D.L. LAMAR and D.N. DOUGLASS

GEOLOGY OF AN AREA ASTRIDE THE BILLEFJORDEN FAULT ZONE, NORTHERN DICKSONLAND, SPITSBERGEN, SVALBARD

NORSK·POLARINSTITUTT

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Cover: Billefjorden fault zone along the north side of Ålandselva. Hecla Hoek gneiss in centre against Old Red Sandstone on left (west) along Balliolbreen fault. Ebbadalen Formation (Carboniferous) on right (east) against Hecla Hoek gneiss along Odellfjellet fault. Light patches are slivers of Mimerbukta Sandstone along Odellfjellet fault. Stepped talus cones are shown on the shore of Ålandsvatnet.

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The area investigated is located astride the north-south trending Billefjorden fault zone, a major structural feature of central Spitsbergen. Basement rocks consist of Precambrian Hecla Hoek schist, gneiss, and amphibolite, which occur within a fault-bounded block. Devonian Old Red Sandstone rocks of the Wood Bay and overlying Grey Hoek Groups are exposed within and west of the Billefjorden fault zone. From bottom to top the Wood Bay Group is divided into the Kapp Kjeldsen, Keltiefjellet, and Stjørdalen Formations which consist of conglomerate, sandstone, and mudstone comprising a fining-upward fluvial sequence; the Wood Bay Group has a maximum thickness of 2600 m in the western portion of the area and thins to less than 1000 m in the eastern portion of the area. Fluvial channel processes predominated during deposition of the lower portion of the Wood Bay sequence; the middle portion was a transition from channel to levee and flood basin environments, and the upper portion consists of flood basin sediments with calcareous paleosol horizons. Interbeds within these fluvial sediments contain trace fossils suggesting periods of marine and brackish water conditions. The Grey Hoek Group, represented by the Skamdalen Member of the Gjelsvikfjellet Formation, consists of 100 to 400 m of interbedded mudstone and minor sandstone with abundant plant debris deposited on floodplains and in marginal marine swamps. Devonian Old Red Sandstone rocks of the Wood Bay and Grey Hoek Groups and older units exposed northwest of the area studied were deposited in a half-graben with an active western margin and inactive eastern margin. Devonian Mimerbukta Sandstone consisting of quartzite, shale and siltstone occurs as tightly folded fault bounded slices within the Billefjorden fault zone; the stratigraphic relationship of the Mimerbukta Sandstone to the other Devonian rock units is not known.

The oldest Carboniferous unit, the Hørbyebreen Formation of the Billefjorden Group, consists of fluvial to marginal marine conglomerate, sandstone and shale. These sediments occur as erosional remnants of variable thickness resting unconformably on an irregular surface of Hecla Hoek and Devonian Old Red Sandstone throughout the area. A 155 m thick section of the overlying Svenbreen Formation of the Billefjorden Group is exposed east of the fault zone. The Svenbreen Formation consists of a series of fining upward, fluvial cycles composed of sandstone, conglomerate, and mudstone. The 540 to 780 m thick Ebbadalen Formation, lowermost unit of the Gipsdalen Group, rests unconformably on the Svenbreen Formation east of the Billefjorden fault zone. The lower portion of the Ebbadalen Formation is composed of sandstone and black coaly shale overlain by shelly limestone. The middle part consists of anhydrite, limestone, sandstone and mudstone deposited on supratidal sabkhas, as well as subtidal to intertidal sand and mud flats. Middle Ebbadalen Formation strata interfinger with sandstone and conglomerate of upper Ebbadalen Formation deposited in alluvial fans. Foraminifera collected from the Ebbadalen Formation on Trikolorfjellet suggest a late Viséan to early Namurian age based on correlations with the Lisburne Group of Alaska. The overlying Nordenskiöldbreen Formation of the Gipsdalen Group consists of limestone resting unconformably on the Hørbyebreen and Ebbadalen Formations. Quaternary sediments consist of glacial, beach, lake, tidal flat, and marine deposits, alluvium, talus, and landslide debris.

The Billefjorden fault zone is a 2 to 4 km wide zone of parallel and anastomosing faults trending N4°W. Movement on two east-west trending faults occurred prior to displacement on the Billefjorden fault zone. The Balliolbreen fault, the principal strand of the Billefjorden fault zone, has reverse separation which juxtaposes Hecla Hoek metamorphic rocks on the east against Devonian Old Red Sandstone on the west. Prior to being overlain by Carboniferous rocks, the Balliolbreen fault dipped 61° to 63°E; other strands of the Billefjorden fault zone dip 39° to 68°. Near the fault zone folds are tight and overturned; away from the fault zone to the west folds are open and upright. Fold axes and thrust faults with maximum separations of a few hundred meters have sinuous patterns and trends ranging from N40°E to N45°W; they do not intersect the fault zone with the consistent trend charaeteristic of strike-slip faults. The moderate dip of individual strands of the Billefjorden fault zone and the pattern of associated folds suggest east-west compression and predominantly reverse-slip. Major displacement occurred after deposition of Devonian Old Red Sandstone and prior to deposition of Carboniferous sediments.

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Introduction

Background and purpose

The Billefjorden fault zone is a major tectonic lineament striking north-south through central Spitsbergen (Fig. 1). In the area between Austfjorden and Billefjorden, the fault consists of a 2 to 4 km wide zone of several nearly parallel faults; the Balliolbreen fault, the major strand forms a distinct boundary between Devonian Old Red Sandstone on the west and metamorphosed pre-late Silurian Hecla Hoek rocks on the east. Hecla Hoek rocks are also extensively exposed in Ny Friesland, east of the inferred northern continuation of the fault zone beneath Austfjorden-Wijdefjorden (Fig. 1). Faulted and folded Old Red Sandstone rocks composed of siltstone, sandstone and conglomerate of early and middle Devonian age are exposed west of the Billefjorden fault zone (Harland et al. 1974). Based primarily on the regional distribution of the Hecla Hoek and equivalent pre-late Silurian Caledonide rocks in Spitsbergen, Greenland and Arctic Canada, Harland (1969, 1978), Harland & Gayer

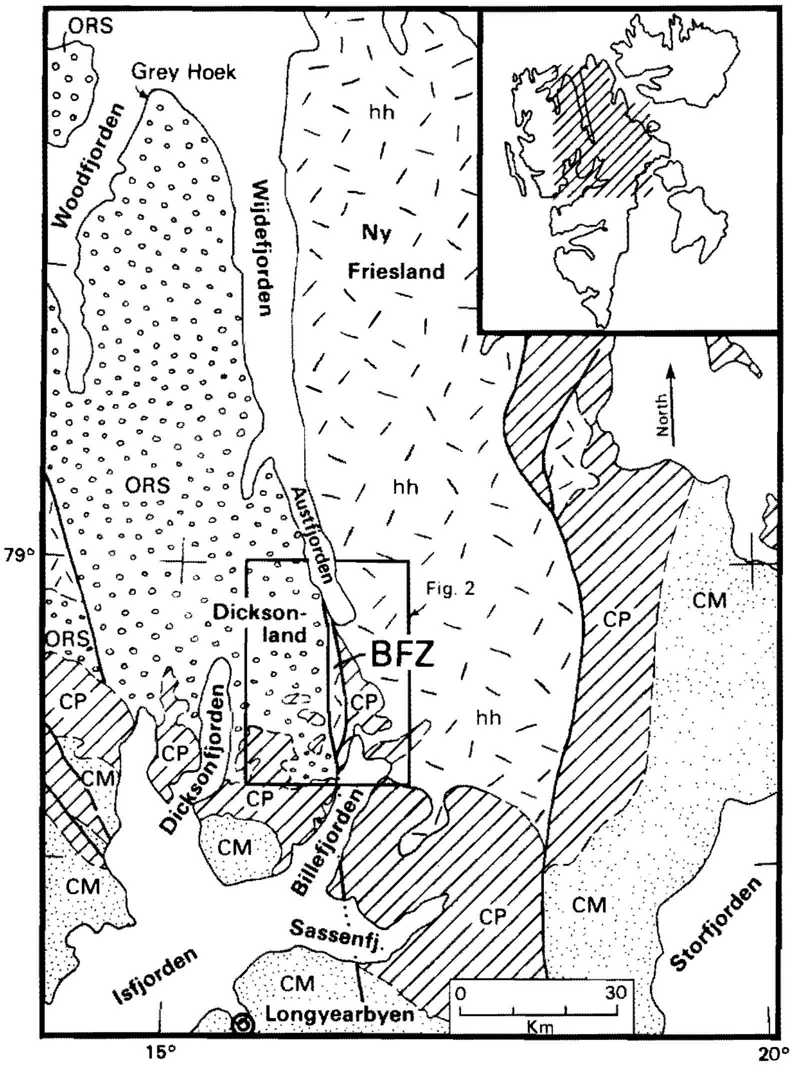


Fig. 1. Geologic map of a portion of Spitsbergen generalized from Orvin (1940) and showing Billefjorden fault zone (BFZ) and outline of Fig. 2. Symbols: CM, undifferentiated Cenozic and Mesozoic rocks; CP, undifferentiated Permian and Carboniferous rocks; ORS, Old Red Sandstone; hh, Hecla Hoek.

