks to immeasurable levels and the mag-

netisation being of very low blocking temperature and coercivity. Red siltstones have erratic orthogonal projections and exhibit time-varying behaviour (pers. comm. from D. E. T. Bidgood 1960 and D. Watts 1984).

2.7 Correlation within northeastern Svalbard

Correlation of the major lithostratigraphic units between Nordaustlandet and Ny Friesland is straightforward on the basis of excellent stratigraphic markers despite the paucity of fossils. This is not surprising as both outcrop areas are near the narrow strait that separates them. Correlations are shown in Figs. 3, 4 and 5. The higher two members of the Tokammane Formation of Ny Friesland correlate with the Kap Sparre Formation and the lowest member of the Tokammane with the upper sandstones of the Klackberget Formation. The Dracoisen Formation correlates with the rest of the Klackberget Formation. In particular, members D4–6 correlate with the uppermost member of the Klackberget Formation, and the distinctive pale basal dolostones and possibly the dolomitic shales of the lower part of both formations also match closely.

The Wilsonbreen Formation, with its diamictites containing much exotic material is the direct equivalent of the Sveanor Formation. However, within the formation individual beds are laterally impersistent and the three members identified in northeastern Spitsbergen do not have direct counterparts within the Sveanor Formation.

The Elbobreen Formation, which is dominated by dolomitic shales, matches the Backaberget Formation exactly. Their pale dolostone units just below the diamictites are similar, and the dolomitic diamictite-rhythmite complex, known throughout northeastern Spitsbergen as the Petrovbreen Member, has been observed in one place in Nordaustlandet. The lower member equivalent to the Elbobreen Formation is not sufficiently well exposed on Nordaustlandet to permit correlation.

The base of the Elbobreen and Backaberget Formations is characterised by the distinctive stromatolitic dolostone at the top of the Backlundtoppen and Ryssø formations respectively. Macrofossils in the highest formations in each area and the rather sparse microfossils in the remainder support the correlations.

3 Oscar II Land

3.1 Introduction

Most of Oscar II Land comprises the northern segment of the Eocene West Spitsbergen Orogen (Harland & Horsfield 1974). Vendian rocks crop out throughout the western mountains along the coast (Fig. 23) and are covered by Carboniferous and younger rocks in the east. The western boundary is a Cenozoic graben mainly covered by the water of Forlandsundet. East–west valleys afford traverses through the structure that runs NNW–SSE. St Jonsfjorden cuts the whole Vendian outcrop.

In the north the structure swings to the north-west parallel to Kongsfjorden. In Brøggerhalvøya, Vendian strata crop out south of a belt of altered rocks. They are well displayed in Engelsbukta and inland in Comfortlessbreen. To the south the exposed coasts of Isfjorden truncate the older Vendian strata. The whole terrane is affected by the Eocene folds and easterly directed thrusts but the main tectogenesis and metamorphism was mid-Paleozoic.

3.2 History of research

The earliest substantive studies in Oscar II Land were those of Holtedahl (1913). Orvin (1934) subsequently mapped the pre-Devonian rocks of Brøggerhalvøya, work that remains the definitive study for that area. Investigations by expeditions from the University of Birmingham to the St. Jonsfjorden area in 1948, 1951 and 1954 resulted in publications, of which that of Weiss (1953) is most relevant here. Geologists from the Norsk Polarinstitut resumed work in the area intermittently since 1955, with greater emphasis on mapping.

Investigations by the Cambridge group were begun by C.B. Wilson in 1958. After Wilson's death in 1959, from visits to St. Jonsfjorden, Comfortlessbreen and Hermansenøya, Harland established a glacial influence in the Comfortlessbreen rocks with their granitoid and stromatolitic-bearing dolostones. He adapted Wilson's succession, correlating the glaciogenic sediments with those of the Polarisbreen Group and the Tillite Group in East Greenland (Harland 1960). In 1966 the Cambridge Group moved base to Ny-Ålesund for studies in western Spitsbergen, especially of Oscar II Land and Prins Karls

Forland. W.T. Horsfield began investigating the Oscar II Land succession in 1967, and in 1968 Harland and Horsfield worked out an approximate sequence for St. Jonsfjorden and central Prins Karls Forland. Horsfield first found fossils at Motalafjella (Scrutton, Horsfield & Harland 1976). He completed his Oscar II Land studies and the stratigraphic results were combined with results from Prins Karls Forland by Harland, Horsfield, Manby and Morris submitted in 1975 (Harland et al. 1979) Norsk Polarinstitut geologists simultaneously reported results, also using C.B. Wilson's original mapping (Hjelle, Ohta & Winsnes 1979). By 1975 it was clear that the succession in Oscar II Land had not been adequately worked out, nor had the metamorphosed diamictites been sufficiently exploited stratigraphically, so Waddams was invited to work on this problem from 1977 to 1979. At about the same time Hambrey joined the group and regularly contributed to these studies. Already by 1975 it was clear that the succession in Western Spitsbergen was radically different from those in the northeast and southern Spitsbergen, and this led in 1975 to the postulate of the juxtaposition of originally far-distant terranes in 1975 (Harland & Wright 1979). They concluded with the suggestion to honour Holtedahl's pioneering work in the west by naming the western sequence the Holtedahl Geosyncline.

Morris, after completing his study of southern Prins Karls Forland in Cambridge, moved to Wayne State University, Detroit, and formed a group working in St. Jonsfjorden. One of his students, L. Kanat, came to work in Cambridge with Harland on the structure and stratigraphy of the area just south of St. Jonsfjorden, completing his work in 1986 (Kanat & Morris 1988). Since the publication of results by Cambridge and Norsk Polarinstitut groups (Harland et al. 1979; Hjelle, Ohta & Winsnes 1979), we have attempted to reconcile the differences. Norsk Polarinstitut geologists have also modified their stratigraphic scheme, introducing new formation names on their maps (Ohta 1985), but without defining or describing the new units.

The key to the stratigraphy of Oscar II Land is held by two, thick meta-diamictite formations. A formation mapped along with other diamictites by Hjelle, Ohta & Winsnes (1979) proved to be the much earlier conglomeratic unit of Wilson (W4 in Harland 1960). This had been described as the Trondheimfjella Formation by Harland et

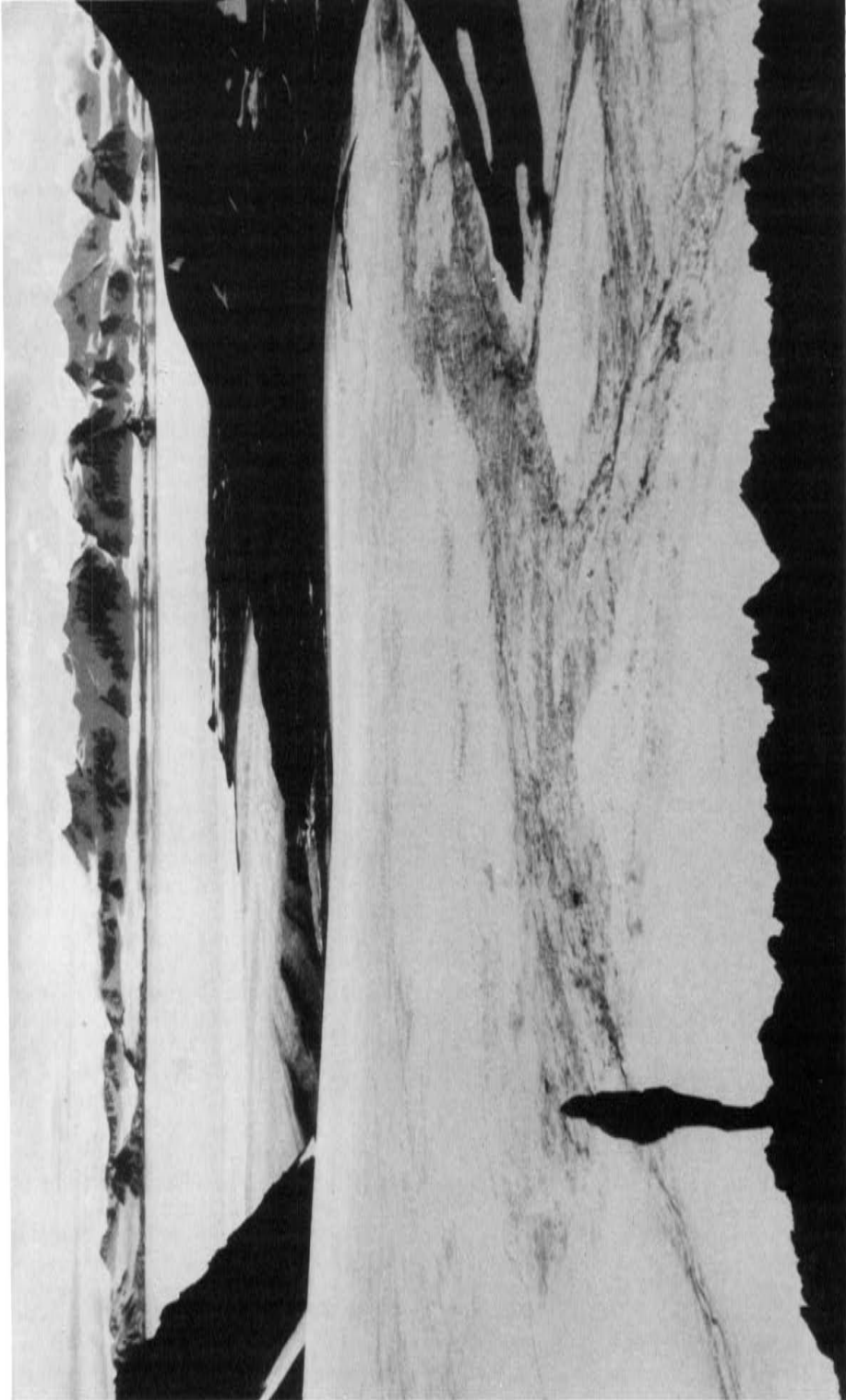


Fig. 23. Oscar II Land landscape: view to Prins Karls Forland, over Erikkabreen (foreground) and the snout of Aavatsmarkbreen. The rocks on either side of Erikkabreen belong mainly to the Haaken formation, the uppermost of the two tillite-bearing units. Along the margin of Aavatsmarkbreen the Annabreen and Aavatsmarkbreen formations, and the Bullbreen Group are exposed. The flat area beyond (Sarsøyra) is made up of Tertiary rocks of the Forlandsundet graben. The mountainous backbone of Prins Karls Forland, which rises to over 1100 m is dominated by probable Ordovician-Silurian rocks of the Gramplan Group.

Table 3. Comparison of stratigraphic schemes for Oscar II Land, by groups from the Norsk Polarinstittutt and the University of Cambridge.

OSCAR II LAND and PRINS KARL FORLAND		SOUTHERN OSCAR II LAND		OSCAR II LAND		This Work		
Hjelle, Ohta & Winsnes 1979		Ohta, Hirajima & Hiroi 1986		Harland, Horsfield, Manby & Morris 1979		Thickneses from Waddams 1983 in m.		
				Formation		Age		
				Group		Carbonif.		
Upper	Bulltinden Fm	Bulltinden Fm	Silurian - Ordovician	Holmslettjella (+ Bulltinden cgl mbr) Motlafjella Sarsøyra Fm	Bullbreen	Holmslettjella Motlafjella	450	Early Silurian - Ordovician
Hecla								
Hoek	Tillitic conglomerate Δ	Eocambrian tillite fm Δ	VENDIAN	Engelsbukta Δ Annabreen Haaken Δ	Comfortless-breen	Aavatsmarkbreen Annabreen Haaken Δ	1000 2000 2-3000	Ediacara ?
Middle	Calc-argillo-volcanic fm	Jørgenfjellet Fm		Alkhorn Løvliebreen Moefjellet		Alkhorn Løvliebreen Moefjellet	1000+	Varanger
Hecla	Quartzite-shale fm	Calc-argillo-volcanic fm			St. Jonsfjorden	St. Jonsfjorden	5-800	Mortensnes Smalfjord
Hoek	Quartzite-sst fm + Black shale fm	Quartzite-shale fm		Trondheimfjellet		Trondheimfjellet Δ	300	
?	Vestgotabreen Fm	Older limestone fm	LATE RIPHEAN	Nielsenfjellet (+ Müllerneset)		Müllerneset + Nielsenfjellet	2000 1500+	
Lower	Garnet-biotite-schists and quartzite shales	Vestgotabreen Fm		Steenfjellet Bogegga	Kongsvegen	Steenfjellet Bogegga	100 500	
Hecla	Iron-ore bearing pelites			Vestgotabreen		Vestgotabreen Complex		
Hoek	Sillimanite-garnet-biotite-schist	Vestgotabreen Fm						

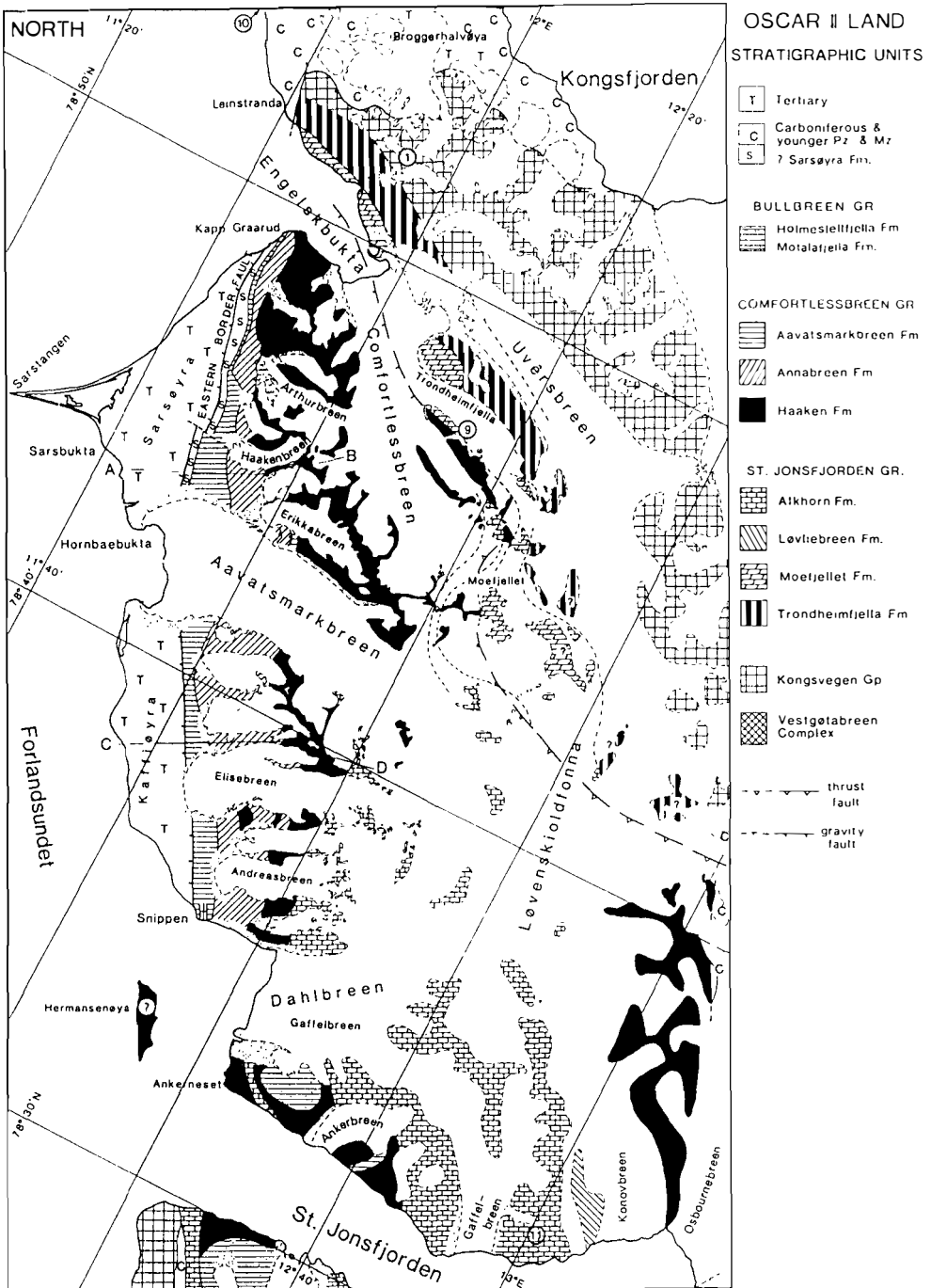
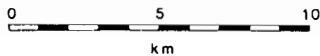
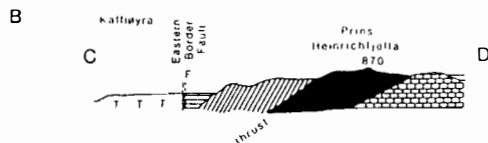
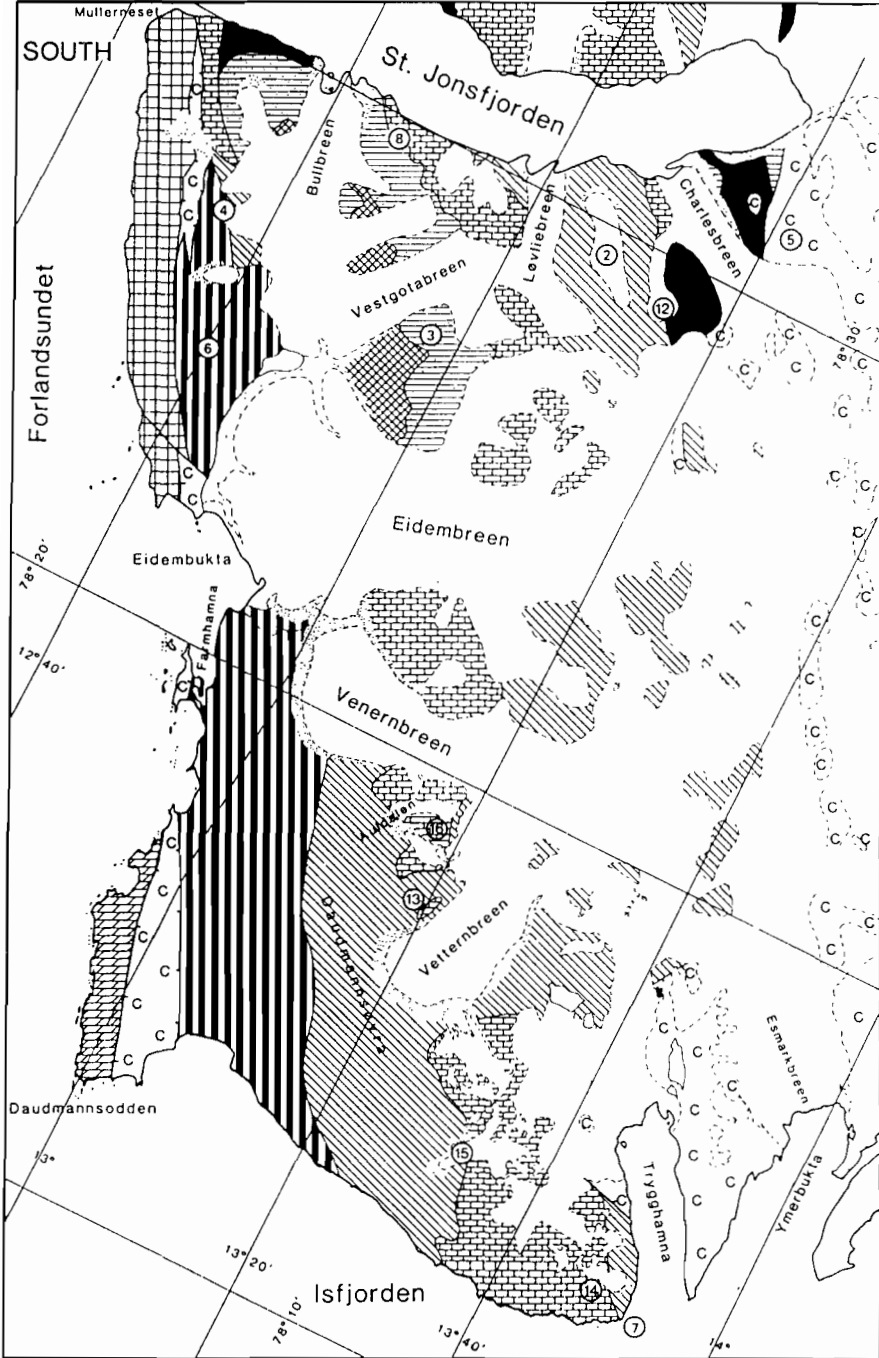


Fig. 24. Outcrop map of major rock units of Oscar II Land. Based on a variety of sources: Hjelle, Ohta & Winsnes (1979) north of St. Jonsfjorden (especially eastern parts), and Ohta (1985) south of St. Jonsfjorden, incorporating revised stratigraphy of this paper; and Waddams (1983a) for the area between north Engelsbukta and Dahlbreen, together with new mapping. Question marks refer to uncertainty as to whether a particular diamictite formation is the upper or lower one. Place names: Steenfjellet 1; Gunnar Knudsenfjella 2; Motalafjella 3; Svartfjella 4; Vegardfjella 5; Jørgenfjella 6; Alkhornet 7; Holmeslettjella 8; Bull-Simonsenfjellet 9; Kulmodden 10; Lowzowfjella 11; Anna Sofiebreen 12; Holtedahlvarden 13; Protektoraksla 14; Torgnybreen 15.



vertical exaggeration x2

al. (1979) and Waddams recognised this as the same early glacial horizon (Waddams 1983b).

This earlier glacial formation is distinguished by an apparent lack of exotic stones (matrix and stones are mainly carbonates). It is generally less resistant to denudation so it is not so conspicuous as the later one, but easy to confuse with it. There is now no doubt that the two diamictite formations (Haaken and Trondheimfjella) are glacial and reflect widespread climatic events separated by a long time interval. They are therefore good for correlation even in tectonised situations.

3.3 Stratigraphic outline

It may help at the outset to tabulate our essential conclusions (Table 3):

Bullbreen Group	(Wenlock (?) Caradoc)
Comfortlessbreen Group	(Later Vendian: Ediacara and Late Varanger)
St Jonsfjorden Group	(early Vendian-early Varanger)
Kongsvegen Group	(?transitional and pre-Vendian)
Vestgøtabreen complex	(?pre-Vendian)

3.4 Bullbreen Group

The Bullbreen Group in central Oscar II Land comprises an upper Holmesletfjella Formation of dominantly flysch facies and a lower Motalafjellet (or Bulltinden, Ohta 1985) Formation with three members – a conglomerate with limestone olistostromes containing late Ordovician to early Silurian faunas; a sandstone shale member; and a basal limestone member with early to mid Ordovician faunas (Scrutton, Horsfield & Harland 1976; Armstrong, Nakrem & Ohta 1986).

The limestone member rests unconformably on the Vestgøtabreen high pressure metamorphic complex. Contacts with Vendian strata are tectonic.

At the margin of the graben to the north-west, a strip of rocks occurs (Sarsøyra Formation 450 m) from which a conglomerate pebble containing a lykophyllid coral was obtained. This was first taken as part of the Bullbreen group (Scrutton, Horsfield & Harland 1976); however, C.L. Forbes (pers. comm.) suggested that a Carboniferous age

is as likely. We are inclined to accept a late Paleozoic age for this strip of limestone and think it is faulted against the uppermost Vendian strata at Sarsøyra.

3.5 Comfortlessbreen Group (Figs. 24 and 25)

Harland (1960) used the name “Comfortlessbreen Schists” for the metamorphosed diamictites of western Oscar II Land. These were subsequently mapped by W.T. Horsfield as the “Comfortlessbreen Formation”, comprising three units. Harland et al. (1979) upgraded the formation to group status and the three units named from the top: Engelsbukta Formation (diamictite), Annabreen Formation (quartzite) and Haaken Formation (diamictite). Hjelle, Ohta & Winsner (1979) referred to the Group as the Tillitic Conglomerate. Waddams (1983a) demonstrated that only one diamictite unit (Haaken) occurs in the group, which was defined as consisting of the Aavatsmarkbreen (top), Annabreen and Haaken formations. The Comfortlessbreen Group is well exposed in the hills east of Sarsøyra and Kafføyra, and at the mouth of St. Jonsfjorden (Fig. 24).

3.5.1 Aavatsmarkbreen Formation (1 km)

This is the uppermost formation of the Comfortlessbreen Group. Its name derives from the large westward-flowing glacier in central NW Oscar Land. It comprises a thick succession of dark grey phyllite, volcanic rocks, psammite and subordinate carbonate. At the type locality, in a meltwater stream section along the northwest margin of Aavatsmarkbreen, it may reach 1000 m in thickness, although isoclinal folds preclude accurate measurements (Fig. 25). Variations of thickness are a reflection of faulted contacts to the west with the Sarsøyra Formation. The lower boundary is not exposed, but gradational contacts with the underlying Annabreen Formation are suggested by the appearance of thin psammite and conglomerate interbeds.

Three informal divisions have been recognised:
(3) About 300–400 m: highly deformed grey and black phyllite, with thin black marble, white marble, sandy dolostone and quartzite interbeds.

(2) About 6–100 m: dark green-black slate and light green fibrous serpentinite, to the north of Aavatsmarkbreen. To the south of the glacier it thickens and becomes more variable with green-black slate and minor slate and quartzite beds. At

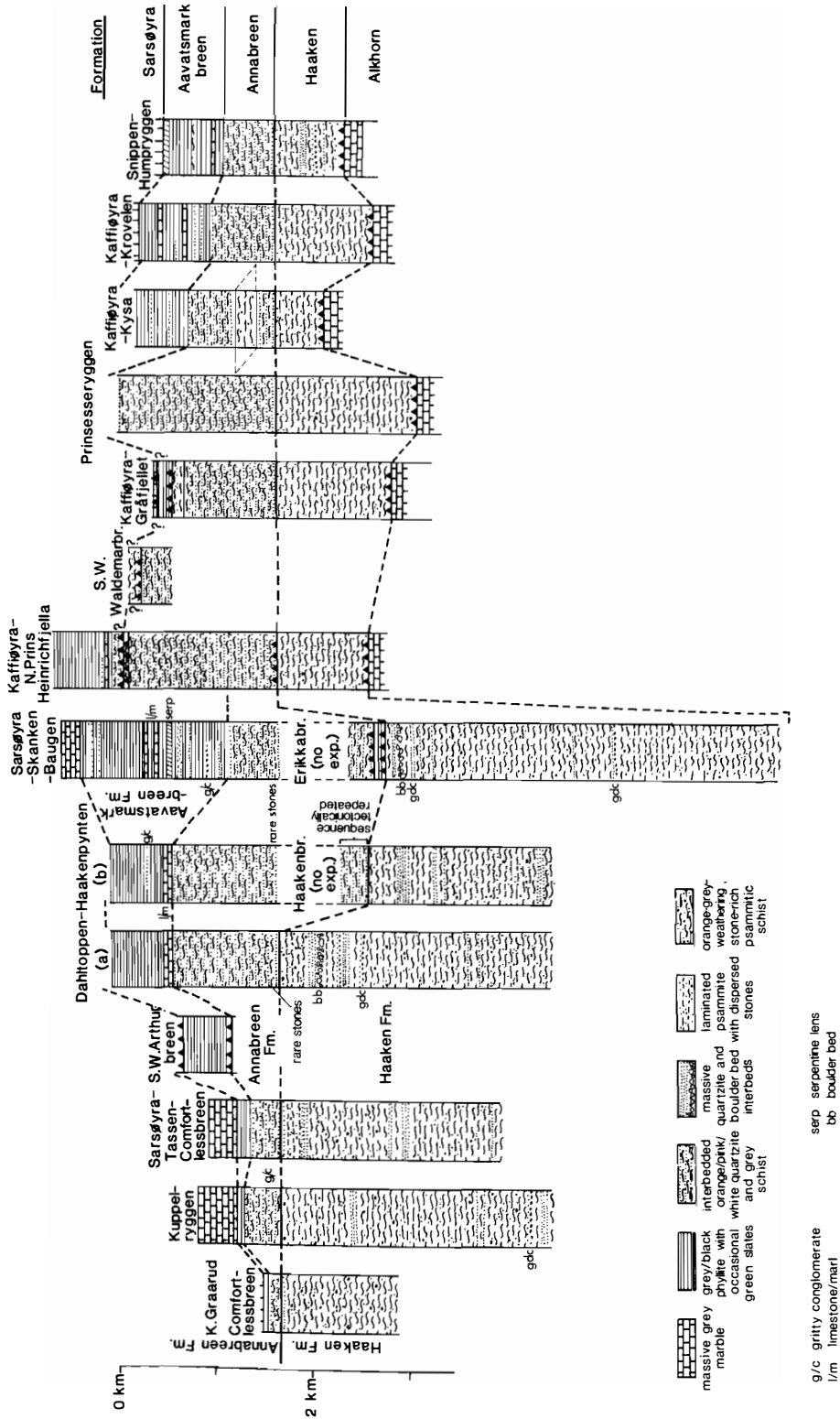


Fig. 25. Schematic sections through the Comfortlessbreen Group in northern Oscar II Land.

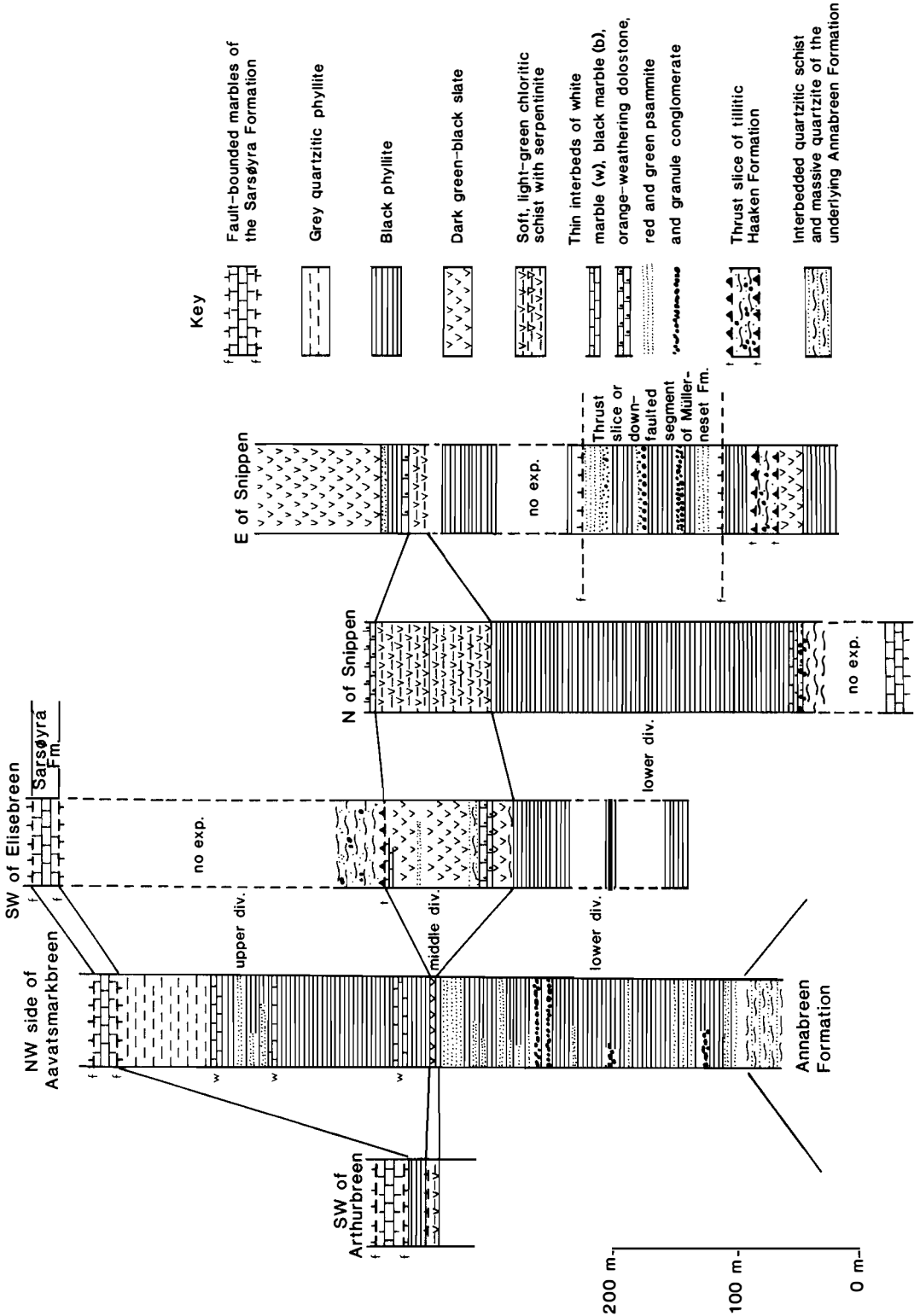


Fig. 26. Sections through the Aavatsmarkbreen Formation, discontinuously exposed on Sarsøyra and Kaffiøyra in northern Oscar II Land (after Waddams 1983a).

Arthurbreen and Snippen the division is characterised by soft, light green and purple banded shales.

(1) About 400 m: dark phyllite and black limestone with thin conglomerate and pink psammite interbeds.

Although facies vary substantially, the distinctive middle division permits broad correlations throughout northern Oscar II Land. The formation has recently been recognised by L. Kanat (private communication) in the St. Jonsfjorden area, but it does not seem to occur further south.

The phyllite probably accumulated by slow settling from suspension. Volcanic activity provided the source for much of the sediment, and in particular gave rise to the tuffaceous metasediments of the lower and middle divisions. Thin dolostone units, dark limestone interbeds and symmetric, parallel-crested ripple marks suggest deposition in shallow water. The formation must have accumulated in a protected nearshore area.

3.5.2 Annabreen Formation (2 km)

This somewhat inappropriate name derives from the glacier Anna Sofiebreen on the south side of St. Jonsfjorden and was first identified by Wilson as the Annabreen Quartzites (Unit W8 in Harland 1960; Harland et al. 1979). The rocks were renamed the Irenebreen Quartzites (Cutbill & Challinor 1965). Hjelle, Ohta & Winsnes (1979) incorporated them into the much younger Bullbreen Group. The original name was retained by Waddams (1983b).

The formation varies considerably in thickness (Fig. 24) reaching 2000 m on Prins Heinrichfjella just south of Aavatsmarkbreen but thinning to 250 m at Kapp Graarud in the north and to 1500 m near Snippen. In the St. Jonsfjorden area it is poorly exposed below a thrust on Ankerfjella and is only ca. 20 m thick. The contacts with the bounding formations may be transitional. Thin psammitic beds occur in the overlying Aavatsmarkbreen Formation, and dispersed dolostone and quartzite pebbles, 15–30 mm in diameter at Dahltoppen (Fig. 26) imply a gradational junction with the underlying stone-rich Haaken Formation. However, elsewhere, e.g. Humpryggen, the style of folding near the contact suggests a thrust.

The principal lithologies are alternating pink, orange or white-weathering quartzite or psammite, and green or grey quartzitic schist (Fig.

27), the former comprising 80–90% of the formation. The quartzite beds are 5 cm to 3 m thick, are finely banded, and sometimes have a thin, graded granule conglomerate at the base. Thick, massive quartzite beds, resistant to weathering, occur towards the top of the formation. They are sometimes interbedded with dolostone conglomerate lenses up to 1 m thick and 10 m long. At Dahltoppen faint trough cross-bedding was observed.

The formation displays signs of extensive shearing, jointing, possible mylonitisation, and thrusting at the base of the competent quartzite beds.

The alternating psammite and schistose beds represent a proximal turbidite sequence. However, sedimentary structures which would support this interpretation have been obscured by deformation. Towards the top of the formation, shallowing of water is indicated by an increasing predominance of massive psammite, together with some cross-bedded psammites and dolostone conglomerate lenses. This upward transition from crudely graded psammite and schist to purer, ungraded, crossbedded psammite represents the basinward progradation of a continental margin turbidite fan system.

3.5.3 Haaken Formation (2–3 km)

The term “Haaken schists” was used by C.B. Wilson for a thick diamictite succession (his horizon 7) in northwestern Oscar Land. They have also been referred to as the “Comfortlessbreen schists” (Harland 1960), the Haaken Formation (Harland et al. 1979 and redefined version by Waddams 1983b), and the Tillitic Conglomerate Formation (Hjelle, Ohta & Winsnes 1979).

The east–west trending ridges between Engelsbukta and St. Jonsfjorden expose well the Haaken Formation (Figs. 24 and 25). The steeply dipping rocks have an outcrop width of some 6 km, along the northern margin of Aavatsmarkbreen, but the formation has been tightly folded and repeated by thrusting, and Waddams (1983b) estimated that the true thickness was nearer 2–3 km. North of Aavatsmarkbreen the formation is truncated by a reverse fault, but to the south it maintains an outcrop width of 1–1.5 km as far as Dahlbreen. On the north shore of St. Jonsfjorden it is much thinner, for example about 300 m near Ankerbreen (Fig. 25), but south of the fjord it attains a maximum thickness of about 3 km, between Svartfjella and Jørgenfjella.

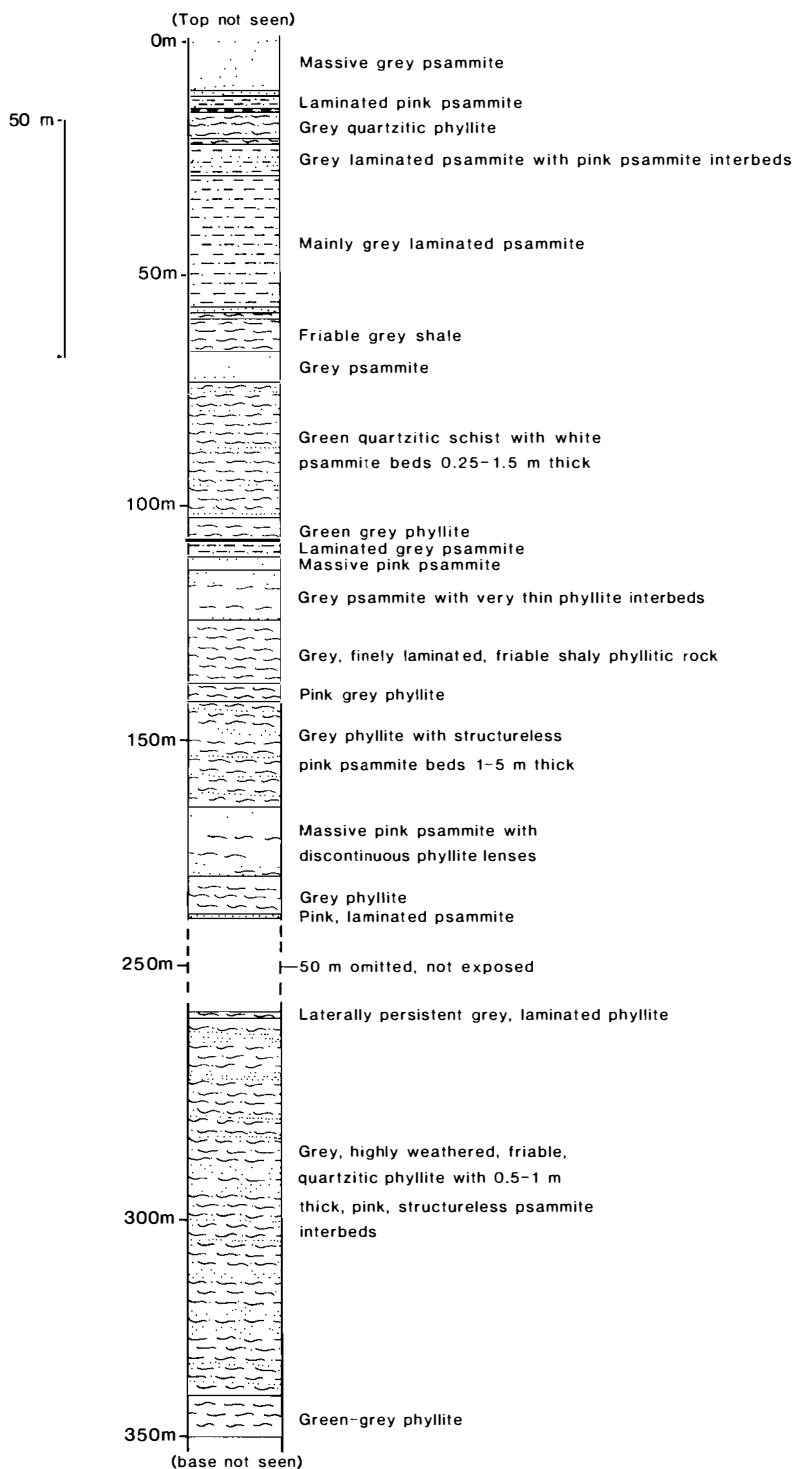


Fig. 27. Measured section through part of the Annabreen Formation, south flank of Dahltoppen (after Waddams 1983a).

An eastern belt of schistose diamictite occurs both north and south of inner St Jonsfjorden as mapped by W.T. Horsfield, who also recorded granitoid stones (Ph.D. dissertation). The lower part of that unit is devoid of such stones but from similarity of matrix we correlated it with the Haaken Formation.

The upper contact of the Haaken Formation varies from gradational (on Dahltoppen) to tectonic (on Humpryggen and Lowzowfjella). The lower contact with the Alkhorn Formation is mainly tectonic, but locally is gradational (at Gjertsenodden, St. Jonsfjorden).

The formation consists of stone-bearing, orange to grey weathering psammitic schist ("schistose diamictite"), interbedded with blue and grey weathering quartz-rich schist and occasional grey, laminated quartzite (Fig. 28A–E). Towards the top of the formation, orange and pink weathering, finely banded quartzites occur in beds 0.1 to 3 m thick. Dolostone conglomerate beds 1 to 4 m thick, displaying normal coarse-tail grading occur, notably near Haaken Mathiesenfjella. In the St. Jonsfjorden area the formation includes stone-free psammitic schists and limestone. At the east of a coastal section on the south side of the fjord the formation includes interbeds of ungraded polymict conglomerate, whereas to the west stone-rich pinkish grey and green schist is tightly infolded with black, calcareous slate and dark grey phyllite.