(1972) and Harland & Wright (1979) have proposed 200–1000 km of late Devonian left-slip on the Billefjorden fault zone. The Balliobreen fault, the principal strand of the Billefjorden fault zone, and folded Old Red Sandstone rocks are overlain unconformably by Carboniferous sediments; thus the postulated major strike-slip was pre-Carboniferous (Harland et al. 1974).

If the strike-slip occurred in the late Devonian following deposition of early and middle Devonian Old Red Sandstone rocks, these strata should more clearly display secondary structures related to strike-slip than the older, metamorphosed Hecla Hoek rocks. Old Red Sandstone rocks within and directly adjacent to the Billefjorden fault zone are best exposed in our area of investigation in central Dicksonland (Fig. 2 and Fig. 3, map at back). The primary purpose of our study was to improve knowledge about this postulated major strike-slip fault by comparing pre-Carboniferous structures (Lamar et al. 1986) and sediments (Reed et al. 1986, 1987) along the Billefjorden fault zone with structures and sediments associated with well-documented strike-slip faults. This paper documents the conclusions of the above referenced papers with the detailed geologic map and structure sections (Fig. 3) and descriptions of the lithologies and geologic structure.

Because previous work (Harland et al. 1974) suggested that major strike-slip on the Billefjorden fault zone was pre-Carboniferous, the major thrust of our investigation was study of the pre-Carboniferous rocks and structures. We only studied the post Old Red Sandstone rocks in sufficient detail for mapping; detailed observations of facies changes and current directions in post Old Red Sandstone rocks were not made. Previous studies (Cutbill & Challinor 1965; Holliday & Cutbill 1972; Gjelberg & Steel 1981; Steel & Worsley 1984) have described these rocks over a wider area; we compare the results of these regional studies with our observations.

Previous work

In addition to the work referred to above, McWhae (1953) described the fault zone and presented a map of the area between Austfjorden and Sassenfjorden. A portion of the area is shown on a map presented by Winsnes et al. (1960). Friend (1961) and Friend & Moody-Stuart (1972) have described the Devonian Old Red Sandstone rocks west of the fault zone. Murashov & Mokin (1979) also described the Devonian deposits of Spitsbergen, including those in our study area. Burov & Smevskij (1979) show the generalized structure of the fault zone on a regional tectonic map of western Spitsbergen. The area is also shown on a geologic map of the northern part of Spitsbergen (Hjelle & Lauritzen 1982). These papers include references to earlier studies. Our field mapping at a scale of 1:12,500 (reduced to 1:25,000, Fig. 3, map in pocket at back), is more detailed than previous regional studies.

Physical features

The area is situated on the southwest shore of Austfjorden and west of the glacier, Mittag-Lefflerbreen, which flows north into Austfjorden (Fig. 4). Ålandselva, the southernmost stream valley, is dammed by Mittag-Lefflerbreen to form a lake, Ålandsvatnet; drainage from Ålandsvatnet follows the west side of Mittag-Lefflerbreen and empties into the head of Austfjorden. To the north, Zeipeldalen and Jäderindalen are major stream valleys which drain northeast directly into Austfjorden. Nathorstdalen drains west into Dicksonfjorden, 12 km southwest of our map area (Fig. 1). The head waters of the major stream valleys contain glaciers whose meltwater provides the major portion of stream flow. During the warmest part of the season in early July even small streams, such as that in Jäderindalen, had sufficient flow to make crossing difficult. In contrast, during late August when temperatures were lower it was quite easy to cross the mouth of Zeipeldalen, the largest stream in the area.

Gråpiggen, the highest point within the area mapped has an elevation of 1132 m. Hillslopes have an average slope of 20 to 25°. Steep, near-vertical slopes occur near the west margins of Mittag-Lefflerbreen and Cambridgebreen, where previously higher levels of these glaciers have removed bedrock. Steep slopes also occur in flat lying Carboniferous sandstone and conglomerate on Abeltoppen and Gråpiggen and along the margins of resistant Hecla Hoek metamorphic rock outcrops on Odellfjellet and Sentinelfjellet. Because of a fairly widespread cover of talus and colluvium on the hillsides, the best rock exposures occur on ridges and along streams.

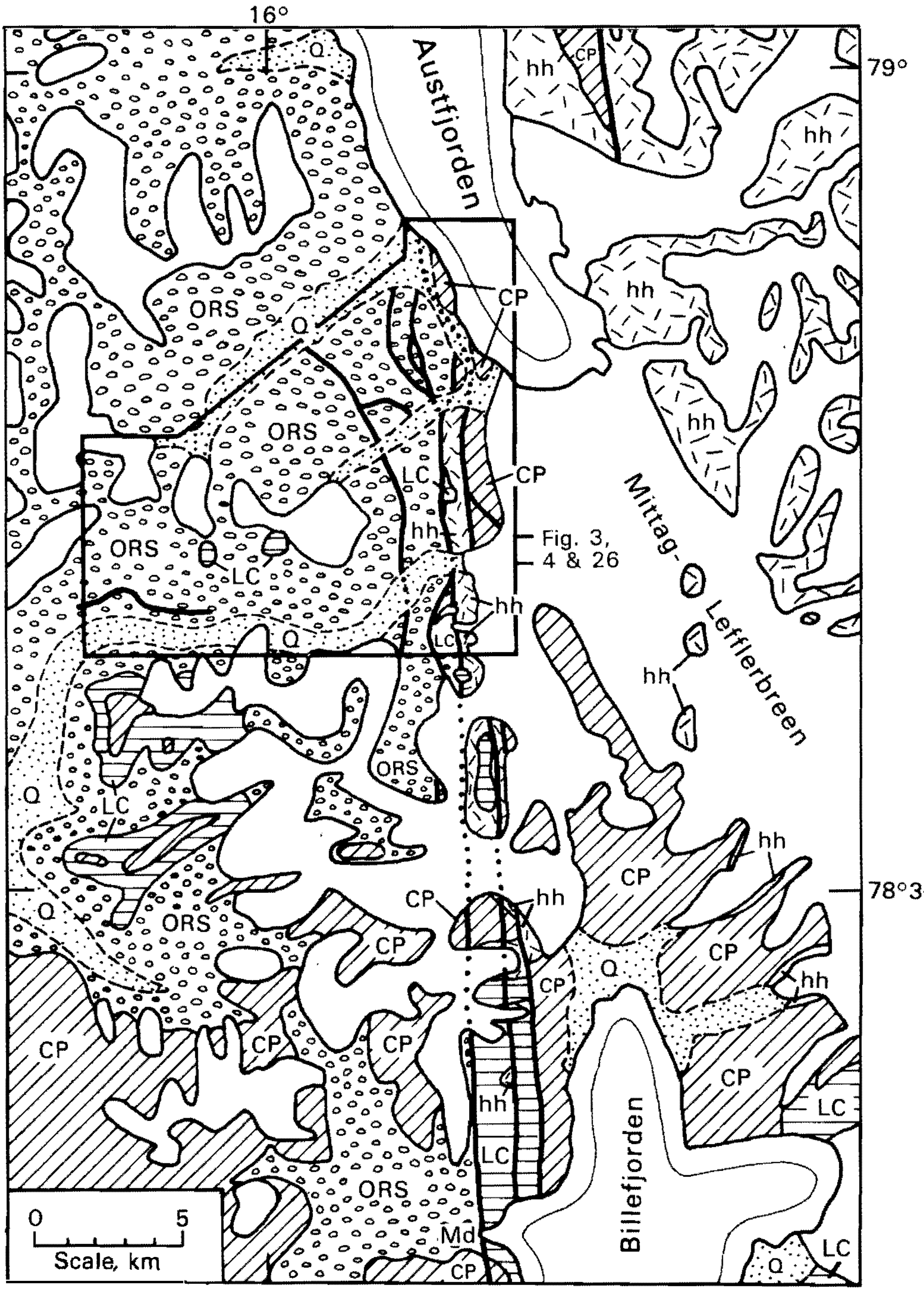


Fig. 2. Generalized geologic map of Billefjorden fault zone in Dicksonland between Austfjorden and Billefjorden showing location of area studied in detail (Fig. 3), modified from Hjelle and Lauritzen (1982). Symbols: Q, Quaternary Deposits; CP, middle to upper Carboniferous; LC, lower Carboniferous; ORS, Old Red Sandstone; hh, Hecla Hoek; Md, Mimerdalen.