The schistose rocks have a foliation which generally is parallel to the primary compositional lamination. This lamination is defined by alternating fine, orange dolomitic psammite layers 1–30 mm thick and dark schistose layers 1–3 mm thick (Fig. 28B–D). Where least disturbed, these layers are laterally continuous for several metres, e.g. above the northwest flank of Haakenbreen. However, more often the layers have been extremely attenuated by the first phase of deformation.

The psammitic schist contains a variety of stones, dispersed thinly throughout the rock and rarely comprising more than 10% of the rock by volume. These include principally dolostone, limestone, quartzite and both foliated and unfoliated granitoids (Table 4, Fig. 29A–D). The (small percentage of) granite stones have not been matched with any bedrock in Svalbard. In one boulder horizon, 11 m thick, above the north-western margin of Haakenbreen, the granites form a much higher proportion of the stones

(Table 4). Many of these boulders are over 1 m long and the largest seen of granite measures approximately 2 x 1 x 0.7 m. The boulder bed is composite with two horizons separated by gravel. It has a sharp lower contact and rests on grey schist with scattered stones. Most stones in the schistose diamictite are less than 5 cm in length, but occasionally cobbles, and boulders up to 0.5 m are present. All the stones are deformed, but to varying degrees. The degree of deformation follows the pattern: unfoliated granite < dolostone < quartzite < foliated granite < limestone. Axial ratios for granite stones are typically around 2:1 and for limestone 20:1 (Hambrey & Waddams 1981). Another boulder bed at Gaffelbreen, St. Jonsfjorden is dominated by dolostones.

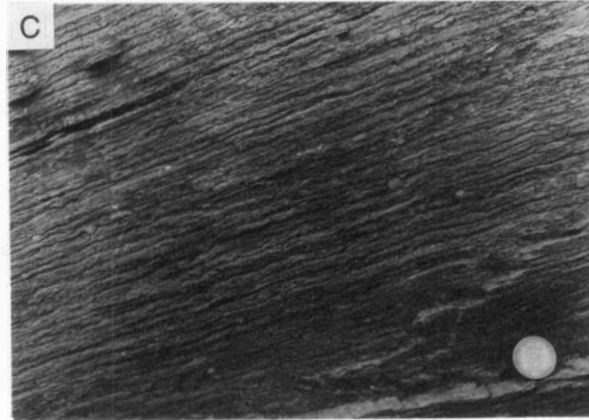
Few sedimentary structures have survived deformation, but it is evident that the bulk of the Haaken Formation was deposited as thin laminae of sand and mud, possibly in rhythmic fashion. To these fine sediments the dispersed stones were added. Deposition as distal turbidites is the most likely process to have generated these rhythmically laminated sediments, whereas ice-rafting gave rise to the coarse component within the schistose diamictites. The bulk of the sediments are thus distal glaciomarine, but higher concentrations of clasts (up to 20%) suggest occasionally a more proximal position in relation to the ice margin.

The rare but persistent boulder beds in the Haaken Formation may record dumping of coarse debris from icebergs, or the winnowing action of bottom currents on poorly sorted waterlain till, or subaqueous debris flowage, the last process being the most likely.

Together, the Haaken and Annabreen formations represent the basinward progradation of a continental margin turbidite fan system, comprising the following elements in order of occurrence: distal turbidites with ice-rafting (Haaken Formation), proximal turbidites (lower Annabreen Formation psammite-schist interbeds), and well-sorted, cross-bedded shelf sandstones, deposited by traction currents (upper Annabreen Formation with purer massive psammites).

3.6 St. Jonsfjorden Group

The St. Jonsfjorden Group was defined by Harland et al. (1979) as comprising four formations: Alkhorn (top), Løvliebreen, Moefjellet and



Trondheimfjella. It lies between the diamictite-bearing Comfortlessbreen Group and the metamorphically higher grade Kongsvegen Group. The St. Jonsfjorden Group is equivalent to Hjelle, Ohta & Winsnes (1979) "Middle Hecla Hoek" Calc-argillo-volcanic and Quartzite-shale formations. Waddams (1983b) redefined the Trondheimfjella Formation to embrace a schistose diamictite, compositionally different from the Comfortlessbreen diamictite, and which was first distinguished in southern Brøggerhalvøya. We follow Harland et al. (1979). However, before proceeding we must first consider an alternative scheme by Kanat & Morris (1988).

From a detailed study around St. Jonsfjorden, Kanat & Morris (1988) used the same unit names but reversed the order of the Lovliebreen and the Alkhorn formations. This part of their succession is listed thus:

Lovliebreen Formation	
Quartzite and pelite	(5L2) 300 m
Lower volcanics	(SL1) >20 m
Alkhorn Formation	
Marble	(SA2) 50 m
Calcareous psammo-pelite	(SA1) >100 m

From the (bracketed) symbols on their map it was easy to identify their rocks on the ground in 1989. Their case would seem to rest on mapping SL1 north and south of St. Jonsfjorden adjacent to SA2 and placing SA2 in the core of an anticline to the south.

We confirmed the conclusion of Harland and Horsfield in 1968 (Horsfield's dissertation map) that S11 is an intrusive dolerite (e.g. at Piriepynten) and that the thick amygdaloidal basalts, so well displayed in the west cliff of Anna Sofiebreen where the Lovliebreen volcanics were first identified, had not been mapped by Kanat and Morris. Nor had they mapped the (Alkhorn) marbles east of the Charlesbreen diamictites. Moreover, in an area with so many thrust faults a sequence would need to be tested over a much

greater area than they mapped, as indeed was done by Horsfield and from which the Harland et al. 1979 succession was based.

3.6.1 Alkhorn Formation (1 > km)

Holtedahl (1913) introduced the term "Alkhornkalk" for the dominantly calcareous unit, the lower part of which is well exposed in Alkhornet west of the mouth of Trygghamna in southernmost Oscar II Land (Fig. 30A). The name was retained by Major, Harland & Strand (1956), but in the north a similar unit was named the Dahlbreen limestone by Harland (1960). In view of Holtedahl's prior description of probably coeval rock, the term Alkhorn Formation was adopted by Harland et al. (1979) and used by us subsequently (e.g. Waddams 1983b). However, this formation is also known as the Calc-argillo-volcanic Formation, metavolcanic and intrusive rocks having been recognised in the upper part of the formation (Hjelle, Ohta & Winsnes 1979).

The formation extends SSE from Comfortlessbreen in a linear belt throughout Oscar II Land (Fig. 23). The maximum outcrop width is to the north and east of Dahlbreen, but the formation is best exposed on the north side of St. Jonsfjorden. It thins rapidly to the north and is thrust out at the east end of Comfortlessbreen. In the north it is in thrust contact with the overlying Haaken Formation, but in the St. Jonsfjorden area gradational contacts occur with the bounding formations. In the south the lower part of the formation is well exposed as flat-lying units in the upper parts of the hills west of Trygghamna. The contact with the underlying formation is conformable but sharp at Holtedahlvarden, gradational over a few centimetres below Protektoraksla and gradational over 0.5 m in Auladalen.

The formation consists of interbedded dark grey, well-bedded limestone, basic volcanic or intrusive rocks, marble and minor carbonate breccia and phyllite (Figs. 30 and 31). The limestones and marbles contain abundant dolostone clasts.

Fig. 28. Haaken Formation. A. Clast-rich diamictite with flattened and folded quartzite cobbles, south flank of Skanken, Aavatsmarkbreen. B. Medium coarse layering and small pebbles, north margin of Aavatsmarkbreen. C. Typical schistose diamictite with dispersed stones of mainly pebble size. Stones have been flattened and quartz veining has developed parallel to S_1 , which in turn has been folded in chevron fashion by F_2 . South flank of Skanken. D. Higher percentage and somewhat larger stones in schistose diamictite near (B), with similar deformation characteristics. E. Strongly deformed stone-rich diamictite below northeast ridge of Dahltoppen above Haakenbreen. The foliation penetrating the granite cobble above the compass is S_1 , which itself has been folded by F_2 .

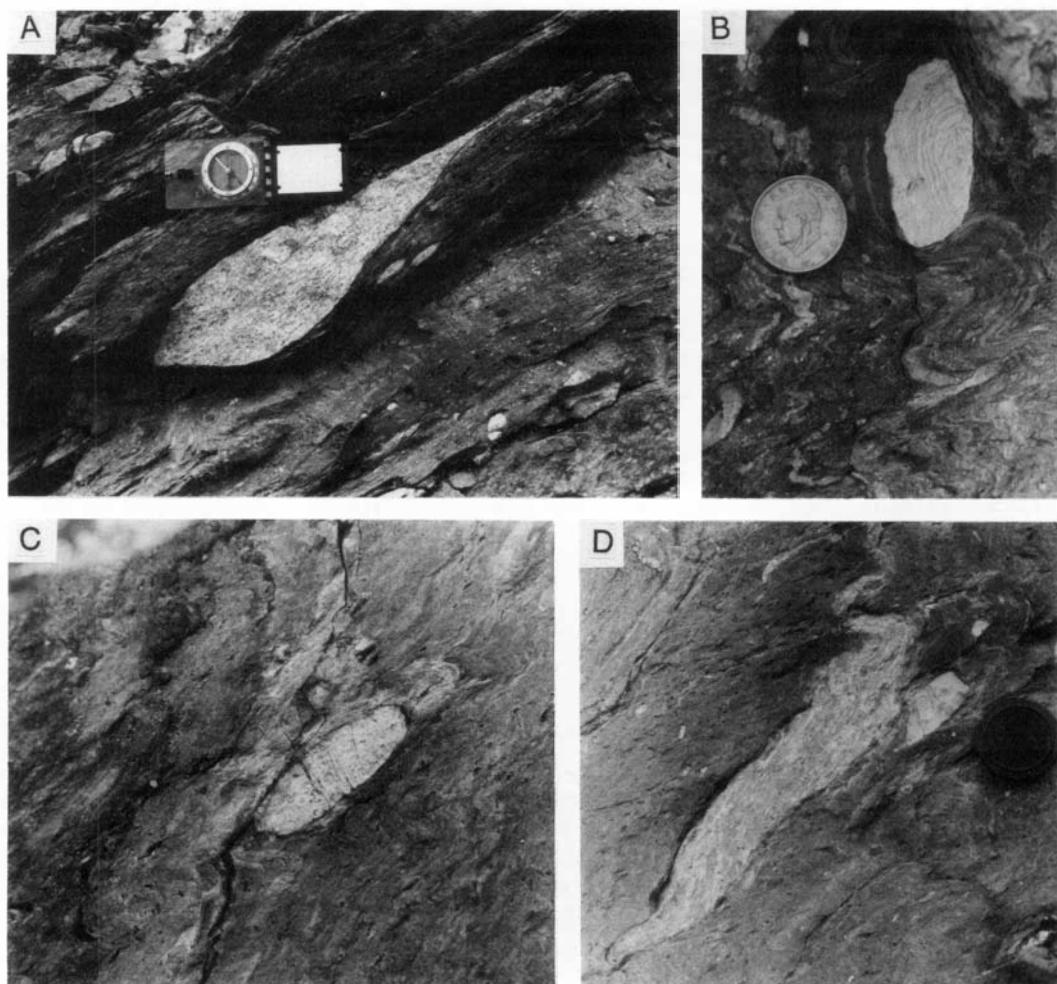


Fig. 29. Stones in the Haaken Formation, north margin of Aavatsmarkbreen. A. pear-shaped, weakly foliated granite. B. Stromatolitic dolostone. C. Pisolitic dolostone. D. Elongated gneiss with folded tail, alongside relatively undeformed angular dolostone.

It has a transitional contact with the underlying formation. Although the rocks have been metamorphosed, the degree of deformation reflects differences in competence. The well-bedded dark limestones have only a slight flattening of clasts, whereas the marbles have pronounced isoclinal folds. Phyllites frequently show crenulation folds, and the basic volcanics a rather weak foliation.

The lower part of the formation exposed in a shallow syncline on the south face of Proktoraksla (Fig. 30C) comprises a sequence of well-bedded limestones, basic metavolcanics and strongly folded marbles. Following is a description of the sequence, from the top:

(6) >160 m: dark grey, well-bedded limestones, partly graded and oolitic (Fig. 30B). Rounded to subrounded (a few subangular) grains and pebbles of dolostone up to 1 cm occur locally in a dark limestone matrix; these have been flattened about 2:1. The limestone is non-ferroan calcite and contains quartz silt. Aggregates of sand-sized quartz grains may be remnants of the original lamination. Minor trough cross-bedded dolostone is present. This is a dolomicrite with chlorite laths and shows about 40% replacement by ferroan dolomite. Concentrations of haematite occur in laminae; these have been isoclinally folded in places.

Table 4. Composition of schistose diamictites, Oscar II Land (estimated percentages).

HAAKEN FORMATION				TRONDHEIMFJELLA FORMATION			
Schistose diamictite		Boulder bed		Schistose diamictite			
Aavatsmarkbreen (N margin)		S.E. Ankerbreen		N.W. Haakenbreen		N. Engelsbukta	
Cream/white dolostone	27	Dolostone	65	Granite	65	Dolostone	75
White/grey quartzite	23	Quartzite	24	Quartzite	15	Limestone	20
Black/grey limestone	18	Limestone	9	Dolostone	10	Quartzite	5
Orange dolostone	11	Granite	2	Limestone	< 5		
Unfoliated granite	9			Sandstone	< 5		
Foliated granite	4						
Stromatolitic dolostone	3						
Onolitic dolostone	3						
Red Quartzite	1						

(5) 90 m: coarsely crystalline, green metabasalt or metadolerite. The original texture has been largely overprinted. Pyroxene has been altered to the actinolite-tremolite series. Plagioclase has been albitised, and oxides (probably of Ti) have been pseudomorphed mainly by sphene. Chlorite is abundant, and the epidote mineral-group, clinzoisite, is indicative of greenschist facies metamorphism.

(4) 25 m: medium-grey, variably laminated to foliated limestone, with up to 15% outsize dolostone clasts, some of which are oolitic, and around which the laminae are draped. The calcite contains silt (occasionally sand) grains, which form well-defined, millimetre-scale, largely discontinuous laminae. This could have been, prior to deformation, a rhythmite of calcite and silt.

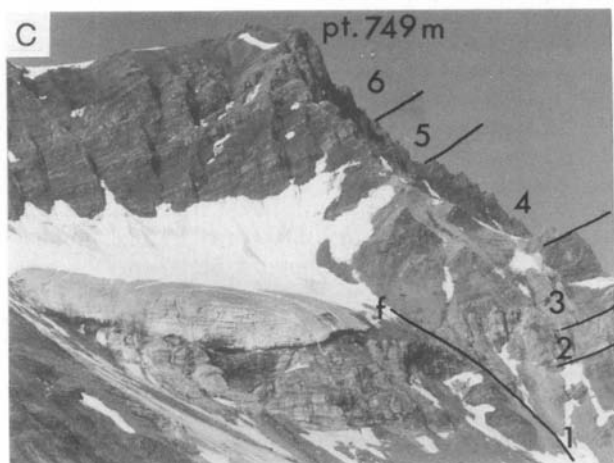
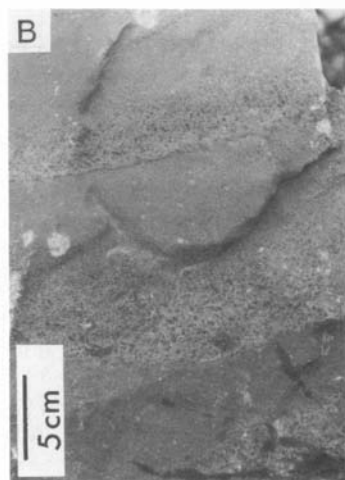
(3) 85 m: brown-weathering grey marble of non-ferroan calcite with about 10% silt. It has been subjected to intense intra-unit isoclinal folding (Fig. 30D). Lithologies include white-grey banded marble (partly stylolitic), marble diamictite, finely laminated dolostone with sheared calcite marble and small clasts of dolostone and limestone. Submillimetre haematite blebs define a weak planar fabric.

(2) 35 m: green basic foliated meta-igneous rock, originally a tholeiitic porphyritic dolerite or

gabbro. This highly altered rock contains relict orthopyroxene and clinopyroxene, the latter having been metamorphosed to fibrous brown amphiboles of the tremolite-actinolite series. Also plagioclase has been altered to chlorite, but relict plagioclase is present in albite, and oxides have been altered to leucoxene and haematite. Greenschist facies metamorphism is suggested by the mineral assemblage.

(1) >85 m: variable grey to blue shaly limestone and marble with some greenish phyllite in the lower part. Near Torgnybreen, 8 km to the west, this unit includes much clastic material, comprising dispersed dolostone clasts in well-bedded limestone (45–60% microspar, 20–25% sparite, 20–30% clasts and subordinate silt), to matrix-supported limestone or dolostone breccia. A thin dolostone breccia bed comprises subrounded to subangular clasts up to 30 cm long, almost entirely of dolospar with practically no quartz except as veins (Fig. 30F). Minor chert replacement of oolitic dolostone has occurred.

Other lithologies observed in the scree of Protektoraksla include oolitic dolostone with undeformed and well-preserved ooids, where silicified, and c. 20% silt. Banded chert with intraformational brecciation also occurs.



A broadly similar succession occurs 16 km to the north-west, in Heidenstamtoppen, Auldalen. With thicknesses this comprises:

- (5) black limestone with assorted carbonate clasts (unknown thickness) (Fig. 31A);
- (4) white-grey marble and limestone (50 m) (Fig. 31B);
- (3) phyllitic dolostones (100 m);
- (2) basic-igneous rock (50 m);
- (1) dark grey limestone with much calcite veining (>150 m) (Fig. 31C).

On the other side of Auldalen, unit (5) comprises typically micrite (50%) and sparite (10%), with as many as 40% dolospar stones and a little silt (Fig. 31D). The stones are mainly rounded to subrounded, and some are oolitic. Some are undeformed, but others have been flattened or even boudined with calcite pressure shadows. A few stones could have been concentrations of sand that behaved more competently during deformation. Most striking, however, are a number of outsize stones, with deformed laminae around them. One measures 8 x 3 cm and others look like dropstones (Fig. 31E). The basic metaigneous rocks in this area are similar to those at Protektoraksla, but are less altered. Large 1–3 mm relict clinopyroxene phenocrysts altered to tremolite-actinolite occur in a microcrystalline groundmass, rich in plagioclase that has been albitised and altered to epidote. The rock possesses a good metamorphic fabric, but was formerly an olivine basalt, porphyritic dolerite or gabbro.

It is not clear how our Alkhorn Formation matches with the Calc-argillo-volcanic Formation of the Norsk Polarinstitut, as no type localities were proposed. In the northern part of Oscar II Land, on Trondheimfjella, Hjelle, Ohta & Winsnes (1979) include 550 m of limestone, slate and shale in their Calc-argillo-volcanic Formation, which for us is Moefjellet Formation. Along the northern side of St. Jonsfjorden the Calc-argillo-volcanic Formation equates with our Alkhorn Formation. Here Hjelle, Ohta & Winsnes (1979) observed the following succession:

- (4) 300 m grey-green phyllite;
- (3) 100 m black slate;
- (2) >100 m limestone-rich unit;
- (1) 80 m slate.

Also two small basic intrusive bodies of hornblende gabbro and porphyrite occur in the lower slate. They may have been feeders of the eruptive rocks now represented by the green phyllites.

On the top of Gunnar-Knudsenfjella, Hjelle, Ohta & Winsnes (1979) found a volcanic complex comprising basalt, agglomerate and phyllite, amounting to 150 m in thickness.

Hjelle, Ohta & Winsnes (1979) recognised a further belt of this formation (principally limestone, slate, phyllite and quartzitic sandstone) along the Forlandsundet Eastern Border Fault. However, exposure is poor, and we find little evidence to equate the two belts.

The basic igneous rocks of the Alkhorn Formation have been examined petrographically and geochemically by Ohta (1985) (his Calc-argillo-volcanic Formation). In general, the rocks are metadiabase-gabbros, occurring in discontinuous lensoid masses up to 25 m thick. They are high Fe-rich tholeiites of oceanic affinity.

Although deformation has obliterated many of the primary features in the Alkhorn Formation, certain units have remained relatively competent, especially some distinctive bluish grey limestone and pale grey dolostone beds, and these provide clues as to the nature of the environment. On Protektoraksla and in Auldalen sedimentary structures preserved include well-defined bedding, trough cross-bedding, intraformational conglomerates and oolites. Some oolites form graded units. Locally, rounded to subrounded stones of pale dolostone are set in the dark limestone matrix. They are outsized with respect to the lamination, possibly dropstones. In addition there is a proportion of quartz sand dispersed through some carbonate units. All this points to deposition in a shallow-marine, tidally influenced setting, with a certain amount of reworking by gravity flows. Clastic input is indicated by outsized dolostone clasts and sand grains. These may have

Fig. 30. Alkhorn Formation. A. Alkhornet, the type locality near Trygghamna, with Alkhornbreen below. B. Graded oolitic limestone from supraglacial debris, Alkhornbreen. C. Section through black limestones, volcanics and marbles, east face to Protektoraksla, Trygghamna. D. Strongly folded marbles just below Alkhornbreen (far right of photo (A), above). E. Calcareous pebble breccia, partly intraformational, partly oncolitic, southeast flank of Humpryggen, northwestern Oscar II Land. F. Limestone breccia with dolostone matrix supporting the clasts, immediately east of snout of Daudmannsbreen, southern Oscar II Land.

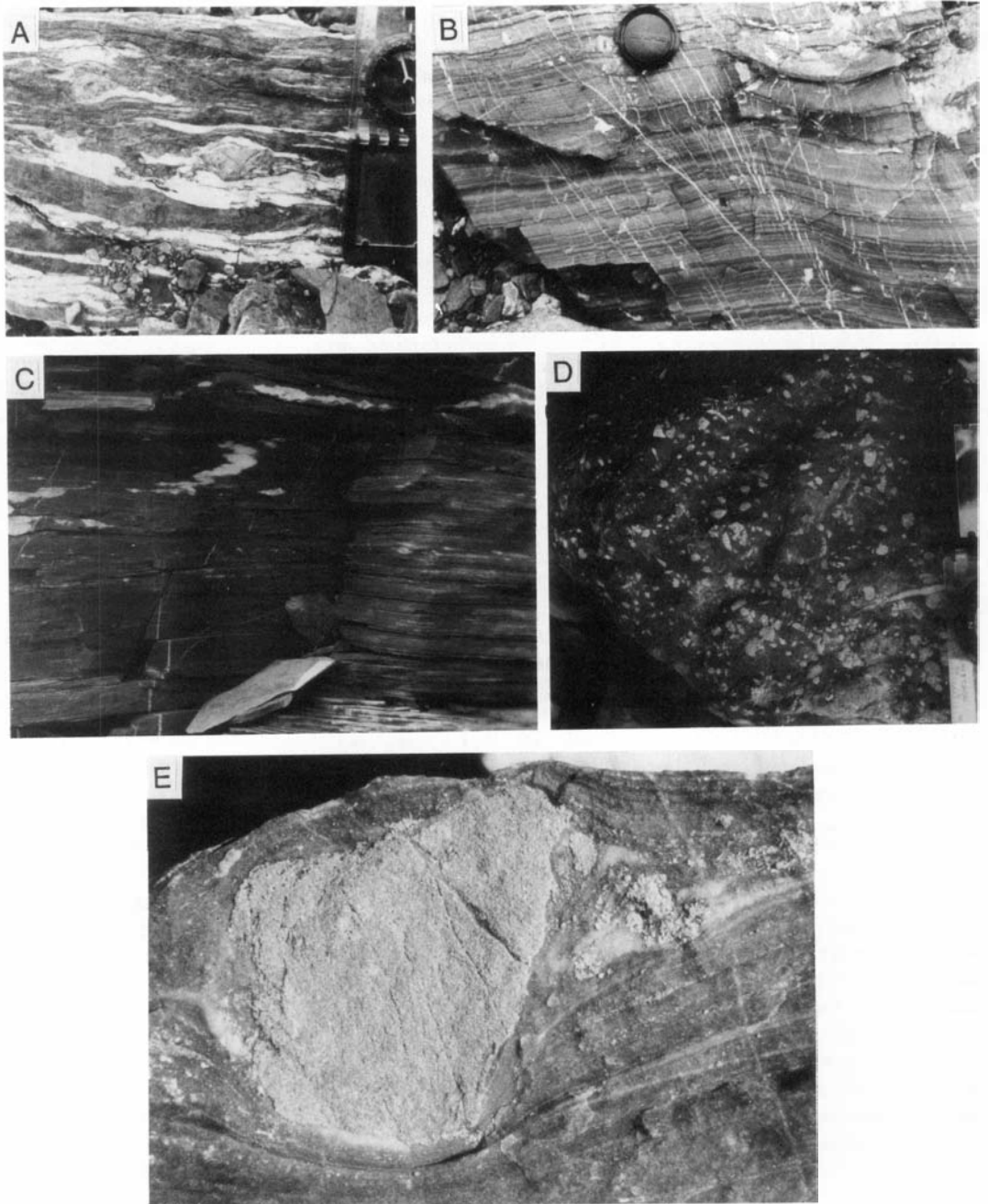


Fig. 31. Alhorn Formation, Auldalen, Southern Oscar II Land. A. Dolostone pebbles in calcitised, isoclinally folded (F_1) limestone matrix. B. Finely laminated limestone, not significantly deformed by F_1 , but with well-developed spaced (calcitised) S_2 cleavage. C. Blue-grey shaly limestone, with well-developed transposition foliation, and minor calcitised F_1 folds. D. Small, variably shaped pebbles of dolostone in a relatively massive limestone matrix. E. Probable dropstone of dolostone in laminated, little deformed limestone.

been derived from a littoral source by rafting by sea ice; glacier ice is also a possibility.

The few beds of dolostone breccia that have been observed are thin and contain no sand; they are inferred to be subaqueous debris-flows with only minimal transport, perhaps related to fault scarp activity.

Widespread basic volcanic activity is represented by metadiabase-gabbros (high Fe-rich tholeiites) of oceanic type (Ohta 1985). This association of shallow marine sediments and oceanic igneous rocks, Ohta suggested, indicates a possible actively consuming plate margin, although rifting of an ensialic marine basin also seems likely (Chap. 6).

3.6.2 Løvliebreen Formation (1 km)

This formation was named by Harland et al. (1979) after a glacier on the south side of St. Jonsfjorden, where an estimated thickness of 1000 m was recorded. The formation corresponds to the dark quartzites of Høltedahl (1913) at the bottom of his Alkhornet sequence, and to the massive quartzite bodies of Weiss (1953) in eastern Holmesletfjella and in Gunnar Knudsenfjella. It is also broadly equivalent to the Quartzite-shale Formation of Hjelle, Ohta & Winsnes (1979) who mapped its distribution south of St. Jonsfjorden. A modified map (Ohta 1985) shows that it forms a broad belt from Løvliebreen to Isfjorden, but north of St. Jonsfjorden it crops out only for a short distance. Ohta (1985) also has a belt extending from Venernbreen south across Daudmannsøyra, but we interpret most of the rocks in this belt as Comfortlessbreen Group (Fig. 24).

At the type locality the formation consists of interbedded pelites and meta-volcanic rocks within a recumbent syncline. The base is not visible, but the following two members have been identified (Harland et al. 1979):

(2) *Upper*: massive quartzites with intercalated pelites. Dark quartzites are cut by thin white quartz veins. The quartzites are equigranular, fine-grained, with well-rounded, well-sorted grains of fine sand size. Some grains have sutured outlines. Pelites account for less than 10% of this member and are dark, fine-grained, fissile rocks.

(1) *Lower*: foliated volcanic rocks (as on Gunnar-Knudsenfjella), weathering dark brown, green and purple. They are fine-grained and contain amygdalites. Judging from their presence in morai-

nes, this member is widespread in inland Oscar II Land. Kanat (1984) recorded: albite, calcite, chlorite with minor stilpnomelane, phengite, pyrite and rutile.

Ohta (1985) noted that the volcanic rocks (his Trollheimen volcanics) include thin lavas up to 15 m thick containing calcite amygdalites and with possible pillow structures; also pyroclastic rocks and tuffs. A particularly well-developed pyroclastic and lava sequence occurs at Trollsløtten in upper Eidembreen. Geochemically these rocks are very different from the meta-gabbroic rocks of the Alkhorn Formation; they are Na-alkaline with smaller amounts of calc-alkaline, probably non-oceanic, material.

The Løvliebreen Formation immediately east of Daudmannsøyra, on the low ridge of Høltedahlvarden, attains a thickness of about 1500 m. Its upper contact with the Alkhorn Formation is sharp and apparently conformable. However, small-scale isoclinal folds in these rocks do not rule out a tectonic relationship.

On the lower south flank on Protektoraksla in southernmost Oscar II Land a gradational contact over a few centimetres has been observed, although the rocks are highly contorted and calcite-veined at this boundary. This confirms Ohta's (1985) suggestion of a stratigraphic rather than a tectonic contact. In Protektoraksla only the upper part of the formation is present. This consists of an alternating succession of phyllite, quartzite and psammite. The phyllite is a fine-grained micaceous rock with minor silt and sand laminae, and small current scour structures. Locally the rock is crenulated. This may originally have been a tuffaceous deposit, though a preliminary examination has not revealed volcanic glass. The quartzite and psammite contains sand-sized grains, partially floating in a fine silt-muscovite matrix, together with a few subrounded elongated flakes up to 1 cm long which may have been intraclasts. The succession here also contains a 0.5-m-thick diamictite, the lower contact of which is sharp. It contains a poorly sorted admixture of limestone, dolostone and quartzite stones of variable shape (angular to rounded). In thin section the original lamination has been obliterated, and some muscovite defines the foliation (S_1). The larger stones are of dolostone (angular to subrounded), but they are slightly flattened and partially altered to ferroan dolomite.

The nature of the lower contact of the for-

mation has not been observed. In most places it is obscured by scree.

The igneous rocks of the Løvliebreen Formation are somewhat different from those in the Alkhorn Formation in that they include Na-alkaline lava flows, some with possible pillow structures, with smaller amounts of calcalkaline material (Ohta 1985). Geochemically, therefore, they are of non-oceanic type and may have formed in a shallow-marine setting in association with shelf to shelf-edge sediments (Ohta 1985). Associated with the lava flows are pyroclastic rocks, some of which are reddened, suggesting subaerial exposure. A rift basin could yield such an association, though with more crustal contamination of magmas than in the Alkhorn Formation. The greenish and purple phyllites are highly deformed, having behaved in ductile fashion during D_1 . At least some are metamorphosed tuffs.

Few sedimentary structures have been observed in the clastic sediments. However, the interlaminated psammitepelite unit at Protektoraksla contains current-scour structures. Such sediments may have been deposited by minor turbidity flows. At the same locality, a single bed of diamictite, 0.5 m thick, with a sharp base is probably a subaqueous debris-flow. There is little to suggest how the quartzites and pelites were deposited elsewhere. They are likely to be near-shore (or shoreface) and offshore respectively.

3.6.3 Moefjellet Formation (500–800 m)

This formation was named by C.B. Wilson after a prominent dolostone nunatak in Løvenskiöldfonna, northern Oscar II Land. It is dominated by a massive, uniform, unfoliated, cream weathering, bluish grey dolostone that is often sandy and having a gritty surface texture. Calcite veining, and small-scale brecciation picked out on weathered surfaces, are common. Occasionally the rock is banded, defined by alternations of cream and grey dolostone or cherty layers. In some places, a very fine lamination of possible algal origin occurs on highly weathered surfaces.

The Moefjellet Formation is well exposed north of Engelskbukta where it conformably overlies the Trondheimfjella Formation and attains a thickness of over 800 m. It extends southeast through Bull-Simonsenfjellet to Moefjellet, then south through the scattered nunataks of Løvenskiöldfonna towards the head of St. Jonsfjorden (Fig. 24). However, at St. Jonsfjorden it is only exposed in Vegardfjella, where about 200 m

of dolostone are infolded with schistose diamictite of the Trondheimfjella Formation. The Moefjellet Formation may not crop out south of St. Jonsfjorden unless at Daudmannsodden. The nature of the upper contact and its relationship with the Løvliebreen Formation is not understood. On Bull-Simonsenfjellet it is in fault-contact with the Haaken Formation, and elsewhere the few observed upper contacts are probably thrust.

On the north shore of Engelskbukta, Waddams (1983b) recorded:

(4) approximately 30 m: dark calcareous shales;

(3) approximately 40 m: light grey sheared dolostone;

(2) approximately 60 m: interbedded quartzite and blue-grey schist;

(1) approximately 350–400 m: massive, grey, finely crystalline, extensively sheared dolostone. It is best exposed in the Leinstranda cliffs. Black streaks and bands up to 2 m wide represent carbonaceous or organic-rich layers. Discontinuous grey slaty beds 0.5–1.5 m thick, pick out the bedding.

Overall, the Moefjellet Formation, unlike the other main carbonate unit, the Alkhorn Formation, has a significant dolostone component and preserves few sedimentary features. The fine lamination could be of algal origin, suggesting deposition in shallow water.

The *Daudmannsodden Formation* was named – but not correlated – by Ohta (1985). The exposures examined (by Harland in 1989) are of highly sheared marble with alternating limestone and dolostone bands which reveal the fine structure of extreme isoclinal folding and sinistral shear with boudinage suggesting a major N–S sinistral transcurrent shear zone. The rock could either be a unit not elsewhere exposed beneath the Trondheimfjella (lower diamictite tillite) Formation, or more likely it is a sheared representation of the Moefjellet (Dolomite) Formation and while juxtaposing a Carboniferous–Permian fault slice its nearest older neighbour is the Trondheimfjella Formation to the east.

3.6.4 Trondheimfjella Formation (1.3 km) (Fig. 27)

The name Trondheimfjella Formation was proposed by C.B. Wilson in 1958 (W4 in Harland

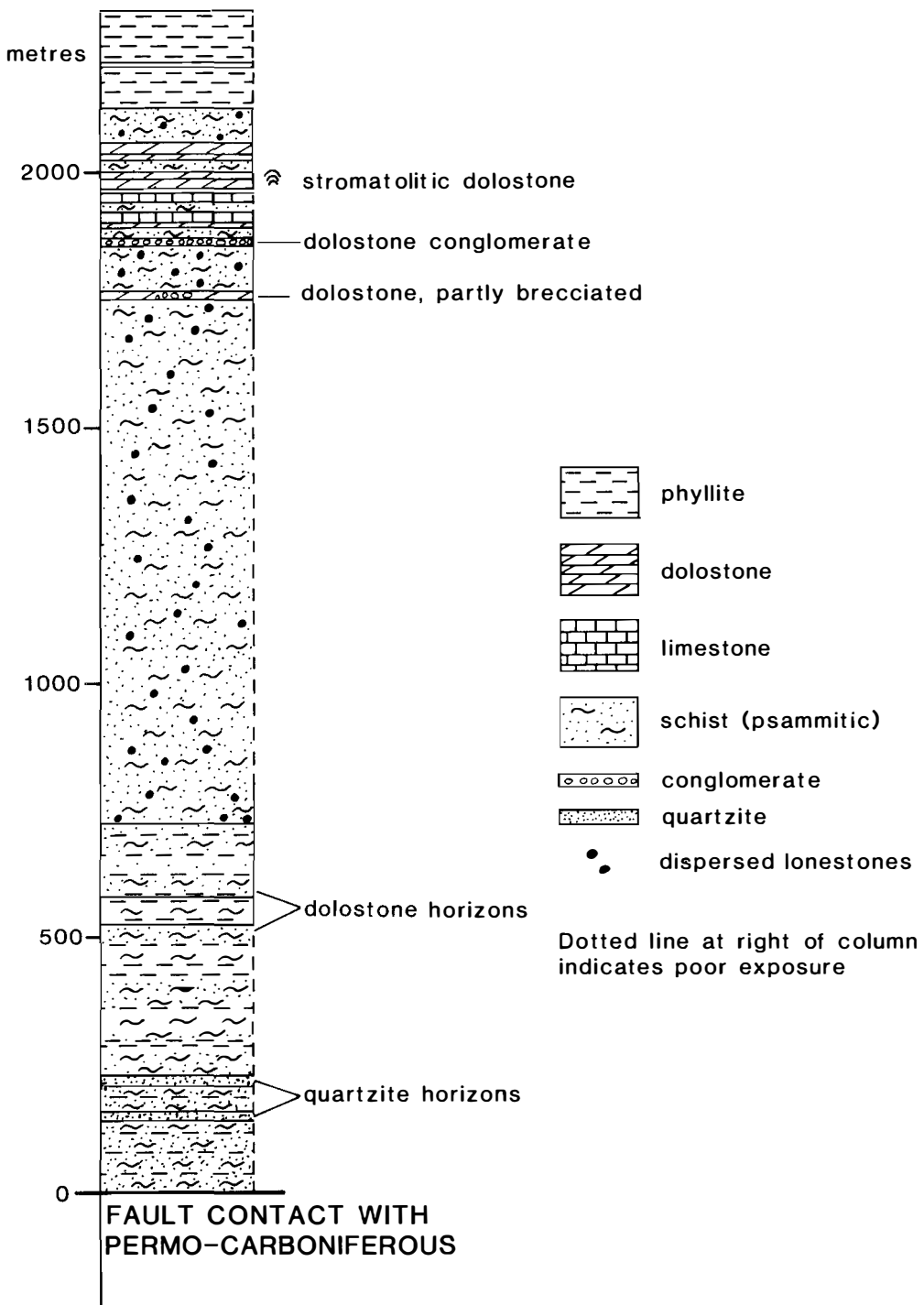


Fig. 32. Paced section through the Trondheimfjella Formation, east of Farmhamna. Base of succession faulted against Permo-Carboniferous rocks at the coast.

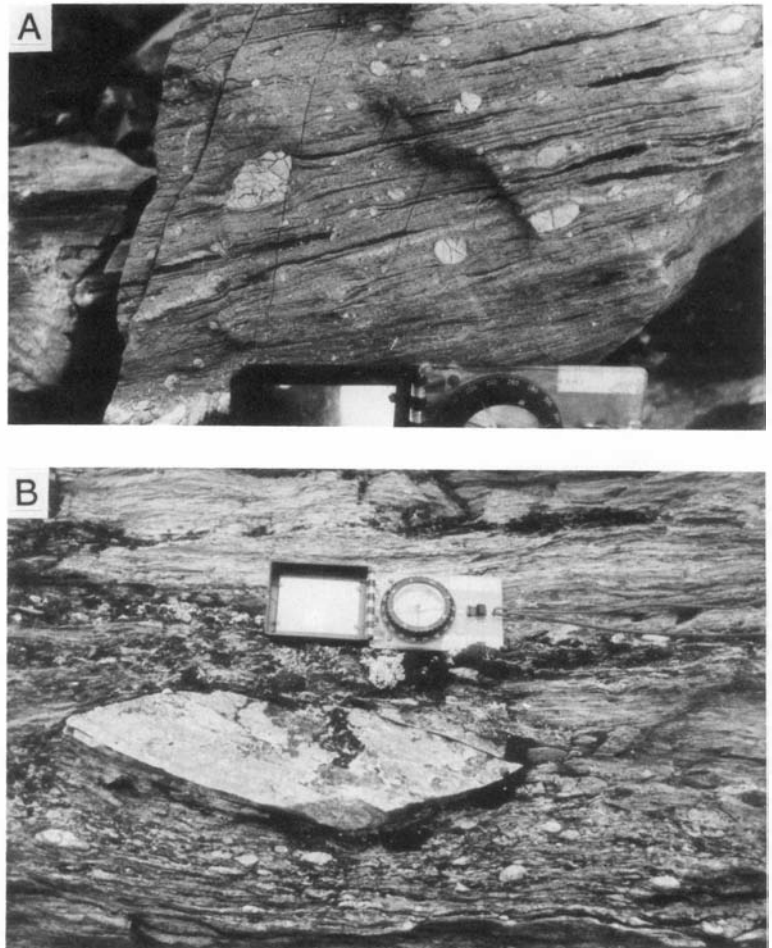


Fig. 33. Trondheimfjella Formation. A. Dolostone and quartzite stones in strongly foliated silty-sandy calcareous marble, north shore of Engelsbukta. B. Elongated quartzite stone near top of diffuse pebble-rich layer in section east of Farmhamna, Eidembukta.

1960; Harland et al. 1979). He mapped the ridge south of Uversbreen in northern Oscar II Land. The ridge is composed almost entirely of this formation. Wilson's map, noting conglomerates, was available to Hjelle, Ohta & Winsnes (1979) who remapped it as their Tillitic Conglomerate Formation.

Thus in 1979 Harland et al. had arrived at our favoured stratigraphic sequence without recognising this conglomerate as glacial while Hjelle, Ohta & Winsnes recognised the glacial origin of their schistose diamictites and so included it with the Haaken Formation as one younger diamictite unit.

More accessible sections were discovered in 1979 in streams on the north side of Engelsbukta by Waddams where a composite section was esti-

mated to have a thickness of 1300 m (Waddams 1983b, p. 246). He recognised a polymict diamictite, texturally similar to the Haaken Formation, but containing a different assemblage of stones, notably a lack of granitoid and metamorphic stones. It was thus analogous to the earlier Varanger tillite of Finnmark (Reusch 1891) and to the Hansbreen tilloid division in Hornsund (Harland 1978). In the same year the earlier diamictite division in Northern Wedel Jarlsberg Land was also so interpreted by T. S. Winsnes and Harland.

Thus Waddams, having already found the Horsfield/Harland sequence in Oscar II Land to work (Harland et al. 1979), and by distinguishing the Trondheimfjella Formation as glacial, could show that almost the whole of the pre-Carboniferous outcrop is Vendian.

Measurement by pacing by Hambrey of a near-complete section in the stream descending from the west glacier of Steenfjellet, revealed a thickness of just over 700 m (Fig. 32). Here, the top of the formation is hidden by alluvial deposits, and the base is faulted against probable Carboniferous rocks. Elsewhere, the upper boundary with dolostones of the Moefjellet Formation is sharp but conformable, and the base, although not well exposed, is inferred to be in thrust contact with the high-grade metasediments of the Kongsvegen Group (Waddams 1983b). The succession north of Engelskbukta (Fig. 32) contains alternating orange-weathering calcareous low-grade schist, orange weathering psammite, dark green and black phyllite, black and white limestone, marble and orange and grey weathering bluish dolostone. Some horizons have dispersed outsized stones in concentrations up to 5%, and one horizon of schist has a sufficient concentration of stones (>5%) to be a diamictite (Fig. 33A). Stones are mainly pebble-size but several more than 30 cm long have been observed. All stones are elongated, typical axial ratios for the commonest lithology, dolostone, being about 3:1. Elongate lenses of limestone, with axial ratios of 15 or 20:1, were probably outsized stones before deformation. Rarer quartzite stones have axial ratios of about 1.5:1. The original lamination in these rocks has been isoclinally folded, boudined and transposed into a new foliation which dominates the area (D_2), but which has developed parallel to the gross major stratigraphic boundaries. This foliation in turn has been locally chevron folded (D_2).

The stone-bearing marble is a particularly distinctive lithology within the Trondheimfjella Formation, which together with the limited range of stone types, notably the absence of granite stones (Table 4), generally provides a means of distinguishing it from the Haaken Formation.

The Trondheimfjella Formation continues in a belt southeastwards from Trondheimfjella, into the nunataks of western Løvenskiöldfonna to be truncated by a fault running NW–SE from Engelskbukta (Fig. 33A).

In 1987 Harland, observing the cliffs of the bird sanctuary Hermansenøya from a rowing boat, noticed that the rock matrix was grey and that many clasts exceeding 10 cm and up to 30–40 cm in diameter were present. All of these, as seen through binoculars, looked pale coloured as if dolostones or quartzite. No pink coloured rocks

were seen, so keeping open the possibility that the island diamictite corresponds to the lower tillite (Trondheimfjella Formation). However, its resistance to marine erosion to form the island may suggest a lower facies of the Haaken Formation as assumed by Harland in 1959.

Another belt of Trondheimfjella Formation, newly distinguished, extends across much of the strandflat SSE of Eidembukta to the mouth of Isfjorden. This was mapped as the Tillitic Conglomerate Formation by Hjelle, Ohta & Winsnes (1979) and a fault-contact with the Quartziteshale (Løvliebreen) Formation inferred. Ohta (1985) mapped this as Jørgenfjellet Formation to the west and the Calc-argillo-volcanic Formation to the east. Compositionally, it resembles the outcrops north of Engelskbukta. Its position directly below the Løvliebreen Formation, we suspect, indicates a normal stratigraphic contact, although this contact has not been observed directly.

In this outcrop south of St. Jonsfjorden the formation is best exposed between Farmhamna and Venernbreen. A rapid traverse normal to strike from inner Farmhamna revealed a succession dominated by psammitic, partly calcareous, low-grade schist with dispersed stones (Fig. 33B). Other lithologies include phyllite, carbonates and minor conglomerate, breccia and quartzite. The succession is faulted against Permo-Carboniferous rocks in the west, and the near-vertical dip there gradually declines inland to an easterly dip of 30°, before being covered by proglacial alluvium from Venernbreen. The thickness here, if not tectonically repeated, exceeds 2000 m (Fig. 34). In general the succession is sandier than at Engelskbukta, but the dispersed stones (mainly dolostone with lesser amounts of quartzite), are mainly <10 cm in length, although one of the quartzite stones measured 32 x 10 cm. However, further SSE, in the middle of Daudmannsøyra, subrounded dolostone boulders up to 110 x 80 cm occur within a limestone marble unit. Locally, the schist, especially where more phyllitic, has sufficient stones to take on a diamictite-like appearance. Stone concentrations increase and decrease imperceptibly, but no dropstone structures have been preserved. Some concentrations of stone-rich layers occur either with diffuse boundaries or a sharp top, and they are often associated with limestone-dolostone interbeds a few centimetres thick. A stromatolitic dolostone unit near the top

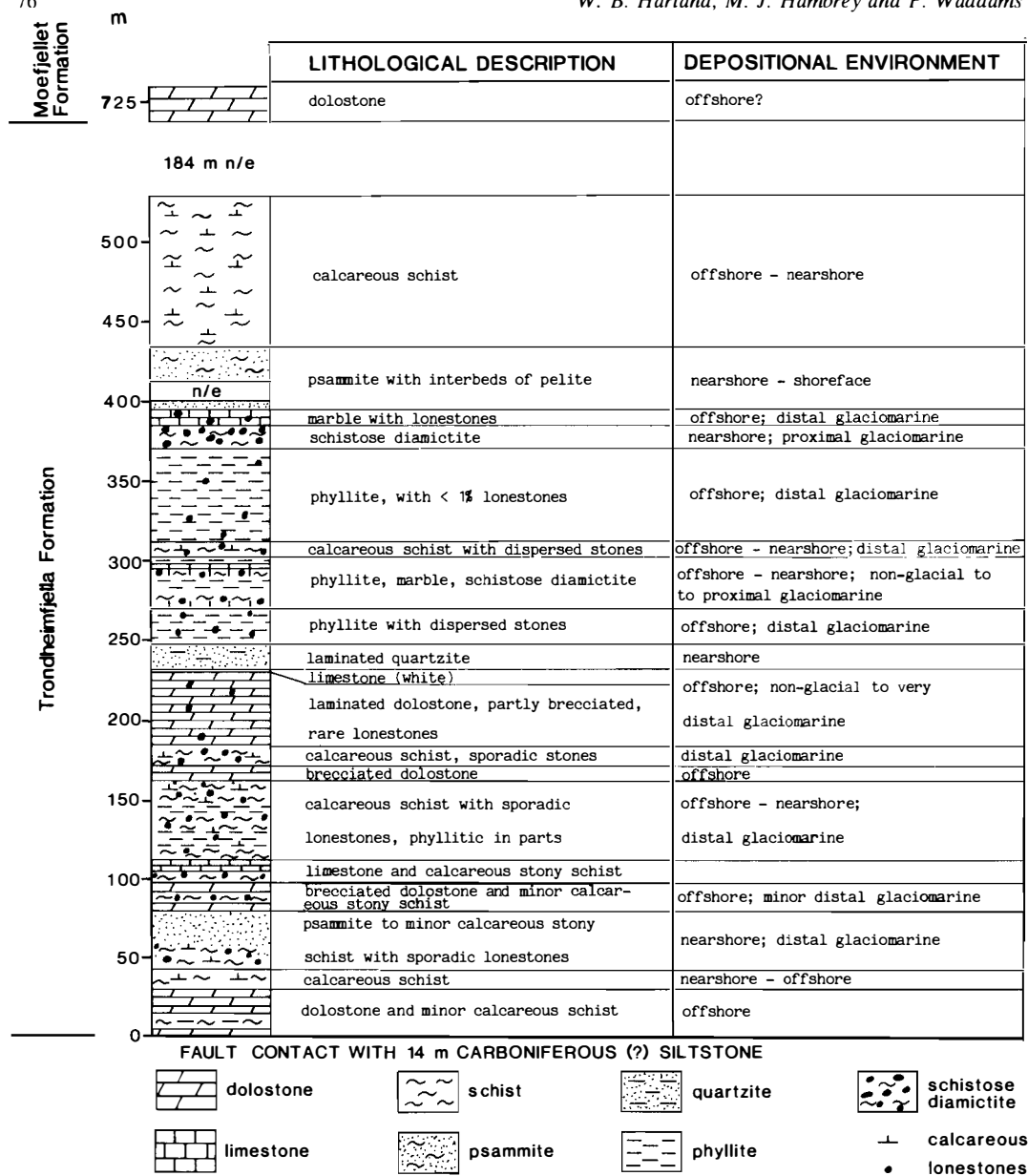


Fig. 34. Paced section through the Trondheimfjella Formation, recorded in stream that descends from the small glacier west of Steenfjellet, north of Engelsbukta, with environmental interpretation. The bulk of the succession is considered to be a distal turbidite sequence, with a varying ice-rafted component. The stratigraphic top of the section is on the shore of the bay.

of the succession (Fig. 34) indicates younging eastwards. Although totally recrystallised chert laminae give a hint of the original irregular stromatolitic structure. The bottom surface of the dolostone unit is planar, the upper being a series of rounded humps infilled with clast-bearing schist and (laterally) carbonate. These bioherms have a

height of 0.5–1.5 m and are 2–3 m across. There is some local chevron folding of the cherty lamination which is clearly tectonic (D_2).

The schistose diamictites of the Trondheimfjella Formation are texturally similar to those of the Haaken Formation, but in contrast have a much more calcareous matrix and contain no

granitoid stones. A similar mode of deposition has been proposed for this formation, namely ice-rafting into a distal turbidite basin. The proportion of stones is rarely more than a few per cent, but some are large in comparison with the thickness of the laminae. On the whole, the formation was deposited in a predominantly distal glaciomarine setting, as summarised for a section north of Engelsbukta in Fig. 32. Thin conglomerate layers represent the input of sediment from small-scale subaqueous debris-flows. Background carbonate deposition occurred throughout, and some stone-free marble horizons are probably shallow marine. The band of stromatolites near Farmhamna (Eidembukta) also indicates shallow-marine transitions from marine carbonate shelf to distal turbidite basin deposits, superimposed on which were variable inputs of ice-rafted material.

3.7 Kongsvegen Group

Orvin (1934) set up 11 units of metamorphosed rocks in Brøggerhalvøya and named units 1–9 the “Quartzite and Mica Schist Series”, unit 10 the “Steenfjell Dolomite”, and the lower unit 11 the “Bogegg Mica Schist”, underlain by “Dolomites and Limestones at Forlandsundet”. Unit 1 was youngest. Wilson took the opposite view (W1–3 of Harland 1960) with the Forlandsundet rocks (Trondheimfjella Formation) younger than the Bogegg strata. Harland, Wallis & Gayer (1966) followed Orvin’s order because of the overturned Carboniferous unconformity (confirmed by Challinor 1967). Harland, Wallis & Gayer (1966) introduced the name Kongsvegen Group and Challinor (1967) named units 1 to 9 as the Nielsenfjellet (sic) Formation. These three formations were adopted by Harland et al. (1979). Orvin’s fourth unit (Challinor’s Bjørvigfjellet Formation) being the same as the Trondheimfjella Formation. However after further work in Oscar II Land we confirm Wilson’s order. Moreover, we are not convinced that there is any significant stratigraphic break between the Trondheimfjella Formation and the underlying Bogegg strata which must then pass down into the Steenfjella Dolomites and the oldest units (the Nielsenfjellet schists). The three formations make the backbone of Brøggerhalvøya. Harland et al. (1979) also included the Müllerneset Formation in this group south of St Jonsfjorden, correlating it with the Kongsvegen Group.

3.7.1 Müllerneset Formation (>2 km)

This formation consists of phyllitic and schistose pelites interbedded with semipelites and white quartzites. It occupies the west coastal strip of the strandflat (Svartfjellstranda) between St Jonsfjorden and south to Eidembukta (Harland et al. 1979; Hjelle, Ohta & Winsnes 1979; Kanat & Morris 1988). To the north the eastern boundary is a thrust-faulted strip of Carboniferous and Permian rocks and a similar wedge is seen on the coast at Eidembukta. However, a little north of Eidembukta the Müllerneset Formation appears to be in concordant contact with the Trondheimfjella Formation to the east. Indeed there is no obvious boundary in these NS striking strata and the possibility must be considered that (with or without minor thrusting) the Müllerneset Formation underlies the Trondheimfjella Formation conformably. The metamorphic contrast may be more apparent than real because pelitic compositions alter more readily than carbonates. Both are essentially phyllites. Garnets are present in the north (e.g. Hjelle, Ohta & Winsnes 1979, who included it in their Lower Hecla Hoek Supergroup). Ague & Morris (1985) suggested recrystallisation at 460–517°C and Armstrong, Nakrem & Ohta (1986) correlated this event with the post-late Ordovician-early Silurian tectonism of the Bullbreen Group.

3.7.2 Bogegg Formation (1.5 km)

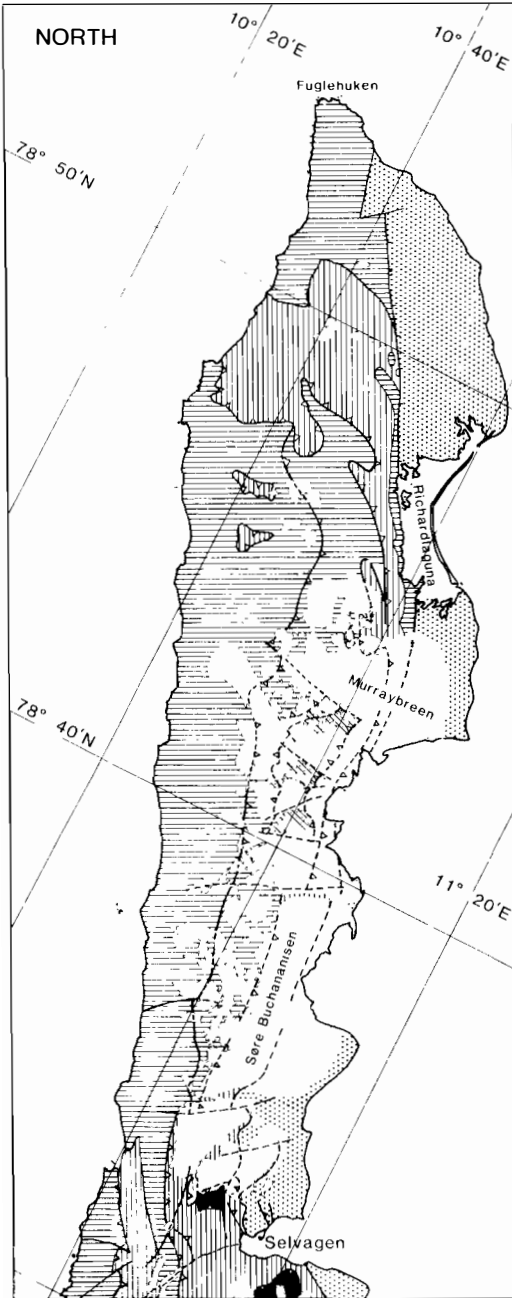
This formation appears in dark mountain cliffs as monotonous phyllitic semipelites interspersed with paler, dolomitic quartzite bands. It extends from Åmdalen eastwards. Along the south side of Brøggerhalvøya it crops out parallel to the Trondheimfjella Formation. Harland et al. (1979) suggested that an ancient fundamental fault might separate them but it now seems as likely that there is approximate stratigraphic continuity broken only by the manifest Paleogene north-easterly overthrusting. The contiguous formations are concordant. A similar argument to that above may apply.

3.7.3 Steenfjellet Formation (100 m)

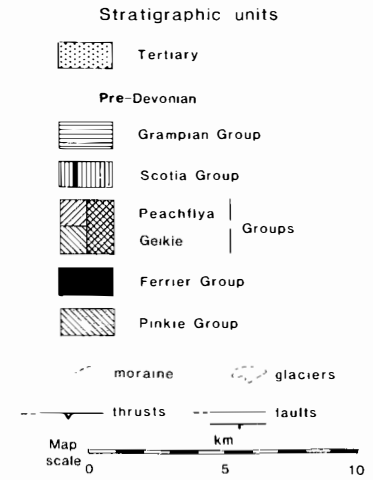
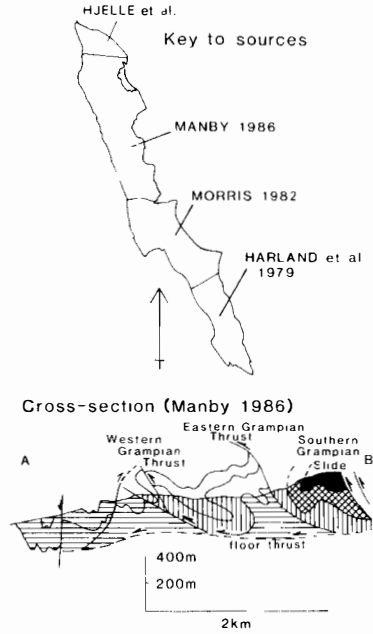
This formation appears as a grey to cream-coloured band of marbles separating the formations above and below.

3.7.4 Nielsenfjellet Formation (2.5 km)

This formation is a varied sequence of schistose and gneissose psammites, pelites, semipelites,



PRINS KARLS FORLAND



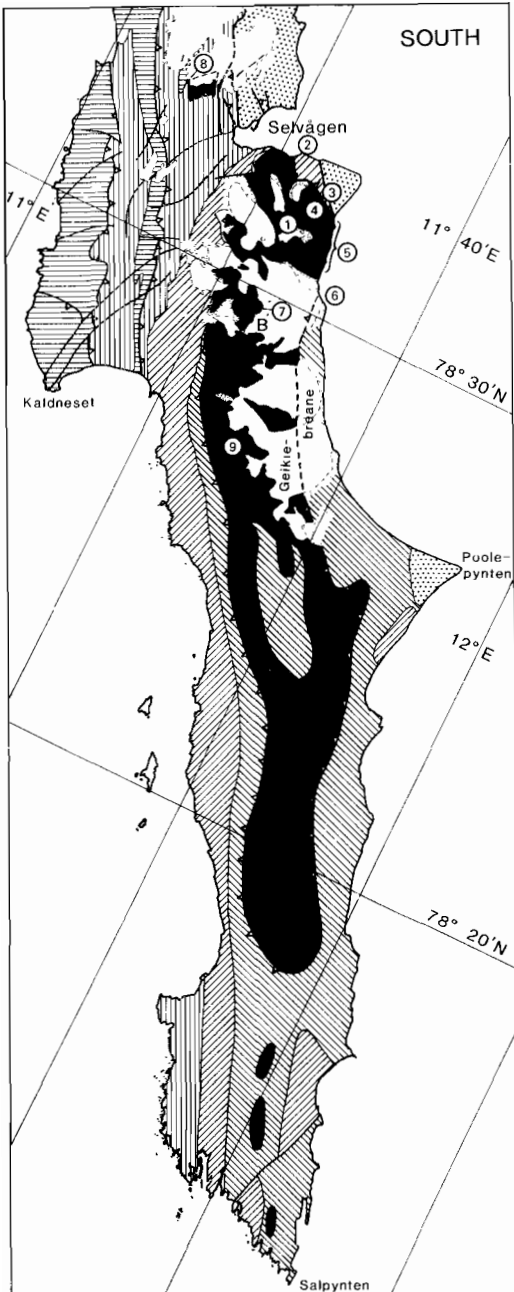


Fig. 35. Outcrop map of principal rock units in Prins Karls Forland, from sources indicated. Place names: Doddsfjellet 1; Selvågflya 2; Fyllitknausen 3; Ferrierpiggane 5; Peterbukta 6; Tritoppen 7; Alfred Larsentoppen 8; Isachsenfjellet 9.

pale dolomitic marbles, pink feldspathites and dark amphibolites. It is divisible into three members each of about 0.5 km thickness (Orvin 1934; Harland et al. 1979). In so far as a metamorphic contrast is evident, this formation differs from the others and could represent a pre-Vendian basement. Clearly these matters are unresolved.

3.8 Vestgotabreen Complex

This is a thrust suite of metamorphic rocks containing blueschist facies south of St Jonsfjorden. C.B. Wilson discovered loose blocks of the rock in 1957 and D.G. Gee located the source in Motlafjella. It was then investigated by Horsfield (1972). It has subsequently become a major point of interest in Svalbard geology (Ohta 1979; Ohta, Hiroi & Hirajima 1983, Hirajima, Hiroi & Ohta 1984; Kanat 1984; Ohta 1985; Ohta, Hirajima & Hiroi 1986; Kanat & Morris 1988).

The age is constrained as pre-Caradocian (Armstrong, Nakrem & Ohta 1986). It is presumed to be pre-Vendian but has yielded only mid-Paleozoic isotopic dates so far.

4 Prins Karls Forland

4.1 Introduction

The island Prins Karls forland is elongated along a north-south structure comprising rocks metamorphosed to biotite grade in several thrusts or nappes apparently verging westward in the opposite sense, at least to the later structures of Oscar II Land. Its eastern margin is defined by the Forlandsundet Graben, with its extensive Cenozoic deposits. Otherwise, with the exception of two allochthonous thrust units (Pinkiefjellet and Alfred Larsentoppen), the whole comprises a 7 km sequence of probably early Paleozoic through Ediacara (Late Vendian) to late Varanger (Early Vendian) rocks (Fig. 35).

This stratigraphic span is more complete for late Vendian history than any other in Svalbard. General correlation with Oscar II Land is feasible, but not in detail. It is probable that both a sinistral transpression zone in Devonian time and a dextral transpression then transtension zone in Paleogene time separated them, but with what net displacement remains uncertain.

Table 5. Lithostratigraphic schemes for the pre-Devonian strata of Prins Karls Forland, and suggested correlation with Oscar II Land.

PRINS KARLS FORLAND			OSCAR II LAND			
Tyrel 1924	Atkinson 1960	Hjelle, Ohta & Winsnes, 1979	Harland et al. 1979, Waddams 1983b			
Ferrier Peak Series	Ferrier Group Geikie Group Gordon Group	Upper Hecla Hoek Middle Hecla Hoek Lower Hecla Hoek	Ordovician	Grampian Group (5 formations) Scotia Group (3 formations) Peachflya Group (4 formations) Geikie Group (2 formations)	Bullbreen Group Comfortlessbreen Group	Holmesletfjella Fm. Motafafjella Fm. Aatvatsmarkbreen Fm. Annabreen Fm.
			Vendian	Ferrier Group (4 formations)	St. Jonsfjorden Group	Haaken Fm.
North Grampian Series	Fugelhuken Group	Calc-argillo volcanic Fm. Quartzite - sandstone Fm. (conglomerate)			Alkhorn Fm. Løvliebreen Fm. Moefjellet Fm. Ironheimfjella Fm.	Kongsvegen Group
Mt. Scotia Series	Scotia Group Barents Group	Black shale Fm. (Pelite with Fe-ore)	Riphean	Pinkie Fm.		Vestgotabreen Fm.

4.2 History of research

Prins Karls Forland was first surveyed by the Scottish Spitsbergen Expeditions of 1907 and 1909 (Bruce 1910), work which resulted in Tyrrell's (1924) account of its geology. The next significant work, on metamorphism and structure, was that of Atkinson (1956, 1960). From 1966 to 1969 stratigraphic reconnaissance studies were carried out by Harland with various Cambridge parties. From this and the above basis, G.M. Manby and A.M. Morris were invited to make detailed surveys respectively of the areas north and south of Selvågen, their work being primarily structural and petrographic.

All stratigraphic conclusions were combined with those from Oscar II Land in 1975 (Harland et al. 1979). Structural-metamorphic studies appeared, later (Morris 1982; Manby 1986). Systematic field mapping was carried out by the Norsk Polarinstitut between 1968 and 1975 (Hjelle, Ohta & Winsnes 1979), which led to the erection of an alternative lithostratigraphic scheme. Furthermore, Hjelle, Ohta & Winsnes (1979) made precise correlations across Forlandsundet (one scheme for both areas). These various schemes are summarised in Table 5.

The Harland et al. (1979) scheme adopted the

original stratigraphic names of Tyrrell and Atkinson as far as was possible. However, the island consists of a number of thrust sheets (Atkinson 1956, 1960), each with a distinctive succession, and in which it is often difficult to discover the way-up. In this connection a critical observation is the occurrence of phyllite and other stones in the Sutorfjella conglomerate, indicating that the Barents Formation, of which we (confirming Atkinson) believe it to be a part, is younger than the Scotia Group.

The following stratigraphic account is based mainly on Harland et al. (1979) with additional observations, on the diamictites by Waddams. The most recent work has focused more particularly on the sedimentology of the Vendian succession. A summary of the principal lithologies is presented in Table 6, and the main qstratigraphic units are shown in Fig. 35.

4.3 Age of sequence

The Barents Formation (500 m) in the Grampian Group could be Ordovician or Silurian by litho-correlation with the Bullbreen Group in Oscar II Land.

The underlying Conqueror (850 m) and Utnes (80 m) formations are not yet datable. An Ordovician age is postulated because a significant pre-

Table 6. Summary of pre-Devonian succession on Prins Karls Forland (from Harland et al. 1979).

Group	Formation	Dominant Lithology	Thickness (m)
Grampian	Geddesflya	Quartzite and siltstone	1800
	Fugelhuk	Massiv quartzite	400
	Barents	Siltstone, slate, conglomerate	500
	Conqueror	Quartzite and slate	850
	Utnes	Mainly slate	80
Scotia	Roysha	Dark slate	400
	Kaggen	Green and purple slate	300
	Baklia	Dark slate and carbonates	2-300
Peachflya	Knivodden	Grey and green phyllite	400
	Hornnes	Phyllite, sandstone, limestone	350
	Alasdairhornet	Tuffs and lava flows	190
	Fisherlaguna	Dark phyllite	350
Geikie	Rossbukta	Dark phyllite	300
	Gordon	Dolostone, limestone, phyllite	470
Ferrier	Neukpiggen	Siliceous schist with stone	300
	Peterbukta	Psammitic schist with stones	160
	Hardiefjellet	Psammitic schist with stones	120-500
	Isachsen	Quartz chlorite schist	150+
	Pinkie	Metavolcanics	200+

Bala (pre-Late Ordovician) diastrophism is evident both in Oscar II Land and in Prins Karl Forland where schistose pebbles of Scotia-type lithologies occur in the Sutorfjella Conglomerate (Barents Formation). There is thus probably an unconformity here as can be seen in Oscar II Land.

The Scotia Group (1000 m) is almost certainly Ediacara (Poundian) in age.

The underlying Peachflya Group (1300 m) could be Ediacara (Wonokan) and the Geikie (>770 m) Group of late Mortensnes age.

The Ferrier Group (>730 m) is almost certainly late Varanger Mortensnes and the Pinkie Formation probably pre-Vendian.

4.4 Grampian Group

This group was defined as comprising the Geddesflya (top), Fugelhuk, Barents, Conqueror and Utnes formations (Harland et al. 1979), and gives rise to much of the mountainous terrain of north-central Prins Karls Forland. The group consists of some 3600 m of quartzite, dolostone, siltstone, breccia, slate, sandstone and conglomerate. In view of its similarity with the Bullbreen Group (especially turbidites of the Barents Formation), the Grampian Group is probably of Ordovician and Silurian age.

4.5 Scotia Group

Harland et al. (1979) defined the Scotia Group as comprising three formations: Roysha (top), Kaggen and Baklia.

The Roysha Formation (about 400 m) lies conformably below the Utnes Formation and consists of soft, black, carbonaceous slate underlain by alterations of grey, dolomitic siltstone and thin, black slate. The Roysha Formation was renamed the Omondryggen Formation by Manby (1986) with a more detailed outcrop map.

The Kaggen Formation (about 300 m) lies gradationally below rocks of the Roysha Formation. It comprises green and purple striped slate, grey slate with thin quartzite interbeds and chloritoid-bearing slate. It is strongly reminiscent of part of the Aavatsmarkbreen Formation northeast of Snippen in Oscar II Land.

The Baklia Formation (about 300 m) is characterised by black slate with thin dolostone, limestone and intraformational conglomerate interbeds. The lower part comprises alternations

of grey, frequently cherty, dolomitic siltstone and black slate.

4.5.1 Microfossils from the Black Carbonate Pelite (BCP)

An important development was the discovery of microfossils in chert nodules from carbonaceous, dolomitic shales in Northern Prins Karls Forland (Knoll & Ohta 1988). This black carbonate pelite unit (BCP) consists of slaty dolomite and dolomitic slates interbedded with black shale dolostone units up to 20 m thick. The dolostone contains oolitic beds. Chert nodules occur near the base of the BCP unit within the slaty dolomites and are not cleaved. The following taxa were described and figured: *Eomycetopsis robusta* Schopf emend. Knoll & Golubic (1979); *Eomycetopsis* sp.; *Siphonophycus inornatum* Zhang; *Siphonophycus* sp.; *Myxococcoides* spp.; *Obruchevella* Reitlinger (1959); ?*Obruchevella* Sp.

Poorly preserved acritarchs include leiosphaerid-like vesicles and rare spheres with vesicles and with an outward layer of hollow processes. Such forms had been described from Late Riphean and Vendian strata and are especially similar to *Vandalosphaeridium* from the Doushantuo Formation of central China and to *Cymatiosphaeroides* from the Pertatateka Formation of central Australia, both occurrences being of latest Proterozoic age.

From the known ranges of the other taxa, "the most likely age for the BCP beds is late Vendian – i.e. post-tilloid but pre-Cambrian in age". Knoll & Ohta stressed the uncertainty in this assessment bearing in mind that Hjelle, Ohta & Winsnes (1979) placed the unit in question below the diamictite horizon. However, in that paper they did not argue that the units they recognised were in stratigraphic sequence. On the other hand, Harland et al. (1979) gave a succession of defined formal units which they intended as a time sequence and which is adopted here. In that succession the Black Carbonate Unit (BCP) of Knoll & Ohta is the "Black Shale formation" of Hjelle, Ohta & Winsnes (1979) and appears at first to be the Roysha Formation of Harland et al. (1979), renamed the Omondryggen Formation (Manby 1986). This is the uppermost of three (above the Kagga and Baklia) formations in the Scotia Group. It is not impossible that there has been some confusion, for Harland et al. (1979) described the Baklia Formation as having cherts. Nevertheless the chert localities on Knoll &

Ohta's map fall within the Omondryggen Formation outcrop on Manby's map. It seems likely that our whole Scotia Group corresponds to the Black Shale Formation of Hjelle, Ohta & Winsnes (1979) and the BCP of Knoll & Ohta, and some further elucidation of the formations comprising it may be needed.

4.6 Peachflya Group

The Peachflya Group comprises four formations: Knivodden (top), Hörnnes, Alasdairhornet and Fisherlaguna.

The Knivodden Formation (about 400 m) lies conformably below the Scotia Group and comprises pale grey, dark grey and pale green phyllite with rare sandstone lenses. The Hörnnes Formation (about 350 m) lies beneath the Knivodden Formation. It is characterised by dark or green, siliceous phyllite with thin, discontinuous limestone and sandstone interbeds. The Alasdairhornet Formation (about 190 m) is in gradational contact with the Hörnnes Formation and consists of banded and welded tuffs with some basic lava flows. Thin carbonate interbeds occur towards the top, and the base is marked by reworked sediment of volcanogenic and siliciclastic material. The Fisherlaguna Formation (350 m) is poorly exposed and the nature of the contact with the overlying rocks is not clear. Incompetent phyllite, with a characteristic blue sheen, makes up most of the formation. Phyllite-limestone intercalations occur towards the base.

4.7 Geikie Group

The Geikie Group consists of two formations: Rossbukta (top) and Gordon. Thrusting between the Peachflya, Geikie and Ferrier Groups has reduced the outcrop width.

The Rossbukta Formation (about 300 m) is in thrust contact with the overlying Fisherlaguna Formation. It comprises dark, siliceous phyllite which becomes increasingly calcareous towards the base. There are a number of impure, coarsely crystalline sandstone beds near the top. The Gordon Formation (about 470 m) is in gradational contact with the overlying Rossbukta Formation but is in thrust contact with the underlying Ferrier Group, so the original thickness is unknown. The upper part comprises a calcareous phyllite with a 3–4 m massive dolostone unit. Most of the formation consists of dolomite-limestone laminated

horizons, massive dolomite bands, intraformational breccias and carbon-rich beds. Pisolitic limestones are common.

4.8 Ferrier Group

Harland et al. (1979) defined the Ferrier Group as comprising four formations: Neukpiggen (top), Peterbukta, Hardiefjellet and Isachsen. The group dominates the stratigraphy of central Prins Karls Forland south of Selvågen. It is characterised by psammitic schist, psammite and phyllite containing dispersed outsized stones of variable lithologies.

4.8.1 Neukpiggen Formation

Harland et al. (1979, p.129) proposed the name from the peak at the head of Archibald Geikiebreane. It is best exposed on central Selvågflya and northern Fyllittknausen and Ferrierpiggen. Morris (private communication) calculated a thickness of about 270 m in the north and 275 m further south. The top is in thrust contact with rocks of the overlying Geikie Group and the bottom grades down into calcareous schist of the Peterbukta Formation.

The formation consists of calcareous and chloritic schist with discontinuous psammite, marble and conglomerate beds. For example, the ridge ascending from the south shore of Selvågen to Ferrierpiggen exposes a variable sequence comprising white-weathering, finely laminated siliceous schist (Fig. 36B); pink-grey weathering, laminated psammitic schist; dark-grey phyllite; dolostone orthoconglomerate beds (not graded), about 1.5 m thick; and thin, pink psammite and orange dolostone beds, each 20–80 mm thick. Dispersed dolostone and quartzite stones occur throughout the schist and phyllite (Fig. 36A). Harland et al. (1979) also described granite stones 10 mm to 0.4 m long and marble stones 50–100 mm long. Small, folded psammite blocks suggest slumping, penecontemporaneous erosion and resedimentation of some horizons.

4.8.2 Peterbukta Formation

This name was proposed by Harland et al. (1979, p.130) after the bay on the south-east margin of Ferrierstranda. It extends from Selvågflya through Ferrierpiggen and Doddsfjellet to south-central Prins Karls Forland (Fig. 35). Isolated outcrops occur on western Ferrierstranda and inland from Peterbukta. The formation dips 20–

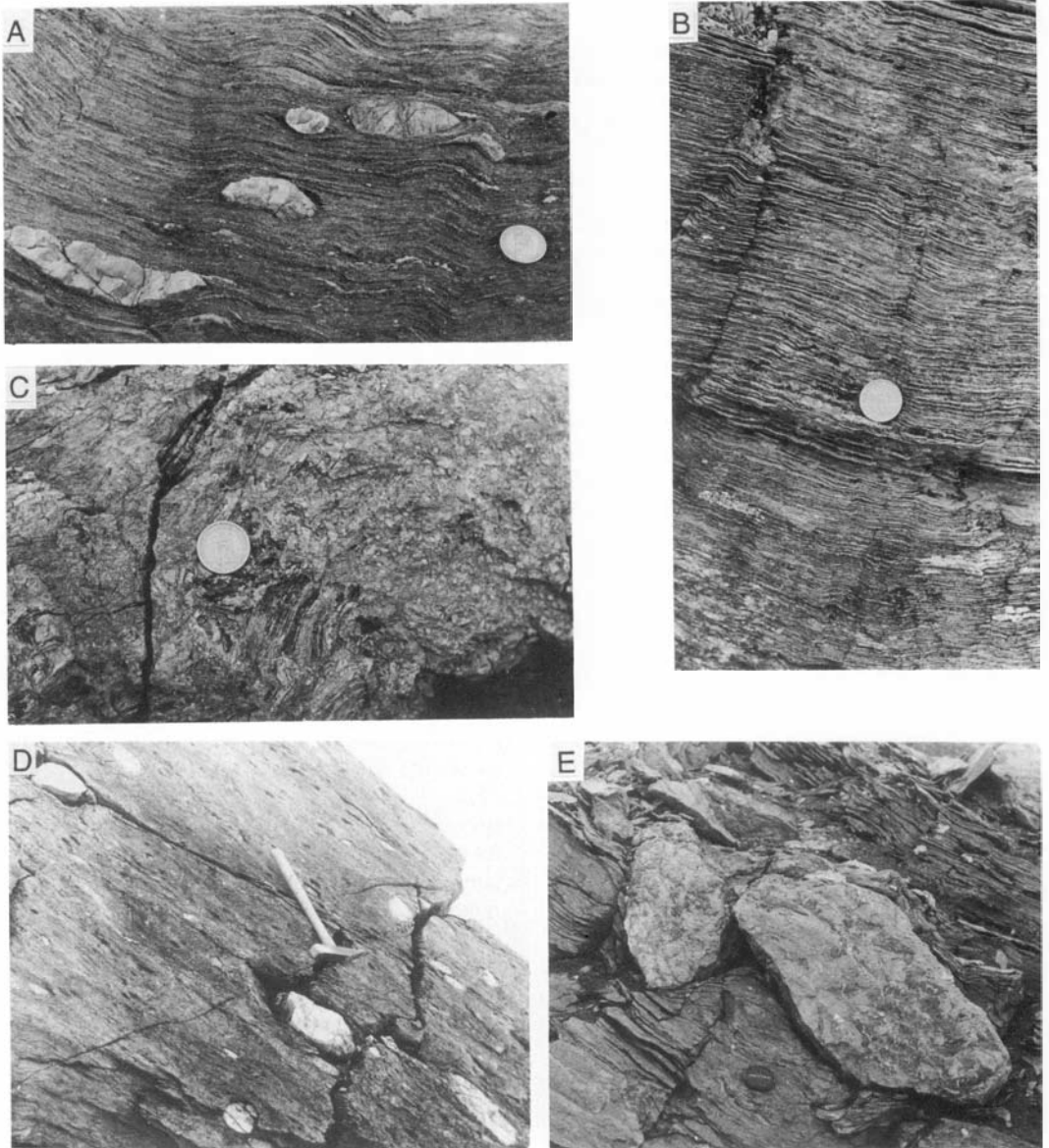


Fig. 36. Ferrier Group, Prins Karls Forland. A. Grey-weathering, finely laminated psammitic schist with dolostone and quartzite stones, Neukpiggen Formation, northwest slopes of Ferrierpiggen. B. Grey-weathering, finely laminated, stone-free psammitic schist, Neukpiggen Formation, northwest slopes of Ferrierpiggen. C. Intraformational conglomerate and breccia in the Peterbukta Formation, north ridge of Tritoppen. D. Pale orange-weathering dolostone boulders in grey, laminated psammitic schist, undifferentiated Ferrier Group, Alfred Larsentoppen. E. Orange-weathering dolostone boulders in orange to grey-weathering massive, coarse-grained, dolomitic psammitite.

80°W, is in gradational contact with the underlying Hardiefjellet and overlying Neukpiggen formations, and has an average thickness of 160 m. Pink-grey weathering, psammitic schist; grey calcareous schist, and dark pelitic schist predominate. Discontinuous beds of pink, "clean", crystalline psammite, 0.06–0.2 m thick and dolostone orthoconglomerate, 0.3 m thick are common. Intraformational conglomerates (Fig. 36C) occur between Doddsfjellet and Tritoppen and suggest periodic shallowing and erosion during deposition. Outsized stones occur throughout, a feature not recognised by Harland et al. (1979). Although they are less abundant than in other west coast diamictite formations, stone lithologies are in similar proportions.

4.8.3 Hardiefjellet Formation

The name was used by Harland et al., (1979, p. 130) for the schistose diamictites which extend from central and southern Ferrierstranda, south-eastwards to the peak of the same name. Morris (pers. comm.) estimated that the thickness is 120 to about 500 m. The formation is in gradational contact with overlying and underlying formations.

Morris described an upper division of pale, calcareous siliceous schist, and a lower division of dark-green schist with dolostone conglomerate beds. Harland et al. 1979 thought it similar to the "upper mixtites" of the Neukpiggen Formation, but considered the Hardiefjellet Formation to be darker in colour, more siliceous and higher in metamorphic grade.

4.8.4 Isachsen Formation

This formation extends as a narrow strip from the east flank of Tritoppen southwards to Isachsenfjellet and lies conformably beneath the diamictites of the Hardiefjellet Formation. The base is not exposed, so the estimated thickness of 150 m is a minimum.

The formation comprises dark green, quartz-chlorite schist, with brown interlayers and numerous pressure solution quartz segregations. Thin layers (approximately 1 m) of diamictite occur, but the rock is generally fine-grained, thinly laminated (10–20 mm) and fairly well sorted. Beds, 1–2 m thick, of volcanic (tuffaceous) strata are dispersed throughout the formation.

4.8.5 Ferrier Group rocks of uncertain stratigraphic position

Schistose diamictites on Prins Karls Forland are

almost exclusively restricted to the central part of the island, south of Selvågen, but a small outcrop of stone-rich psammitic schist, only about 50 m long, occurs on the crest of the eastern ridge of Alfred Larsentoppen, to the WNW of Selvågen, and in the south of Prins Karls Forland. These polymictic diamictites (similar to Haaken rocks) rest on the Scotia Group occurring as an isolated klippe on the Ferrier Group. Two distinct lithologies are present. The upper about 20 m comprises an orange-weathering, coarse-grained, dolomitic psammite containing dispersed stones of orange or cream-weathering, grey dolostone (Fig. 36A, E). They have an average diameter of about 60 mm and a maximum length of 1.5 m. Other stones consist of quartzite, grey marble and granite. This unit differs from rocks in the Ferrier Group to the south in that the stones are more abundant and larger; there are no psammite, orthoconglomerate, dolostone or limestone interbeds, and the unit generally lacks any primary stratification. The unit is pervaded by a closely spaced schistosity but there is little sign of any original compositional banding. The rock was therefore, originally a massive, sandy diamictite. Passing westwards along the ridge it is abruptly underlain by a second lithology of unknown extent, which consists of dark, sandy-grey weathering, phyllitic schist containing dispersed stones of dolostone and quartzite.

As a whole, the Ferrier Group appears to have been deposited in shallower water than the Haaken Formation in Oscar II Land. The dispersed stones suggest ice-rafting into a basin in which background sedimentation was rapid and non-turbiditic. The diamictites on Alfred Larsentoppen appear to represent deposition of till close to or under a glacier, either grounded or floating, although other diamictites on the island were deposited away from the ice margin. It is not impossible that the Klippe is allochthonous, originating nearer to Oscar II Land.

4.9 Interpretation of glacial sequence

4.9.1 Problem of Ferrier Group stratigraphy

All four formations within the Ferrier Group consist of a variable assemblage of siliceous, calcareous or phyllitic schist and are difficult to distinguish in the field. Previously, the lack of outsized stones was the main criterion for identifying the Peterbukta Formation. As the latter is a diamictite, a reconsideration of Ferrier Group

litho-stratigraphy might be necessary. Furthermore, there seems to be no noticeable difference between rocks of the Hardiefjellet, Peterbukta and Neukpiggen Formations. Whereas Harland et al. (1979) thought that both the Ferrier Group and the Comfortlessbreen Group had two distinct diamictite horizons, we now believe that the respective sequences are much more variable, although the broad correlation of the two groups across Forlandsundet still holds. Both the Comfortlessbreen and Ferrier groups are considered to be correlative with the upper of the two tillite horizons of Varanger age in northern Norway and northeastern Svalbard (e.g. Hambrey 1983). A lower diamictite, such as that represented by the Trondheimfjella Formation of Oscar II Land, is not known from Prins Karls Forland.