Fieldwork

A 1:25,000 scale topographic map was prepared by Ertec Airborne Systems, Inc. from 1:50,000 scale black and white air photographs borrowed from the Norsk Polarinstitutt, Oslo. Field mapping was accomplished on 1:12,500 scale enlargements of the topographic map and the air photographs were used for guidance during the field work. Detailed stratigraphic sections were measured using a Jacob's staff and clinometer.

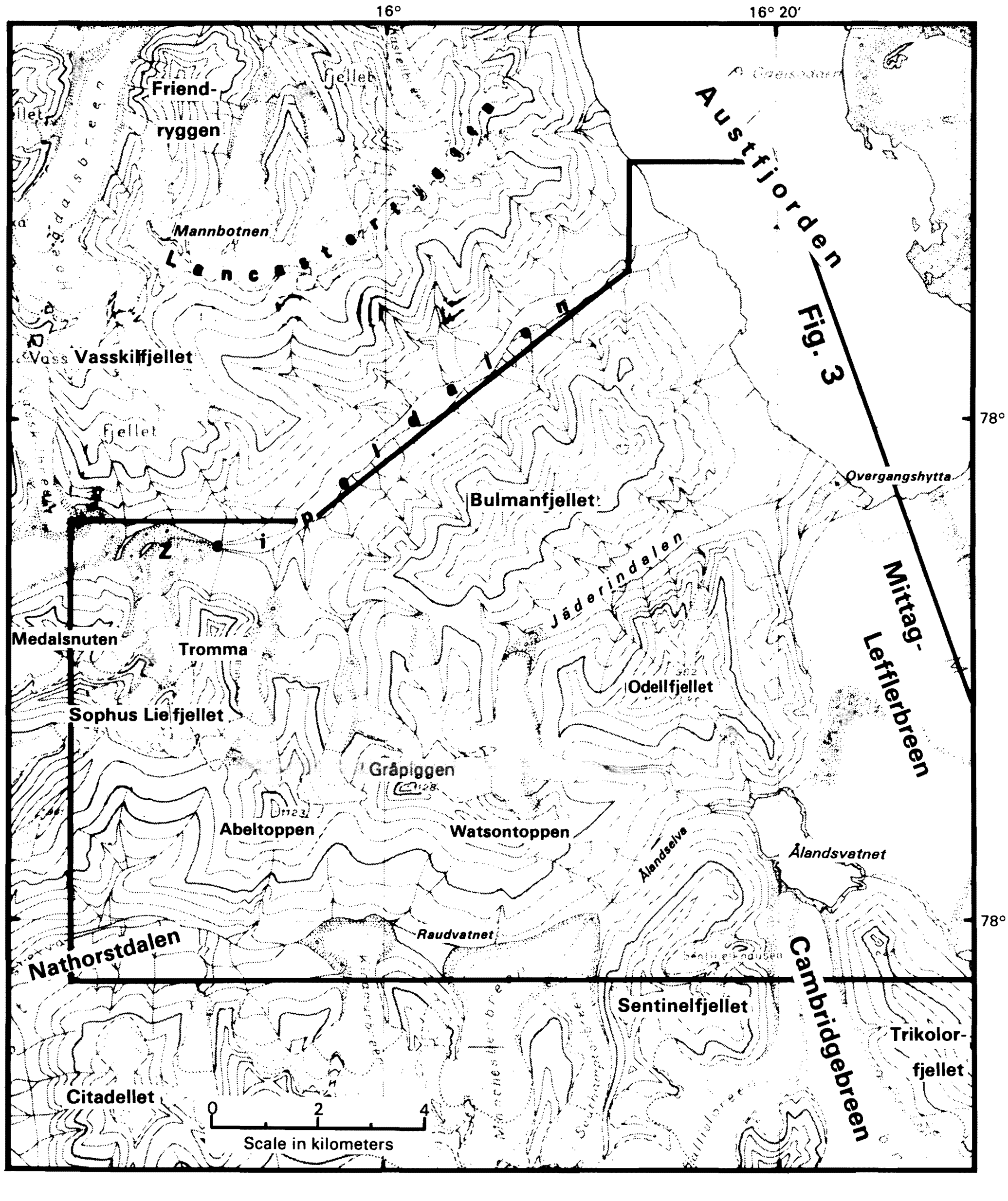


Fig. 4. Index map showing physical features in the area of geologic map (Fig. 3). From Norsk Polarinstitutt 1:100,000 Dicksonfjorden topographic map.

Stratigraphy (includes contributions from W.E. Reed)

Fig. 5 summarizes the thicknesses and stratigraphic and structural relationships of the pre-Quaternary rock units in relationship to the Billefjorden fault zone. Pre-Quaternary rock units consist of: a fault slice of Hecla Hoek series metamorphic rocks, Devonian Old Red Sandstone and Carboniferous sediments. Quaternary sedimentary rock units consist of alluvium, talus, landslide debris, glacial, beach, lake, tidal flat, and marine deposits.

Hecla Hoek

Metamorphic rocks of the Hecla Hoek series exposed on Spitsbergen (Fig. 1) and Nordaustlandet range in age from Precambrian to Ordovician. Metamorphic grade of the Hecla Hoek generally increases downward in the stratigraphic sequence; the youngest rocks are only mildly metamorphosed, whereas Precambrian rocks of north-central Spitsbergen consist of a crystalline basement complex of gneissic rocks (Harland 1959; Birkenmajer 1981).

Hecla Hoek rocks within the mapped area are confined to a north-south trending, fault bounded zone which has a maximum width of 900 m (Fig. 3). These rocks consist of amphibolites, schists and gneisses; augen gneiss is abundant locally. Primary compositional foliation stands nearly vertical, and the rocks are commonly highly sheared. Locally the unit contains small scale (meters) isoclinal folds; fold axes trend a few degrees west of north, and plunge about 45° north. Major joint sets are oriented at approximately N30°E, N10°W, N60°E and N70°W. According to Harland et al. (1974) these rocks belong to the Precambrian Harkerbreen Group.