4.9.2 Late glacial sequence

The Prins Karls Forland post-glacial sequence is somewhat different from that on the mainland perhaps because it is more complete. Carbonates of the Geikie Group record the permanent retreat of the ice-front. Further shallowing is indicated by the intraformational conglomerates and pisolites of the Gordon Formation. Terrigenous input, slight at first, increased as is evident from the mixed calcareous muds and sandstones of the Rossbukta Formation. The Peachflya Group reflects rapid clastic deposition, though with periodic breaks of terrigenous input indicated by interbedded carbonates. During one such quiescent period, a short burst of basic volcanic activity produced the thin lava flows and waterlain tuffs of the Alasdairhornet Formation. The Scotia Group is similar to the Aavatsmarkbreen Formation and records volcanogenic sedimentation in quiet water.

4.10 Pinkie Formation

The Pinkie Formation occurs in a thrust slice between overlying Conqueror quartzites and underlying siltstone and thin quartzite of the Geddesflya Formation. It comprises quartz-biotite schist, feldspathic-magnetite-biotite schist, felsite and a calcareous, brecciated slate with much biotite. Because of its high metamorphic

grade, the formation is probably older than the Ferrier Group metasediments. However, the compositions appear to be similar to those of the volcanic facies in the (Vendian) St. Johns-fjorden Group.

5 Nordenskiöldkysten

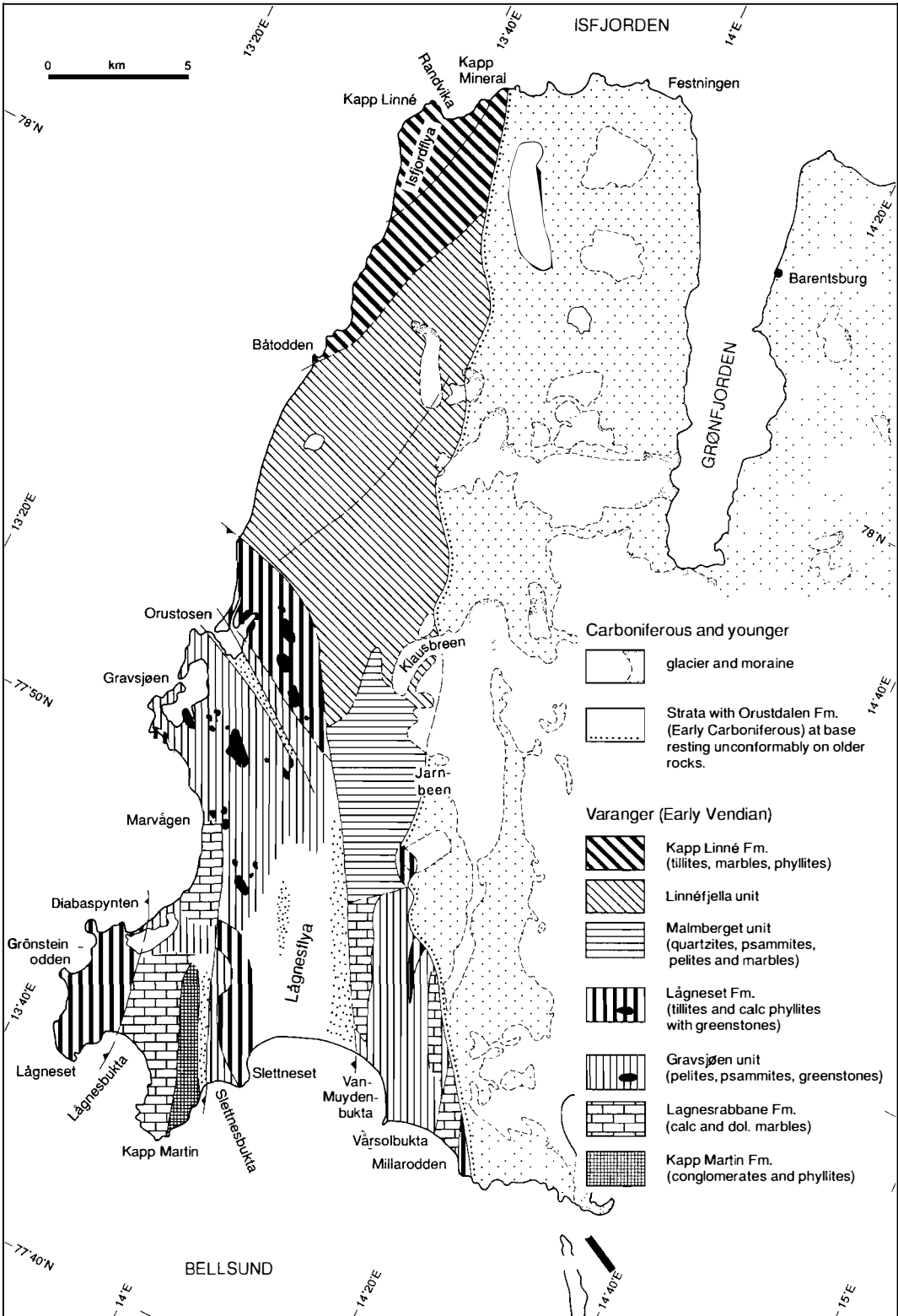
5.1 Introduction

Western Nordenskiöld Land (west of Grønfjorden) boasts the classic Festningen section along the Isfjorden coast where Paleogene down to vertical early Carboniferous strata are displayed in sequence younging eastwards. The Orustdalen Formation rests with (vertical) angular unconformity on the older rocks, which occupy a wide strandflat west of the mountains along which this unconformity is exposed south to Bellsund. To anticipate our conclusion, the older rocks cropping out throughout the strandflat are entirely of Varanger age (i.e. Early Vendian). The Nordenskiöldkysten strandflat itself seldom exceeds 50 m above sea level (Fig. 37).

5.2 History of research

The presence of tillite-like rocks was first noted by Hoel in 1913 at Kapp Linné (Frebald 1935, p. 11). The earliest comprehensive investigation of the coastal region was the mapping by Orvin in 1925 (Orvin 1940; Hjelle 1969), following which he outlined the main elements of the pre-Carboniferous succession (generally referred to as Pre-Devonian Hecla Hoek). A reconnaissance by H. Major and T.S. Winsnes in the Kapp Linné and Kapp Martin areas in 1956 was followed by mapping at a 1:100,000 scale by Hjelle (1962), from which he outlined a stratigraphic succession (Table 7). Later he recognised a tillite-like rock at Lågneset in the south, from which he correlated the strata across Bellsund (Hjelle 1969). The similarity of the Kapp Linné diamictites to those in Oscar II Land, in terms of general appearance, metamorphic grade and boulder content, was recognised by Wilson & Harland (1964, p. 214).

Fig. 37. Generalised map of Nordenskiöldkysten, modified from Hjelle et al. 1986 according to the scheme proposed in this paper (Fig. 38 and Table 9).



More systematic studies of the alleged glacial units and associated lithologies have been undertaken by us east and west of Kapp Martin (Waddams 1983b) in the south, and at Kapp Linné. Soviet authors (Turchenko et al. 1983^a) erected a stratigraphic scheme based on one for the whole west coast (Table 8), and then Hjelle et al. (1986) presented a stratigraphic outline in association with the 1:100,000 geological map of Van Mijenfjorden. This included the southern three quarters of Nordenskiöldkysten.

5.3 Discussion

From our several reconnaissance traverses and studies of the diamictites and associated rocks we offer our interpretation of the stratigraphic sequence combining the results of previous investigations with our own observations.

In Oscar II Land to the north and in Wedel Jarlsberg Land to the south. We can demonstrate that there are two diamictite or conglomerate-

bearing stratal units separated by a considerable thickness of variable facies mainly of rocks lacking rudites. In each area the upper unit is often (but not always) rich in granitoid stones which are lacking in the lower unit. In each area there are basic igneous rocks which are generally volcanic and occasionally intrusive. These are more closely associated with the lower diamictite unit than the upper. Hjelle (1962) drew attention to the similarity of the basites in Nordenskiöld Land and in Chamberlindalen to the south. Turchenko et al. (1983a, b) pointed to the geochemical similarity of the same rocks with metabasites at Vimsodden still further south. We note further the analogous position of the lower Livliebreen basic volcanics in Oscar II Land to the north. We also find, especially to the south, that diamictite facies are liable to be coeval with or directly associated with conglomerate facies. Applying these considerations in Nordenskiöld Land there are still two kinds of difficulty, both of which obtain throughout the west coastal terranes: the structural com-

Table 7. Norsk Polarinstitutt stratigraphic schemes for western Nordenskiöld Land. Thickness in metres.

W. Nordenskiöld Land (general) (Hjelle 1962)	North Bellsund (western sequence) (Hjelle 1969)	W. Nordenskiöld Land (general) (Hjelle et al. 1986)
Kapp Linné Tillite 200-300	Lågneset Tillite	10 Tillite : Slettneset Lågneset, Lonevatna > 500?
Linnéfjellet Sandy Phyllite and quartzite >1500	Lågneset-Kapp Martin grey and green shales	9 Phyllite & shale with quartzite : Slettnesbukta -Gravsjøen > 200
Lågnesflya Dolomite - Limestone with oolite 600-800 [Slate and Phyllite c50]	Lågnesrabbane calcareous beds	8 Limestone/marble with Greenschist : Lågnesbukta - Orustosen c250?
Bellsund Dolomite Conglomerate >1000?	Kapp Martin Conglomerate beds	7 Quartzite c40 6 Dolomite with chert layers >180
		5 Conglomerate and lime stone : Kapp Martin, Lågnesrabbane ~150?
		4 Phyllite and shale < 200
		3 Limestone/marble Malmberget - Orustdalen c200
		2 Phyllite & shale: Skardkampen -Kosterfj 150?
		1 Quartzite : Jarnbreen > 400?

Table 8. Summary stratigraphic succession for Nordenskiöld Land after Turchenko et al. 1983a. Thickness in metres.

Age	Complex	Succession	Thickness (m)	Lithology
Vendian	Carbonate - detrital	8	>800	Conglomerate (tillitic), phyllite, sandstone
Middle Upper Riphean	Carbonate	7	~600 - 800	Grey/black massive dolostone, intercalations of quartzite; schist and volcanite in upper part
		6	~1200	Carbonate-micaceous carbonate schists with lenses and intercalations of siliceous schist, dolomite, green schists of basic volcanic derivation. Intrusive and extrusive gabbro, andesite, andesite-basalt, now schistose
		5	~700 - 800	Rhythmic interstratification of metasandstone and argillaceous schist with rare carbonate
		4	600	Rhythmic argillaceous schist, quartzo-feldspathic metasandstone and dolostone, brecciated dolostone
	Sedimentary - volcanicogenic	3	~500	Light grey dolostone, quartzo-feldspathic metasandstone, quartz-mica schist (derived from acid extrusive rocks), interstratified on cm-scale. Also metagabbro
		2	~300	Rhythmic alternation of quartzite, light grey dolomitic and calcareous marbles with thin green schists
		1	~600	Quartz-muscovite schist with feldspar and quartz phenocrysts derived from acid effusive rocks; green schists derived from basic tuffs, metagabbro and grey dolostone
Lower Riphean		0	?	Volcanogenic rocks (including basites) altered into schists

plication due to combined Paleozoic and Cenozoic deformation, and the sedimentary variety due to deposition in a highly mobile environment. Nevertheless the strata are thick and broadly folded so that a general succession can be seen through the structural and sedimentary complexity.

This leads us to favour the scheme put forward by Hjelle 1962 and not to support some of the later modifications based on the detailed mapping of Hjelle et al. (1986) seemingly based partly on what may be miscorrelation outside Nordenskiöld Land. Taking such a broad view there are two main sequences separated by a fault (probably thrust) zone running northwest from Van Muydenbukta to the west coast of Orustosen. To the east of this line is a general succession from the upper Kapp Linné diamictite in the north down to the lower Millarodden diamictite in the southeast. To the west of this line only the older part of the succession is seen with the oldest unit being the Kapp Martin conglomerates and phyllites. The western terrane appears to be thrust over the eastern one and there are further thrusts and many cross faults to complicate the successions. The whole terrane on this view would thus be Varanger (Early Vendian) in age. We see no reason to correlate any rocks with older strata in Ny Friesland.

Our tentative Nordenskiöldkysten sequence differs from that of Turchenko et al. (1983a) which was based on the general west coast sequence by Krasil'shchikov (1979). It seems to us that the two widely separated diamictite/conglomerate units recognised by us are forced into one by them.

5.4 Tentative sequence of rock units

Lacking our own first-hand observations of the middle area of Nordenskiöldkysten our stratigraphic proposals are more tentative than in all the other areas considered. Nevertheless, we have some confidence from analogous successions to the north and south to propose the following general sequence (Table 9):

Kapp Linné Formation
Linnéfjella unit
MalMBERGET unit
Lågnesbukta Group
Lågneset Formation
Gravsjøen unit
Lågnesrabbane Formation
Kapp Martin Formation

The names employed reflect prior usage and are informal. We distinguish tentative *formations*, which we have investigated from *units* which we interpret from publications mainly by Hjelle.

5.5 Kapp Linné Formation

Hjelle (1962) named the diamictite-bearing succession here the "Kapp Linné Tillite Series", which we follow with our "Kapp Linné Formation".

The beds strike roughly north-south and dip moderately to the west. The top of the formation is not seen because the youngest beds occur in the core of a syncline which trends south-southeast into central Isfjordflya (Fig. 38).

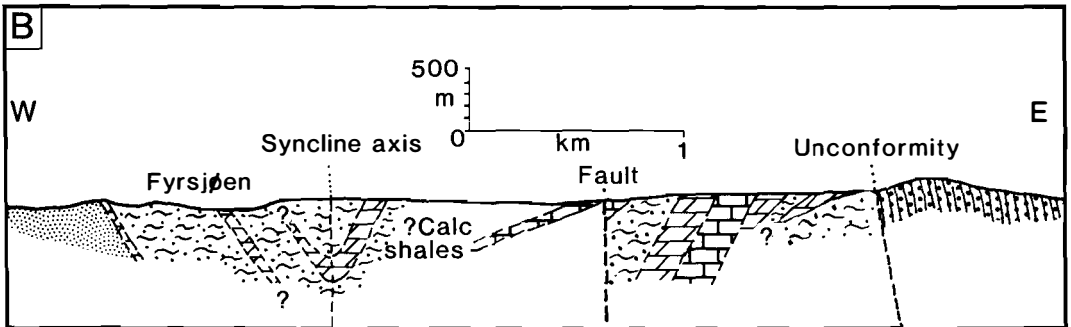
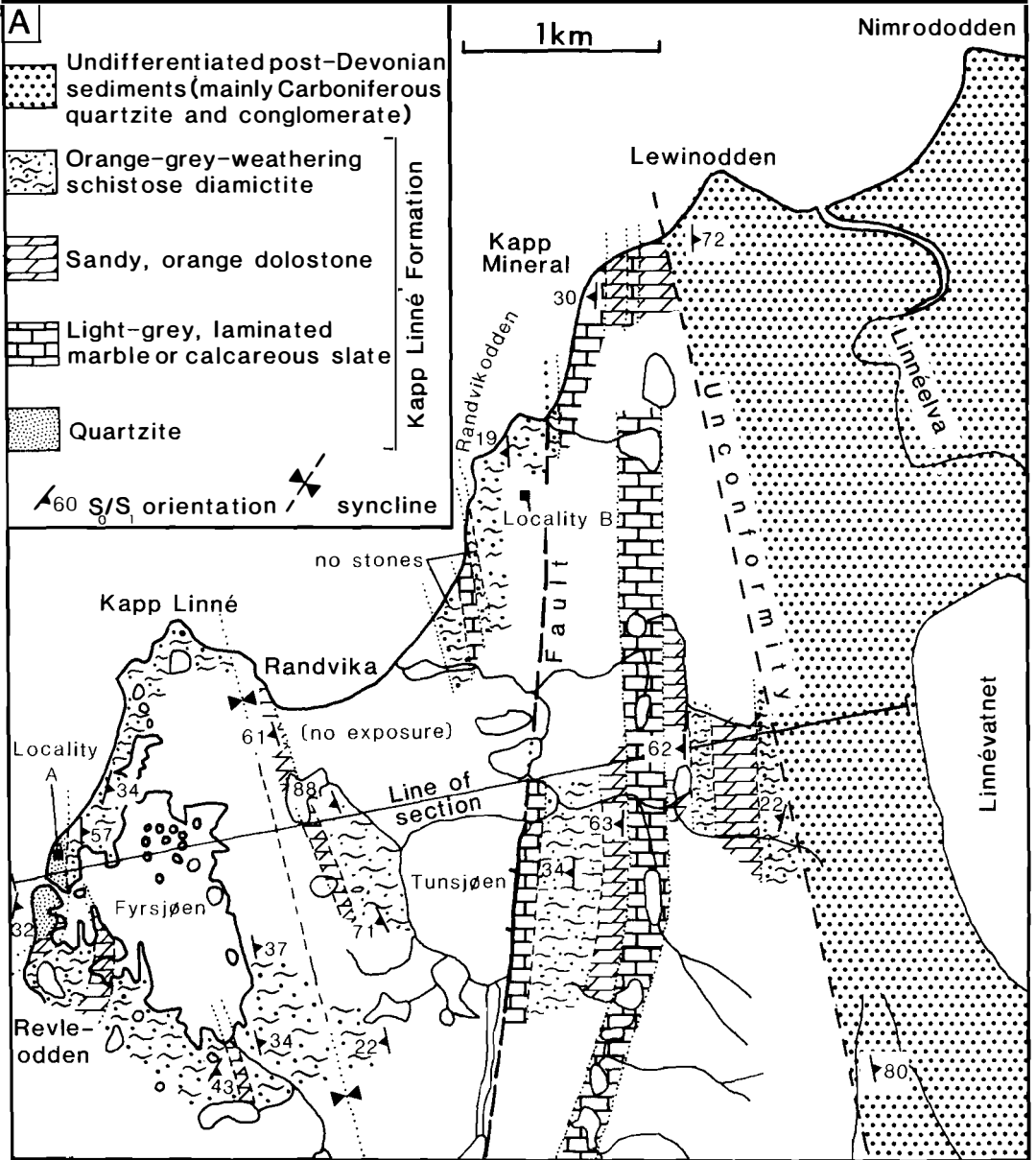
A minor fault trends SSW from Kapp Mineral to the coast north of Båtodden (Fig. 37). According to Hjelle (1962), the Kapp Linné formation occurs only to the west of this feature, but we have found further schistose diamictites to the east. The formation has a minimum thickness of 2.5 km.

The youngest part of the succession lies in a syncline to the SSE of Kapp Linné. Passing westwards from the axis of the syncline, over 1000 m of stone-rich, orange to grey-weathering psammitic schist, with thin greenish grey-weathering schist and sandy dolostone interbeds, are exposed (Fig. 38). The schist is mostly banded as a result of a fine alternation of discontinuous orange-weathering psammitic layers 1–3 m thick, and darker quartzitic schistose layers 5–15 mm thick (Fig. 39A and B). Thin competent sandstone beds 20–30 mm thick, enhance the original compositional banding. The stones are dominated by quartzites, dolostones and granites (Table 10). The dolostone and quartzite stones average 20–60 mm in length. Granite stones have an average length of 0.15 m, but boulders 0.3–0.5 m in diameter are common and one 1.8 m long was seen (Fig. 40A). Geochemically, these granite stones resemble the Hornemantoppen granite of northwestern Spitsbergen (Table 11) (Turchenko et al. 1983a), but that is most probably a Devonian granite (Gayer et al. 1966). The stones rarely form more than 10% of the rock by volume. Nearly all the stones are flattened tectonically (in S1) and some are boudined. The large granite boulders have suffered the least deformation and retain their sub-rounded shapes.

To the west of Fyrsjøen, the schist is abruptly underlain by about 90 m of medium-bedded, light

Table 9. Stratigraphic scheme for the pre-Carboniferous rocks of Nordenskiöldkysten.

Stratigraphic scheme in this paper	Dominant rock types	Hjelle 1962	Hjelle 1969	Hjelle et al. 1986	Turchenko et al. 1983 a
Kapp Linné Fm. > 2,500m — Båtødden Mbr.	Granitoid-bearing tillites in calc-phylrites with marble and quartzite beds marble at base	Kapp Linné tillite 200–300m			Unit 8 Vendian tillitic conglomerate
		Linné fjella > 1500m		Units 5 4 and 3	Unit 6 ~ 1200m
Malmberget unit	Limestone marbles			Unit 3 (at Malmberget)	Unit 4 in SE Middle–Upper Riphean
	Pelites and psammites			Unit 2 (at Skardkampen)	
	Quartzites			Unit 1 (at Järnbreen)	
Lågneset Fm.	Schistose tillite (without exotic stones)	Lågnesfjella limestone (with oolites), slates and phylrites 600–800m	Lågneset tillite	Unit 10 tillite (at Slettneset, Lågneset and Lonevatna)	Unit 8 Vendian tillitic conglomerate
	Phylrites with volcanic component, quartzite and limestone beds. Basite bodies			Unit 9 phyllite, shale and quartzite (at Slettnesbukta and Gravsjøen) and Units 7–8 elsewhere	Units 4 (in SE) Upper 1 (in SW) Riphean Unit 0 (in W) basites Lower Riphean
Lågnesbukta Group	Limestone Mbr		Lågnesrabbane calcareous beds	Units 8 limestone and marble with greenschist at Lågnesbukta	Units 2 ~ 200m 1 ~ 600m (Middle–Upper Riphean)
	Dolostone Mbr	Dolostones	Bellsund dolomite	Unit 6 dolomite with chert limestone	
Kapp Martin Fm.	Conglomerates and phylrites	Conglomerate	Kapp Martin conglomerate beds	Units 5 conglomerate 4 phyllite and slate (at Kapp Martin)	Unit 8 Vendian tillitic conglomerate



grey, coarsely crystalline quartzite (Locality A, Fig. 38). Immediately to the east of Fyrsjøen, around Tunsjøen and Randvika, exposure is poor but there may be up to 1000 m of a soft, possibly calcareous, unit underlying the more resistant schist to the west.

To the east of Randvika, about 600 m of dark grey dolomitic phyllite with dispersed stones, principally quartzite, grey flaggy limestone and stone-free psammitic schist overlies about 800 m of schistose diamictite. The latter is characterised by the appearance of a large number of flattened, green, chloritic, schistose (possibly meta-volcanic) fragments up to 0.2 m in length. Dolostone and granite stones average 80–120 mm in length.

Between Randvikodden and Kapp Mineral, the succession is cut by a NNE–SSW trending fault. To the east of the fault, about 200 m of stone-rich schist is underlain by about 600 m of light-grey, laminated limestone, pale-yellow-weathering dolostone and cream-coloured, crystalline marbles. The outcrop width increases rapidly to the south (Figs. 37 and 38), and diamictite horizons become more abundant, as beds emerge from beneath the unconformable Carboniferous rocks.

The upper part of the Kapp Linné formation is lithologically similar to much of the Haaken Formation in Oscar II Land both being characterised by exotic stones; and we correlate them, although individual units are somewhat different. However, the Kapp Linné diamictites are more stone rich, and it is possible that ice lay over the site of deposition for a time, releasing waterlain till, or that glacial sediments were remobilised as subaqueous gravity flows, though background sedimentation was probably turbiditic when direct glacial deposition was less.

The body of dolomite cropping out along the shore north of Båtodden is assumed to be conformable with the Kapp Linné succession and is taken as its lowest division (Båtodden member) which in turn defines the top of the seemingly conformable Linnéjella unit.

5.6 Linnéjella unit

The Linnéjella rock unit (not investigated by us)

is taken from the maps by Hjelle (1962) and Hjelle et al. (1986). Hjelle (1962) proposed Linnéjella for approximately this unit of more than 1500 m. It is numbered by Hjelle et al. (1986) on their map as units 5? and 3–4?. It appears to be a thick conformable sequence of phyllites and quartzites with limestone beds and, dipping ENE, extends south to Klausbreen. It is steeply folded; a thickness estimate can only be approximate and is suggested at about 2 km. Turchenko et al. (1983a) suggested about 1200 m for their unit 6 which is a part of this unit.

5.7 Malmberget unit

Below the Linnéjella unit the same map shows a succession of limestone marble (unit 3), phyllite (unit 2) and quartzite (unit 1). These may be regarded as members of a potential formation or as three formations. The quartzite is located at Jarnbreen and the marble at Malmberget.

Hjelle et al. (1986) regarded these as the oldest units in the area but we think that their sequence was made on the assumption that there was only one main diamictite formation at the top and not another at the bottom of the succession.

5.8 Lågneshukta Group

The Lågneshukta Group comprises four formations with further divisions with gradational boundaries. The upper and lower formations are rich in polymict stone-bearing strata of various facies. The stones generally flattened in a well-developed penetrative foliation. Although the clastics have lost their primary orientations, visible sedimentary structures are sometimes well preserved (notably large flame structures). The upper two units are associated with greenstones referred to variously as amphibolites (altered) and metabasites (and even gabbros) which are clearly coeval and are seen as contributing a volcanic component to the sediments, with lavas and intrusive bodies not easy to distinguish. Correlatives of these rocks occur throughout the southern half of Nordenskiöldkysten while the succession from Lågneshukta to Kapp Martin from way-up evidence places three of the formations in order. There is an element of doubt

Fig. 38. Geological sketch map showing setting of Kapp Linné Formation. mouth of Isfjorden (south side), with schematic cross-section.

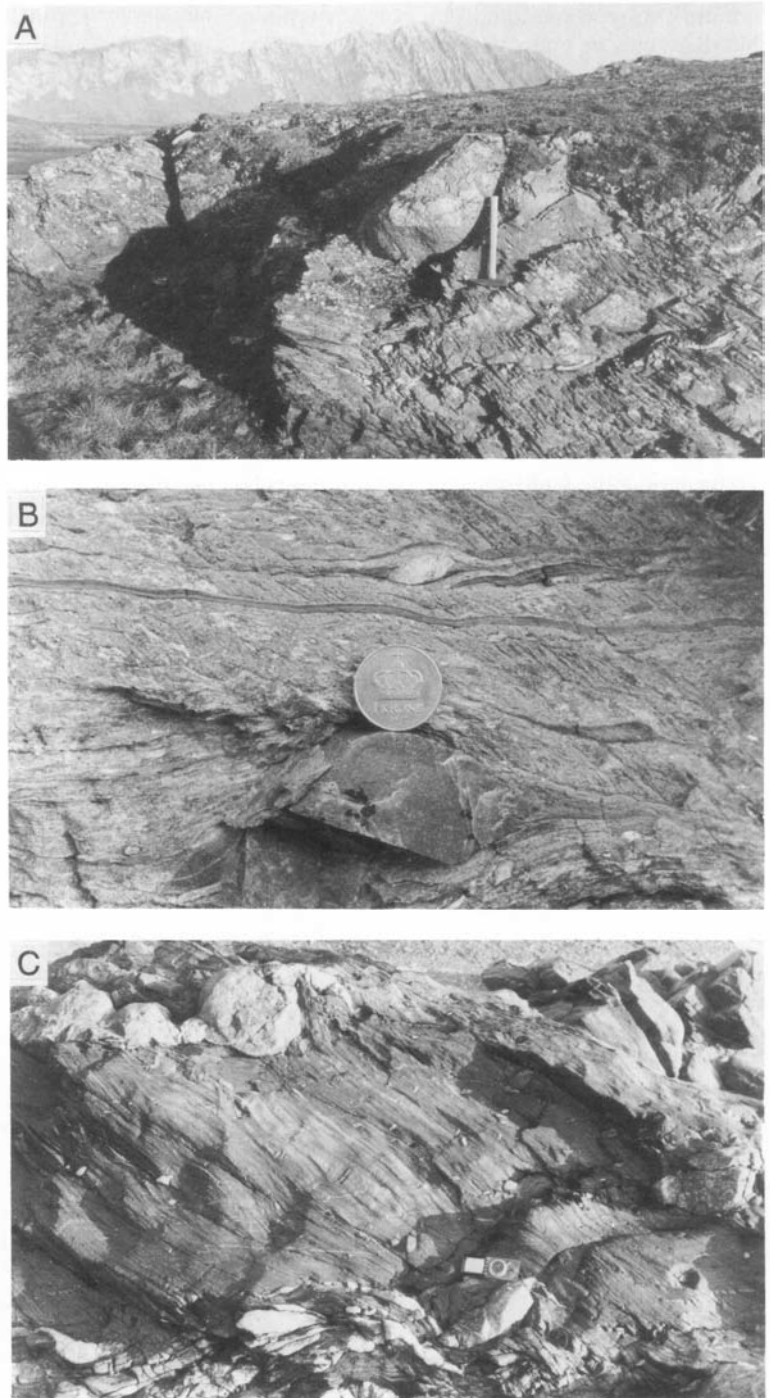


Fig. 39. Kapp Linné Formation, south side of Isfjorden. A. Orange-grey psammitic and pelitic schist with large granite boulder, top of section, east of Fyrsjøen. B. Same rock unit with strongly streaked out calcareous sandstone layer, and slightly deformed stones of quartzite (below coin) and dolostone (above coin). C. Green-weathering phyllite, containing dolostone and quartzite stones in highly deformed matrix. Note boudined layer of quartzite top left.

Table 10. Estimated stone composition of psephites in Nordenskiöld Land.

KAPP LINNÉ		KAPP MARTIN		MILLARODDEN
Kapp Linné Formation (Upper : schistose diamictite) (Lower : schistose diamictite)		Kapp Martin Formation (conglomerate)	Lågeset Formation (schistose diamictite)	Millarodden unit (schistose diamictite)
White/grey quartzite	33%	Limestone	Dolostone	Dolostone
Orange quartzite	20%	Quartzite	Quartzite	Vein quartz
Cream/white dolostone	30%	Dolostone	Limestone	Quartzite
Oncolitic dolostone	1%	Calcite #	Calc. green schist	Black limestone
Granite	12%	Calc. green schist	5%	Sandstone
Dark grey limestone	4%			Phyllite
Quartz diorite*	< 1%			Basic volcanic
Dolostone conglomerate	< 1%			

* Reported by Hjelle (1962)

Recrystallised from dolostone or limestone

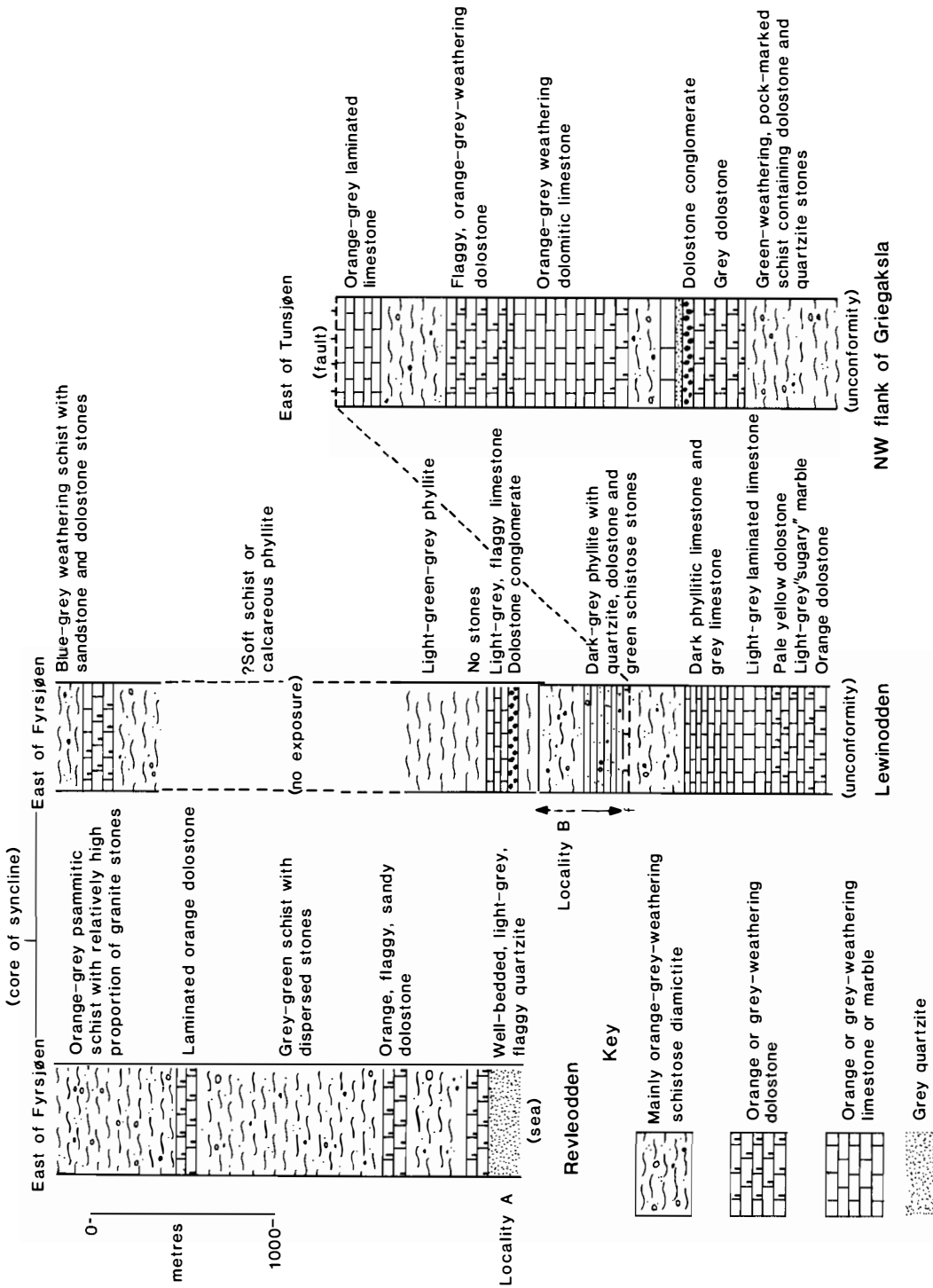


Fig. 40. Stratigraphic sections through the Kapp Linné Formation at the type locality. Fig. 38 shows locations of sections.

Table 11. Chemical analyses of boulders of granitoids from the Kapp Linné Formation diamictites and from Hornemantoppen, Magdalenefjorden, northwest Spitsbergen (Turchenko et al. 1983a).

	Kapp Linné Formation			Hornemantoppen
SiO ₂	70.47	66.16	73.39	70.60
TiO ₂	0.50	0.94	0.31	0.34
Al ₂ O ₃	13.20	11.90	12.72	14.05
Fe ₂ O ₃	0.93	1.89	0.79	0.49
FeO	2.40	3.61	2.06	2.34
MnO	0.06	0.08	0.02	0.12
MgO	1.85	4.05	0.86	1.43
CaO	2.04	2.15	1.60	0.78
Na ₂ O	5.06	3.45	4.78	4.30
K ₂ O	1.82	2.30	1.08	2.72
Loss on ignition	1.77	3.18	2.17	1.18
P ₂ O ₅	0.18	0.24	0.02	0.08
Total	100.28	99.95	99.70	98.42

as to whether the Gravsjøen unit is above or below the Lågneset Formation with which it is closely associated both by common juxtaposition on the map and by the common basic igneous elements.

5.8.1 Lågneset Formation

The Lågneset Formation is well displayed at Lågneset, and similar facies at six other localities are tentatively correlated. These include the diamictite formation at Slettneset and at Millarodden. It was probably included in the Lågneset tillite unit of Hjelle (1962), certainly with the Lågneset tillite of Hjelle 1969 and is unit 10 (the top of the sequence) in Hjelle et al. (1986). It is included in the Vendian tillite conglomerates of Turchenko et al. (1983a) (their unit 8).

Our description is based on the sequence at Lågneset where it crops out as two N-S-trending bands, each 70–90 m thick. They are separated by 100–125 m of dark or light calcareous phyllite, white marble, oolitic limestone and pale-green, chloritic schistose diamictite containing dispersed dolostone and quartzite stones. The unit may therefore comprise one thin diamictite horizon, repeated by folding or faulting, or two horizons with a cumulative thickness of 350–450 m.

The diamictite layers consist of orange to greyweathering phyllite containing dispersed stones of grey dolostone, pink and grey quartzite and grey limestone (Table 10, Fig. 39B) with

an average diameter of 20–100 m. One quartzite stone 0.5 m long was seen. Coarse, orange to grey-weathering, sandy tuffaceous beds, containing isolated quartzite stones, are common near the top. Pods of massive, orange-weathering dolostone, up to 5 m thick, and stone-free, green-grey slate interbeds, 0.1–2 m thick, occur within the division further north. Alternating beds of conglomerate and finer sediments with dispersed stones also occur, often wedging into each other. The tops of the conglomerate beds are fairly smooth, but the bottoms are irregular with stones projecting into the underlying oolitic sediment. Flame structures of limestone project into the conglomerates. The Lågneset Formation is probably the result of ice-rafting across a shallow carbonate sea with periodic inputs of fine-grained clastic material and tuffs. Conglomerate layers were probably deposited as subaqueous debris flows, that were emplaced onto unconsolidated oolitic sediment in shallow water.

Diabaspynten is one of three headlands to the northwest of Lågneset (Fig. 37) dominated by dark-green amphibolite. The top of the formation ends abruptly in the sea. The base is characterised by tuffaceous metasediments, which gradationally are interbedded with the top of the underlying Lågneset division. Similar tuffaceous contact is seen to the south at Grønsteinodden. Hjelle (1962, p. 92) showed some igneous rocks to be intrusive south of Orustosen (about 15 km north of Vestervågen). Much of the Diabaspynten division we therefore believe to comprise metamorphosed lava flows and pyroclastic deposits with occasional related intrusions. It is possible that neither top nor bottom of the formation is exposed at Lågneset.

At Millarodden the probable equivalent of the Lågneset Formation is about 200 m thick and consists of a greybrown weathering, highly dolomitic schistose diamictite containing mainly dispersed dolostone stones, as well as limestone, vein quartz, quartzite, sandstone and phyllitic stones (Table 10). These proportions vary, becoming more quartzose westwards. Although deformed, the original stone shapes can be estimated. From a sample of 50 extracted from the schistose diamictite the following proportions were obtained: angular 10%, subangular 30%, subrounded 44% and rounded 16%. The Millarodden unit probably represents part of the Lågneset Formation repeated by thrusting. The western (probably lower) division is about 200 m

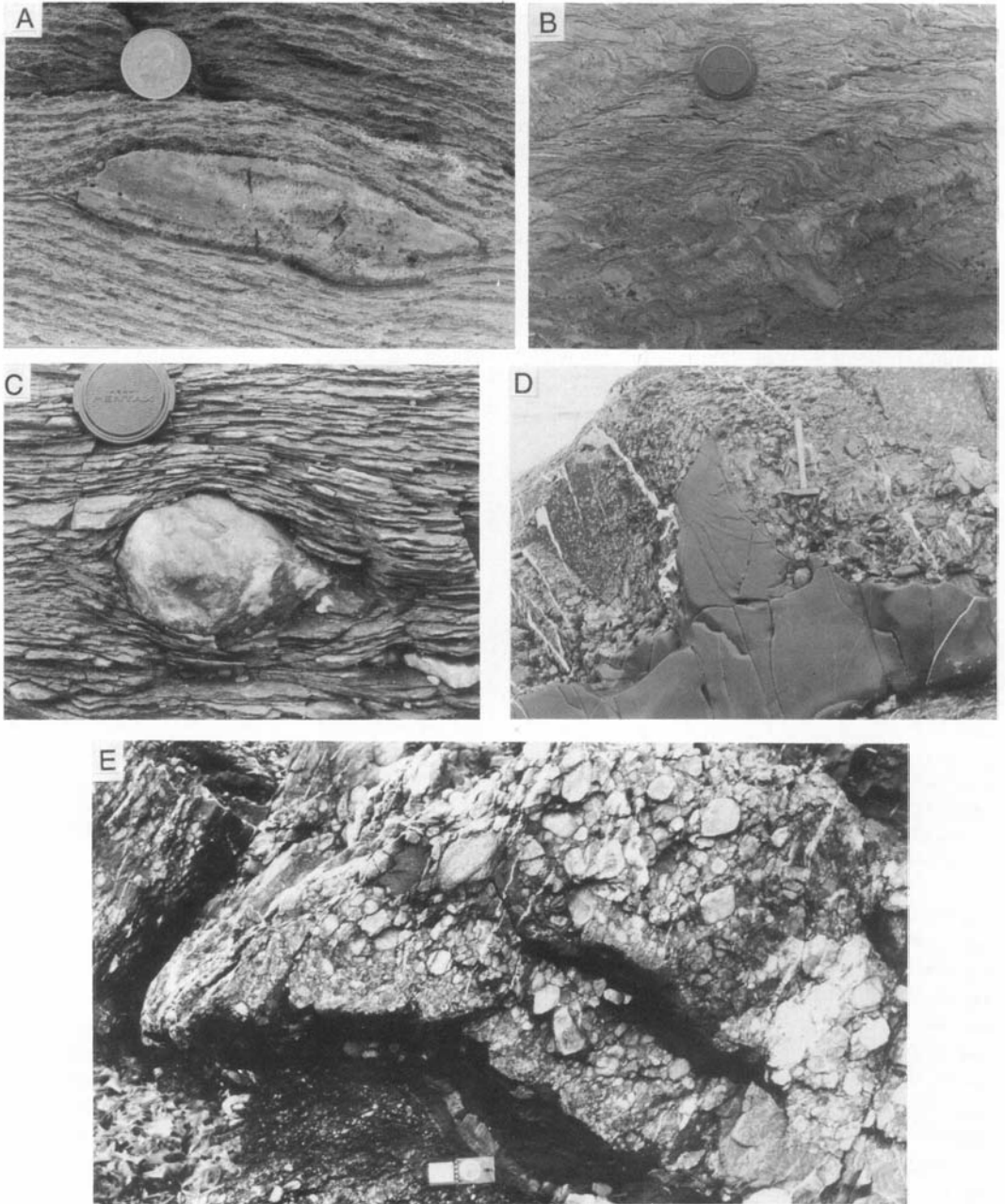


Fig. 41. The Lågnesbukta Group, north Bellsund. A. Orange dolostone stone in coarse psammite, northwest of Lågneset. B. Orange to grey weathering phyllitic psammite containing abundant quartzite, dolostone and limestone stones, Lågneset Formation, Lågneset. C. Isolated dolostone cobble in dark, laminated limestone of the Lågnesrabbane Formation, north shore of Lågnesbukta. D. Large-scale flame structure of limestone penetrating dolostone-quartzite conglomerates, Kapp Martin Formation, Kapp Martin. E. Crudely developed inverse grading in conglomerates of Kapp Martin Formation, Kapp Martin.

thick and comprises fissile limestone with rare dolostone stones, which are up to 0.8 m long in the west.