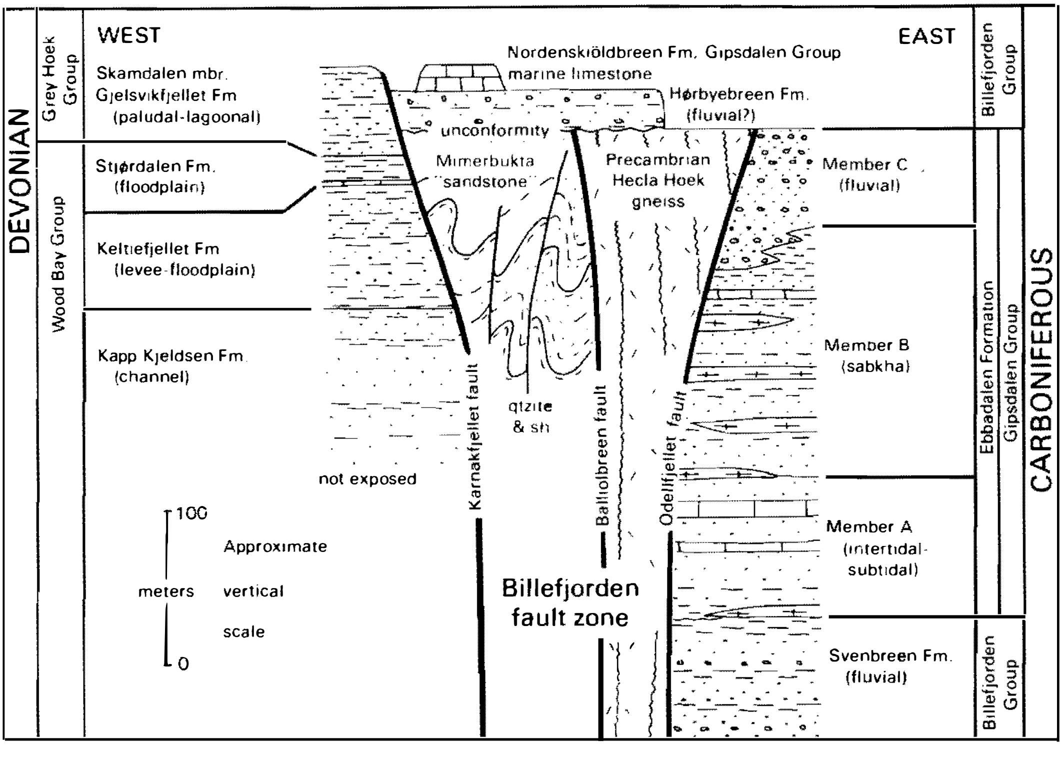


Fig. 5. Diagrammatic section showing pre-Quaternary rock units across area adjacent to the Billefjorden fault zone. Thicknesses of sedimentary rock units shown approximately to scale. The repetition of the Billefjorden Group on the side bar illustrates the offset of the group by the Odellfjellet fault.

Devonian Old Red Sandstone

Devonian Old Red Sandstone rock units within the area are the Kapp Kjeldsen, Keltiefjellet and Stjørdalen Formations of the Wood Bay Group overlain by the Skamdalen Member of the Gjelsvikfjellet Formation of the Grey Hoek Group; the Mimerbukta Sandstone occurs as fault bounded blocks and slivers within the Billefjorden fault zone (Fig. 5). These rocks are of Siegenian, Emsian and possibly Eifelian age (Friend 1961; Murashov & Mokin 1979).

Wood Bay Group

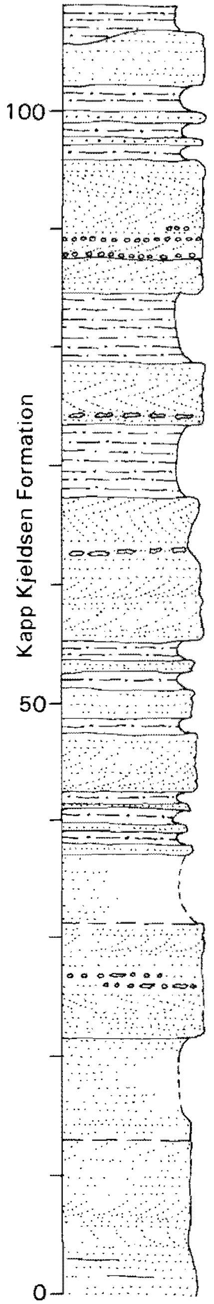
Previous Work.—Strata exposed around Woodfjorden (Fig. 1) were originally named the Wood Bay Series by Holtedahl (1914a,b). Based on more detailed study of exposures in the same area, Føyn & Heintz (1943) divided the Wood Bay Series into the Kapp Kjeldsen, Lykta, and Stjørdalen Faunal Divisions. Friend (1961) renamed the Lykta Division the Keltiefjellet Division. In Dicksonland, Friend (1961) divided the Wood Bay Series into the Austfjorden and Dicksonfjorden Sandstones. More recently Friend et al. (1966) abandoned the above lithologic divisions and redefined the Wood Bay Series as the Wood Bay Formation with local members.

According to Murashov & Mokin (1979) the divisions originally defined by Føyn & Heintz (1943) can be recognized throughout the area of Devonian exposure in north-central Spitsbergen, including the area covered by this investigation. Murashov & Mokin (1979) redefined the Wood Bay Group to include the Kapp Kjeldsen, Keltiefjellet and Stjørdalen Formations. In our detailed geologic mapping, we have recognized the three formations in the Wood Bay Group defined by Murashov & Mokin (1979).

Kapp Kjeldsen Formation.—Føyn & Heintz (1943) report 1000–1500 m of Kapp Kjeldsen on Grevefjellet at the south end of Woodfjorden, 60 km to the northwest of the area studied (Fig. 1). The base of this formation is not exposed in the area studied. The maximum thickness of 710 m within the mapped area occurs on the south side of Ålandselva. We measured 210 m of Kapp Kjeldsen Formation (Figs. 6 and 7) on the south side of Jäderindalen on a northwest trending ridge located N45°W, 1.4 km from the summit of Odellfjellet (Fig. 3).

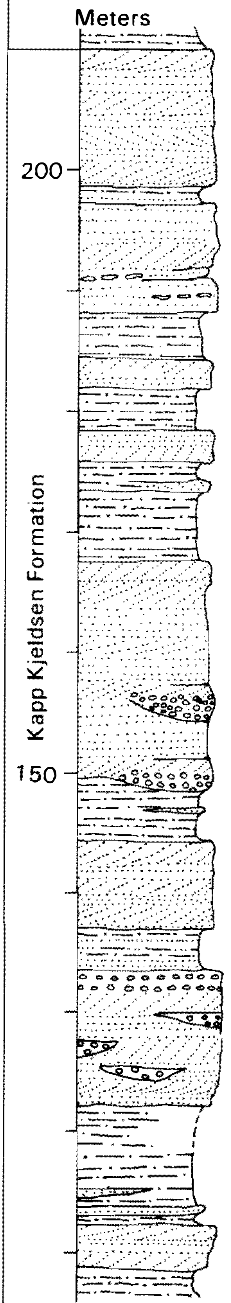
The unit consists primarily of carbonate cemented, medium-grained, yellow-gray, lithic arkosic wackes, with subordinate red-brown siltstones and mudstones. Areas underlain by Kapp Kjeldsen Formation are dominated by flaggy talus composed of yellow sandstone. The contact between the Kapp Kjeldsen Formation and the overlying Keltiefjellet Formation occurs at the top of the "pale beds," i.e., a transition from predominantly yellow gray, flaggy sandstones to primarily red or green beds (Friend 1961). The transition is abrupt and clearly defined in the local area of the measured section in Jäderindalen (Fig. 7); however, to the north the contact is gradational, and transitional strata, consisting of yellow gray flaggy sandstone characteristic of the Kapp Kjeldsen Formation, interfinger with red and green sandstone and mudstone (up to 25%) typical of the overlying Keltiefjellet Formation. Individual sand bodies within the Kapp Kjeldsen and Keltiefjellet pinchout to the east. These interfingering relationships, shown diagrammatically on the structure sections (Fig. 3), could not be shown in detail on the geologic map because the contacts cannot be followed beneath talus and ice between the ridge crest exposures. We have defined a map unit (Dkkg, Fig. 3) comprising these transitional rocks between the Kapp Kjeldsen and Keltiefjellet Formations.

The sandstone bodies of the Kapp Kjeldsen Formation are divided into two types with distinct sedimentary structures: 1. parallel, wavy or ripple cross-lamination, 2. pronounced planar to epsilon cross-beds (Allen 1963) and channels (Figs. 6 and 7). Beds exhibiting channel structures often contain zones of pebble conglomerate composed of sandstone, quartzite and metamorphic clasts. These cross-bedded and channeled sandstones are interpreted to be fluvial channel deposits. Finer grained, ripple-cross laminated sand bodies occur either as thin beds intercalated with brown to green mudstone or as thicker, rippled to plain laminated beds. The thin, interbedded sandstone and mudstone units are interpreted as fluvial channel-proximal (levee) deposits. The thicker, often graded sandstones are interpreted to be single event, crevasse-splay deposits. Where we measured section (Figs. 6 and 7) the Kapp Kjeldsen Formation is interpreted to be composed of approximately 60% fluvial channel facies, 34% levee facies and 6% crevasse-splay facies (Fig. 8).