Westwards this unit passes into about 10 m of largely stone-free dark grey quartzite, more diamictite, then gradationally into dark calcareous phyllite. The phyllite shows much calcite segregation parallel to S1, and contains some lenses of psammite with dispersed stones, before the unit disappears under the beach.

5.8.2 Gravsjøen unit

A detailed map of Gravsjøen (Hjelle et al. 1986, p. 12) shows a complex dominantly of phyllites with metavolcanics and quartzite beds and with massive greenstone bodies. Thinner beds of dolostone and limestone (including sandy limestone) are present. Such a formation is mapped by the authors variously as units 7, 6 and 9 and from the map the unit would underlie the diamictite formation. It is however missing, or greatly thinned, in what we take to be a thrust zone where there is no expanse east of the diamictite outcrop at Lågneset.

5.8.3 Lågnesrabbane Formation

Hjelle (1969) tabulated the Lågnesrabbane calcareous beds as overlying the Kapp Martin conglomerate beds; we agree and so follow this nomenclature. We distinguish two members which are depicted on the 1986 map: limestone overlying dolostone.

The *limestone member* crops out discontinuously around the shore of Lågnesbukta. Exposure is poor inland but the strata probably strike NNW and occupies the low ground with lakes to the west of Lågnesrabbane (Fig. 37). Much of the member comprises dark or light-grey, laminated, partly oolitic limestone, variably interbedded with green or grey calcareous phyllite, black phyllite, white crystalline marble and minor conglomerate. Isolated pods of massive, orange-weathering dolostone occur towards the top and thin bands of pale-green, chloritic schist towards the base. Angular to rounded, tectonically elongated limestone, dolostone and quartzite stones are dispersed throughout (Fig. 39A, C). A thickness of 1–2 km is tentatively suggested, but the soft fissile rocks would be particularly susceptible to over-thickening as a result of tight folding. This succession probably represents similar environments to the Lågneset Formation, but without any glacial influence.

The *dolostone member* is a stone-free dolostone succession 600 m thick which forms the rocky headlands to the west of Kapp Martin. It comprises light grey, well-bedded dolostone with occasional thin interbeds of green, calcareous schist of shallow marine origin. This member may also be seen in eastern Varsolbukta and to the north.

5.8.4 Kapp Martin Formation

This distinctive formation is only exposed along the coast from Slettnesbukta to Kapp Martin (Fig. 37). It comprises 800 m of phyllite, coarsely crystalline black limestone, polymict conglomerate and subsidiary quartzite and dolostone (Waddams 1983b). Finely laminated, brown or grey weathering, calcareous and non-calcareous phyllite occurs in beds 0.2–2 m thick. Some phyllitic beds contain stones of dolostone up to 30 mm in diameter and slate or phyllite intraclasts up to 0.2 m long. The dark limestone forms beds 0.15–1 m thick. It is finely laminated and interbedded with irregular pellet and oncolite horizons. Occasionally, beds are graded with a thin, basal granule conglomerate. Dolostone or quartzite stones, 30–40 mm in diameter, and phyllite intraclasts are common.

The Kapp Martin Formation is dominated by a massive, polymict conglomerate (Table 10), occurring in beds 0.05–4 m thick. The clasts are strongly elongated; quartzites and dolostones typically have axial ratios of 6:3:1, but limestones are totally streaked out. Some more competent clasts exceed a metre in length. Intraclasts probably derived from the earlier and interbedded limestone are also present. On average the dolostone and quartzite clasts are 50–70 mm in diameter reaching at least 0.55 m. The matrix consists of a black, finely crystalline limestone, which may be oncolitic. Although some conglomerate beds are massive and show no vertical change in grain size, most display normal or coarse-tail grading. In some beds inverse grading is well developed (Fig. 41E). Exceptionally large and well-developed 'flame' structures occur in the phyllites or limestones directly beneath some normally or coarse-tail graded conglomerate beds. They are commonly 0.04–0.3 m high, but unusually large structures measure 0.85–1.0 m in height and 0.5–0.75 m across the base (Fig. 41D). Incipient rip-up structures of limestone or mudstone also occur in the base of conglomerate beds (Waddams 1983b).

The Kapp Martin conglomerates are a spectacular manifestation of deposition in a mobile environment. As discussed more fully in section 9.3.1, the conglomerates were probably deposited by gravity-driven sediment flows from a proximal debris source that was dominated by material released directly from ice on an unstable slope.

6 Northwestern Wedel Jarlsberg Land

6.1 Introduction

The area considered in this chapter is shown in the map (Fig. 42). The best known outcrops of the Vendian and older rocks lie mainly to the west of Recherchebreen and to the north of Tor-ellbreen.

The Vendian rocks occupy a broad syncline plunging NNW so that the youngest strata appear around Kapp Lyell. Older rocks crop out east of Recherchefjorden and in the southwest. However, the nature and age of the nunataks southeast of Recherchebreen are not known to us.

The area was first reconnoitred by geologists of the Norsk Polarinstitut (e.g. Orvin 1940; Hjelle 1969) and then surveyed systematically by a group from Wisconsin University (Kowallis & Craddock 1984; Craddock et al. 1985; Bjørnerud 1990). These observations are summarised in Dallmann et al. (1990). Our own stratigraphic traverses have enabled us to discuss the above observations in relation to the other areas in Svalbard (Harland 1978; Hambrey & Waddams 1981; Waddams 1983a).

6.2 History of research

A diamictite was discovered at "Fox Point" (Renardodden) and interpreted as glacial by Garwood and Gregory as early as 1898. As such it was the first pre-Pleistocene tillite to be claimed in Svalbard, and only the third of Precambrian age anywhere (after the Port Askaig Tillite in Scotland and the Bigganjarga Tillite in northern Norway).

They described a rock with a fine-grained matrix. "Scattered through the groundmass are huge boulders, of which the largest was 5 feet high and 7 feet long. The boulders are roughly rounded and the surfaces are sometimes marked by indefinite groovings. The boulders consist of a miscellaneous collection of granites and gneisses, none of which have at present any outcrop near the locality where the deposit occurs. The general aspect of the deposit is strikingly like that which a moraine would probably adopt if solidified, uptilted and subjected to extreme pressure. The age of the deposit is probably the same as that of the old glacial conglomerate on the Varanger Fjord described by Reusch and Strahan (Garwood & Gregory 1898, pp. 216–217). Kulling (1934) thought that this "Fox Point tillite" represented the same conglomerate-forming epoch as the Sveanor tillite in Nordaustlandet.

During fieldwork in 1975, Harland and Pickton logged the Paleocene succession at Renardodden (Fox Point) but their description of the units was inadvertently omitted from the resulting paper (Thiedig et al. 1980). Their section (p. 140 of that paper) shows a unit resting unconformably on the "Varangium" and underlying the Skilvika Formation. The description of this unit, named informally the *Rochesterpynten formation* is summarised here.

The basal conglomerate of the Skilvika Formation rests unconformably on a confused mixture (of material) derived from Precambrian meta-diamictites (tillites). Earlier work had included the conglomerate within the pre-Devonian succession, but Harland considered it to be a tectono-sedimentary mélange that would have been produced at an active fault scarp. Indeed it appears to have been subjected to slight folding and compaction prior to the deposition of the Skilvika Formation. It is therefore considered to be a separate formation 50–100 m thick of Paleocene age. It is best exposed near a small waterfall at Skilvika. The upper part of the formation comprises generally sandstone or quartzite with folded stratification. It is followed by a slump complex of sandstones and quartzites, and at the base a tumbled, slipped mass of Precambrian blocks up to tens of metres across. The latter is separated by scree and a fault breccia

Fig. 42. Generalised geological map of northwest Wedel Jarlsberg Land. Place names: Lognedalsflya 1; Skilvika 2; Fløykalven 3; Calypsostranda 4; Tomtvika 5; Asbestodden 6; Gaimardtoppen 7; Langköllbreen 8; Krassnilken 9; Turrsjødalen 10.

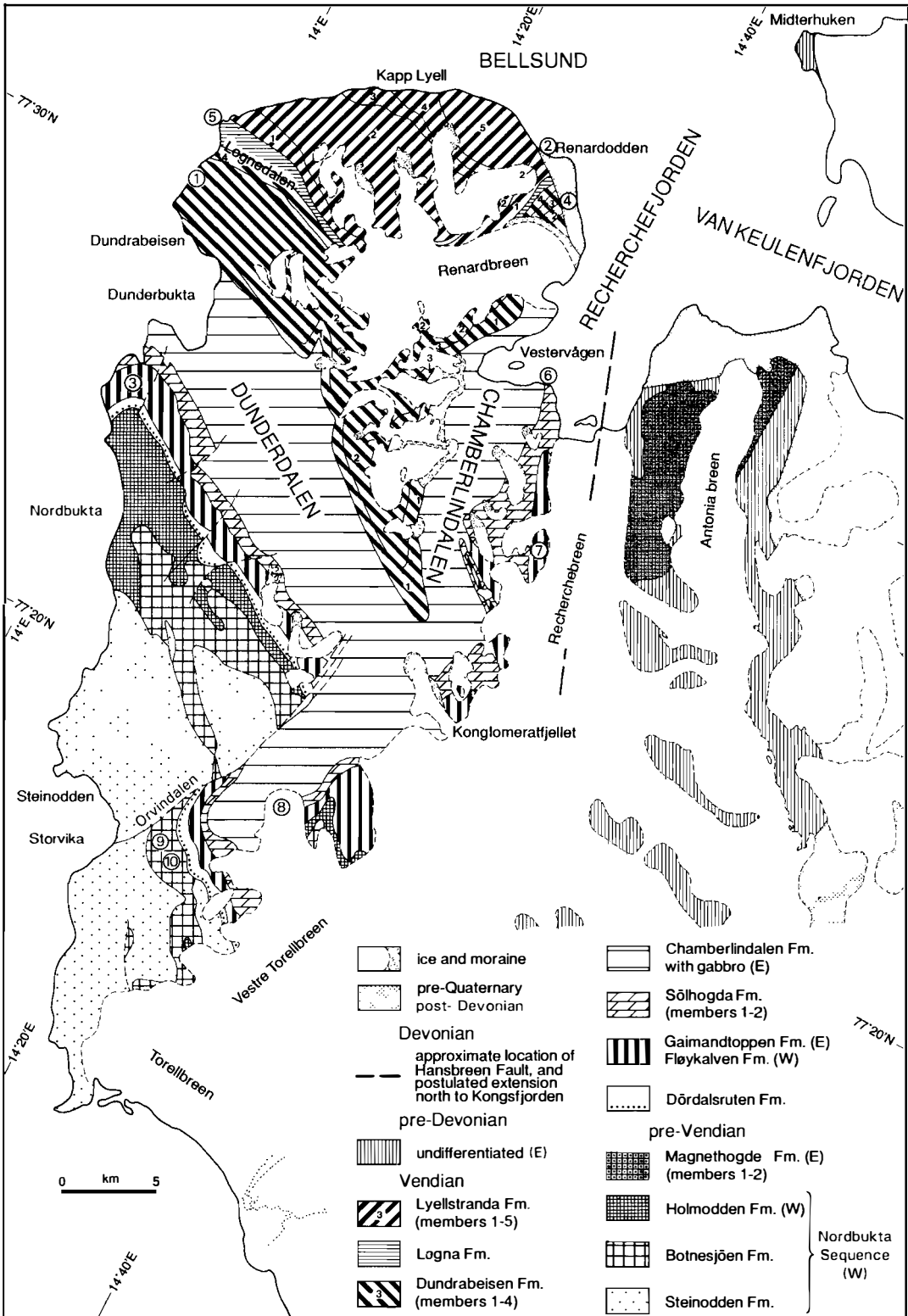


Table 12. Stratigraphic scheme for the pre-Carboniferous strata of northwest Wedel Jarlsberg Land.

Earlier informal names proposed e.g. Harland 1978 and in informal use in Cambridge Group (Hjelle 1969 5 divisions)	Consolidated scheme for this paper. Descriptions of rock units largely from work of Wisconsin Group, Kowallis and Craddock 1984, Bjornerud Ms. map 1989, Craddock et al. 1985	Wisconsin Group names after Bjornerud 1990 and Dalland et al. 1990 (with their correlations)
VARANGER (VENDIAN) SEQUENCE		
<p>Kapp Lyell Unit (5)</p> <p>Lyellstranda Division</p> <p>Renardbreen Division (in east)</p>	<p>Kapp Lyell Group</p> <p>Lyellstranda Fm. 1 3</p> <p>Logna Fm. 0 2</p> <p>Dundrabeisen Fm. 1 4 (in west)</p> <p>Mbr. 5 Upper dolostone clast unit</p> <p>Mbr. 4 Upper no dominant clast unit</p> <p>Mbr. 3 Middle dolostone clast unit</p> <p>Mbr. 2 Upper quartzite clast unit</p> <p>Mbr. 1 Lower no dominant clast unit</p> <p>Phyllite</p> <p>Mbr. 4 Limestone clast unit</p> <p>Mbr. 3 Lower dolostone clast unit</p> <p>Mbr. 2 Lower quartzite clast unit</p> <p>Mbr. 1 Clast poor unit</p>	<p>10 unnamed map units as described here (Vendian ?) 2000-3000m</p>
<p>Chamberlindalen Unit (4) (3) (in east)</p> <p>Solhøgda (2) Upper Middle Lower</p> <p>Gaimardtoppen and Foldnutane (1) 0.5 0.5</p>	<p>1000 2000</p> <p>Dunderdalen Fm. (in west) Phyll with minor lst olistoliths</p> <p>Chamberlindalen (E) Phyll + greenschist with minor dst + qtze with volcaniclastic + pillow basalts</p> <p>Slettjellidalen Solhøgda 5</p> <p>Dolostones + limestones 4</p> <p>Gaimardtoppen Fm. (in E) Cgl, sst + siltst. 700 3</p> <p>Fløykalven Fm (in W) Diamiccite</p> <p>Thiisfjellet Fm Black pyritic lst 0-100 2</p> <p>Local unco. cgl. 0-50 1</p>	<p>Dunderdalen Fm (in west) (Gashamna phyllite)</p> <p>Slettjellidalen Fm (in west) (Hoferypynten dolomite)</p> <p>Konglomeratfjellet Fm (b) Green (a) Brown (Slyngfjellet cgl) 800-1700m</p> <p>Thiisfjellet Fm (Slyngfjellet cgl)</p>
Unconformity pre-Vendian sequences		
Nordbukta sequence Western Magnethøgda sequence Eastern		
<p>Magnethøgda Unit (E)</p> <p>Storvika (W)</p>	<p>8 Dørdalen Fm 150- heterogeneous dst + phyll. Banded dst/white marble</p> <p>7 Thiisdalen Fm 200 red-brown phyll. + qtze Dark phyllite</p> <p>c Ferroan dst 150 pink marble Yellow dst</p> <p>6 Trinitane Fm b Resinous phyll. 30 Grey-green qtze</p> <p>a Pink 200 Feldspathic qtze - augen gneiss</p> <p>crossbedded qtze</p> <p>5 Seljehangfjellet Fm b Grey dst 150 Grey dst with hematite</p> <p>a Black lst 50</p> <p>4 Botnedalen Fm 300 Platy lst, dst + phyll.</p> <p>3 Peder Kokkfjellet Fm 60 Sandy dst</p> <p>2 Evafjellet Fm 1000? Layered quartzite</p> <p>1 Kapp Berg Fm 1000? Phyll. + qtze</p>	<p>(Deilegga Gp)</p> <p>Dordalen Fm</p> <p>Thiisdalen Fm</p> <p>Trinitane Fm</p> <p>Seljehangfjellet Fm</p> <p>Botnedalen Fm</p> <p>Peder Kokkfjellet Fm</p> <p>Evafjellet Fm</p> <p>Kapp Berg Fm</p>

from coherent Precambrian rock to the west. Amongst the blocks are large granitoid rocks which, with the other material, appear to be reconstituted diamictites, the boulders being larger than any seen in situ.

A search by Harland in 1975 and Waddams in 1978 failed to locate within the in situ diamictites any occurrence to match that described by Garood and Gregory, and we conclude that it is most likely that they were describing an occurrence in the Rochesterpynten Formation which we could not match exactly. On this basis the Rochesterpynten boulders could have derived from a part of the Lyellstranda Formation which is no longer exposed. The map in Thieding et al. 1980 (p. 137) follows the traditional view and takes no account of the above observations.

Results of reconnaissance surveys by earlier geologists of the Norsk Polarinstitut were summarised by Orvin (1940). From the same institute Hjelle (1969) outlined a stratigraphic eastern sequence as follows:

- (5) Bellsund-Dunderdalen tillite
- (4) Konglomeratfjellet shale and quartzite beds
- (3) Konglomeratfjellet volcanic beds
- (2) Konglomeratfjellet calcareous beds
- (1) Konglomeratfjellet calcareous beds

These he correlated with the coast of north

Bellsund. Further reconnaissance mapping was recorded in the 1:500,000 sheet (Flood, Nagy & Winsnes 1971).

Harland (1978) presented a brief description of the rocks and an informal stratigraphic nomenclature based on brief visits to the Bellsund area between 1966 and 1978 (Table 12). Additional observations were made in 1977 and 1978 and then in 1979 with T. S. Winsnes; who drew the attention of Harland to the older diamictite at Fløykalven, south of Dunderbukta. Structural aspects of the diamictites were described (Hambrey & Waddams 1981) as was the sedimentology of the spectacular conglomerates at Kapp Lyell (see Table 13) (Waddams 1983b).

Turchenko et al. (1983b) described the Sedimentary-volcanogenic complex beneath the Kapp Lyell unit in Chamberlindalen and divided it as follows:

1300–1500 m: schistose andesite-basalts and tuffs.

500–1800 m: andesite-basalts, basalts and picrites with sills of gabbro and peridotite, and dolomite.

150–200 m: marbles with basalt and andesite-basalts, transformed into greenschists. Also diabase, gabbro and peridotite dykes: some pillow structures.

Table 13. Informal nomenclature for the Late Precambrian rock succession of northwest Wedel Jarlsberg Land (based partly on Harland 1978, table 6), from Waddams 1983a.

Western sequence (Kapp Lyell to Dunderbukta)			Eastern Sequence (Kapp Lyell to Vestervågen)		
Unit	Division	Lithology	Unit	Division	Lithology
Kapp Lyell	Lyellstranda	Graded polymict conglomerate and buff-weathering dolomitic psammite (3.0)	Kapp Lyell	Lyellstranda	Graded polymict conglomerate and buff-weathering dolomitic psammite (1.8)
	Kolvebekken	Grey laminated quartzite with rare beds of conglomerate (0.7)		Renardbreen	Orange-grey-weathering psammitic schist with dispersed stones (tillite) (4)
	Logna	Black phyllite. No dispersed stones. No conglomerate beds (0.16)		Vestervågen	Grey shale, slate and massive quartzite (0.34)
	Dundrabeisen	Orange-grey-weathering psammitic schist with dispersed stones (tillite) (3.64)			

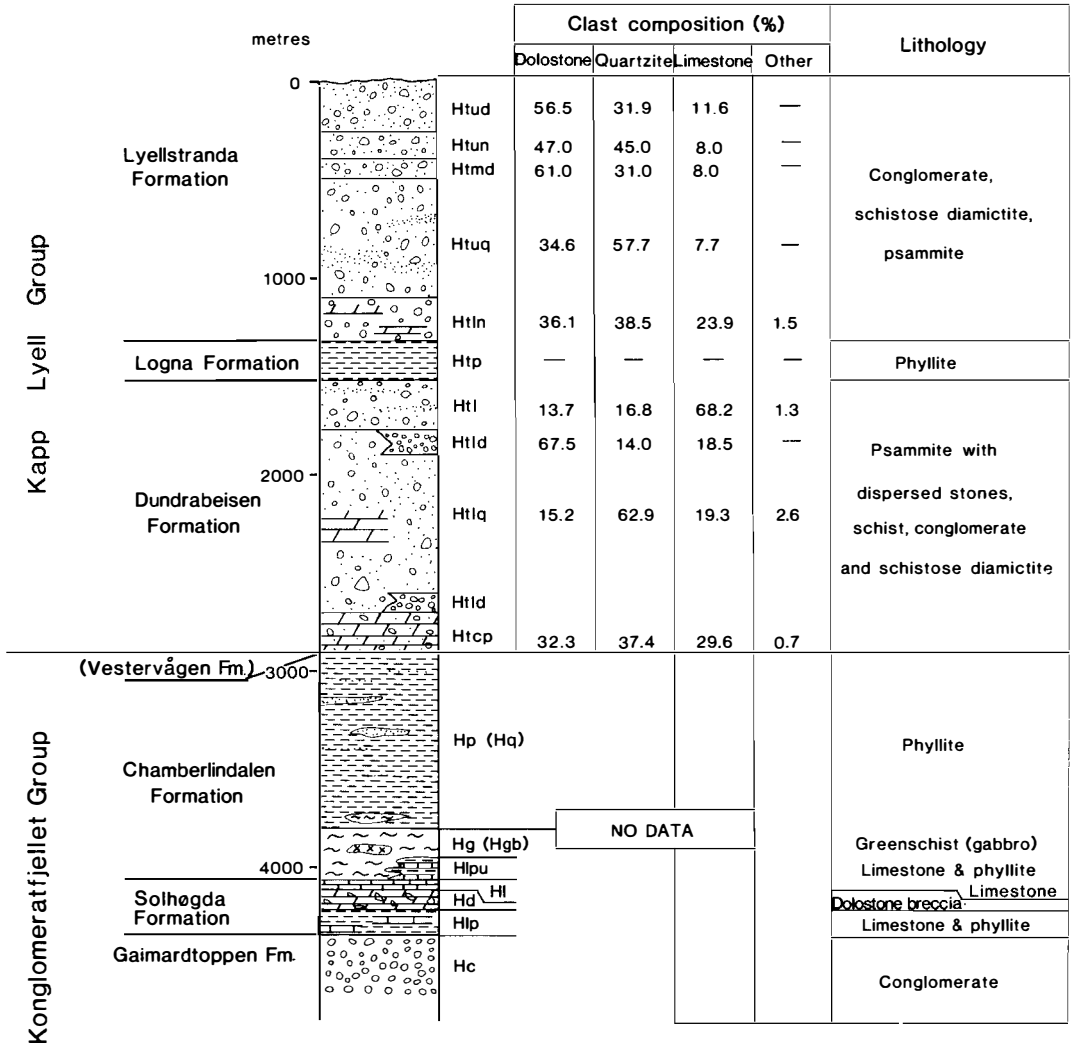


Fig. 43. Composite schematic section through the Kapp Lyell and Konglomeratfjellet groups in the area south of Bellsund including Chamberlindalen, from Kowallis & Craddock (1984), with formational names proposed in this paper. Clast composition also from Kowallis & Craddock (1984).

In 1978 Craddock initiated a series of detailed investigations on the structure and stratigraphy of the area immediately south of Bellsund with a more detailed map than previously (Kowallis & Craddock 1984). His units were as follows:

- phyllite-quartzite unit 900 m:
- greenschist-phyllite-limestone unit 2000 m:
- dolomite-limestone unit 180 m:
- limestone-phyllite unit 120 m:
- conglomerate unit 150 m:

These (Wisconsin) studies extended through the whole area considered in this chapter. A notable discovery was that the rocks south-west of Dunderdalen (Nordbukta sequence) represent part of a large nappe, truncated by erosion and overlain unconformably by a sequence which is the main subject of this chapter (Bjørnerud 1990). Moreover Bjørnerud correlated the older Nordbukta rocks with the previously described Magnehögdga sequence (east of Recherchebreen) so that an unconformity would underlie Recher-

chebreen rather than a terrane boundary as postulated earlier by Harland & Wright (1979) for the course of their West Spitsbergen Fault Zone. We welcome these findings which help our interpretation in this paper. The Wisconsin publications referred to here were based on unpublished degree dissertations of the following: M. Bjørnerud, C. Craddock, E. Hanser, A. Bray, A. Cheng, P. Cochrane, J. Kalinec, B. Kowallis, D. McCord, J. Nania, T. Phillips, G. Rogers, and C. Wills.

6.3 Proposed stratigraphic scheme (Table 12)

Our scheme reflects our conclusion throughout Spitsbergen that two main rudite horizons (diamictites and conglomerates) represent the early and late Varanger glacial epochs. It adopts published names as convenient according to priority. The main difficulty now lies not in the successions themselves nor in correlations between them but in the differences between the facies and thicknesses to the east and west of the synclinal axis. This entails some dual nomenclature even within this area. It reflects significant tectonic (and igneous) activity here throughout the Varanger Epoch.

There seems to be little question about the division into two groups. The upper Kapp Lyell Group and the lower Konglomeratfjellet Group. The latter name was used by Hjelle (1969) for his units 1-4. The brief lithological description from Table 12 (some of which identify numbered but unnamed members are taken from the Wisconsin maps and descriptions.

6.4 Kapp Lyell Group

This is described from top to bottom with supposed map units (see Figs. 42 and 43) of Kowallis & Craddock (1984) in parentheses. Thicknesses are modified from that paper, Waddams' (1983a) estimates probably being too great.

6.4.1 Lyellstranda Formation (*Htud-Htln*) (about 1300 m)

This formation is well exposed on the coastal edge of the strandflat from Calypsostranda to northern Lognedalsflya, and it extends southwards into the hills north of Renardbreen. It consists of two members: The lower one was not recognised by Kowallis & Craddock (1984), although Waddams

(1983b) considered it as a separate (Kolvebekken) division.

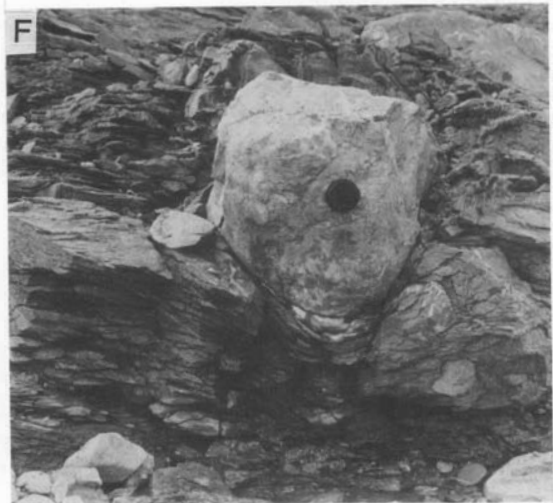
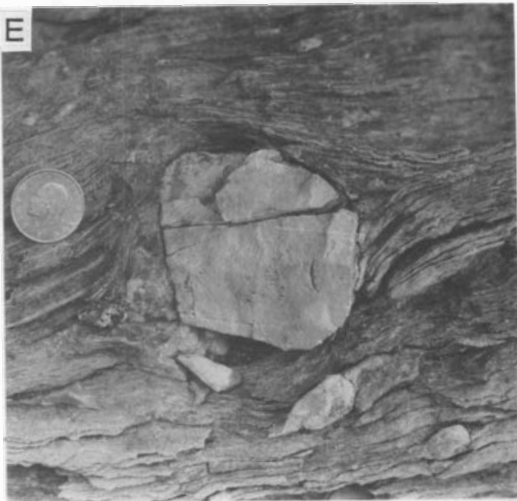
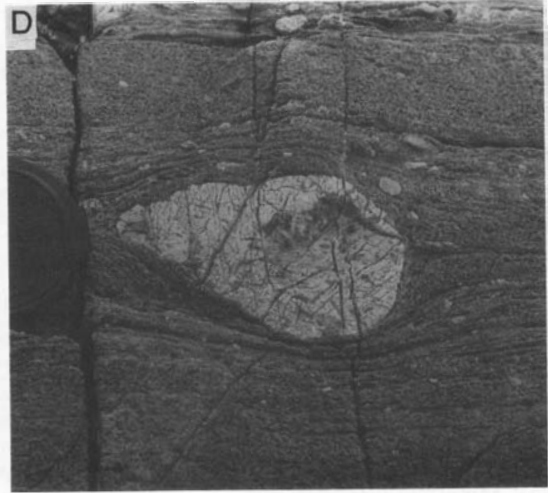
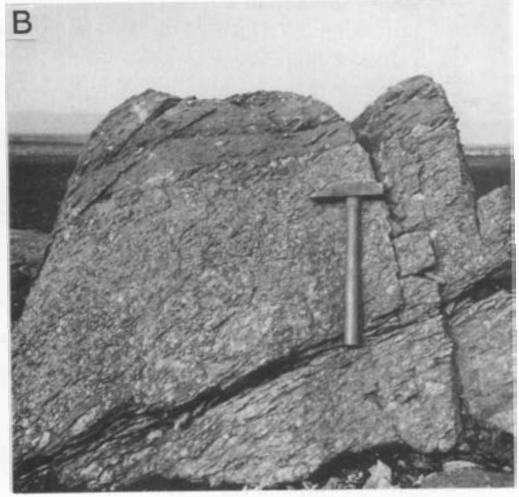
The *Upper Member* comprises dolomitic psammite (Fig. 44) and dolostone conglomerate (Fig. 44B) (Waddams 1983b), interbedded with occasional calcareous slate and phyllite containing dispersed dolostone and quartzite stones up to 1.6 m in length (Fig. 44C). The stones in the conglomerates are flattened in the plane of a well-developed cleavage (S^1), which is normally bedding-parallel.

The medium- to coarse-grained, buff-weathering dolomitic psammite occurs in beds 0.1–1 m thick, some of which are graded (Figs. 44A and 45). Dolostone or quartzite stones, 10–50 mm in diameter, are dispersed throughout most beds in widely varying proportions. Some have deformed and perforated underlying lamina forming good dropstone structures (Fig. 44D, F), although deformation has modified other such structures (Fig. 44E).

The coarse, crudely foliated conglomerate occurs in laterally extensive beds 0.1–4.0 m thick. A variety of lithologies, including granitoids not known from western Svalbard, are present (Table 14). There are significant variations of the proportions of stone types from one bed to another (Fig. 43), but dolostone (sometimes stromatolitic or oolitic) and quartzite are normally the most abundant, followed by limestone, with just a few per cent of other types (including granitoids). The degree to which these stones are deformed depends markedly on their composition, limestones being particularly stretched.

Some of the conglomeratic beds are massive and structureless (Fig. 47A) (except for cleavage), but most exhibit a well-developed, normal, coarse-tail grading (Fig. 47B). Some beds show both coarse grading and compound grading, i.e. recurrent grading in a single bed. Irregular wedge-shaped bodies of psammite occur within conglomerate beds (Fig. 46B). Boundaries between these lithologies are often diffuse (Fig. 46C).

At the base of some conglomerate beds, fingers or wedges of the underlying psammite protrude at low angles into the overlying conglomerate. These structures are 0.1–1.0 m long, and are aligned parallel to the tectonic foliation (S^1) which pervades both lithologies (Fig. 46D). Many psammite beds show signs of erosion, resulting in bed thickness variations from 0.5 to 0.1 m. A few beds show cross-bedding (Fig. 46C), but their use as palaeocurrent indicators is limited.



The *Lower Member* (Kolbebekken division of Waddams 1983b, but not recognised by Kowallis & Craddock 1984) is a grey quartzite and psammite which occupies the coastal plain northwest of Lognedalen and extends inland; it has not been observed on the eastern limb of the syncline. Thin interbeds of quartzite appear towards the base of the upper member and a gradational contact is inferred. The quartzite is coarsely crystalline, devoid of penetrative foliation (although lineated) and contains no dispersed stones. Thin dolostone conglomerate beds occur in the vicinity of Tomtvika.

The Lyellstranda Formation was formed by a variety of glacially influenced processes. The best indications of glacial deposition are the dropstones in the psammitic diamictites, units which would have formed in a proximal glaciomarine environment by ice-rafting. More distal glaciomarine conditions are reflected in the phyllitic units with dispersed stones. These units show transitional contacts, supporting a glaciomarine setting. The conglomerates comprise similar material to the diamictites, and probably were the result of reworking of glacially deposited material. Most were deposited from gravity-driven sediment flows in a similar manner to the older Kapp Martin conglomerates (Waddams 1983b), often accompanied by partial erosion and loading of the underlying bed.

6.4.2 Logna Formation (Htp) (about 200 m)

This formation is a dark grey phyllite. Its name derives from the river flowing westwards from Lognedalen (Fig. 42). Neither the top nor the bottom of the formation can be seen on the strandflat, but it has a concordant attitude with its bounding formations. It has also been mapped (as Htp) on the eastern limb by Kowallis & Craddock (1984) between the snouts of Scottbreen and Renardbreen. In the river section the phyllite is

soft, finely laminated (Fig. 46F) and with isoclinal minor folds parallel to the regional bedding. Dispersed stones have not been observed in this formation.

The origin of the Logna Formation is difficult to elucidate, but it does not appear to be glacially influenced. Most likely it accumulated slowly in deep water much further offshore than the adjacent formations.

6.4.3 Dunderbeisen Formation (Htl-Htcp) (about 1400 m)

This variable formation consists of alternating beds of psammite and phyllite, often with dispersed stones, conglomerate and stone-rich diamictite (Figs. 47 and 46B). It is named after the isolated peak to the north of Dunderbukta, and occupies much of southern Lognedalsflya as well as a small area north of the outwash area in front of Renardbreen to the east. In the western area most of the formation is an orange-grey weathering psammitic schist containing dispersed stones of dolostone and quartzite, together with lesser amounts of limestone and granitic stones. Proportions of different lithologies vary considerably, however (Table 14, Fig. 43). Dark grey phyllitic interbeds up to 3 m thick contain quartzite stones up to 0.75 m in length (Fig. 46A, B). On the eastern limb of the syncline the formation includes much laminated psammite-pelite with pebbles and boulders dispersed through the beautifully crenulated or isoclinally folded matrix (Fig. 46A, B). The largest stones in the east are 1 m in diameter and many are pitted and occur in beds of stone-rich diamictite a few metres thick (Fig. 46B, D, E). Conglomerate units often have gradational contacts with psammitic and phyllitic diamictites (Fig. 46A), but a few have sharp contacts. A good dropstone structure was observed in the psammite, but pelitic beds are strongly deformed (Fig. 46B, F). Four members may be

Fig. 44. The Lyellstranda Formation, Kapp Lyell Group on Lyellstranda and Dyrstadflya, northern Wedel Jarlsberg Land. A. Well-bedded, medium- to coarse-grained, buff-weathering dolomitic psammite with thin discontinuous limestone laminae and dispersed dolostone and quartzite stones. The lowermost psammite bed is graded and has a basal granule conglomerate. B. Coarse-tail graded conglomerate with clast flattening fabric (S1) at an angle to the bedding. C. Cream to grey-weathering dolostone boulder, 1.6 m long, in a grey, laminated, calcareous phyllite. D. A good example of a dropstone: a cream-weathering dolostone cobble in a coarse- to very coarse-grained dolomitic psammite. Note deflection and attenuation of laminae beneath the stone, but the parallel nature of the laminae draped over the top of the stone. E. An ambiguous dropstone: a quartzite cobble in grey quartzitic phyllite. Note roughly symmetric nature of laminae both above and below the stone; this may be the result of compaction during D, flattening. F. Probable dropstone in grey, laminated and calcareous phyllite. The stone is a 1 m long dolostone boulder.

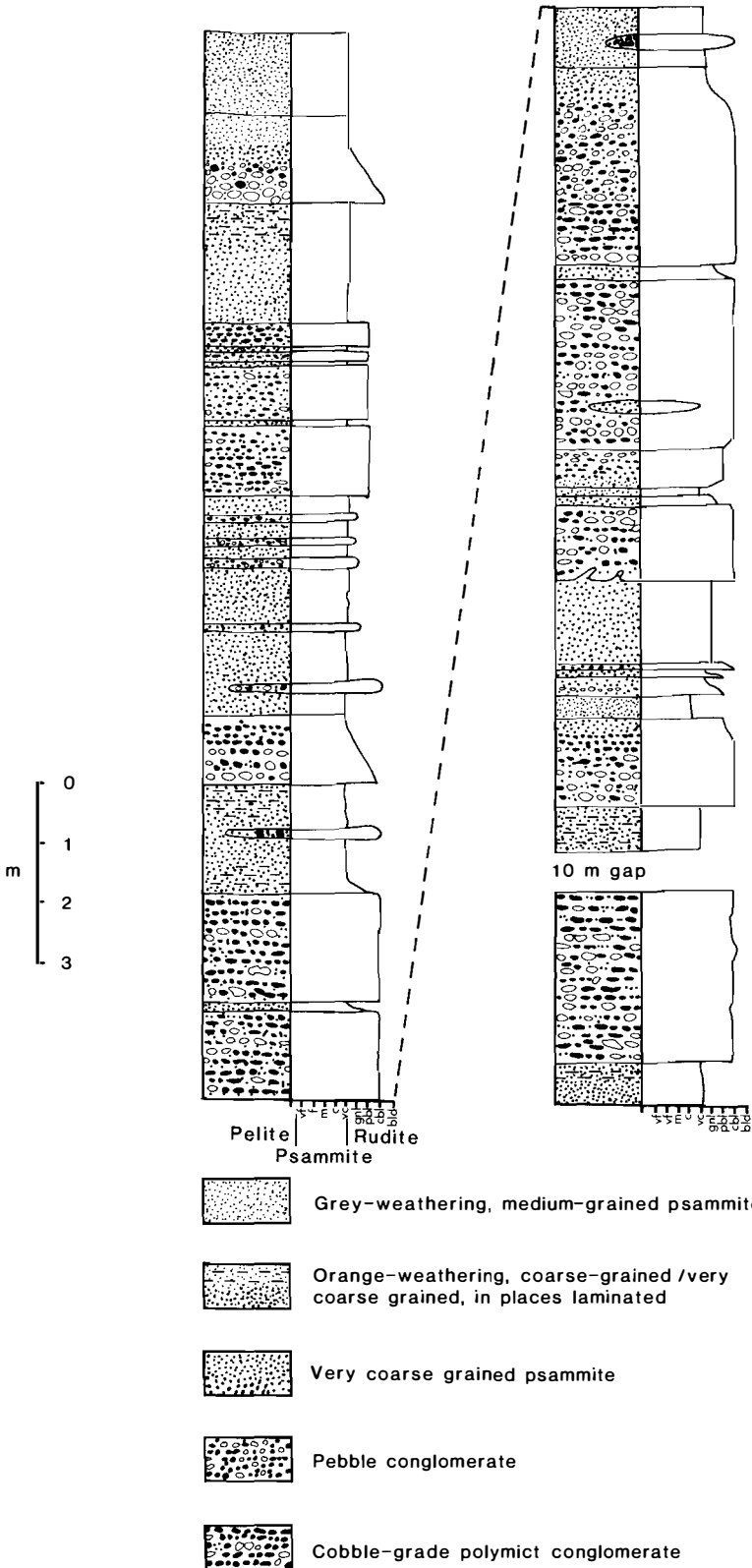


Fig. 45. Sedimentary logs through graded conglomerate and sandstone units of the Lyellstranda Formation, Lyellstranda.

distinguished, the upper three being stone-bearing with different compositions (Table 12).

The Dunderbeisen Formation, like much of the Lyellstranda Formation, is probably the result of deposition in a glaciomarine environment, largely proximal to a floating ice mass, though occasionally as a result of direct deposition from the floating glacier near the grounding line, as indicated by the boulder-rich horizons. There is no indication, however, of deposition from grounded ice. Reworking of till by subaqueous gravity flows was much less significant than in the Lyellstranda Formation.

6.5 Konglomeratfjellet Group

This is defined with four main formations in the east (following Hjelle 1969; Harland 1978; Waddams 1983a) and a basal one where the underlying unconformity is exposed in the west (Bjørnerud 1990).

The upper unit (Chamberlindalen and Dunderdalen formations) is of phyllites with occasional dolostone and quartzite beds and in the east with a conspicuous basic igneous component. The *middle unit* (Solhøgda and Slettjellaldalen formations) is of variable facies dominantly carbonate (dolostone and limestone one). The *main lower unit* is of extremely variable rudites: mainly conglomerate in the east (Gaimardtoppen Formation) and with diamictite in the west (Fløykalven Formation). The lowest *Thiisfjellet Formation* is an intermittent basal conglomerate and limestone seem only in the west.

Facies and thickness contrast greatly between east (thicker and coarser) and west; but there is no doubt about their general correlation because the outcrops are continuous in the south. Facies variation would suggest a transport direction from east to west. Thicknesses in the east of the non-conglomeratic units were estimated as 2950–3500 m (Turchenko et al. 1983b), 1540 m (Kowallis & Craddock 1984) and 3350 m (Craddock et al. 1985).

6.5.1 Vestervågen Formation (about 340 m)

The name (as a division) was given by Waddams (1983b) to a succession of massive grey quartzite, interbedded with quartzitic slate and soft phyllite, which is poorly exposed along the west shore of Vestervågen. It is equivalent to Hjelle's (1969) Konglomeratfjellet shale and quartzite beds and Harland's (1978) slate and quartzite division. It

does not appear to have been distinguished from a thick phyllitic unit by Craddock et al. (1985).

However, the outcrop disappears along the NE–SW strike and contacts with the bounding formations are obscured. The succession dips towards the northwest and probably lies conformably beneath the overlying Kapp Lyell Group, from which it is distinguished by the absence of stones. It does not crop out in the west.

No indications of the depositional environment of this formation have been observed, but it probably represents a near to offshore deposit with no glacial influence.