Thickness (m)	
12.8	Interbedded sandstone (fine to medium), yellowish gray (5Y 7/2), yellowish orange (10YR 6/6) and yellowish brown (10YR 5/4) arkosic wacke and siltstone, olive gray (5Y 3/2). Beds 0.5 to 1 cm, bed sets 0.05 to 0.1 m.
	Sandstone (medium), yellow gray (5Y 7/2) lithic arkosic wacke. Micaceous. Beds 0.1 to 1 cm, bed sets to 10 cm. Small-scale epsilon and ripple cross lamination.
5.3	Sandstone (medium) light olive gray (5Y 6/1) lithic arkosic wacke; and pebble conglomerate, pebbles include sandstone (fine to very fine), vein quartz, red quartzite, and dark metamorphics. Zones exhibit epsilon cross-beds.
3.0	
8.7	Interbedded sandstone (medium), yellowish brown (10YR 6/2) arkosic wacke, grading into grayish orange (10YR 7/4) arkosic wacke, and mudstone, olive black (5Y 2/2), dark greenish gray (5G 4/1), yellowish gray (5Y 7/2) and brownish gray (5YR 4/1). Sandstone beds at base are lenticular. Thinly laminated, beds 0.5 to 2 cm, bed sets to 0.5 m, epsilon cross-beds.
4.5	Sandstone (medium to coarse), yellowish gray (5Y 7/2) arkosic arenite. Calcite cement. At base of unit is mud clast conglomerate.
6.0	Mudstone, variegated (reddish brown, 10R 3/4; grayish brown, 5YR 3/2; and light greenish gray, 5GY 8/1).
12.3	Sandstone (medium) moderate yellowish brown (10YR 5/4) lithic arkosic arenite. Calcite cement. Beds 3 to 5 cm, bed sets to 3 m. Epsilon and planar (?) cross-beds. At 7.4 m above base is a mud clast conglomerate, 5% to 10% clasts, pale olive gray, (10YR 8/2).
	Interbedded sandstone (medium to very fine) yellowish orange (10YR 5/6), dark greenish gray (5GY 4/1), and greenish gray (5GY 6/1), quartz wacke, arkosic wacke and lithic arkosic wacke, friable with concretions, siltstone, dark greenish gray (5G 4/1) and dark reddish brown (10R 3/4), and mudstone, grayish brown (5YR 3/2), fissile micaceous.
7.6	Sandstone (medium) greenish gray (5GY 6/1) and yellowish gray (5Y 7/2) arkosic wacke and quartz wacke. Finely laminated to 5-10 cm beds. Wavy cross-beds, flame structures, complex epsilon cross-bedding, slump folds, ball and pillow structure; rapid vertical and horizontal variation in sedimentary structures.
5.0	
5.5	Interbedded sandstone (fine) pale yellowish brown (10YR 6/2) quartz wacke; finely laminated, ripple drift cross-lamination; and mudstone, grayish brown (5YR 2/2), micaceous. Unit is ca. 45% sandstone.
5.8	Covered. Talus indicates sandstone (very fine), grayish red (5R 4/2) arkosic wacke. Micaceous.
9.6	Sandstone (medium to coarse), yellowish gray (5Y 7/2) arkosic arenite. Zones of pebble conglomerate including mud clasts, quartzite. Epsilon cross-beds, beds 3-10 cm., bed sets to 1.5 m.
8.8	Sandstone (fine), dark greenish gray (5GY 4/1) arkosic wacke. Fissile, flaggy, partly covered.
12.8	Sandstone (medium), light olive gray (5Y 6/1) to olive gray (5Y 4/1), arkosic wacke. Several zones with epsilon cross-beds, bed sets 0.05 to 0.5 m. Load casts on some beds. Flaggy.
	Base covered with talus.

Fig. 6. Columnar section of lower portion of Kapp Kjeldsen Formation exposed on southeast side of Jäderindalen, 1.4 km northwest of summit of Odellfjellet; map coordinates: N8758560, E525820 to N8758430, E526060.



Thickness (m)	
	Siltstone, base of Keltiefjellet Formation
11.4	Sandstone (medium), grayish orange (10YR 7/4) lithic arkosic wacke. Beds 1 to 10 cm, bed sets 0.5 to 1.5 m; epsilon and pi cross-stratification.
1.3	Interbedded mudstone, light greenish gray (5G 8/1) and sandstone (fine) yellowish gray (5Y 7/2) arkosic wacke.
9.0	Sandstone (medium), yellowish gray (5Y 7/2) lithic arkosic wacke. Beds 3 to 10 cm, bed sets 0.5 to 1.5 m; epsilon and pi cross-stratification. Several thin (0.3 m) zones of mud clast conglomerates.
9.8	Interbedded mudstone, grayish red (10R 4/2) and light olive gray (5Y 6/1), root mottled, fissile, and sandstone (fine to medium) yellowish gray (5Y 7/2) and grayish orange (10YR 7/4) arkosic wacke. Ripple cross-laminated, beds 0.5 to 1 cm, bed sets to 10 cm.
11.0	Interbedded mudstone, pale brown (5YR 5/2) and moderate brown (5YR 3/4), fissile, silty, abundant calcareous nodules (up to 4 cm) in zones and sandstone (medium to very fine) greenish gray (5GY 6/1) lithic arkosic wacke. Ripple cross-laminated, beds 0.5 to 1 cm, bed sets 0.1 cm.
18.9	Sandstone (medium) yellowish gray (5G 7/2) arkosic wacke. Beds 1 to 2 cm, bed sets 0.15 m. Epsilon cross-beds throughout. Channels (up to 1 m) of pebble conglomerate.
	Mudstone, reddish brown (5YR 3/4), silty; root mottled. Thin (0.3 m) lenses of sandstone (fine), greenish gray (5GY 6/1) arkosic wacke.
7.5	Sandstone (medium) yellowish gray (5Y 7/2) lithic arkosic wacke. Beds to 1 cm, bed sets 0.1 m. Ripple cross-laminated with interbeds of epsilon cross-stratification.
3.6	Interbedded mudstone, yellowish brown (10YR 6/2), sandstone (very fine) yellowish gray (5Y 7/2) and siltstone, moderate brown (5YR 3/4). Thinly laminated.
11.2	Sandstone (medium), yellowish gray (5Y 7/2), lithic arkosic arenite. Beds 1 to 5 cm, bed sets to 1 m. Epsilon cross-beds. Channels (0.5 to 1 m) of pebble conglomerate, pebbles include sandstone (fine) and quartzite. Matrix is coarse sandstone.
4.5	Covered.
5.3	Interbedded mudstone, variegated (grayish red, 5R 4/2; greenish gray, 5GY 6/1; and grayish orange, 10YR 7/4) and sandstone (fine to medium) yellowish gray (5Y 7/2) arkosic wacke, epsilon cross-beds, lenticular.
3.5	Sandstone (medium to fine), dark yellow brown (10YR 4/2) arkosic wacke. Beds 0.5 to 1 cm, internally laminated, bed sets to 0.1 m. Ripple cross-lamination abruptly changing near top of bed to cut-and-fill structures with epsilon cross-beds.

Fig. 7. Columnar section of upper portion of Kapp Kjeldsen Formation exposed on southeast side of Jäderindalen, 1.4 km northwest of summit of Odellfjellet; map coordinates: N8758560, E525820 to N8758430, E526060.

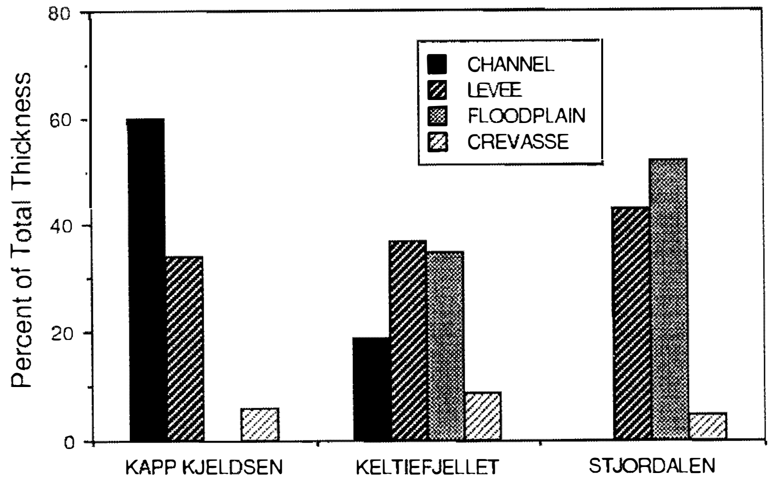


Fig. 8. Bar graphs showing percentages of different depositional facies in the formations of the Wood Bay Group.

Keltiefjellet Formation.—Føyn & Heintz (1943) report 600–700 m of Keltiefjellet Formation on Scott Keltiefjellet directly east of Woodfjorden, 55 km northwest of the area studied (Fig. 1). We measured 158 m of Keltiefjellet Formation south of Jäderindalen (Figs. 9 and 10). The unit thickens rapidly from 100 m in the east to a maximum of 1700 m in the western portion of the mapped area on the slope southwest of Sophus Liefjellet (Fig. 11).