6.5.2 Chamberlindalen Formation (Hp, Hg, Hgb, & Hlpu) (about 1–2 km)

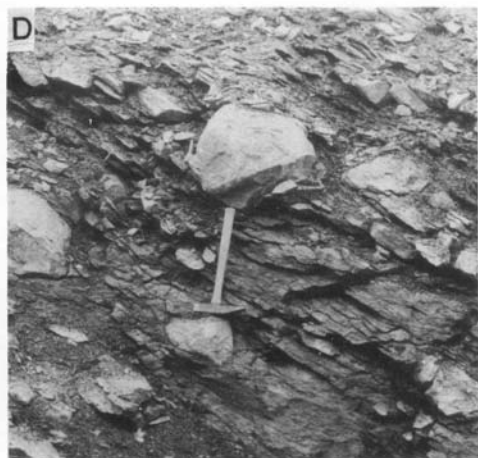
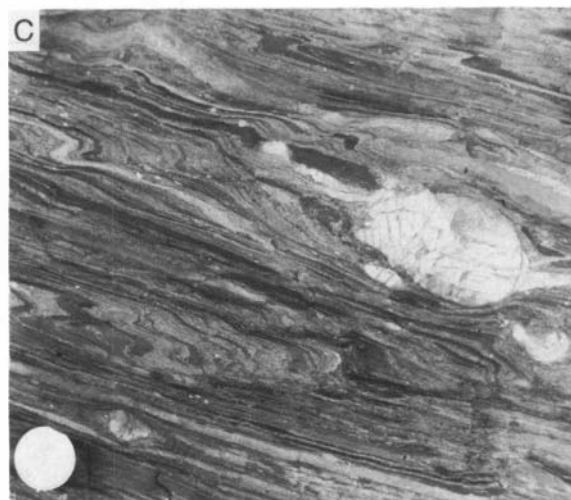
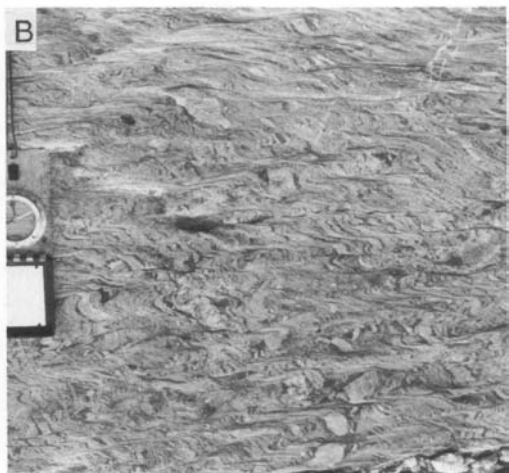
The name is from the eastern outcrop (Harland 1978) where the succession is thicker, more varied in lithology and better exposed (with ridges and knolls) than in the west where the Dunderdalen Formation has been recently proposed as an equivalent (Bjørnerud 1990). The outcrop everywhere define the broad valleys from which the rocks have been named. Isoclinal folding of the dominant pelites resulted in phyllites which are the least well-exposed element in the formation, and so make thickness estimates suspect, especially in the east.

In the east, to the two divisions of Harland (1978) a third is now added at the top making three members.

The *Upper Member* is exposed to the southwest of Vestervågen and consists of grey slate with calcareous concretions, thin amygdaloidal lava flows and calcareous pyroclastic rocks. The grey

Table 14. Estimated stone composition of schistose diamictite and conglomerate. Kapp Lyell Group, northern Wedel Jarlsberg Land (cf. Fig. 43).

Stones	Lyellstranda Formation (W. limb) %	Dunderbeisen Formation (E. limb) %
Dolostone	43	45
Quartzite	40	41
Limestone	7	8
Green schistose metavolcanics	6	6
Granite	4	4



slate interbeds suggest a gradational contact with the overlying Vestervågen Formation.

The *Middle Member* comprises well-bedded grey limestone and marble (top), cream-weathering dolostone, grey oolitic limestone and dark amygdaloidal basalt. Dolostone clasts a few centimetres long have been observed in limestone beds. Some may be altered pyroclastics. These more competent strata appear to be interbedded with phyllites that are not so well exposed.

The *Lower (Asbestodden) Member* is dominated by basic igneous rocks, including pyroclastics, lavas (some pillow) and small intrusions. At Asbestodden basic igneous rocks have altered to asbestos. Pelites and carbonates are interbedded with the volcanic rocks.

The *igneous rocks* have been described by Turchenko et al. (1983b). The principal types are: *picrites*, preserving traces of the original porphyritic texture; *basalts* are both porphyritic and amygdaloidal; *andesites* have a myrmekitic texture with up to 25% quartz; *gabbro-diabases (dolerites)* have a generally massive to poorly schistose texture, preserving original ophitic and porphyritic textures. *Sedimentary rocks*, contain much tuffaceous material (e.g. in green phyllites).

Transitions exist between all these types and all of them belong chemically to a single basalt-trachyandesitic series of tholeiitic character. Crustal stretching may have allowed a certain amount of rifting, resulting in intrusion and extrusion of mantle material (with crustal contamination), into a shallow marine basin dominated by carbonate deposition.

Dunderdalen Formation (equivalent to Chamberlindalen Formation) (more than 1900 m in Orvindalen)

Beneath the Kapp Lyell Group in lower Dunderdalen is a poorly exposed formation. Orvin's map (1940) suggested that the valley was underlain by a thick succession of pelite with discontinuous quartzite bodies. Flood, Nagy & Winsnes (1971) showed pelitic rocks in the central and southern parts, and Harland suspected that

the valley is underlain by pelitic schist and phyllite with a thickness of 0.5–1 km. Bjørnerud (1990) independently named it the Dunderdalen Formation. Silvery, grey and green quartzite and carbonate units (sometimes brecciated, often isolated) have been interpreted as olistoliths.

Traverses in 1983 through Orvindalen and Turrsjødalen gave us a generalised picture of the lower part of the Dunderdalen Formation and the underlying units in the south. In Orvindalen the traverse began at the western margin of Langköllbreen and crossed steeply dipping strata on the lower slopes of Kleppane and Kvassniiken to the mouth of the valley. The Turrsjødalen section traversed the southern slopes of the same mountains along the side of Turrsjøbreen and on to the mouth of the valley. Exposure is often good in isoclinally folded foliated phyllites, while many carbonate beds reveal little deformation, and preserve some sedimentary structures. Graded bedding confirms the synclinal structure with younging towards the east:

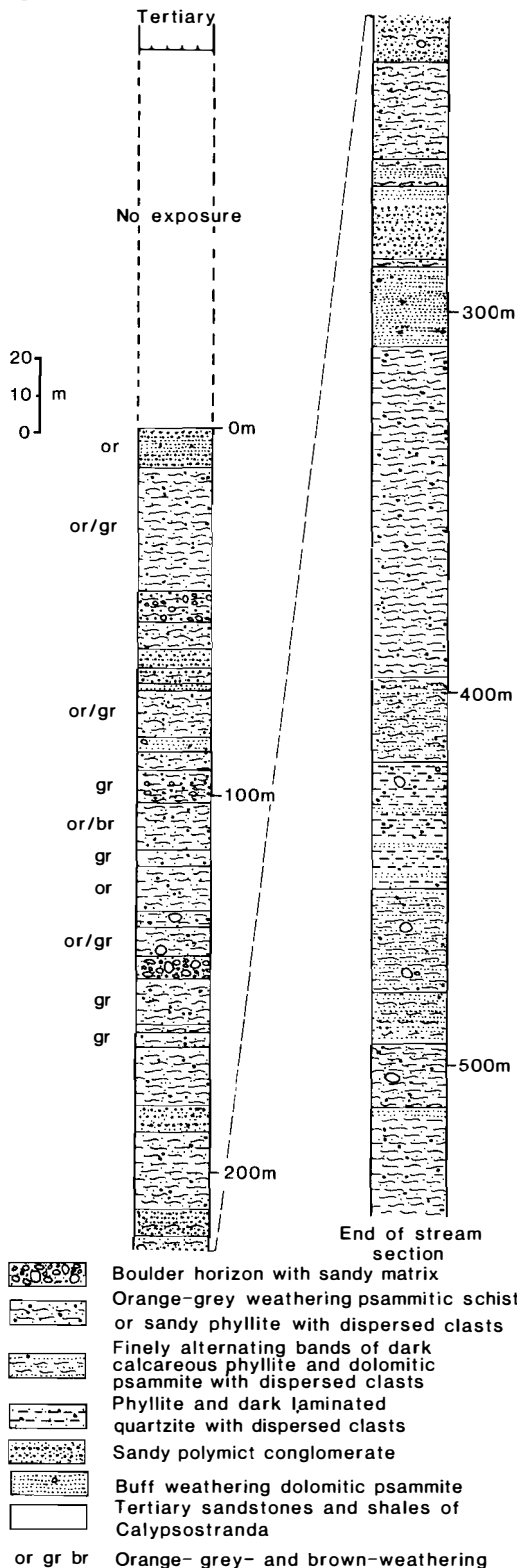
(3) about 140 m: dark grey phyllite with minor dark grey psammite and grey dolostone.

(2) about 50 m: pale grey to cream-weathering dolostone with phyllite interbeds. The dolostone variously is bedded, intraformationally and auto-brecciated, pisolitic and stromatolitic. Bedded units are dolomicritic and contain minor silt. The pisoliths are undeformed and often have formed around quartz grains. The stromatolites occur in scree as complete concentrically laminated round blocks up to 0.4 m in diameter (Fig. 46C). Some stromatolites have developed on brecciated fragments of earlier stromatolites. Stromatolite layers are alternately dolospar and dolomicrite are rather diffuse. Quartz-filled fenestral and vein quartz and chert are also developed.

Deposition of this unit appears to have been in shallow water that was in part affected by strong tidal currents.

(1) about 1700 m: poorly exposed dark grey phyllite with thin interbeds of dolostone. The phyllite consists of tectonically transposed laminae of quartz sand and mixed chlorite/silt.

Fig. 46. Dunderdalen Formation: near northern margin of Renardbreen, south of Bellsund (A–E). A. Gradational contact between boulder-rich horizon and phyllite with dispersed stones. B. Clast-rich, crenulation folded psammite with thin laminae of pelite; F_2 and S_2 are the dominant structures. C. Laminated, carbonate-rich, stone-bearing pelite and psammite, with pronounced F_1 similar and isoclinal folds. Note the relatively undeformed dolostone clast. D. Poorly sorted, boulder-rich horizon with phyllitic matrix. E. Stone-rich diamictite, showing variable deformation of dolostone, quartzite and granitic clasts. F. Stromatolitic dolostone from a thin unit in the Dunderdalen Formation, upper Orvindalen.



Although there is no obvious grading, the laminae may have been graded before deformation. A deformed, poorly sorted conglomerate containing rounded to subrounded quartzite clasts in a greenish matrix was also noted. Much of this unit (like unit (3)) may be a distal turbidite, though the conglomerate suggests that it was deposited from a proximal turbidite.

6.5.3 Solhøgda Formation

In the east more than 300 m of dominantly carbonate units seen in the mountains east of Chamberlindalen and the cliffs west of Recherbreen with three members distinguished at a distance by colour:

Upper: bedded grey limestone and dolostone predominate.

Middle: yellow weathering marbles dolomitic and black bituminous limestone.

Lower: pale yellow weathering dolomite marbles with dark volcanics and sills.

In the west Bjørnerud defined the thinner equivalent as the *Slettjelldalen Formation* (50–100 m) of dolosites and limestones with much facies variation. Cross bedding, sedimentary breccias, digitate stromatolites, and chert beds show sedimentary structures less deformed than in the east.

In the southwest our traverses east of Storvika crossed this formation (which we referred to as the *Orvindalen Formation* in 1983) estimated about 285 m thickness.

(3) about 200 m: a variable unit dominated by white or cream-weathering, weakly laminated dolostone with thin interbeds of phyllite. Laminated dolostone often contains quartz silt with carbonate and carbonate/chlorite, interlaminated with dolomicrite which has undergone partial neomorphism and replacement by quartz. Dolostones show small-scale scour structures, oolitic beds, stromatolites and autobrecciation. In the middle, a dolostone diamicrite occurs. It contains dispersed stones of dolostone (some showing development of fenestrae) as well as quartz silt and quartz fragments up to 30 mm in diameter in a carbonate/chlorite matrix. In places it is streaky with irregular lamination, clasts showing dis-

Fig. 47. Section through part of the Dundrabeisen Formation, in the stream issuing from the north margin of Renardbreen, extending to the edge of the Tertiary graben near Renardodden.

ruption of the laminae; however, much of it is massive. The massive and laminated diamictites make up a 25-m-wide zone of in situ debris.

(2) about 40 m: dark grey phyllite with a thin band of greywacke.

(1) about 45 m: orange to brown-weathering dolostone.

This formation represents a variety of environments from probable offshore distal turbidites (phyllites) to shallow marine influenced by tidal currents (oolitic and stromatolitic dolostones with channels). The dolostone diamictite could be a shallow marine deposit influenced by ice-rafting (possibly sea ice). In the south the head of Chamberlindalen, on the flanks of Konglomeratfjellet, a substantial thickness of dolostone breccia/conglomerate with clasts up to 0.5 m long occurs at the base of the formation.

The depositional environment for the Solhøgda Formation is poorly known, but a shallow marine sea is envisaged, with minor volcanic activity. The breccia may have been a result of instability triggered by faulting.

6.5.4 Fløykalven Formation (in the west)

This was shown to one of us by T. S. Winsnes in 1979 at Fløykalven west of Dunderdalen. It is a typical diamictite rich in quartzite and carbonate stones. The latter with occasional oncolites and stromatolites. It is in the western outcrop of Bjørnerud's Konglomeratfjellet Formation and is divided by her into two divisions – a lower brown coloured part (400 m) and an upper green coloured part (300 m).

Our 1983 traverse west of Storvika (in the south) confirmed its continuity and stratigraphic relations with a thickness of about 490 m. Two divisions (members) were recognised:

Upper division about 330 m: dark grey phyllite with dispersed clasts, but locally with higher concentrations. Clasts are dominantly dolostone, quartzite and vein quartz up to 0.35 m long. No granitoid clasts have been observed. The matrix is silty carbonate with chlorite defining an irregular foliation.

Lower division about 160 m: light brown weathering dolostone with dispersed clasts to clast-rich dolostone-quartzite conglomerate, one bed showing coarse-tail grading. Some dolostone is laminated with coarse sand concentration and onestones.

This formation resembles the Trondheimfjella

Formation of Oscar II Land, and a similar depositional process is inferred (ice-rafting into distal turbidite basin). The single conglomerate observed suggests a subaqueous gravity flow in a more proximal setting.

Gaimardtoppen Formation (in the east)

This name applies to the conglomerate formation – the most distinctive and lowest of the three formations to which the name Konglomeratfjellet was applied by Hjelle (1969). Accordingly we used that name for the group in the original sense and need a new name for the conglomeratic part of it. Harland in 1978 used Gaimardtoppen and Foldnutane for the two divisions of this unit; but Foldnutane is perhaps inappropriate and is dropped. The two divisions are thus:

Upper member (= Gaimardtoppen division (Harland 1978) and Hylp (phyllite limestone) of the Wisconsin group (about 0.5 km).

It is essentially dark calcareous psammites and pelites, exposed in cliffs below the summit of Gaimardtoppen along the western flanks of Recherchebreen. Some moraine samples are laminated fine-grained rocks with dispersed stones of subangular limestone, dolostone and quartzite; other samples are more pebbly and bouldery. This unit (Hylp) was mapped by the Wisconsin group systematically above the more obvious conglomerate unit.

The lamination in this formation suggests deposition in a distal turbidite basin into which there was a limited supply of ice-rafted material by glacier or sea ice.

Lower member (= Konglomeratfjellet conglomerate beds of Hjelle 1969; Foldnutane division of Harland 1978; Konglomeratfjellet Formation of Bjørnerud 1990). This is the lowest exposed formation in the western sequence between Chamberlindalen and Recherchebreen and is dominated by conglomerate.

The conglomerate comprises well-rounded quartzite clasts, deformed into elliptical shapes as long as 1 m. Minor dolostone and limestone clasts are also present. These clasts are set in a matrix of phyllite (Craddock et al. 1985), which only rarely supports the clasts. The well-rounded, well-sorted nature of this conglomerate suggests long distance transport in a powerful flow regime. Possibly it represents an outwash deposit in view

of its association with apparent glacially influenced sediments.

Bjørnerud (1990) remarks that about 5% of the Konglomeratfjellet conglomerate stones are granitic or gneissic and may be derived from the Magnethøgda sequence a few kilometres to the east.

6.5.5 *Thüsffjellet Formation (0–50 m)*

This is the basal unit (0–50 m) resting on the unconformity described by Bjørnerud (1990) as a “gritstone/conglomerate with grey- to orange-weathering dolomitic matrix” and intermittent in outcrop. It is overlain by black, pyritic, phyllitic limestone (50 to 100 m) with isolated beds of quartz pebble conglomerate. If developed in the east it is obscured by Recherchebreen. In 1983 we did not distinguish the unit or the unconformity, suspecting faulting.

6.6 *The older rocks*

From our observations in the east older rocks include our Magnethøgda unit east of Recherchefjorden (Harland 1978) and referred to by Bjørnerud (1990) as the Magnethøgda Sequence with six units. In the west an extensive terrane beneath and west of the unconformity was mapped by Bjørnerud and colleagues who distinguish 11 rock units combined into 8 formations. The bottom two were referred to by us as the Storvika formation and the next two as the Thurosfjorden Formation in the first draft of this paper submitted in 1987.

We show these units in Table 12 but do not detail them here as we are confident from Bjørnerud's work that both sequences are pre-Vendian.

6.7 *Correlation problems*

We are not aware of any significant difference between workers in Oslo, Wisconsin and Cambridge on the correlation made in this chapter within Wedel Jarlsberg Land. The rocks were formed in a mobile environment so that detailed correlation is premature but their general equivalence is clear.

There are differences between us, however, in

correlating outside the area considered in this chapter. Table 12 (in parentheses) shows the correlations postulated in Bjørnerud (1990) and Dal-land et al. (1990) with the area immediately to the south around Hornsund on the basis of the stratigraphic scheme set up by Birkenmajer and his colleagues (Birkenmajer 1959, 1981). Correlation via Hornsund is then made with Ny Friesland and on this basis most of our Konglomeratfjellet Group would be pre-Varanger whereas we are confident that it is early Varanger. Our own reinterpretation of the southwest Wedel Jarlsberg Land sequence in the next chapter if correct would put the alternative correlations in doubt.

One consequence of further field work is that we no longer correlate the Magnethøgda rocks with the Revdalen or any rocks to the south. We now regard all the rocks west of Hansbreen to the south and west of Recherchebreen as belonging (with all the sequences treated in our chapters 3 to 6) to the Western terrane – west of the Western Spitsbergen Fault Zone. The lineament is now postulated to lie along Recherchebreen and Hansbreen and no longer along Torellbreen.

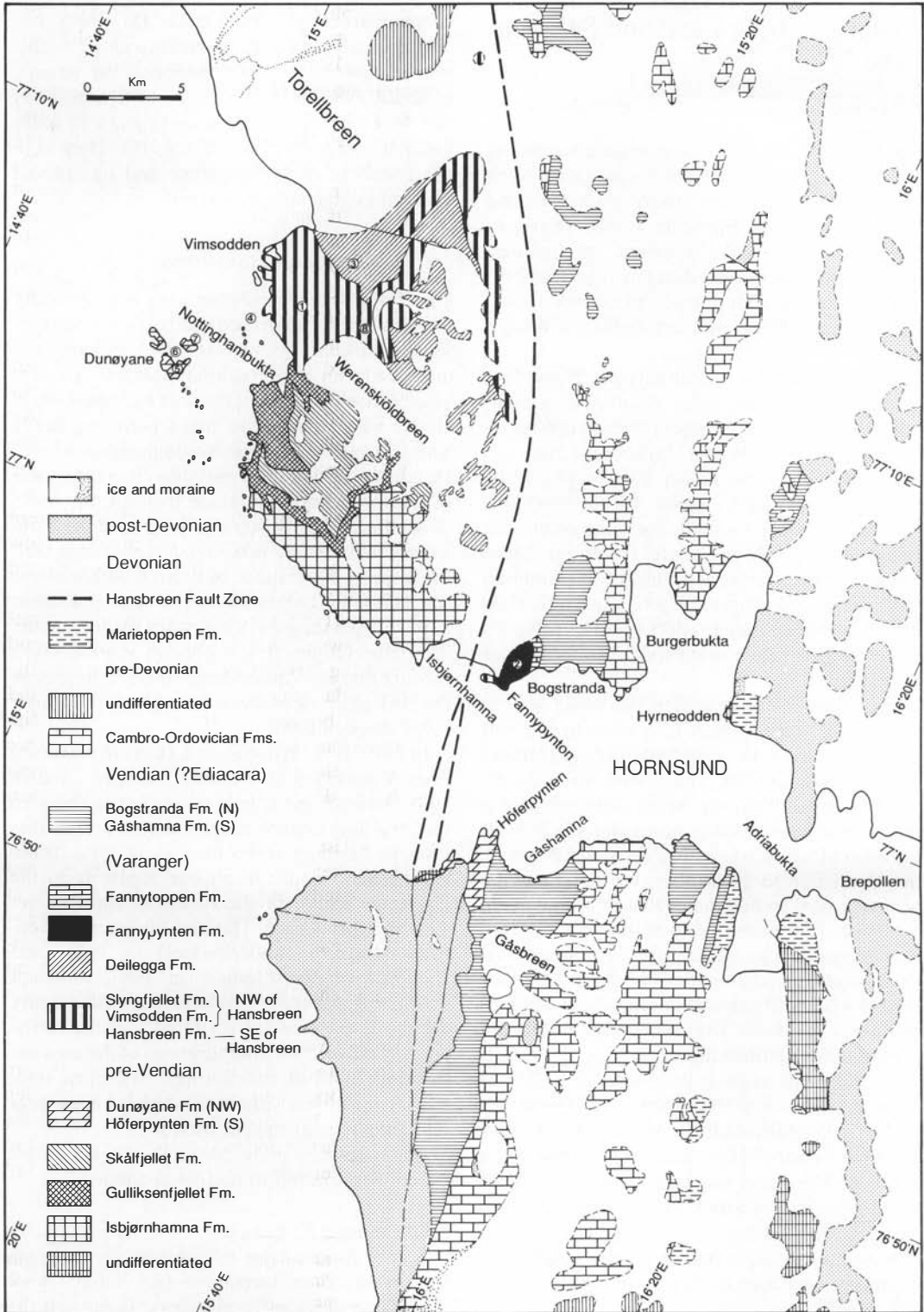
Bjørnerud (1990) demonstrated a major unconformity between the Nordbukta sequence and the overlying Vendian rocks. We agree that the Magnethøgda sequence is also pre-Vendian and might even be coeval. However, it differs significantly from the Nordbukta sequence and we think they belong to different terranes – this argument will be developed in a paper on pre-Vendian rocks.

The criticism of our terrane boundary by Bjørnerud, Decker & Craddock (1991) rightly, as we think, rejected that fault as passing out to sea at Torellbreen. We redefine this Kongsfjorden – Hansbreen Fault (separating the central and western terranes) with arguments for its realignment in the next chapter.

6.8 *Western Nathorst Land*

Marbles and quartzites crop out at the western tip of Nathorst Land across Van Keulenfjorden to the north. We correlated these rocks with the Magnethøgda Group and therefore consider them to be pre-Vendian as also do Dallmann et al. (1990).

Fig. 48. Generalised geological map of the area north and south of Hornsund based on maps by Major & Winsnes 1955, Birkenmajer 1960a,b, 1978, and Flood, Nagy & Winsnes 1971. Place names: Elveflya 1; Fannytoppen 2; Tonedalen 3; Pytholmen 4; Støre Dunøya 5; Dunøyhamna 6; Fjørholmen 7; Jens Erikfjellet 8.



7 Southern Spitsbergen: southwest Wedel Jarlsberg Land and Sørkapp Land

7.1 Introduction and history of research

For discussion it is convenient to treat separately the area south of Torellbreen because most work there has been done from bases around Hornsund, and the literature mainly relates to that area. Moreover, previous stratigraphic schemes have been derived largely from the north and south coasts of Hornsund and extended north into Wedel Jarlsberg Land and south into Sørkapp Land.

Sørkapp Land was first surveyed by Norsk Polarinstitutt geologists, their results being summarised by Major & Winsnes (1955) and Winsnes (1955). Southern Wedel Jarlsberg Land was explored mainly by Polish parties (e.g. Birkenmajer 1958, 1959, 1960a, b). In 1960 Birkenmajer produced a unified scheme combining results from north and south Hornsund. More comprehensive syntheses of the late Precambrian succession in southern Spitsbergen were published by Birkenmajer (1975, 1981). Table 15 abstracts these schemes for rocks that we take to be Vendian.

Since 1966 we have visited Hornsund several times and in some respects have come to different conclusions from the other authors (e.g. Harland 1978). In our opinion, the reason for such differences stems from the initial assumption of a fixist tectonic evolution in which all rocks in Svalbard were formed approximately where they now are in relation to each other. On this basis the sequence here should match that of northeastern Svalbard. Consequently some diamictites were not interpreted as tillites, possibly because on that correlation scheme they did not fit. Another difficulty is the difference between the successions northwest of outer Hornsund, and north and south of inner Hornsund.

We discuss the rocks in three sections: (7.2) that from Torellbreen to Hansbreen (in Hornsund); (7.3) middle Hornsund; i.e. on the north shore of Hornsund east of Hansbreen and on the south shore of Hornsund (Sørkapp Land); and (7.4) south western Hornsund. These areas are shown on the revised geological map (Fig. 48), which is modified from Birkenmajer (1960b, 1978). His comprehensive map (1990) was not available for this paper.

We begin by tabulating Birkenmajer's scheme as summarised in 1975 (Table 15) which was intended to embrace the whole area under discussion in this chapter. We then give the scheme of Krasil'shchikov & Kovaleva (1979) which has been used as the basis for correlation of older rocks in western Svalbard (Table 16). They were not confident of the sequence and interpreted diamictites generally as tectonic.

7.2 Torellbreen to Hansbreen

The Torellbreen/Hansbreen area is tectonically complex and the map used was that shown in Fig. 48 from Birkenmajer (1960a, 1978), supported at that time by an outline stratigraphic text. There is a detailed map of part of the area by Smulikowski (1968) who studied the rocks petrographically where accessible from the Nottinghambukta base. He concluded that the Vimsodden Formation was of lower metamorphic grade than are the rocks of the Eimfjellet Group and he placed the Vimsodden rocks, as did Birkenmajer, above the Guliksenfjellet Formation, but also possibly above the Skålfjellet Formation rather than equivalent to it, so separating the Vimsodden rocks from the Eimfjellet Group. It is implicit in Smulikowski's account that the Vimsodden Formation lies below the Deilegga rock as was assumed by Birkenmajer (1959 through 1990).

In 1979 T. S. Winsnes and Harland traversed from Vimsodden to Lower Tonedalen, and in 1983 Harland and Hambrey worked in the area for a few days from Nottinghambukta with further visits by Harland and colleagues in 1992. There has been no doubt in all our minds as to the glacial nature of the rocks (as Birkenmajer 1959 first proposed). Harland observed a drop-stone structure (under water) in 1979, and Hambrey observed others in 1983, although weathering generally obscures fine sedimentary details. Exposures are scattered and the stratigraphic and tectonic complications of the area are therefore difficult to interpret. We draw only broad conclusions without the detailed discussion that Smulikowski's paper merits.

The succession in the Nottinghambukta area is described from top to bottom as follows.

7.2.1 Deilegga Formation

Whereas Birkenmajer referred to the Deilegga Group with three formations (see Table 15) we rank these divisions as members. Being soft the

Table 1.5. The Hornsund sequence according to Birkenmajer (1959–1975). Symbols in parentheses refer to his 1960a map.

Super-group	Group	Formation	Diastrophism	Age	Correlation with Ny Friesland
D Z C S	Sørkapp Land 1.4 km	(several formations (O))		mainly Early Ordovician	
	Sofiekammen	Nordsteintinden (N)	(HORNSUNDIAN)	Middle & Late Cambrian ?	Oslobreen
		Gnålberget Marble (G)		Middle Cambrian ?	Group
		Slakli (S)		Early Cambrian ?	
H O R N S U N D	Sofiebogen 1.6 - 3.7 km	Blåstertoppen Dolomite (B)	(JARLSBERGIAN)	Early Cambrian ?	
		Gåshamna Phyllite (Ga) Höferpynten Dolomite (H) Slyngfjellet Conglomerate (Sy)		Vendian and Late Riphean (Carolinidian)	Polarisbreen Group Akademikerbreen Group Veteranen Group
Z N F E N	Deilegga more than 3.5 km	Upper Bergskardet (Du)	(TORELLIAN)		
		Middle Bergnova (Dm)			
		Lower Tonedalen (D1)			Planetfjella Group
R F E L L B R E N N	Eimfjellet 0.6 -3.5 km	South-East	(WERENSKIÖLDIAN)		
		North-West			
		Skålfjellet Subgroup (Sk)			Harkerbreen Group
		Vimsodden Subgroup(V)			
T O R E L L I A N	Isbjørnhamna 1.7 - 3.0 km	Gulliksenfjellet (Gu)			
		Revdaalen (R)			
		Ariekammen (A) Skoddefjellet (Sd)			Finlandveggen Group

Table 16. General stratigraphic scheme for the Proterozoic sequence of western Svalbard, based on successions south of Isfjorden, according to Soviet authors (Krasil'shchikov & Koraleva 1979).

Age	Group	Formation	Thickness (m)	Lithology
Vendian	Bellisund	Kapp Lyeil	>500	Schistose conglomerate with 5-40% dolomitic psephite material
		Kapp Linné	250 - >300	Phyllite with boulder beds, stone content small; associated with clastic dolostone and limestone
		Slyngfjellet	300 - 800	Quartzite conglomerate
Middle - Upper(?) Riphean	Sofiebogen	Höferpynten	200 - 300	Limestone, dolostone, quartz-carbonate schist, quartzite, quartz gritstone
		Gashamma	400 - 1200	Sericitic shale with occasional sandstone and carbonate (metamorphosed)
	Werenskjold-breen	Dunderbukta	300 - 500	Black shale and phosphate - carbonaceous limestone
		Vimsodden	700 - 800	Quartzite, chlorite mica and carbonate schist, black shale and amygdaloidal basalt
Middle - Upper Proterozoic (undiff.)	Isbjørnhamna	Skålfjellet	>800	Actinolite schist with coarse-grained actinolite gabbro-dabase bodies, and chlorite-muscovite schist with quartzite bands
		Revdalen	1500 - 2000	Crystalline schist
		Ariekammen		Marble and crystalline schist } amphibolite facies metamorphism
		Skoddefjellet		Crystalline schist

Base of successions exposed in individual areas are as follows:

- Oscar II Land - Dunderbukta Formation
- Nordenskiöld Land - Vimsodden/Dunderbukta Formation
- N. Wedel Jarlsberg Land - Vimsodden Formation
- S. Wedel Jarlsberg Land - Skoddefjellet Formation

rocks have been exploited by glacial erosion. They are commonly dark grey to black phyllites, often crenulated, with some marbles in the lower part, passing up into more calcareous and coarser turbiditic rocks, typically of flyschoid character. We take Birkenmajer's thickness of 3.5 km and reduce the thickness of the Vimsodden Formation to 4 km by removing the uppermost phyllites.

With the Polish group we agree that the Deillegga rocks are younger than the Vimsodden Formation; but we are not satisfied that the Slyngfjellet Conglomerate is even younger.

The *Slyngfjellet Conglomerate* near to its eponymous locality at the head of Werenskiöldbreen and overlooking Hansbreen, has a similar composition to the Vimsodden diamictites (Fig. 55C). It is a moderately sorted sandstone-pebble conglomerate, dominated by quartzite stones in a carbonate/silt-sand matrix. We agree with Smulikowski (1968) that these conglomerates are unlike the so-called Slyngfjellet Conglomerate of Birkenmajer 1960a, b at Fannypynten in Hornsund.

By analogy with the situation further north, where the Gaimardtoppen Formation (similar to the Slyngfjellet facies) is, by mapping, shown to correlate with the Fløykalven Formation (similar to the Vimsodden diamictites), we favour the hypothesis that the Slyngfjellet Conglomerate is an eastern facies derived from Vimsodden tills as seen in the west.

7.2.2 The Vimsodden Formation

The Vimsodden Formation was first described by Birkenmajer (1959) as glacialic and it was correlated (also by Harland 1960 and Wilson & Harland 1964, p. 217) with the Rittervatnet tilloid in the Harkerbreen Group in Ny Friesland. We agree with the glacial origin but now correlate the Vimsodden Formation with the older Varanger tillites that we describe above in all Spitsbergen outcrops. The succession measured from Vimsodden to Tonedalen gives a stratal thickness of nearly 5 km (Fig. 49) but with gaps and occasional diamictites which match well in appearance and stone content the rocks further north (e.g. Fløykalven), especially because of their content of dolostones and lack of feldspathic rocks.

A paced traverse made in 1983 by Hambrey through part of the Vimsodden Formation inland over Elveflya from the tombolo opposite Pytholmen (off Vimsodden), yielded the following

sequence, although exposure in the upper (inland) part of the sequence is poor and thicknesses of the upper units (7) to (5) are crude estimates. It corresponds in part to the lower part of the section shown in Fig. 49:

(7) >250 m: chloritic phyllite with minor quartz, psammite and a thin band of whitish quartzite. Mixed phyllites and psammites extend along strike into the base of Jens Erikfjellet.

(6) 300 m: brownish psammite with isoclinal folds, consisting of alternating laminae of quartz silt, and minor carbonate and silt.

(5) 300 m: brown, fissile, stone-rich diamictite, passing down into a variable phyllite horizon, with dispersed stones of quartzite and carbonate predominating (Fig. 50A). The matrix is chloritic with some feldspar. The lower boundary is gradational.

(4) 150 m: a highly calcareous rock or marble with dispersed stones of dolostone up to 10 cm long, and some of quartzite. The matrix consists of carbonate with quartz silt and sand.

(3) 200 m: brown-weathering psammitic diamictite with stone content declining downwards. There are abundant stones of white vein quartz and grey quartzite (80%), and fewer stones of dolostone. They reach 0.25 m and are flattened in the main foliation (S¹). Their shapes vary from rounded to angular, with a preponderance of subangular and subrounded varieties. The matrix is laminated and probable dropstone structures, which disrupt it, indicate younging to the north. The matrix contains roughly equal amounts of quartz silt and carbonate with minor chlorite. This grades over 1.5 m into:

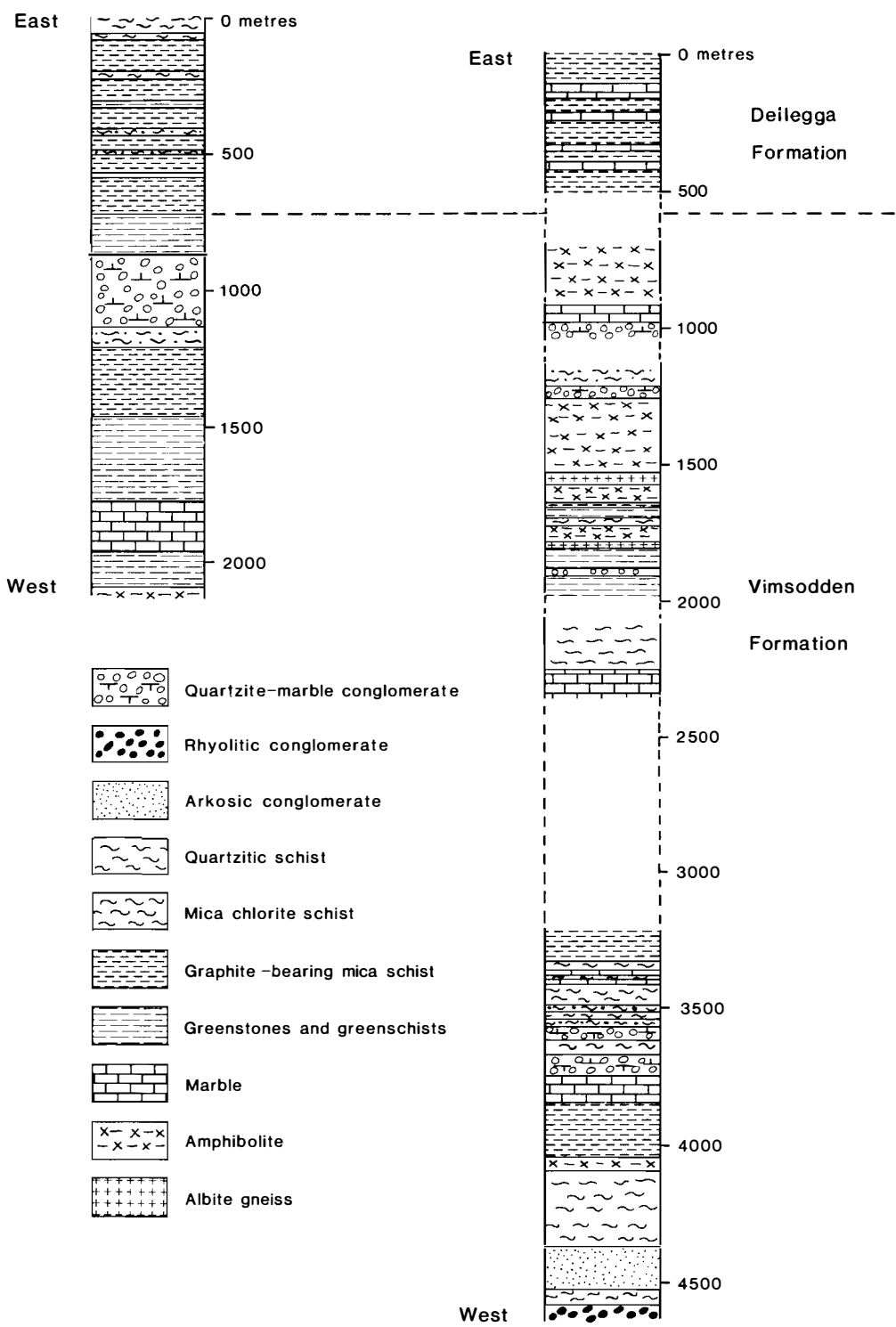
(2) 250 m: black to dark grey phyllite.

(1) 120 m: greenish phyllite (Fig. 50B) with quartz veining some of which is disrupted into isolated fold hinges and boudins. It is also weakly crenulated and cut by a dolerite dyke 1.5 to several metres wide opposite Pytholmen.

The general similarity of the psammitic diamictites, psammites, phyllites and marbles with the Trondheimfjella Formation in Oscar II Land, and in particular the dispersed nature of stones (some probably dropstones) in a finely laminated matrix, suggests that it formed by ice-rafting into a distal turbidite basin, with background carbonate sedimentation. The lateral transition into Slyngfjellet-type conglomerates suggests reworking of the glacialic sediment by aqueous

North side of Werenskioldbreen

Pyttholmen - Tonedalen



processes, possibly involving submarine gravity flows.

The Vimsodden Formation is also rich in metamorphosed presumed volcanic rocks, mainly tuffs (e.g. green schists) and possibly lavas (e.g. amphibolites), all interstratified with a variety of facies in which diamictites form only a small proportion, but being distributed throughout. The petrology of these rocks was described by Smulikowski (1968). On the basis of the dropstones, the steeply dipping succession is believed to be slightly overturned and younging towards the NNE (i.e. towards the Deilegga Formation).

7.2.3 Skålfjellet and Gulliksenfjellet formations

The Skålfjellet Formation is largely made of basic igneous material (Smulikowski 1968). Birkenmajer (1959), considered it to be the southeastern lateral equivalent of the Vimsodden Formation, whereas Smulikowski (1968) thought it to be older because it was more intensely metamorphosed. In any case, both formations are rich in basic volcanics, and both overlie the Gulliksenfjellet quartzites. Moreover, the Vimsodden Formation seems to be in stratigraphic contact with the Gulliksenfjellet quartzites by the Nottinghambukta coast. The Gulliksenfjellet quartzites, like the overlying metasediments, are carbonate-rich. They become more pelitic upwards (Fig. 50D).

7.2.4 Discussion of revised Vendian stratigraphy

Birkenmajer placed the Vimsodden, Skålfjellet and Gulliksenfjellet formations in the Eimfjellet Group, and we concur that they are difficult to separate. The map, Fig. 48, suggests that the Gulliksenfjellet Formation is the oldest.

In accepting this grouping, we would go further and, as argued above, include also Birkenmajer's Deilegga Group (our Deilegga Formation).

We regard the Deilegga and Vimsodden formations as closely associated and belonging to one subgroup between 7 and 8 km thick. We correlate the rocks with the Konglomeratfjellet Group further north and especially with its lower diamictites (Fløykalven Formation) or conglomerates (Gaimardtoppen Formation), and the associated carbonates, basic volcanics and pelites. Krasil'shchikov & Koraleva (1979), in their composite diagrammatic section "Dunderbukta and

Konglomeratfjellet", correlated the Deilegga with their Dunderbukta Formation and placed it above the Vimsodden Group, with which we agree; however we disagree with their making the Slyngfjellet Conglomerate everywhere younger.

Thus we propose one large group of variable facies and thickness possibly exceeding 10 km. Birkenmajer divided his Eimfjellet and Deilegga groups by a Werenskiöldian diastrophism. We find no particular break to correspond to this, but rather see the whole group of four formations united by mobile and volcanic environments at a time when glacial climates allowed the formation of glaciomarine sediments with derived conglomerates. On the other hand the pre-Vendian unconformity clearly demonstrated a short distance to the north is probably best referred to by Birkenmajer's name – *Torellian*.

Adapting the terms Werenskiöldian (e.g. Birkenmajer 1972) and Werenskiöldbreen Group (Krasil'shchikov & Koraleva 1979; Table 16), we combine these four formations into one distinctive *Werenskiöld Group* (Table 17). It could all be Vendian, but the Deilegga and Vimsodden formations certainly are. It is not impossible that the pre-Vimsodden formations are separated from Vimsodden glaciogenic sediments by the Torellian unconformity and just happen in this area to appear related.

The recent results further north in Wedel Jarlsberg Land confirm our general correlation of the Werenskiöld Group with the Konglomeratfjellet Group, and especially Deilegga Formation with Chamberlindalen, Gaimardtoppen with Slyngfjellet conglomerates, and Fløykalven diamictites with Vimsodden rocks. However, it must be remarked that the thickness and facies contrast greatly across Torellbreen, the facies comparing with eastern outcrops to the north. This correlation supports a postulated NE–SW trending dextral shear zone under Torellbreen.

7.2.5 Pre-Vendian Rocks (*Dunøyane Formation and Isbjørnhamna Group*)

Although there is a certain coherence in the above conclusions we are not certain where to look for the next older rocks. The Gulliksenfjellet Formation seems to rest directly on the more highly metamorphosed Isbjørnhamna Formation to the

Fig. 49. Sections through the Vimsodden Formation, east of the type locality just south of Torellbreen, with lithological divisions and thicknesses extracted from the geological map of Smulikovsky (1968).

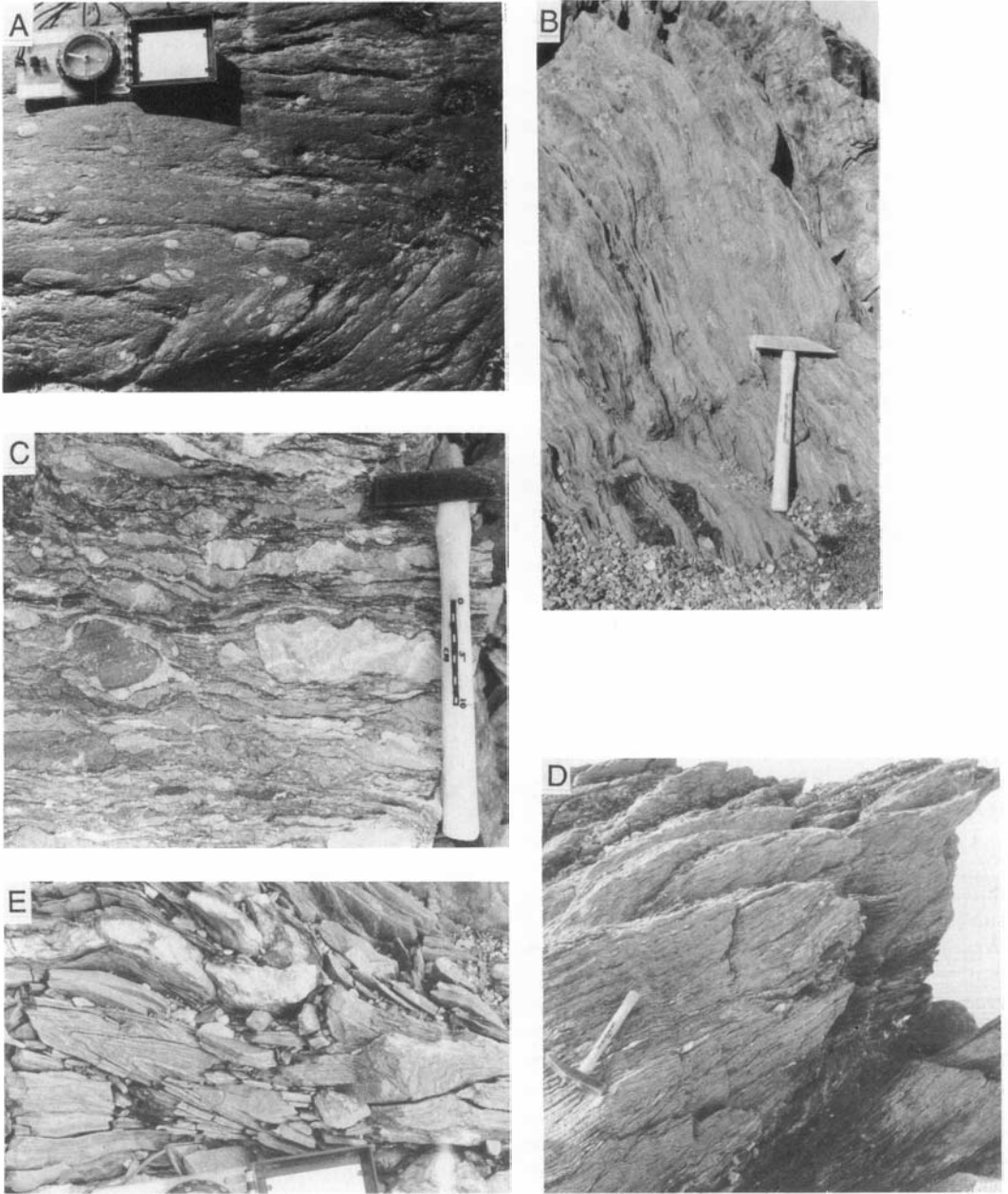


Fig. 50. Rock types of the area between Torellbreen and Nottinghambukta. A. Deformed stone-bearing phyllite of the Vimsodden Formation at Vimsodden. B. Stone-free phyllite of Vimsodden Formation at Vimsodden. C. Quartzite-dolostone conglomerate with deformed, laminated matrix, at Slyngfjellet. This is probably the lateral equivalent of the Vimsodden Formation, south shore of Nottinghambukta. D. Strongly foliated pelite with quartz veins and a few flattened stones, Vimsodden Formation, south shore of Nottinghambukta. E. F_2 similar folding with associated incipient axial plane cleavage in psammite-pelite; forefield of Werenskioldbreen.

Table 17. Comparison of Birkenmajer's (1959–1975) stratigraphic succession in the Torellbreen to Hansbreen area compared with that proposed in this paper.

Birkenmajer	This paper			
Slyngfjellet Conlomerate (Sofiebogen Group)	Dielegga Formation			
Dielegga Group				
— Werenskioldian diastrophism —				
	{ Vimsodden Formation (with Slyngfjellet Conglomerate) Skålfjellet Formation Gulliksenfjellet Formtion }	Werenskiold Group		
			Dunøyane Formation to West	hiatus to South-East
Isbjørnhamna Group			{ Revdalen Formation Ariekammen Formation Skoddefjellet Formation }	Isbjørnhamna Group

south, but those rocks could be very much older. We think it more likely that the next oldest rocks are found to the west in the islands of Dunøyane 3 km offshore from Nottinghambukta, and these are named here the Dunøyane Formation (= Høferpynten Formation of Birkenmajer 1960).

The demonstration of a pre-Vendian Torellian Orogeny north of Torellbreen makes it likely that different pre-Vendian formations lie beneath a sub-Varanger unconformity in different places. We therefore treat each potentially older formation separately.

Dunøyane Formation: These rocks were correlated by Birkenmajer with the Høferpynten rocks south of Hornsund. As will be seen, either or both may be of the same age as the Akademikerbreen Group of Ny Friesland and Olav V Land, and so are at least mostly pre-Vendian. From observations by T. S. Winsnes and Harland in 1979, the rocks (about 1.8 km thickness above sea level) young south-westwards (based on stromatolites). Tectonic complications may therefore be expected.

The formation probably lay beneath Vimsodden rocks and is faulted against them. There are no such massive carbonates in the rocks onshore north of Hornsund.

The following succession was recorded on:

Store Dunøya	
West of:	platy quartzites and phyllites 100 m
West:	dark banded rock with breccia and conglomerate layers and bands, some slightly tilloidal 200 m
Central:	pale stromatolitic dolostone 200 m
East:	pale pisolitic dolostone, 150–200 m
	banded dolostone with chert. 100 m
Dunøyhamna:	softer rock just covered at low tide 500 m
Fjørholmen:	varied dark and pale marbles 350 m

The uppermost unit might represent a transition from Vimsodden glaciogenic sediments into pre-Vendian carbonates. Correlation with the Høferpynten Formation is reasonable but not in detail. There could be a major fault separating the Vimsodden rocks from the older rocks to the south and/or west, and it may lie beneath the Torellian unconformity. We leave this problem

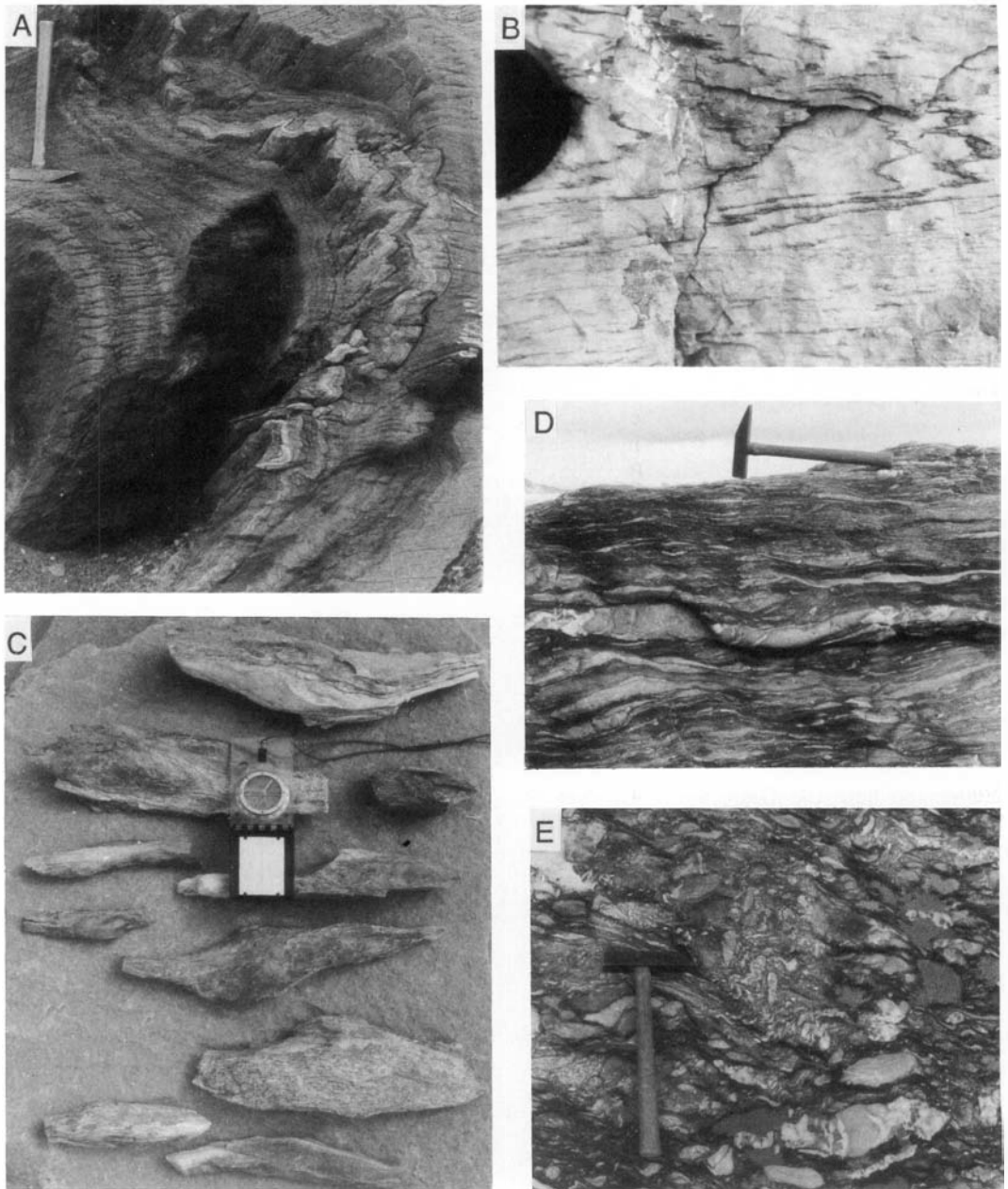


Fig. 51. Rock types of the inner Hornsund succession, north shore. A. Bogstranda Formation phyllites at type locality, showing open F_2 folds and associated axial plane cleavage. B. F_1 folds in marble of the Fannypynten Formation, western slopes of Fannypynten. Dark laminae are concentrations of sand, perhaps marking former stylolitic surfaces. C. "Cigar-shaped" stones extracted from the diamictite of the Fannypynten Formation at Fannypynten. Their shapes were obtained during D_1 deformation. D. Fannypynten Formation, with strongly flattened stones seen in XY plane. E. Same outcrops as above, but showing stones in YZ plane. Note also the fine foliation in the matrix.

here as it concerns pre-Vendian rocks, post-Vendian tectonics or both.

Isbjørnhamna Group: As first defined (Birkenmajer 1958 et seq.) the Isbjørnhamna Group comprises the

Revdalen Formation,
Ariekammen Formation, and the
Skoddefjellet Formation (oldest).

These were and still are considered to be the oldest rocks in south Spitsbergen and they must certainly be pre-Vendian.

7.3 Middle Hornsund

This area is taken as the coastal outcrop area immediately east of Hansbreen in the north, and around and to the west of Gåshamna in the south. The succession in Table 15 from Birkenmajer gives the Sofiebogen Group with three formations, each named to apply to both north and south of Hornsund. The scheme was questioned by Harland (1978), and to facilitate discussion independent nomenclatures for north and south were instituted and are followed here.

7.3.1 Succession north of Hornsund

A traverse from east to west provides the following succession.

Sofiekammen Group (of Birkenmajer). – Mainly Cambrian:

Grey limestone with *Protolenus*.
Shale with *Olenellus*.
Blåstertoppen dolomite (age?).
(Contact not seen)

Bogstranda Formation (about 2.5 km)

Phyllite: upper part calcareous, lower part pelitic, passing down into purple and green phyllite suggesting a volcanic component (Fig. 51A).
Basal quartzite unit (5 m).

Fannytoppen Formation (about 100 m)

Pisolitic member (0–24 m): dolostone with fine oncolitic structures. Radwanski & Birkenmajer (1977) described and correlated it with the Höferpynten Formation.

Dolostone member 14 m: with stromatolites (observed by T.S. Winsnes with Harland in 1979).

Limestone member 80 m: this is the Fannytoppen Member of Birkenmajer's Höferpynten Formation (Fig. 51B).

Fannypynten Formation (about 500 m)

Polymict reddish diamictite with a great range of size and composition of stones up to boulder size (Fig. 51C–E). Estimates of stones given by Hambrey & Waddams (1981) are: quartzite 60%, pink feldspathic rocks 20%, dolostone 15%, limestone 5%. They are either dispersed or in contact and are highly deformed. Granite and quartzite stones have axial ratios of up to 6:1, and some are boudined. Limestones are much more deformed. All tend to be cigar-shaped. No sedimentary structures have been preserved, but a transposed foliation suggests modification of a finely laminated sandy matrix. The thickness, poorly sorted nature, high stone content and remnant lamination suggest that the formation developed in a proximal glaciomarine environment. However, a subaqueous gravity flow origin, cannot be ruled out. The degree of deformation precludes a more detailed assessment of these rocks (Figs. 51C–E).

Unnamed division (about 300 m)

A break in the exposure suggests less resistant rocks, possibly phyllites. This break corresponds to the gravel tombolo spit extending westwards from Fannypynten.

Hansvika Formation (about 500 m)

Originally this unit was named the Hansbreen tilloid division (Harland 1978). It has just been discovered that in the same year Birkenmajer used the name Hansbreen for a unit in his Cambrian Nørdstetinden Formation. Without investigating priority we modify the name for the bay at the mouth of Hansbreen.

It is a polymict diamictite, greyish with dolostone, limestone and quartzite dispersed stones and no feldspathic rocks. This contrast in composition noted earlier was confirmed by Winsnes (with Harland) in 1979. The colour contrast had been reported by Birkenmajer who referred to the Fannypynten and Hansbreen formations as divisions of the Slyngefjellet Conglomerate at the base of his Sofiebogen Group. The Hansvika Formation occupies the rocky promontory at the end of the tombolo and opposite the Polish buildings at Isbjørnhamna; it was formed by similar processes as the Fannypynten Formation.

The maps (Birkenmajer 1960a and Fig. 48 here) might suggest (i) that the Hansbreen For-

mation could be very much thicker than is exposed and (ii) that it could correlate with the Slyngfjellet Conglomerate to the north. However, contrast of facies and coherence of the mid-Hornsund successions in our opinion do not favour these possibilities.

7.3.2 Succession south of Hornsund

The succession, younging east and steeply dipping to the west is as follows:

Hornstullodden dolostones and limestone (80 m)

This is possibly equivalent to the early Ordovician Gråkallen rocks further south.

Phyllitic limestone (5 m)

This contains early Cambrian fossils, possibly equivalent to the Slakli Formation to the south (Major & Winsnes 1955). The contact with the Gåshamna Formation is not seen.

Gåshamna Formation 1.5 km (Winsnes 1955)

Upper division: about 500 m of black shale and phyllite exposed near shore.

Middle division: crops out south of Gåsbreen

Lower division: variable with green and grey slate and phyllites, equivalent, we think, to the lower part of the Bogstranda Formation.

The lower boundary is tectonic, as first pointed out by Winsnes (1965) and confirmed by us in 1977 (see Gåshamna diamictite unit below).

Höferpynten Formation (Winsnes 1955; Birkenmajer 1972; Harland 1978)

This unit is well exposed at the eponymous promontory and is divided as follows:

(6) *Quartzite member (>300 m):* three prominent ribs of quartzite surrounded by phyllite (combined in Gåshamna Formation by Birkenmajer).

(5) *Oolitic limestone member (40 m):* with conspicuous stromatolite bed at the top, grey limestone with oolite (Winsnes 1955), and pale-weathering dolomitic oolite and pisolite (Birkenmajer 1972, and named his Dunøyane Member). This facies has been correlated with the pre-Vendian, Backlundtoppen and other formations in the Akademikerbreen Group of Ny Friesland (e.g. Swett & Knoll 1989).

(4) *Würmbrandegga member (300 m):* massive grey dolostone with occasional current bedding, lacking cherts.

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(3) *Andvika member (300 m):* this is the lower part of Winsnes' dolomite. It contains grey chert layers which are more continuous near the top.

(2) *Knivodden division – upper member (20 m):* complex of grey-greenish and yellowish dolostone. Distinguished by Birkenmajer as his Fannytoppen Member.

(1) *Knivodden division – lower member (10 m):* deformed lenticular yellow and reddish quartzite pebbles and boulders (2–20 cm diameter) within a matrix of deformed quartz phyllite, and interpreted as a silicified intraformational conglomerate, possibly dolomitised before diagenesis. Appears to be conformable with unit above as Harland (1978) incorrectly asserted that it was mapped by Birkenmajer (1960a, b) as the Slyngfjellet Conglomerate, but see section 7.4 below.

Sigfredbogen Formation (>300 m)

Slate and phyllite were mapped by Birkenmajer (1972) as the Bergskardet Formation of his Deilegga Group. We keep an open mind as to its correlation. It is discussed in section 5.4 below.

Gåshamna diamictite unit

A diamictite is found on the eastern slope of Würmbrandegga at about the contact of the Gåshamna and Höferpynten formations. We presume a specimen of this rock (described as a tillite) was collected by Hoel and Røvig in 1917 (Føyn 1937) and referred to by Wilson & Harland (1964, p. 216) as evidence for correlating the Gåshamna phyllites with the Polarisbreen shale of northeastern Svalbard. Harland located the rocks in 1977 (1978) in a narrow talus train of diamictite facies coming from the position of the supposed fault. Subsequent work confirms the suggestion (Harland 1978) that this is a later fault breccia; the clasts are undeformed. It comes at the break originally suggested by Winsnes (1955). It may mask a major break in the sequence.

7.3.3 Correlation across Hornsund

The different names applied here to the rocks north and south of Hornsund enable us to compare in our nomenclature Birkenmajer's correlation (1960a, b) and subsequent papers, e.g. 1972) (Table 18), with our own interpretation (Table 17).

Table 18. Correlation across Hornsund according to Birkenmajer (1960a,b, 1972) presented in the revised nomenclature of this paper.

Age	NORTH HORNSUND	SOUTH HORNSUND
VENDIAN AND	Bogstranda Formation (2,500 m)	Gåshamna Formation (1500 m) Member (6) of Höferpynten Formation
	Fannytoppen Formation (100 m)	Höferpynten Formation, Members (5) to (2), (660 m)
LATE RIPHEAN	Fannypynten Formation (500 m) Hansvika Formation (500+ m)	Slyngfjellet Conglomerate (10m)
	Bergskardet Member (Deilegga Formation 3.5 km)	Sigfredbogen Formation (300+m)

(i) We correlate the *Fannypynten Formation* (rich in feldspathic stones) with the later Varanger glacial horizon (of Mortensnes Stage) and the *Hansvika Formation* with the earlier Varanger glaciation (Smalfjord stage). These two horizons are correlated throughout all the areas considered above. It is noteworthy that the whole Varanger sequence here is about 1.3 km thick compared with 12–15 km immediately to the northwest. We do not find these horizons south of Hornsund and speculate, as did Winsnes (1955) and Harland (1978), that they are missing between the Gåshamna and Höferpynten rocks to the south.

(ii) We take the *Bogstranda Phyllites* to the north and the *Gåshamna Formation* to the south to belong to the same post-glacial sequence. They could be Ediacara in age and/or latest Varanger or earliest Cambrian.

(iii) We do not see evidence to suggest that the *Höferpynten* dolostones south of Hornsund are present on its north side, and believe there to be a tectonic and/or stratigraphic break in the southern succession. In either scheme the Höferpynten Formation is of pre-Vendian age and the rocks listed above it are probably all Vendian. Mil'shtein & Golovanov (1979) reported that the Höferpynten Formation and the base of the Gåshamna Formation have microphytolites. In the former, *Osagia Tenuilamellata* and *Vesicularites rasbenae* are present, indicating an age of R2–R3 (Middle to Upper Riphean).

(iv) There is the problem of identifying Birkenmajer's 10 m-thick *Slyngfjellet Conglomerate* on the south side west of Höferpynten. Harland's

(1978) mistake is now corrected with apology. Evidently Harland's first three visits to the area had coincided with ice foot and snow cover. However, in 1986 the Cambridge party observed a deformed diamictite in Birkenmajer's locality and in 1987 Harland reinvestigated the succession in good conditions. A small valley depression just south of low coastal cliffs exposed conglomerate facies at the eastern end of a highly deformed quartzose succession which is exposed along the shore. No glacial indications were seen, so confirming Birkenmajer's observation. All of the few stones exposed could be examined and no exotic stones characteristic of the upper Varanger diamictites elsewhere were seen. The quartzose rock with the conglomerate seemed to be continuous with the strata running westwards.

There seems to be too little rock and of undistinctive facies to assert a particular correlation. We doubt whether either Slyngfjellet Conglomerate or Deilegga rocks are represented here. The small succession is highly sheared and could well be bounded by major faults or their splays on either side. We refer it to the *Sigfredbogen Formation*.

7.3.4 Other parts of Middle Hornsund and Sørkapp Land

Two older rock units crop out in eastern Hornsund and Sørkapp Land.

(1) At Hyrneodden, Birkenmajer (1960b) referred to a succession comprising the Blåstertoppen Dolomite, the Gåshamna Series (quartzite and slate) and the lower Marietoppen

beds (slates and red conglomerates) of Devonian age. During a brief visit, Harland concluded that the so-called Gåshamna Series here might be upper Marietoppen beds, whereas the dolostones might be Early Paleozoic or older. We think correlation remains open.

(2) In eastern Sørkapp Land there is a strip of more highly metamorphosed rocks as mapped by Major & Winsnes (1955) and visited by our group in 1986. We take these rocks to be of pre-Vendian age.

7.4 The postulated Hansbreen Fault and its extension north and south

The case made by Harland & Wright 1979 for three tectonic provinces in Svalbard – amplified somewhat by Harland (1985) and Harland, Perkins & Smith (1988), rests primarily on stratigraphic comparisons between the stratigraphic-tectonic sequences in different terranes both within Svalbard and in Greenland and northern Canada. The case has been either ignored or questioned on the basis of local structural studies failing to find evidence for a major strike slip component (e.g. Lamar, Reed & Douglass 1986; Bjørnerud, Decker & Craddock 1991). These further studies set some constraints on the hypothesis without undermining it.

The reinterpretation of Vendian stratigraphy in western and south-western Svalbard confirms our opinion as to the contrasts between the Central Province and the Western Province. The case can be made without reference to Vendian geology. The contrasts, however, between the Vendian sequences of the Eastern Province (Chapter 2 above), the Western Province (Chapters 3 to 6 and section 7.2 above) and the Central Province (Middle Hornsund section 7.3) are alone sufficient to suggest a similar division (see section 9.6 below).

We had come to the conclusion that the lineament separating central and eastern terranes could not pass out to sea through Torellbreen because our reinterpretation here links south western Wedel Jarlsberg stratigraphy more closely with the rocks north of Torellbreen than with those east of Hansbreen. Therefore we had to conclude that the lineament must continue directly south into the fault zone mapped by all authors separating Carboniferous and younger rocks in western Sørkapp Land from the older rocks to the east. A major terrane boundary

distinguished by substantial strike-slip would be consistent with such a contrast in Sørkapp Land between a later extensional basin area to the west and the probable Caledonian Horst of Middle Hornsund (Fig. 48).

The postulated fault closely bounds Brøggerhalvøya south of Lovenøyane in Kongsfjorden in the north and we now think it runs along Recherchebreen and Hansbreen in the south. We rename it here the *Kongsfjorden-Hansbreen Fault Zone* (KHFZ) instead of the Central West Fault Zone which was not previously so well constrained. It is subject to concealment by unconformable Carboniferous and younger rocks as well as by Paleogene thrusting. The same Paleogene West Spitsbergen Orogeny also displaced the Fault Zone from a relatively straight line, for example by the NE–SW dextral shear along Torellbreen, across Isfjorden, and in Kongsfjorden.

8 Bjørnøya

Bjørnøya (Bear Island) comprises but a tiny part of Svalbard, and pre-Devonian rocks are exposed only in the southern tip of the island; rocks we believe to be Vendian form a very small part of those rocks. Nevertheless, we can support with new evidence their probable Varanger age.

The older rocks were first investigated by Nordenskiöld in 1864 (Duner & Nordenskiöld 1866) who correlated the dolostones and limestones with rocks at Mt Hecla (Heclahuken) in north-eastern Spitsbergen.

On Nathorst's 1898 expedition Andersson found fossils identified as Ordovician (Lindström 1899). Andersson (1900) described three members:

- (3) red and green slates;
- (2) dolomite and quartzite sandstone;
- (1) dark limestone with *Tetradium*.

Holtedahl (1920) found Ordovician fossils in dolostones underlying the *Tetradium* limestone and he offered a new succession, quoted by Horn & Orvin (1928) as follows:

- (4) *Tetradium* Limestone (340 m): Ordovician
- (3) Younger Dolomite Series (400 m): Ordovician

(2) Slate Quartzite Series (175 m)

(1) Older Dolomite Series: in the upper parts more arenaceous and in the lower parts with oolites, pisolites, and stromatolites.

In spite of conspicuous thrusts, the upper (sandy) part of the Older Dolomite Series was reported as transitional with the overlying Slate Quartzite Series.

Krasil'shchikov & Mil'shtein (1975) gave new names as follows:

<i>Ymerdalen Formation:</i>	<i>Limestone Member</i> (mid-Ordovician) <i>Dolomite Member</i> (Canadian)
<i>Sørhamna Formation:</i>	tectonic contact Slate Quartzite series unconformity
<i>Russehamna Formation:</i>	Older Dolomite series.

They described the Russehamna Formation (suite) in five units from NE (top) to SW:

(5) 10–20 m grey massive sandy dolostone with relict phytolithic texture; in isolated outcrops to west of Røedvika.

(4) 150–200 m light grey dolostone with quartz sandstone laminae; transitional to

(3) 80–120 m grey-fine grained dolostone with up to 5% quartz grains near top with “coagulation texture”.

At the top of unit (4) is assemblage IIIB: *Asterosphaeroides* (?) *ruminatus*, Zabr.; *Vesicularites lobatus*, Reite.; *V. compositus*, Z. Zhur.; *V. aff. botrydioformis*, (Krasnop.); *V. elongatus*, Zabr. *V. enigmatus*, Zabr.; *V. vapolensis*, Zabr.; and *V. Parvus*, Zabr.

At the bottom is assemblage IIIA of micro-phytoliths: *Osagia maculata*, Zabr; *O. Milsteini*, Zabr.; *O. pullata* Zabr.; *Vesicularites elongatus*, Zabr.; and *V. raabena*, Zabr.

(2) 50–80 m alternating units (4–6 m) grey massive dolostone and finely laminated dolostone with iron-stained partings. The bottom 15–20 m is a distinctive marker bed with assemblage II: *Osagia crispa*, Z. Zhur; *O. medwezhella*, Milst.

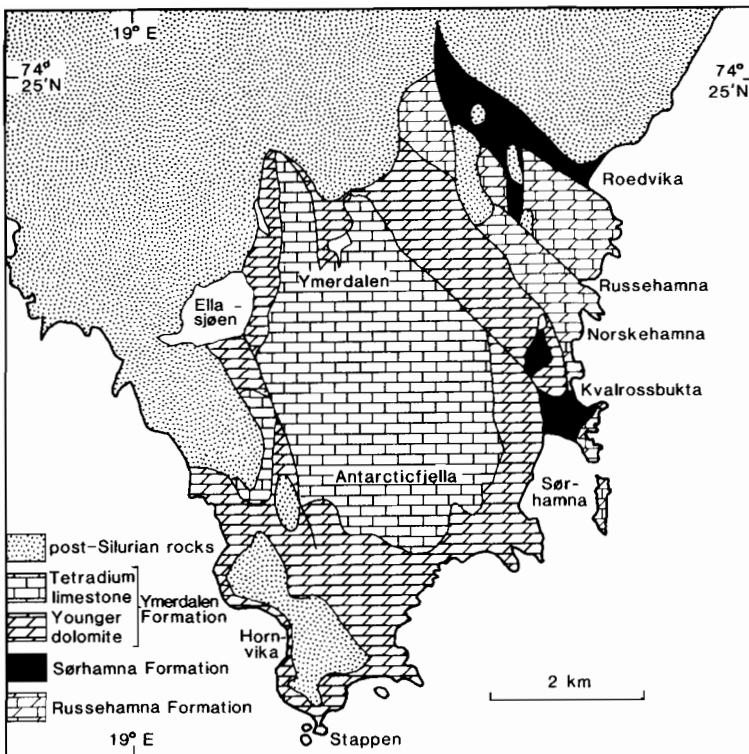


Fig. 52. Geological map of southern Bjørnøya showing the pre-Devonian outcrops based on Horn & Orvin 1928.

and probably *Radiosus aculeatus*, Z. Zhur. is associated.

(1) 150 m grey medium grained dolostone with assemblage I near top: *Vesicularites lobatus*, Reite. and *Nubecularites*, Masl.

Krasil'shchikov and Mil'shtein argued that assemblages II and IIIA are similar to each other and to the Upper Riphean of Zhuravleva (?Sturtian) and that assemblage I is probably older.

Assemblage IIIB compares with Yudoma assemblages i.e. Vendian, and the less identifiable assemblage in unit 5 could be similar. Thus the upper part of unit 3 and units 4 and 5 are probably Vendian with a downwards transition. They suggest an unconformity above unit 5 on which assumption the Sørhamna rocks, for which they had no evidence of age, would be significantly younger.

Harland & Wilson (1956) had suggested that the two older formations could be correlated respectively with the Polarisbreen and the Akademikerbreen rocks of Ny Friesland. We adhere to this correlation, thus making the Sørhamna Formation Vendian. We refer to the Sørhamna and Russhamna formations as the Bjørnøya Group as they do not match closely the Hecla Hoek succession.

In 1986 Harland investigated the Sørhamna Formation where it crops out at Sørhamna and Kvalrossbukta, and also at Røedvika and inland, where it overlies the Russehamna Formation and is unconformably overlain by the Late Devonian Røedvika Formation. The distribution of these older rocks is shown in Fig. 52.

We conclude that the Ymerdalen Formation lies unconformably on the Sørhamna Formation along the poorly exposed contact inland west of Russehamna. The basal Ymerdalen strata were recorded by A.P. Heafford and M.P. Smith as sandy and containing large clasts of dolostone, and on the north cliff of Russeelva, Harland noted a large fissure with overlying rock facies penetrating the Sørhamna Formation.

The southern outcrop is well exposed in cliffs at sea level in Kvalrossbukta and Sørhamna, and in each case angular limestones of 1–2 cm diameter occur within a slaty matrix at a concentration of about one per 1–2 m² of clean exposed rock. The slates are green and patchily red and may represent marine sediments with an ice-rafted component. The stones are more evident in the grey facies. To the east of Sørhamna

the red and grey shales are characterised by load structures and graded beds suggesting turbidites.

The whole succession is tectonically disturbed, being overthrust westwards by the Russehamna rocks in the prelate Devonian Caledonian Orogeny. This tectonic vergence is opposed to the eastwards vergence in middle Hornsund and so in this respect the Bjørnøya terrane (?Southern Province) contrasts with the Central Province.

The Sørhamna Formation is tectonically incompetent and its contact with the Russehamna Formation is thrust. Nevertheless we have no reason to suspect that they are separated by a tectonic episode; they could indeed have been conformable.

In conclusion the Sørhamna Formation, and the upper part of the Russehamna Formation would appear to be Vendian. More precisely: early Varanger might be suggested by the very limited stone content and adjacent Russehamna Formation, and later Varanger by the associated red and green coloration.

9 Svalbard history in the Vendian Period

9.1 Vendian chronostratigraphy

The Varanger Epoch is documented by remarkably rich sequences, correlated throughout (except Prins Karls Forland and Bjørnøya) by the two distinctive major glacial episodes: the earlier Smålfjord Stage and the Mortensnes Stage, with a substantial interglacial record between the diamictite horizons. The Vendian age of these glacialic sediments is confirmed biostratigraphically.

The Ediacara Epoch is only evident from the Scotia Group in Prins Karls Forland, identified by a microbiota. A number of conformable post-glacial successions are plausibly of Ediacara age: the Dracoisen and Klackberget formations in the north-east; the Annabreen and Aavatsmarkbreen formations in Oscar II Land; the Peachflya and Gjeikie as well as the Scotia Group in Prins Karls Forland; and the Bogstranda and Gåshamna Formation in Hornsund. Nevertheless, the second part of Vendian time is as yet poorly demonstrated in Svalbard.

In some localities, pre-glacial strata pass conformably downwards and, depending on the eventual Vendian chronostratigraphic definition, could also be Vendian. The later Vendian and (earlier) Cambrian record is generally lacking.

Our correlation scheme within Svalbard is shown in Table 19. Correlation generally depends on the two diamictite horizons, and especially with East Greenland and north Norway, not only by inspection of sedimentary facies (e.g. Hambrey 1983) but also independently by carbon isotope variations (Knoll et al. 1986) and by biostratigraphy (Knoll 1982a, b; Knoll & Calder 1983; Knoll & Swett 1987). In other areas where only diamictite is observed, less precise correlation is possible even though it is established as Vendian (Table 20).

9.2 Vendian climates in Svalbard

The overall story is broadly of two major glacial episodes preceded, separated and followed by rocks with no glacial indicators (e.g. Harland 1964a, 1989). Moreover, the glacial environments recorded were at or about sea level whether continental, lacustrine or marine. There is sufficient evidence of stones dropped from floating ice into massive sediments to confirm temperatures above or below freezing. Dolostones may have formed in both cold and warm waters (e.g. Fairchild & Hambrey 1984).

9.2.1 Glacial sequences

Within the two glacial episodes there is evidence of considerable variation of deposition which would be consistent with fluctuating glacial-interglacial environments on short-term cycles due to planetary perturbations. On the basis of sediment thicknesses within the Polarisbreen Group (approximately Vendian) glacial climates obtained for 15% or less of the period.

9.2.2 Non-glacial sequences

It seems clear from the well-preserved rocks in northeast Svalbard that the glacial episodes were climatic excursions into a generally warm environment. This has generally been assumed from the preceding and succeeding dominantly carbonate facies. Evidence from stable isotopes confirms this assumption. Fairchild & Spiro (1987) and Fairchild et al. (1989) gave evidence that carbonate rocks immediately underlying glacial deposits were formed in warm waters. It is

necessary to invoke a rapid change from warm to cold conditions and conversely, the close of glacial activity was abrupt in view of the sharp resumption of dolomitic chemical sedimentation represented by the basal member of the Dracoisen Formation. In its upper half (D4–D6) halite pseudomorphs, anhydrite relics, rainpits and desiccation cracks occur.

9.3 Vendian latitude of Svalbard

Paleomagnetic determinations have been made on late Proterozoic and early Paleozoic rocks of Svalbard without success. However, early results from East Greenland (Bidgood & Harland 1961) and Norway (Harland & Bidgood 1959; Harland 1964a) indicated low, even equatorial paleolatitudes. These results, lacking the desirable washing procedures, were commonly discounted as anomalous until too many such “anomalous” determinations became available to ignore the probability of low latitude glaciation at that time (e.g. Frakes 1979).

Global distribution of continents at about that time suggested that Svalbard and East Greenland in particular might have been near the equator. This kind of assessment was based on reconstructions based in part on purely biogeographical climatic zonation, ignoring anomalous glacial facies (e.g. Harland 1964b; Fortey 1976) and in part with paleomagnetic constraints (e.g. Smith, Hurley & Briden 1980; Piper 1987).

An independent isotopic assessment for Svalbard (Fairchild & Spiro 1987) suggested that oxygen isotopes may constrain paleolatitudes of the Late Proterozoic glaciation. Pleistocene and Late Paleozoic glacials known to be polar give a known measure of $\delta^{18}\text{O}$ on the basis that modern snow, glacier ice and meltwaters in high latitudes are depleted therein. The isotopic composition of ambient glacial seawater-meltwater maximum has unexpectedly heavy oxygen for a polar environment.

9.4 Vendian ocean composition

The above conclusions depended on the finding that the salinity of the ambient water in which glacial sediment was laid down was similar to that of present-day oceans. Prior to this finding it had already been argued (Harland & Herod 1975) that the aqueous bodies in which the ice released debris were marine and connected with the

Table 19. Summary of Vendian rock units of Svalbard. Conventions: upper case = group names; lower case = formation names; names in parenthesis = informal names. Members are not included, except for the Elbobreen Formation where they are indicated by E1–E4. Dashed horizontal line = boundary between formations; solid horizontal line = boundary between groups; diagonal line = different locality or tectonic contact. Vertical shading = gap in knowledge due to lack of exposure, loss by erosion or by tectonic transport. Significant unconformities have not been demonstrated by us.

SOUTHERN	CENTRAL		WESTERN			
Bjørnøya	Southern Middle Hornsund	Northern Middle Hornsund	Southwestern Wedel Jarlsberg Land	Cent.- Western Wedel Jarlsberg Land	Northern Wedel Jarlsberg Land	Nordenskiöld Land
Ymerdalen	SØRKAPP LAND SOFIEKAMMEN					
	Slakill	Shales with <i>Olenellus</i> ?Blåstertoppen				
	Gåshamna	Bogstranda				
		Fannytoppen				
Sørhamna		Fannypynten			KAPP LYELL Lyellstranda Logna Dundrabelsen	Kapp Linné [undifferentiated]
		[unexposed]	WERENSKIÖLD	KONGLOMERATFJELLET	Vestervågen	(Linnefjella)
Russehamna		Hansvika	Dellegga	Dunderdalen Slettjelledalen	Chamberlindalen Solhøgda	(Malmberget)
			Vimsodden (Slyngfjellet)	Fløykalven	Galmardtoppen	LÅGNESBUKTA Lågneset (Gravsjøen) Lågnesrabhane
			Skålfjellet	Thistfjellet		Kapp Martin
			Gullksenfjellet			
	Höferpynten		Dunøyane			
	(Snøkrosse)		ISBJØRNHAMNA (3 fms.)	NORDBUKTA	(Magnethøgda)	

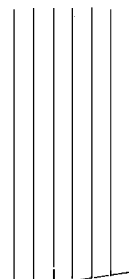
world's oceans at that time on the basis of the extent and thickness of the deposits.

High salinities are indicated by local occurrence of anhydrite relics, e.g. in the Lower & Upper Carbonate Members E1 and E3 of the Elbobreen Formation (Fairchild 1983). High carbonate concentrations are evident locally from the rock flour from a great extent of shallow seas over many kilometres thickness of the preceding carbonate Akademikerbreen rocks (Fairchild 1983). Carbon isotope ratios also yield paleotemperature information (Knoll et al. 1986).

9.5 Svalbard's Vendian biotas

The important discovery of an Ediacara microbiota (Knoll & Ohta 1988) in Prins Karls Forland opens up the possibility of more such finds in cherty facies even in significantly altered rock. Already in Ny Friesland Vendian acritarchs are known for interdiamicrite strata.

These finds are part of a sequence of similar biotas that have been recovered from mid-Proterozoic through Early Paleozoic strata (Knoll & Swett 1985; Knoll, Swett & Birkhardt 1989).

		EASTERN		PROVINCE						
Oscar II Land	Prins Karls Forland	Ny Friesland & Olav V Land	Western Nordaustlandet	Area / Age						
BULLBREEN Holmesietfjella Motalafjella <hr/> Aavatsmarkbreen Annabreen <hr/> Haaken	GRAMPIAN (4 fms.)	OSLOBREEN Valhallfonna Kirtonryggen Tokammane	GOTIA Kap Sparre	oldest younger rocks	CAMBRIAN - SILURIAN					
	COMFORTLESSBREEN	SCOTIA	POLARISBREEN Dracolsen			Klackberget	? Late Vendian	Ediacara Epoch		
		PEACHFLYA								
		GEIKIE	Wilsonbreen	Sveanor	Late Glacial Stage	Mortenases				
FERRIER Neukpliggen Peterbukta Hardlefjellet										
ST. JONSFJORDEN Alkhorn <hr/> Løvillebreen Moefjellet <hr/> Trondheimfjella <hr/> Müllerneset + Nielsentjellet <hr/> Steenfjellet Bøgegga <hr/> Vestgøtabreen	Isachsen  Pinkie	Elbobreen	E4 <hr/> E3 <hr/> E2 <hr/> E1	Backaberget	VENDIAN Varanger Epoch Smaifjord					
						KONGSVEGEN	AKADEMIKERBREEN Backlundtoppen Draken Svanbergfjellet Grusdlevbreen	ROALDTOPPEN Ryssø <hr/> Hunnberg	Young- est older rocks	LATE RIPHEAN- STURTIAN

9.6 Svalbard's provinces

The hypothesis already referred to, of three distinct pre-Carboniferous terranes (Harland & Wright 1979; Harland 1985), was based on tectono-stratigraphic sequences from all pre-Carboniferous rocks of Svalbard of which the Vendian rocks are only a part. A sufficient case for the hypothesis could be made excluding Vendian data. In this paper, however, the case is considered with respect to Vendian data only; the hypothesis is viable with these data and

makes good sense, especially of Varanger stratigraphy.

The three major provinces are East, West and Central (Fig. 53), and each could be divided into two subprovinces. The Southern Province shows a different succession – perhaps more like the Eastern province. However, it is separated from the other outcrops by sufficient distance for significant differences to occur within the same microcontinent.

The two faults dividing the three provinces are: (1) the well documented *Billefjorden Fault Zone*

Table 20. Vendian correlation chart for representative successions of Svalbard and other parts of the North Atlantic-Arctic region. Groups in upper case; formations in lower case letters. Dashed horizontal lines are conformable contacts between formations for correlation where suspected. Solid triangles represent upper tillite; open triangles lower tillite. Sources of data: (1) this paper; (2) Hambrey & Spencer 1987; (3) Dawes 1976; (4) Ragozina & Stepkin 1979; Chumakov 1981; (5) Edwards 1984; (6) Johnson, Levell & Siedlecti 1978; Vidal & Siedlecka 1983; (7) Nystuen 1976, 1982; (8) Anderton 1985.