Sandstones of the Keltiefjellet Formation differ from those of the Kapp Kjeldsen Formation, primarily by their green to red-brown color and thinner bedding. Epsilon crossbeds occur in the thicker units. Although, the frequency of channels and sand bed thickness are less than in the Kapp Kjeldsen Formation, fluvial channel, levee and crevasse-splay sandstones, as described in the Kapp Kjeldsen Formation, all occur in the Keltiefjellet Formation. In addition, there are thick, massive to laminated red-brown mudstones which often exhibit root-mottling (Fig. 12) and contain carbonate nodules (discussed below). These mudstones are interpreted to be channel-distal floodplain deposits. Within the Keltiefjellet Formation measured section (Figs. 9 and 10) channel facies are more prominent in the lower 60 m and floodplain deposits are more abundant in the upper part of the section; the formation as a whole consists of approximately 19% channel facies, 37% levee facies, 35% floodplain facies and 9% crevasse-splay facies (Fig. 8).

Murashov & Mokin (1979) place the contact between the Keltiefjellet Formation and the overlying Stjørdalen Formation at the top of "The last thick (15 m) bed of green cross-bedded sandstone of uniform occurrence." For utility in mapping, we have placed the Keltiefjellet— Stjørdalen Formation contact at the base of an easily recognized, well exposed carbonate unit (Fig. 10) which is persistent throughout our study area. This carbonate bed, discussed below, is interpreted to be a pedogenic calcrete. The calcrete is located 5.7 m above 13.1 m of interbedded cross-bedded green sandstone and mudstone (Fig. 10), which may correspond to the top of the Keltiefjellet Formation as defined by Murashov & Mokin (1979).

Stjørdalen Formation.—Føyn & Heintz (1943) report about 500 m of Stjørdalen Formation directly north of Stjørdalen on the east coast of Woodfjorden (Fig. 1) 70 km to the northwest of our area. We measured 42 m of Stjørdalen Formation south of Jäderindalen (Fig. 10). Mapping indicates a general increase in thickness of the Stjørdalen Formation from east to west; within the mapped area the maximum thickness of 200 m occurs on the northwest slope of Bulmanfjellet (Fig. 13). Variations in thickness of the Stjørdalen Formation (Fig. 13) may be partly the result of erosion prior to deposition of the overlying units. An unconformity also is indicated by a change in the average attitude of bedding from N32°W, 25°W in the Stjørdalen Formation to N67°E, 13°S in the overlying Skamdalen Member of the Gjelsvikfjellet Formation (Fig. 5).

The Stjørdalen Formation is predominantly bright red to brown mudstone and siltstone, with subordinate thinly bedded, gray to green sandstone. Many of the mudstone layers show prominent root-mottling, as well as calcareous nodule horizons (discussed below). The carbonate and mudstone units are interpreted to be distal flood-plain deposits, whereas the interbedded sandstones are interpreted to be channel-proximal (levee) deposits, as described above. In the measured section (Fig. 10) the Stjørdalen For-

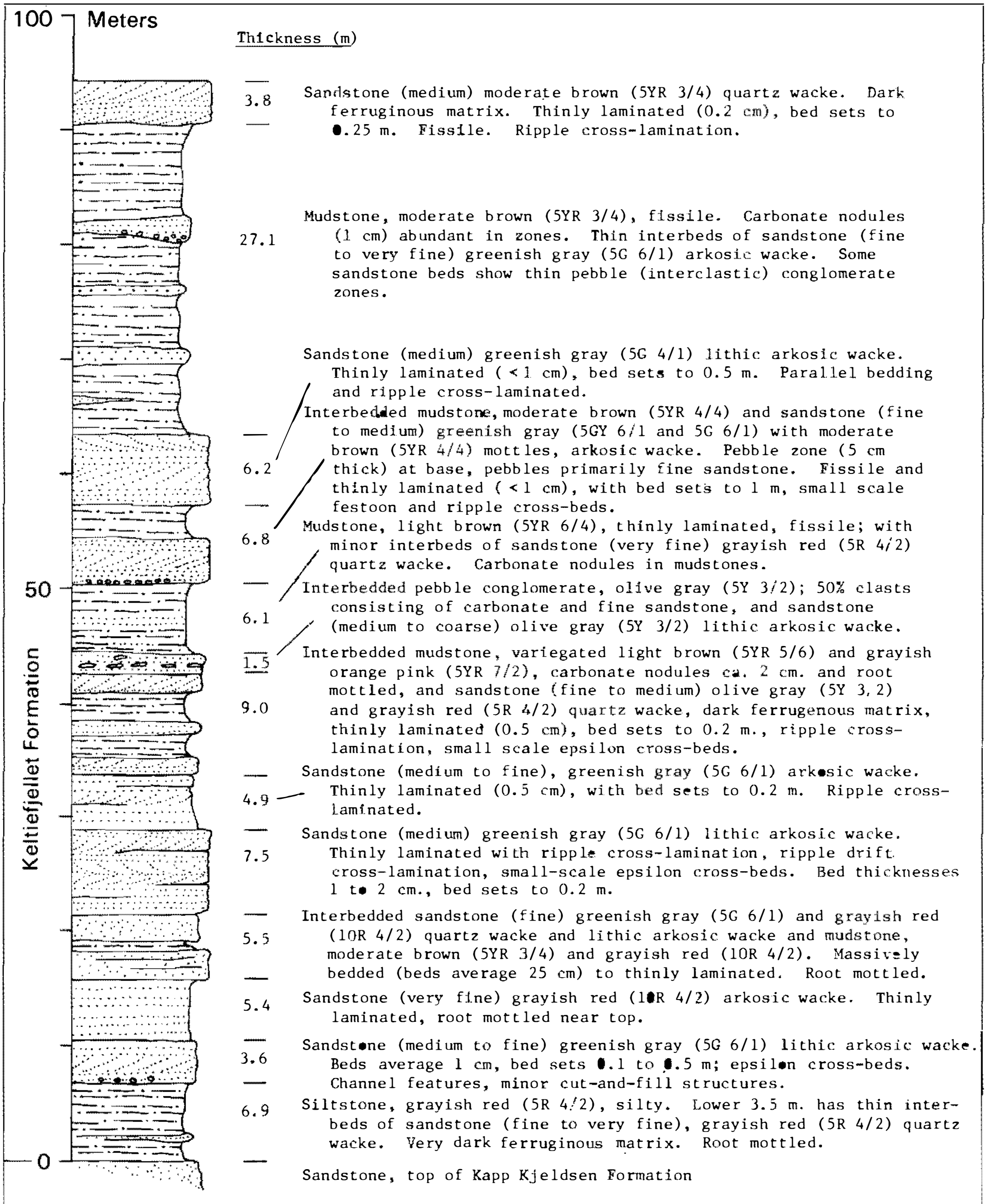
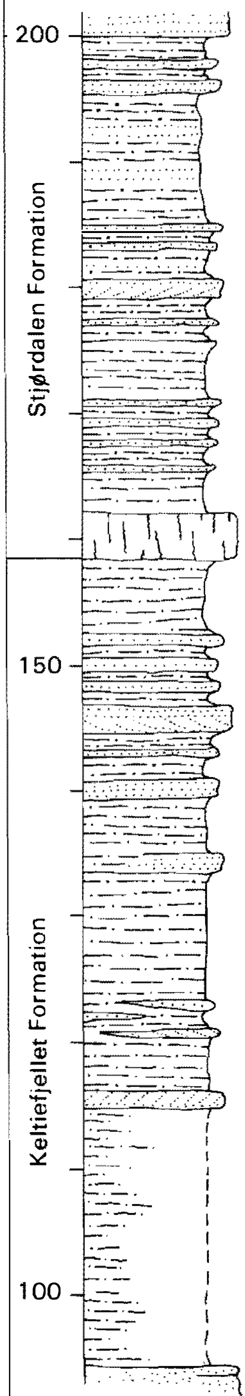


Fig. 9. Columnar section of lower portion of Keltiefjellet Formation exposed on southeast side of Jäderindalen, 4.7 km southwest of Overgangshytta; map coordinates: N8758430, E526060 to N8758310, E526200. See Fig. 11 for location of section.