SPITSBERGEN ¹		GREENLAND		KOLA PENINSULA ⁴ (Sredny Pen.)		FINNMARLEN ⁵ Parautochthon ⁶		SOUTHERN NORWAY ⁷		WESTERN SCOTLAND ⁸		AREA AGE	
Western	Northeastern	East ²	North ³									SILURIAN	CAMBRIAN
BULLBREEN		OSLOBREEN		PORTFJELD		BRELVIK		CAMBRO-ORDOVICIAN UNCONFORMITY		JURA QUARTZITE		VENDIAN	
tectonic		disconformity		unconformity		Stappo gledi		Vangsås		Bonahaven Dolomite		EDDIACARA	
Aavatsmark-breen		Spiral Creek Canyon		Moræness		Mortensnes		Ekre		Port		VARANGER	
Annabreen		Storeelv		Puman		Nyborg		Moelv		Askalg		Mortenses	
Haaken		Arena		Molka/Kuyukan		Smaalfjord		unconformity		Tillite		Smallfjord	
Alkhorn		Ulvesø		LØKVIKFJELL (or fm.)		Smaalfjord		Ring		▲ or Δ			
Levlebreen		Limestone-dolomite series		unconformity		unconformity		Biri		Islay Limestone		EARLIEST VENDIAN	
Moeffjellet		Bed groups 19 & 20		KILDIN		TANAFJORD		Bliskopås		Mullach Dubh Phyllites			
Trondheim-fjella		Bed group 15 & below		VOLOKOVAYA		BARENTS SEA		Bretum		Lismore Limestone			
fjella		AKADEMIKER BREEN		KONGSVEGEN				Bretum		Cull Bay Slates		LATE RIPHEAN - STURTIAN	
Müllerneset + Nielsenfjellet										Ballachullish & Lochaber Subgroups			
Steenfjellet													
Bogegga													
COMFORTLESS BREEN		POLARISBREEN		TILLITE		VESTERTANA		HEDMARK		ARGYLL		APPIN	
ST. JONSFJORDEN				ELEONORE BAY									

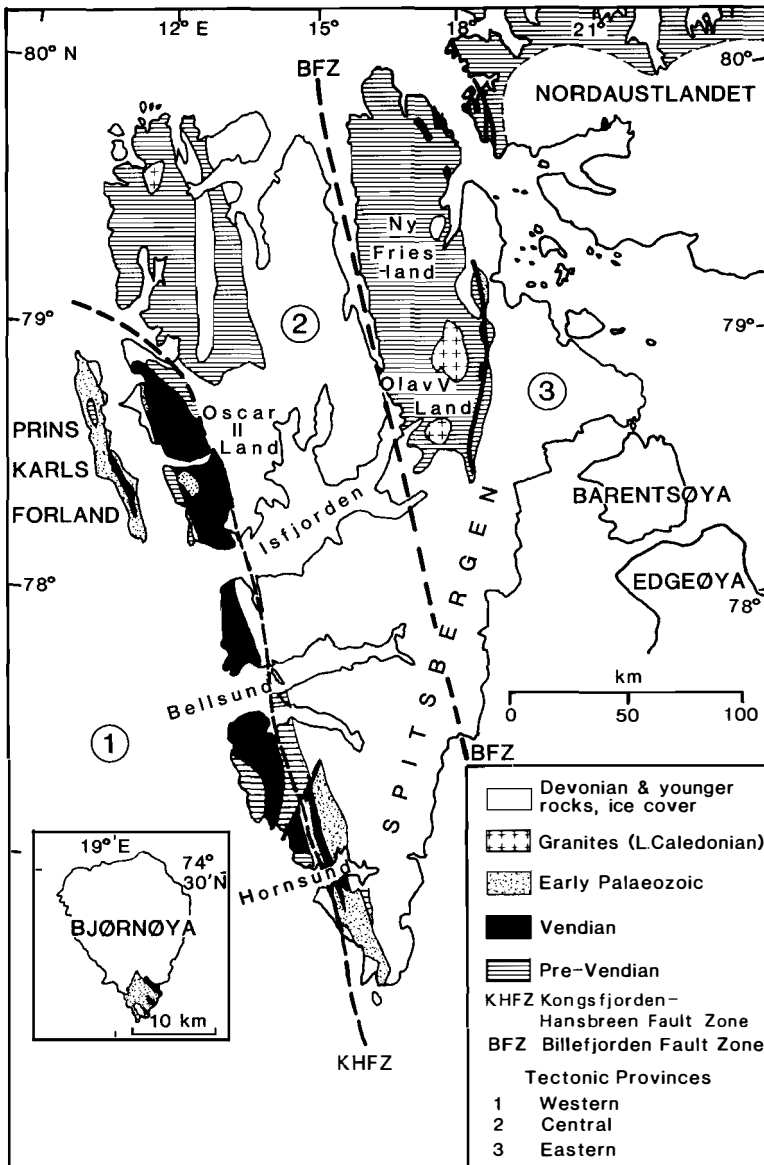


Fig. 53. Distribution of Vendian rocks in Svalbard, as inferred in this paper.

(BFZ) dividing East and Central Provinces (Harland et al. 1974), and (2) the postulated Central (Western) Spitsbergen Fault Zone (CWSFZ or CWFZ) separating Central and Western Provinces (Harland & Wright 1979). The latter has been redefined and renamed in this monograph as the *Kongsfjorden-Hansbreen Fault Zone (KHFZ)* from the two localities where its position can be constrained within a kilometre on each side. It is,

however, generally obscured by later rocks and later deformation. It lies east of all the western pre-Carboniferous outcrops except in Wedel Jarlsberg Land, while in Sørkapp Land it lies west of all exposed pre-Carboniferous rocks.

The principal arguments that the provinces were widely separated before the Late Devonian Svalbardian movements depend on tectono-stratigraphic sequences in each Svalbard terrane com-

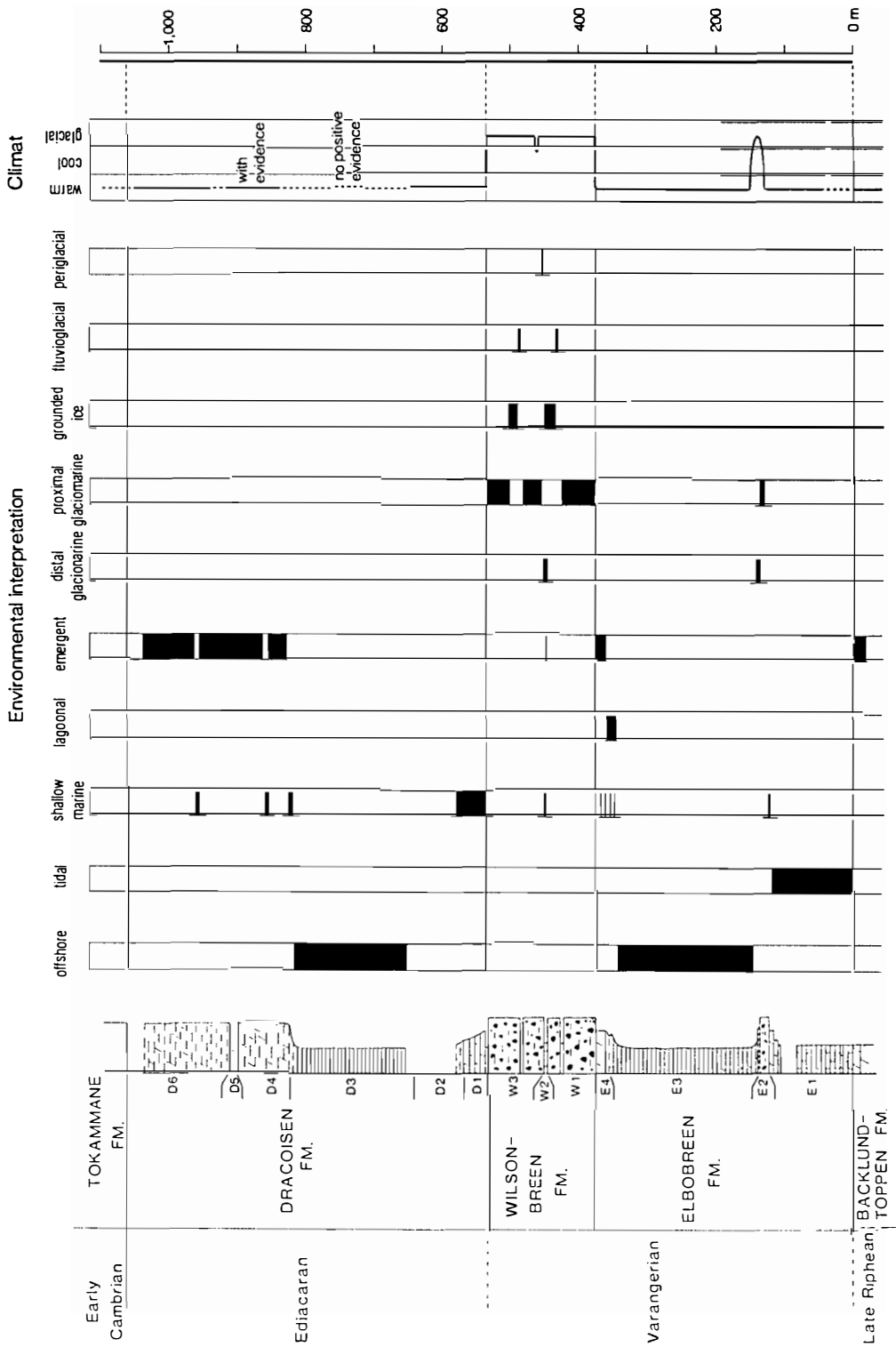


Fig. 54. Environmental interpretation of the Vendian succession of northeastern Spitsbergen. Summary lithological log on the left with interpretation of depositional environments to the right. A generalised climatic curve is shown on the far right. For left hand column legend see Fig. 3.

pared with those in Greenland to which it was previously adjacent.

The Vendian succession (as well as earlier and later rocks) in Svalbard's Eastern Province have long been known to compare very closely with those of Central East Greenland (Kulling 1934; Harland 1959, 1965; Hambrey 1983). Further work (e.g. Hambrey & Moncrieff 1985, Hambrey & Spencer 1987) emphasises the similarities to the extent that they must have formed in close proximity. The successions in the Central and Western Provinces contrast so markedly that they could not have been situated between the Eastern Province and East Greenland as now if Svalbard were placed near East Greenland in Vendian time. It is therefore reasonable to suppose that the Eastern Province was near East Greenland and the other provinces were elsewhere, being finally brought together in Late Devonian time.

We cannot claim such a remarkable match for the other provinces, but the Western Province has some affinity with the North Greenland Fold Belt and especially with the Ellesmere Island sector of it. Such a relationship would be reasonable because that location is about where the whole of Svalbard certainly was from Permian to Paleocene time. The Central Province is somewhat intermediate having more easterly than westerly affinity. These provinces are characterised by three contrasting depositional environments:

(i) Northeastern Svalbard (Eastern Province): a dominantly shallow marine, stable environment with periodic emergence and two periods of glacial influence against a background of carbonate deposition with a thickness of about 1 km.

(ii) Western Svalbard (Western Province): a highly mobile, deep-water turbidite basin, with much volcanic activity and carbonate production. Two periods of predominantly glaciomarine deposition are recorded, associated with which were sporadically generated subaqueous gravity flows. Total thicknesses of more than 10 km are evident for Varanger strata alone.

(iii) Southern Spitsbergen (Central Province), middle Hornsund region: a sporadically mobile, deep-water-shelf environment with thicknesses of >1.5 km.

(iv) Bjørnøya may be a separate (Southern Province) yet with affinity to (i) or (iii). The Vendian environmental sequences in (i), (ii) and (iii) are discussed below.

9.7 Sedimentary environments of the Eastern Province

The unmetamorphosed and little deformed Vendian successions of Ny Friesland, Olav V Land and Nordaustlandet have yielded a comprehensive picture of the environmental, climatic and biological evolution for this period (Fig. 54). Following Hambrey (1982), Fairchild & Hambrey (1984) and Fairchild & Spiro (1987) (for the Polarisbreen Group) the evolution of this environment was as follows (Table 21).

9.7.1 Preglacial sedimentation

During Sturtian to early Vendian time limestones, dolostones (some stromatolitic) and minor sandstones and mudstones of the Backlundtoppen Formation and the Lower Carbonate Member (E1) of the Elbobreen Formation were deposited in a shallow marine environment with interbedded stromatolitic and intraclastic dolostones, oolitic and pisolitic limestones, and limestones with shrinkage cracks.

9.7.2 Sedimentation during the first glacial stage

The first of the Varanger glacial stages (Smålfjord Stage) is represented by the Petrovbreen Member (E2) with a wide range of facies: lodgement and waterlain tillites, comprising material derived almost entirely from the Upper Backlundtoppen Formation and above; glacio-lacustrine rhythmites with dropstones; wedge-fillings of periglacial origin; conglomerate bodies of fluvio-glacial and debris-flow origin; dolostones of glacial rock flour and marine shales. Glaciation close to or at sea level is therefore envisaged, and paleocurrent data suggest movement of ice from the sector between southeast and southwest. The presence of stones from the immediately underlying rock suggests that it was consolidated when eroded, being uplifted in an area beyond the limits of the present outcrops. Furthermore, the absence of supraglacial debris in the Petrovbreen Member suggests continuous glacier ice cover, with few nunataks exposed.

9.7.3 "Interglacial" sedimentation

Following deglaciation a rapid rise in sea level is indicated by the development of offshore or lagoonal dolomitic shales of the Macdonaldryggen Member (E3). These are succeeded by a regressive sequence culminating in peritidal dolostones of the Slangen Member (E4). Such an

Table 21. Comparison of lithologies and environments in the northeastern Spitsbergen and central East Greenland successions. Data from Fairchild & Hambrey (1984) and Hambrey & Spencer (1987) respectively.

Stage	NE SPITSBERGEN	EAST GREENLAND
Early Cambrian transgression	<u>Tokammane Fm., Blårevbreen Mbr. (25-33m)</u> Cross-bedded sandstones of tidal origin, with early Cambrian trace fossils.	<u>Kløftely Formation (c. 70m)</u>
Postglacial (Late Vendian)	<u>Dracoisen Fm. (525 m)</u> 150m (D6): Pale green dolomitic sandstone and maroon dolomitic mudstone, shallow marine or lacustrine to evaporitic. 10m (D5): Cream laminated dolostone and minor limestone; intertidal to evaporitic. 80m (D4): Maroon dolostone and green dolomitic sandstone; shallow marine or lacustrine to evaporitic. 150m (D3): Black paper shales; offshore. 105m (D2): Shaly, laminated dolostone and limestone; shallow marine to offshore. 20m (D1): Grey and maroon, laminated shaly dolostone grading down into yellow/orange laminated dolostone ("CAP DOLOMITE"); shallow marine.	<u>Spiral Creek Fm. (c. 25m)</u> Yellow-grey sandstone, maroon siltstone and yellow dolostone; shallow marine to non-marine, partially evaporitic. <u>Canyon Fm. (c. 300m)</u> 50m: Yellow stromatolitic dolostone, shale, flake breccia; mixed intertidal, lagoonal (?) and deeper water storm deposits. 160-190: Dark grey, sometimes greenish dolomitic shale and siltstone; offshore deposits. 25-36m: Green and maroon dolomitic shale, grading down locally into: 6-13m: Orange or yellow, laminated and cross-laminated dolostone; shallow marine ("CAP DOLOMITE").
Late glacial	<u>Wilsonbreen Fm. (160m)</u> Maroon and grey dolomitic diamictite with clasts of dolostone, limestone, quartzite, red granite, pink and grey granite-gneiss, altered basic volcanics. Discontinuous sandstone and conglomerate bodies, minor dolostone, limestone, dolomitic shale and rhythmites. Deposition from grounded and floating glaciers and icebergs, from streams, and in a shallow marine environment	<u>Storeely Fm. 60-200m)</u>
Interglacial	<u>Elbobreen Fm., members E3-D4 (c. 200m)</u> 14-28m (E4): Cream or white, laminated, oolitic or interclastic dolostone; shallow marine to intertidal, 180m (E3): Grey, laminated, shaly, muddy dolostone with siltstone and pure dolostone; offshore or deeper lagoonal deposits with periodic shallowing.	<u>Arena Fm. (c. 200-360m)</u> Variable laminated, dolomitic shale (offshore) and sandstone (shallow marine), minor diamictite (gravity flow of glacial material) in middle at one locality.
Early glacial	<u>Elbobreen Fm., member E2 (2-42m)</u> Yellowish grey, highly dolomitic diamictite with clasts of dolostone, limestone, quartzite and chert. Also dolomitic conglomerate, rhythmite and shale, and silty homogeneous dolostone. Deposition from grounded and floating ice; reworking by gravity flowage and streams; carbonate deposition as rock flour.	<u>Ulvesø Fm. (c. 20-330m)</u> Yellowish grey, highly dolomitic diamictite with clasts of dolostone, limestone, quartzite and minor schist. Also dolomitic conglomerate, sandstone and rhythmite. Deposition mainly from floating glaciers, but also from grounded glaciers, and from icebergs; reworking by gravity flow and possibly fluvial processes.
Preglacial (?Earliest Vendian)	<u>Elbobreen Fm., member E1 (180m)</u> Stromatolitic and cherty dolostone, dolomitic shale and sandstone, grading down into (the bulk of the member) bluish black or grey laminated limestone with synaeresis cracks. Intertidal to subtidal (occasionally emergent) passing down into lagoonal.	<u>Limestone - dolomite "series"</u> <u>Bed group 20 (only in north) 0-80m:</u> Massive bluish black or grey laminated limestone of shallow marine or lagoonal origin. <u>Bed group 19 (all areas) c. 250m:</u> Grey laminated shale, in part dolomitic and brecciated. Largely of turbidite origin.

environment is indicated by the presence of oolitic and intraclastic grainstones with subordinate silty dolomicrite. Teepee structures associated with fenestrae, and anhydrite inclusions in chert are also present. Early cementation (i.e. prior to Wilsonbreen Formation deposition) is indicated by the formation of breccia-filled wedges in the top of the dolostone. All these features are characteristic of discharge of groundwater or sea water in a supratidal setting. The brecciation is probably the product of frost-wedging marking the onset of the succeeding glaciation.

9.7.4 Sedimentation during second glacial stage

The Wilsonbreen Formation (Mortensnes Stage) is associated with a similar range of glacially related facies as the Petrovbreen Member, but the scale and intensity of glaciation appears to have been much greater. Sedimentation from ice on both land and in the sea was the dominant process, but fluvial and periglacial processes are also much in evidence. The principal difference with the Petrovbreen Member is the presence of igneous and metamorphic stones, together with stones from the immediately underlying formations. Recent investigations in East Greenland, where a similar succession is present (Hambrey 1989; Moncrieff 1989), suggest that the exotic stones could have originated from displaced basement in the so-called foreland region in that area. Paleocurrent data from both areas suggest ice movement from a generally southwest through southeast direction, which would be in keeping with the suggested source area if basement were restored to a more easterly position, as suggested by structural evidence (Manby & Hambrey 1989).

In the middle of the Wilsonbreen Formation (Middle Carbonate Member, W2) a break in glacial deposition is recorded. Although there are stromatolitic and rhythmic limestones, they are so closely associated with clastic rocks (including diamictites) that they are interpreted as a periglacial lake or cold shallow marine assemblage, an interpretation supported by oxygen isotopic evidence (Fairchild et al. 1989).

9.7.5 Postglacial sedimentation

The top of the Wilsonbreen Formation is characterised by a surf-zone disconformity, and is succeeded by shallow sublittoral, fine-grained dolarenites (member D1 of the Dracoisen Formation). These have sedimentary structures

indicative of wave-dominated transport and fine upwards into offshore mudstones (members D2–D3). Then follows a suite of dolomitic sandstones, mudstones and a pure dolostone (D4–D6), with features typical of ephemeral lakes: sandstones have sequences of structures indicative of waning wave-generated flows; mudstones show abundant desiccation cracks and occasional rainpits; and there is abundant precipitated dolomite, some silicified anhydrite nodules and halite pseudomorphs. A return to marine conditions is indicated by acritarchs in locally exposed dark shales, just below the sub-Cambrian disconformity, tidally influenced sandstones (A.H. Knoll in Fairchild & Spiro 1987).

9.7.6 Summary

In summary, the Vendian Period, represented by the Polarisbreen Group (and by analogy the Gotia Group of Nordaustlandet), was a period of deposition of fine-grained sediment in a slowly subsiding basin or shelf, punctuated by influx of coarse material from a distant source as a result of glacial transport (Fig. 55). There is no record of tectonic instability nor of volcanic activity.

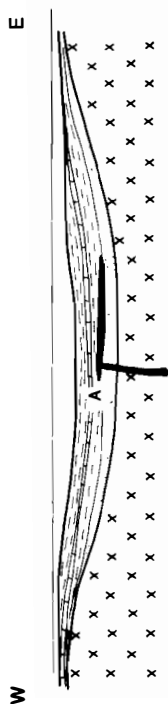
9.8 Sedimentary environments of the Western Province

Sufficient primary structures have survived to permit a confident assessment of the origin of some distinctive units, such as schistose diamictites and associated conglomerates, and some carbonates. On the other hand, searches for consistent paleocurrent indicators have proved unsuccessful, so we have been unable to establish the sources of the sediments. Even if current directions were established, one would need to resolve the question of scale and extent of allochthonous tectonic movements. However, in Wedel Jarlsberg Land there is evidence of uplift and rapid erosion just to the east of Recherchefjorden.

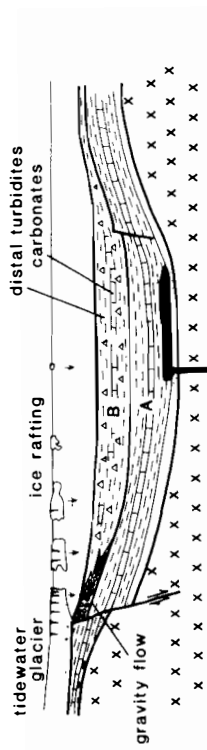
9.8.1 Sedimentation during first glacial stage

Waddams (1983a) recognised that there were two distinct diamictite formations, separated by several kilometres of strata in Oscar II Land. Each formation is texturally similar, and a glacial origin is inferred, for reasons outlined below. On the basis of the correlations made in section 9.1 rocks belonging to this epoch make up the Trondheimfjella Formation, exposed throughout Oscar II Land (but not Prins Karls Forland), as

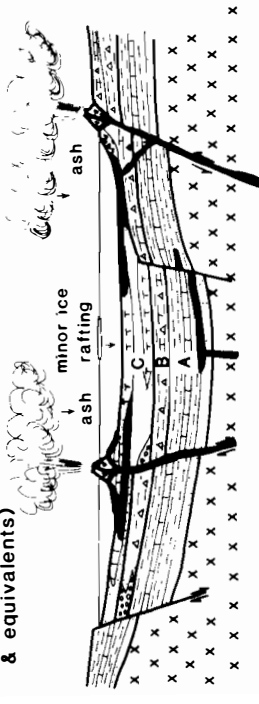
A Preglacial deposition (Kongsvegen Gp.)



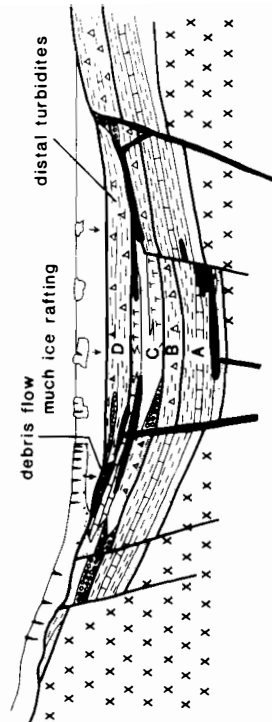
B First glacial epoch (Trondheimfjella Fm. & equivalents)



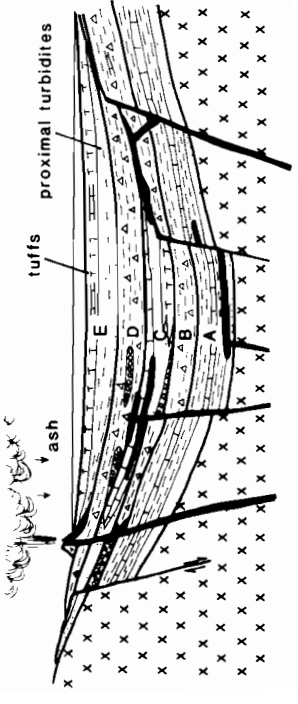
C "Interglacial" epoch (Moefjellet, Løvliebreen & Alkhorn Fms. & equivalents)



D Second glacial epoch (Haaken Fm. & equivalents)



E Postglacial deposition (Annabreen & Aavatsmarkbreen Fms.)



Pre-origenic lithologies

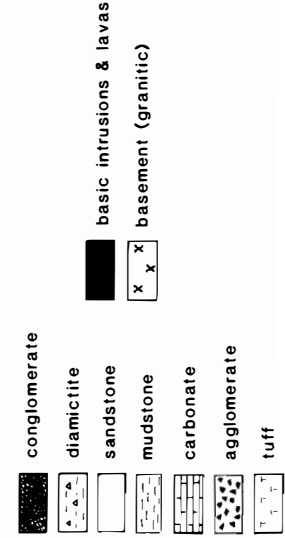


Fig. 55. Preliminary model depicting Late Proterozoic deposition in western Svalbard in a rift-basin setting (based on Oscar II Land successions). Major rock units A, B, C, D, E refer to formations listed in caption headings. Width of rift zone, say, 50 km minimum, final depth of sediment approximately 12 km.

well as in southern Nordenskiöld Land (the Lågneset and Millarodden units) and in middle to south Wedel Jarlsberg Land (the Fløykalven and Vimsodden formations).

The Trondheimfjella schistose diamictites are highly calcareous, often having a rhythmically laminated marble-psammite/pelite matrix through which outsized stones are dispersed. Dropstone structures have been observed at Kapp Martin and Vimsodden. Generally, stones form 1–5% of the rock by volume, but locally form as much as 50%. Stone-bearing beds often grade imperceptibly into stonefree beds. Lonestones sometimes occur within other marine sediments, such as carbonates. The stones, despite deformation, reveal a great range of original shapes and sizes. Although most of them are 0.5 m long or less, a few exceed 1 m in length. Overall, stratigraphic thicknesses of stone-bearing units are of the order of hundreds of metres; their lateral extent is tens if not hundreds of kilometres. None of the diamictites are associated with abraded bedrock surfaces, nor do any of the stones bear any primary surface markings. Neither feature would have survived deformation. The diamictites are associated with stone-free carbonates, psammites, phyllites and coarse boulder conglomerates. The last show signs of soft-sediment deformation in the Bellsund area.

The diamictites are considered to be glaciomarine sediments formed by ice-rafting into a turbidite basin, generally some distance from the source tidewater glaciers.

To establish their mode of deposition three characters are relevant: (1) the fine extensive laminations, (2) the outsized stones dispersed through the rock, and (3) its great thickness and extent (Harland, Herod & Krinsley 1966). Distal turbidites comprise couplets that are laterally extensive and can be some kilometres thick. Whereas most of the characteristic sedimentary structures of distal turbidites no longer survive, it is this type of sediment which most closely matches the schistose diamictites of western Svalbard. Much of the sediment being redeposited was carbonate mud probably mixed with clastic material originally derived from a glacial source. Large stones with diameters many times rhythm thickness (outsized stones), were rafted and dropped into the sediment; the rare dropstone structures confirm this process. Calving from tidewater glaciers some distance away generated icebergs that released their debris over the site of distal

turbidite deposition. The Trondheimfjella Formation depositional environment is pictured in Fig. 55.

The later stages of this early glacial epoch are illustrated by the succession in Orvindalen. Here, towards the top of the diamictite-bearing succession, are dolostones with a range of sedimentary structures: oolites, small-scale channel forms, stromatolites, graded beds and lonestones. These imply shallow-marine (above wave base), near-shore conditions with occasional small-scale gravity flows and ice-rafting.

Most, if not all, of the stones (dolostones, limestones and quartzites) are probably intrabasinal, unlike the Pater diamictites.

The most intensively studied conglomerates associated with the lowermost diamictites are at Kapp Martin, north Bellsund (Waddams 1983b). The lateral extent of the beds, the well-developed graded bedding and the absence of cross-beds suggest deposition from gravity-driven sediment flows. The coarseness of the conglomerates indicates a proximal debris source. The slope down which the flows travelled must have been steep for currents to acquire and transport cobbles and pebbles. The oolitic matrix originated from a shallow marine environment.

Of four depositional models for coarse-grained, resedimented deposits proposed by Walker (1953), the Kapp Martin conglomerates best fit the inverse-to-normally graded model in which deposition occurs from gravity-driven sediment flows in which a suspended load (turbidity flow) and a bed load (grain flow or bed load traction) were present at the same time. The limestone "plumes" resemble large-scale flame structures and they developed by injection when limestone beds with a lower density and high water content were loaded by the conglomerate.

The association of the conglomerates with diamictites suggests that waterlain till was deposited by an advancing glacier on a steep slope. Such material is particularly prone to remobilisation. Thus periodic slumps and slides of till initiated the gravity flows from which the conglomerates were deposited, resulted in mixing with material (oolites) generally associated with high energy, near-shore environments, but into which was added an ice-rafted component.

Elsewhere, the lower diamictite successions contain conglomerate or breccia units, though normally these are less than a few tens of centimetres thick. Sharp upper and lower contacts with

diamictites also suggest that these are subaqueous gravity flows, derived from glacial material.

The diamictites grade vertically into marbles, phyllites and psammites in which few sedimentary structures have survived. One may speculate that carbonate deposition occurred in a shallow marine environment, a suggestion supported by the presence of stromatolites in dolostones in the Trondheimfjella Formation near Eidembukta. The psammites represent clastic input nearshore. The phyllites were probably deposited in deep-water.

9.8.2 "Interglacial" sedimentation and volcanic activity

A record of sedimentation between the two glacial episodes occurs in Oscar II Land, in the Alkhorn (youngest), Løvliebreen and Moefjellet formations; in Nordenskiöld Land (our Linnéfjella and Malmberget units); in North Wedel Jarlsberg Land (units between Kapp Lyell group and Gaimardtoppen/Fløykalven formations); in southwest Wedel Jarlsberg Land (Deilegga Formation).

Volcanic activity was widespread in "interglacial" times (and locally, in earlier glacial times). It is represented by metabasites, corresponding to lavas and intrusions, and phyllites with a volcanic component, all of which are intimately associated with carbonates and clastic sediments.

Evidence for the nature of carbonate sedimentation is best preserved in the Alkhorn Formation, especially in its distinctive bluish grey, silty and sandy limestone and pale grey dolostone beds. Sedimentary structures include well-defined bedding, trough cross-lamination, intraformational conglomerates and breccias, and oolites. Locally, rounded to subrounded clasts of pale dolostone are set in the dark limestone matrix. They are outsized with respect to the lamination and there is a hint that they are dropstones. All this points to deposition in a shallow-marine, tidally influenced setting, with some subaqueous gravity flowage on local slopes, perhaps related to fault scarp activity. Clastic input is indicated by outsized dolostone clasts and sand grains. These may have been derived from a littoral source by rafting. Further south, in Orvindalen, the equivalent carbonates contain stromatolites, again indicating a shallow marine environment. In the north possible stromatolites also occur in the Moefjellet Formation.

The principal "interglacial" clastic formation, is the Løvliebreen Formation of Oscar II Land which comprises quartzites, psammites and pelites, as well as volcanics. Although consisting primarily of sand and metamorphosed clay minerals, the clastic rocks contain a significant amount of carbonate. No sedimentary structures have been observed except in an interlaminated psammite-pelite unit at Protektoraksla (Trygghamna) which contains current-scour structures. Such sediments may have been deposited by minor turbidity flows. At the same locality, a single thin bed of diamictite is probably a subaqueous debris flow. Turbidite deposition is also recorded by the Vestervågen Formation, reflecting a deepening of the basin of deposition prior to the onset of the second glacial epoch.

There is abundant evidence of widespread basic volcanic activity during the "interglacial" period. Coarse-grained igneous rocks occur throughout Oscar II Land, in Nordenskiöld Land and in Wedel Jarlsberg Land associated with purple and green phyllites, following the earlier glaciation.

In southern Oscar II Land igneous rocks occur in both the Løvliebreen and Alkhorn formations. According to Ohta (1984), the former includes fine-grained amygdaloidal Na-alkaline lava flows, some with possible pillow structures, with smaller amounts of calc-alkaline material, which geochemically are of a non-oceanic type, and are associated with typical shelf sediments. Pyroclastic rocks with reddening suggest subaerial exposure. The Alkhorn Formation above includes geochemically different metadolerite-gabbros, also associated with shallow marine sediments.

9.8.3 Sedimentation during the second glacial stage

The second glacial epoch in western Svalbard is represented by the Haaken Formation of Oscar II Land, the Ferrier Group of Prins Karls Forland, the Kapp Linné Formation of northern Nordenskiöld Land and the Kapp Lyell Group of northern Wedel Jarlsberg Land. These stratigraphic units are dominated by alternating finely laminated, orange-weathering psammitic and grey schistose layers up to 10 mm thick, through which stones of all shapes and sizes are dispersed (schistose diamictites). In many respects these sediments resemble the Trondheimfjella Formation and its equivalents. Deposition as distal turbidites is again considered the most likely pro-

cess to generate these rhythmically laminated sediments, whereas ice-rafting gave rise to the coarse component within the schistose diamictites. The bulk of the sediments are thus distal glaciomarine, but occasional higher concentrations of stones (up to 20%) suggest a more proximal position in relation to the ice margin. At Kapp Linné the diamictites are even more stone-rich, including stones of 1 m or more in size. Here it is possible that ice lay over the site of deposition for a time, releasing waterlain till.

Similarly, the diamictites on Alfred Larsentoppen in Prins Karls Forland appear to represent deposition of till close to or under a glacier, either grounded or floating. A few boulder beds in the Haaken Formation may record dumping of coarse debris from icebergs, or the winnowing action of bottom currents on poorly sorted waterlain till, or subaqueous debris flowage; the last process being the most likely. Many spectacular boulder beds in the form of coarse, graded conglomerates occur in the Kapp Lyell Group. These are similar (except for composition) to the conglomerates of the older Kapp Martin division on the other side of Bellsund. They are also considered to have been deposited by subaqueous gravity flows of material deposited on a slope close to a glacier margin.

Overall, the stone content and thickness of stone-bearing horizons suggests that glacial influence was greater during this second glacial epoch. The principal distinguishing feature from the earlier epoch is both the wider variety of stones, (including many exotic stones, especially granites, from an unknown source) and the more resistant matrix. On the other hand, the exotic stones do not bear any resemblance to those contained in the northeastern Svalbard tillites. They indicate that beyond the depositional basin other basement rocks were exposed. It must, however, be said that lack of exotic stones is not a reliable criterion for age. Clearly some (possibly older) facies of the later glacials have a stone content similar to that of the earlier ones. They are distinguished by their position in the succession and by a distinctive matrix. Uncovering of the crystalline basement in the source area may have taken place during rather than before the second glacial episode.

9.8.4 Post-glacial sedimentation

The second glacial episode was followed by deposition of a mixed clastic sequence with a carbonate

and volcanic component. In northern Oscar II Land this is represented by the Annabreen (oldest) and Aavatsmarkbreen formations, and on Prins Karls Forland by the Geikie, Peachflya and Scotia groups. They are succeeded by the Bullbreen and Grampian groups respectively which appear to be of Ordovician-Silurian age. The position of the approximate Vendian-Paleozoic boundary is unknown, however. Further south (and west of the KHFZ), no rocks as young as these in the pre-Devonian sequence of western Svalbard crop out.

The Annabreen Formation, with its alternating psammite and schistose beds, is probably a proximal turbidite sequence. Basinward progradation of a turbidite fan system from a nearby coastline is suggested by the upward transition from crudely graded psammite and schist to ungraded, cross-bedded psammite. This is a transition which began with distal turbidite deposition in the Haaken Formation.

The Aavatsmarkbreen Formation, in contrast, is a dark phyllite of tuffaceous origin that was largely the result of settling from suspension. Thin dolostone and limestone interbeds, and ripple marks suggest deposition in shallow water. The formation probably accumulated in a protected nearshore area.

The Prins Karls Forland post-glacial sequence is somewhat different. Geikie Group carbonates contain intraformational conglomerates and pisolites (Gordon Formation), indicating shallowing of the sea following deglaciation. Then came increasing terrigenous input (Rossbukta Formation). The Peachflya Group is dominated by clastic sediments, with minor carbonates. An episode of volcanic activity is represented by thin lava flows and waterlain tuffs in the Alasdairhornet Formation. The Scotia Group resembles the Aavatsmarkbreen Formation, recording volcanogenic sedimentation in quiet water.

It is in the Scotia Group that the probable Ediacara, biota confirms that in Oscar II Land as well as in Prins Karls Forland much of the post-glacial sequence is indeed Ediacara, as may be the underlying Peachflya and Geikie groups (Knoll & Ohta 1988).

9.9 Sedimentary environment of the Central Province

The top and bottom of the succession are tectonic. However, thicknesses are intermediate between

east and west with not less than 1.3 km Varanger and not less than 1.5 km for probably Ediacara sedimentation. Both Varanger glacial episodes are represented separated by about 300 m of unexposed strata. Early and late episodes are distinctive, the early formation completely lacking granitoids; the later rich in granitoids. Both suggest some mass movement rather than a stable depositional environment. The green facies of the younger Gåshamna phyllites suggests a volcanic component. On Vendian evidence alone the province would seem to be intermediate between east and west. If the overlying rocks are taken into consideration then the Cambrian and Ordovician faunas are quite distinct from those in the east and there is no similarity with facies or faunas in the west (Harland & Wright 1979).

9.10 Post-Vendian tectonic events

Some reference to post-Vendian diastrophism of Vendian rocks is relevant to an interpretation of Vendian paleogeography.

In the Eastern Province the Ny Friesland Orogeny is constrained between mid-Ordovician (Llanvirnian) and the late tectonic granite plutons of early Devonian age. These are extensions of the Caledonian Orogeny (Harland et al. 1992).

In the Central Province a similar constraint obtains between Canadian (Early Ordovician) strata and overlying Early to Mid Devonian strata within a much smaller area. A tectonic episode prior to Early Cambrian has been claimed.

In the Western Province there is evidence in the north of a post-Vendian pre-Caradocian disturbance both at Motalafjella and in the Sutorfjella conglomerates. The main Early Paleozoic tectonism is post-Early Silurian pre-Early Carboniferous. This leaves room for late Caledonian or more likely early Ellesmerian tectonic affinity.

All three provinces show local evidence of severe sinistral shearing along the Billefjorden Fault Zone in the east, the Kongsfjorden-Hansbreen Fault Zone in Hornsund and still further west in Forlandsundet between Oscar II Land and Prins Karls Forland in the north. These movements are established as late Devonian (Svalbardian) in the east and probably of the same age in the west. The evidence suggests that by earliest Carboniferous time Svalbard was united and in a position off eastern North Greenland.

9.11 Vendian geography and geotectonics

From the above tectonic constraints and from a comparison of all pre-Carboniferous tectonostratigraphic sequences three provinces each with at least two subprovinces have been proposed (Harland 1965, 1969, 1985, Harland, Perkins & Smith 1988; Harland et al. 1974; Harland & Wright 1979; Smith 1988; Hambrey 1988). Restoring to their original locations, the Eastern Province would have been near to Central East Greenland. The Western Province would have been near to Peary Land with similarities even in northern Ellesmere Island (Trettin 1987). The Central Province would have been somewhere adjacent to Greenland and between the other two. They achieved their present juxtaposition in Svalbard by Late Devonian sinistral faulting and their present geographical position by dextral transform faulting from north of Greenland.

The remarkable similarity between the Vendian rocks of the Eastern Province and Central East Greenland are now well known (e.g. Kulling 1934; Harland 1965; Hambrey 1983). We know of no two other distant areas with such similarities and conclude that the rocks were formed in the same depositional basin. It is unrealistic to regard the facies of the other two provinces as having formed near or between them.

This basin was the subject of particular study in two NERC supported investigations. The problem addressed in the original proposal by Harland was to constrain the presence, if it then existed, of the Iapetus Ocean. This was on the basis that most tillites in eastern Svalbard and in eastern Greenland show some evidence of shallow water or grounded ice so no ocean could have existed in those areas. If a provenance of such glacial deposits could be established then there could be no intervening ocean – an ice sheet could not have crossed it. From what was then known it seemed that the Ny Friesland glacial deposits might have come from the south east (?Baltica). If so there would be no Iapetus at that time where it was first postulated between Svalbard and Scandinavia (Harland & Gayer 1972). It would have originated later and closed in Ordovician-Silurian time by collision and transpression, the ENE trace probably occurring south of Bjørnøya. A Proto-Iapetus was also suggested by Harland and Gayer initiating the early Ny Friesland eugeosyncline but that was some hundreds of millions of years earlier.

The Ny Friesland and Olav V Land investigations were undertaken by Hambrey in 1981 and 1982. Further work was done in East Greenland in 1984, 1985 and 1988. He and his colleagues concluded that the Svalbard granitoids may have come from an area of basement rocks now exposed to the west of the main sedimentary basin in East Greenland, so the presence of Iapetus at that time is uncertain.

The initial stages of a basin, rift, aulacogen or ocean by extension might be recognised by sedimentation on slopes and volcanicity cf. Harris et al. 1978. While the Eastern Province does not meet these requirements, the Western Province does so admirably. Thus in the north Greenland region, western Svalbard may have developed an incipient ocean in Vendian time. Ohta (1985, 1979) claimed that the volcanic facies in Oscar II Land and the high pressure metamorphic facies of the Vestgötåbreen rocks could indicate a subduction zone in mid-Paleozoic time as Horsfield (1972) originally suggested. In any case, ocean or basin, it would not have had a close relation to Iapetus but to a precursor of the North Greenland-Ellesmere Island fold belt.

Both the Central Province and Bjørnøya have more in common with Eastern Province, a fact which does not help with these speculations.

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