Thickness (m)	
	Sandstone, base of Skamdalen Member of Gjelsvikfjellet Formation
6.0	Interbedded mudstone, moderate brown (5YR 3/4), grayish brown (5YR 3/2) and greenish gray (5GY 6/1), silty, with abundant carbonate nodules (to 7 cm) and sandstone (medium) greenish gray (5G 6/1) arkosic wacke, thinly laminated (< 1 cm), epsilon cross-beds, flaggy.
9.1	Interbedded mudstone, moderate brown (5YR 3/4) to grayish brown (5YR 3/2), silty, and sandstones (fine) greenish gray (5G 6/1) and grayish red (10R 4/2) arkosic wackes.
5.8	Interbedded mudstone, light brown (5YR 3/6) silty, and sandstone (medium to very fine) greenish gray (5G 6/1) arkosic wacke, thinly laminated (ca. 1 cm), bed sets to 10 cm, epsilon cross-beds, root mottled.
3.9	Interbedded sandstone (fine to very fine), greenish gray (5GY 6/1) arkosic wacke, thinly laminated; and mudstone, moderate brown (5YR 3/4). Free of nodules.
4.2	Mudstone, brownish gray (5YR 4/1), moderate brown (5YR 3/4), and grayish red (5R 4/2), silty. Carbonate nodules (to 2 cm).
5.6	Interbedded sandstone (medium to fine), greenish gray (5GY 6/1) lithic arkosic wacke, and mudstone, brownish gray (5YR 4/1) to moderate brown (5YR 3/4), silty, with zones rich in carbonate nodules.
3.3	Mudstone, pale red brown (10R 5/4), silty, calcareous, massive. Carbonate nodules (to 5 cm). Thin (10 cm) interbedded sandstones (medium), greenish gray (5G 6/1), ripple cross-laminated.
3.6	Intraclastic limestone (calcrete?). Clasts (up to 10 cm) of quartzite, dark greenish gray (5G 4/1) and moderate orange pink (10R 7/4), and limestone (N5). Sparry calcite cement, white to greenish gray (5GY 6/1) massive.
5.7	Mudstone, moderate reddish brown (10R 4/6) thin interbeds of greenish gray (5GY 6/1).
4.7	Sandstone (medium) greenish gray (5GY 6/1) lithic arkosic wacke. Epsilon cross-beds throughout, thinly laminated (0.5 cm), bed sets to 0.25 m. Interbeds of mudstone, moderate brown (5YR 4/4)
3.2	Interbedded sandstone (medium) greenish gray (5GY 6/1) lithic arkosic wacke, thinly laminated (0.5 cm), bed sets to 0.25 m, small-scale festoon and epsilon cross-beds, convolute zone, and mudstone, moderate brown (5YR 4/4), silty.
5.2	Interbedded mudstone, pale brown (5YR 5/2), fissile and sandstone (fine to medium) grayish red (10R 4/2) arkosic wacke and lithic arkosic wacke, micaceous, thinly laminated (0.5 cm). Root mottled and bioturbated.
5.9	Interbedded mudstone, light brown (5YR 5/6) and moderate brown (5YR 3/4) and sandstone (fine to medium) grayish red (5R 4/2) lithic arkosic wacke, dark ferruginous matrix, thinly laminated (0.2 cm), bed sets 0.05 m).
12.5	Mudstone, light brown (5YR 5/6) with minor greenish gray (5G 6/1) interbeds. Lenticular sands (0.2 to 1.0 m) near base.
6.3	Interbedded mudstone, light brown (5YR 5/6) and greenish gray (5G 6/1) and sandstone (medium to coarse) grayish brown (5YR 3/2), greenish gray (5GY 6/1) and grayish green (5G 6/1) arkosic wacke and lithic arkosic wacke, ripple cross-laminated, thinly laminated (0.1 to 1.0 cm), bed sets to 0.2 m, thin zones rich in intraclastic pebbles.
20.5	Covered. Probably mudstone.

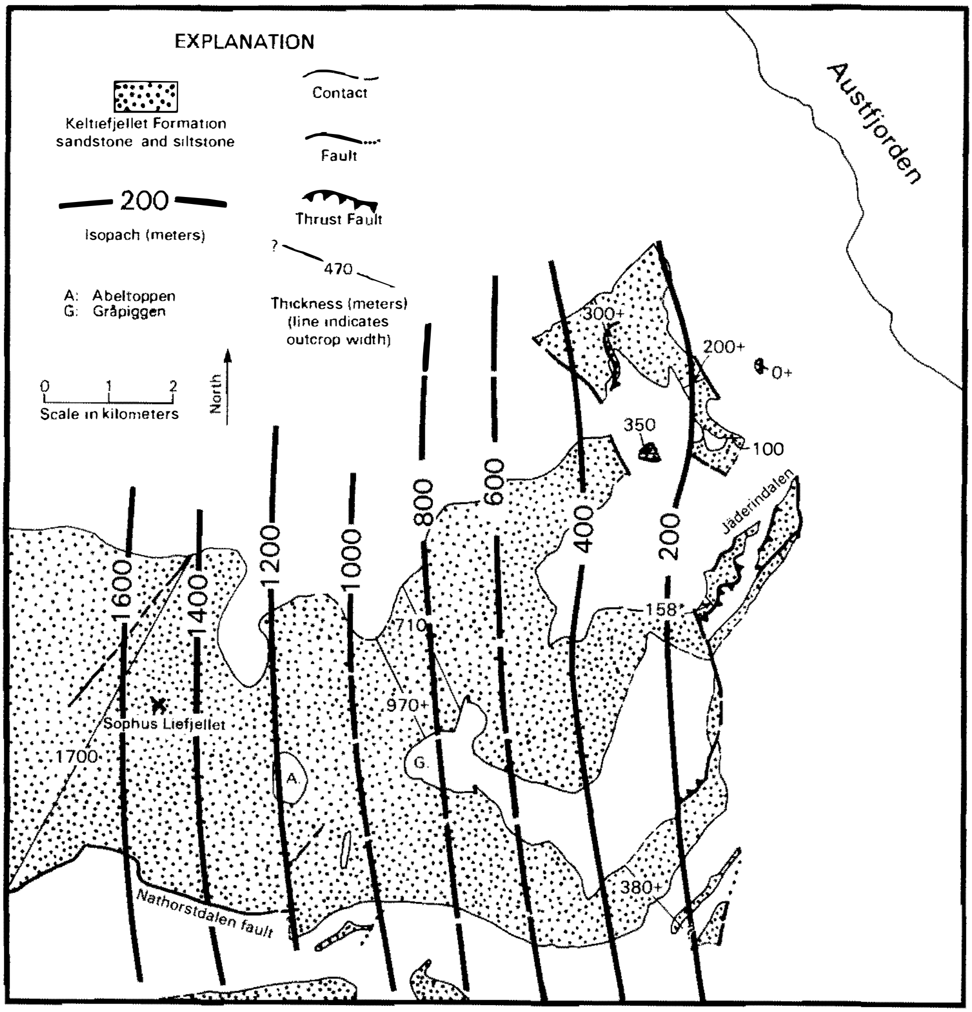


Fig. 11. Isopach map showing distribution and thicknesses of Keltiefjellet Formation scaled from geologic map and measured sections (*) (Figs. 9 and 10).

mation is composed of: 43% channel proximal (levee) deposits; 52% floodplain deposits and 5% crevasse splay deposits (Fig. 8).

Trace fossils from Wood Bay Group (by J.D. Farmer).—Trace fossils, including *Cruziana*, were reported previously from the Kapp Kjeldsen Formation of the Wood Bay Group in other areas of Spitsbergen (Goujet 1984). We have found *Rusophycus* (Fig. 14A) and *Cruziana* (Fig. 14B) in the Keltiefjellet Formation at Jäderindalen and Zeipeldalen, where they are preserved as convex hyporeliefs in channel or crevasse-splay sandstones. These ichnogenera are interpreted to be resting (*Rusophycus*) and feeding (*Cruziana*) traces of arthropods (Hantzschell 1975). Similar bilobate traces of smaller size (Fig. 14E) are identified as *Isopodichnus* on the basis of transverse striae oriented perpendicular to the median groove, and occasional expanded burrow endings

Fig. 10. Columnar sections of upper portion of Keltiefjellet Formation and Stjørdalen Formation exposed on southeast side of Jäderindalen. Keltiefjellet Formation section located 4.7 km southwest of Overgangshytta; map coordinates: N8758430, E526060 to N8758310, E526200. Stjørdalen Formation section located 6.0 km southwest of Overgangshytta; map coordinates: N8757580, E525140 to N8757340, E525230. See Figs.11 and 13 for locations of sections.

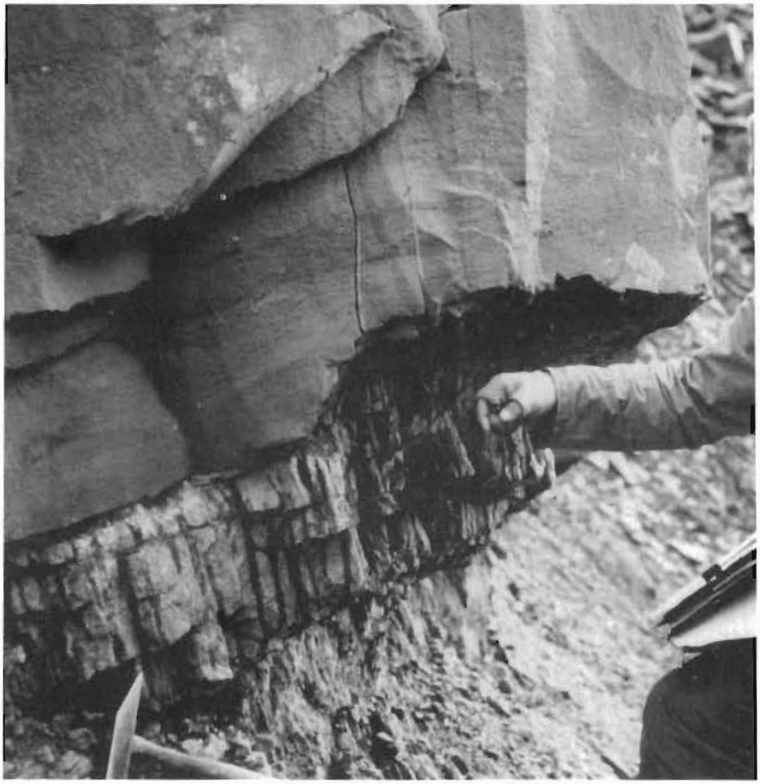


Fig. 12. Root mottled siltstone beneath sandstone, Keltiefjellet Formation south of Jäderindalen.

(Trewin 1976). *Isopodichnus* is preserved as convex hyporeliefs in floodplain siltstones of the Upper Keltiefjellet and Lower Stjørdalen Formations, at Stjørdalen. *Isopodichnus* has been interpreted to be resting and/or feeding traces of small arthropods, perhaps freshwater phyllopods or other entomostracans (Trewin 1976). However, distinction of *Isopodichnus* from small *Cruziana* is difficult (see Trewin 1976; Seilacher 1985), and these traces cannot be used reliably as paleosalinity indicators. *Merostomichnites* (Fig. 14D) is preserved in concave epirelief on the upper surfaces of thinly-bedded, medium-grained channel sandstones of the Keltiefjellet Formation at Jäderindalen. Such traces were interpreted by Størmer (1934) to be trackways of eurypterids or similar arthropods.

Bean-shaped, beaded traces identified as *Lockeia* (Fig. 14C) are preserved in convex hyporelief on the undersurfaces of channel sandstones of the Keltiefjellet Formation at Jäderindalen. Large, back-filled burrows identified as *Taenidium* are abundant in fine-grained levee or channel-margin sandstones of the Keltiefjellet and Stjørdalen Formations at Jäderindalen and Zeipeldalen (Fig. 15A). These typically large, back-filled traces are similar to those described from Devonian, non-marine sequences elsewhere (Webby 1968; Gevers et al. 1971; D'Allesandro & Bromley 1987; Bruck, et al. 1985; Allen & Williams 1981).

Large, longitudinally striated burrows averaging 3.3 cm in diameter and up to 15 cm in length (Fig. 15B), are preserved in convex hyporelief on the bases of thick channel sandstones at two horizons (38 and 128 meters) above the base of the Keltiefjellet Formation. The burrows do not branch. Their cross-cutting relationships indicate a biogenic origin, but their taxanomic affinity is unknown. Their large size suggests they may have been produced by fish. *Planolites*, a smaller unbranched burrow (diameter 15 mm) lacking back-filling, is a common hypichnial and indichnial trace fossil in the Keltiefjellet sandstones (Fig. 15D).

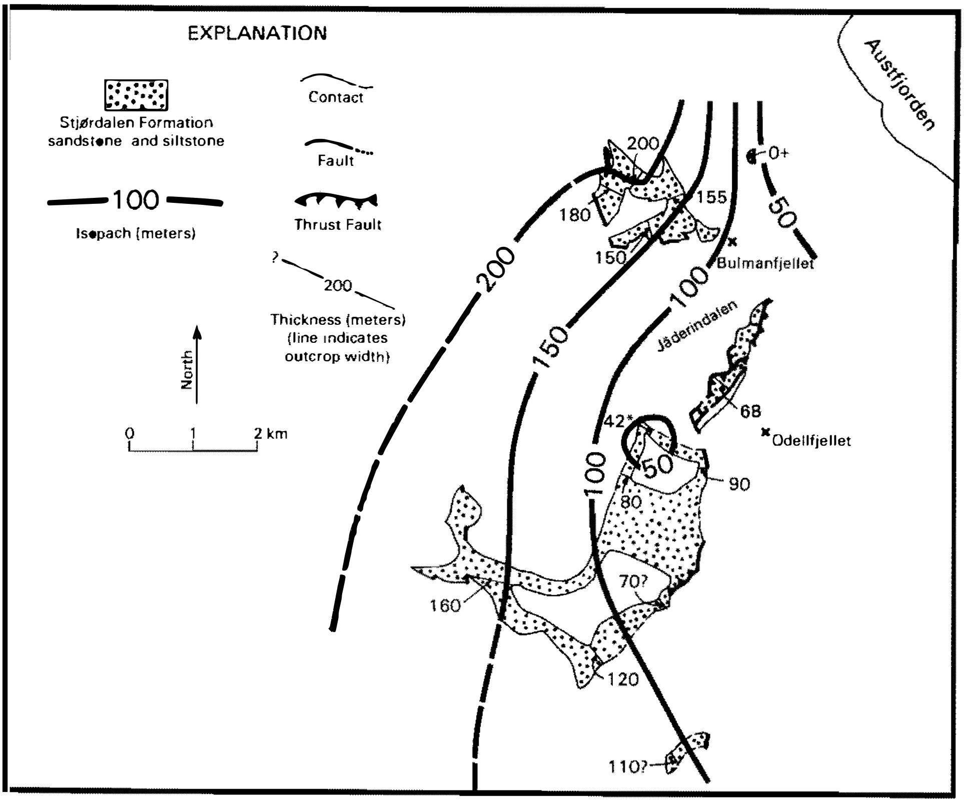


Fig. 13. Isopach map showing distribution and thicknesses of Stjørdalen Formation scaled from geologic map and measured section (*) (Fig. 10).

Mud-filled, branching burrows (Figure 15C) are common in middle sandstones of the Stjørdalen Formation at Zeipeldalen. The burrows bear a superficial resemblance to *Chondrites*, but differ in their style of dichotomous branching (A. Rindsberg, personal communication).

Unique tri-lobate traces (Fig. 15E), are preserved in convex hyporelief on the base of a crevasse splay sandstone near the top of the Keltiefjellet Formation. The traces average 4 cm in width and do not overlap. The tri-lobate morphology is unlike any previously described ichnogenera. They are interpreted to be shallow resting traces of small fish that became stranded in an ephemeral floodplain lake. If this interpretation is correct, they represent the earliest fish trace fossils yet described.

Goujet (1984) and Janvier (1985) have, on the basis of fossil fish faunas, suggested that the Wood Bay Group was deposited in a marginal marine setting. However, the lithologies and sedimentary structures of this succession are more typical of fluvial deposition (Denison 1956; Friend 1965; Friend et al. 1966; Friend & Moody-Stuart 1972). The trace fossil assemblage described here (*Rusophycus*, *Cruziana*, *Isopodichnus*, *Beaconites* and *Merostomichnites*) is consistent with such an interpretation, and supports the idea of coastal plain fluvial environments lying near sea level which were subject to periodic estuarine and marine influences. It is possible that detailed micropaleontological and ichnological sampling of these Wood Bay Group strata may eventually reveal a record of marine incursions similar to those that have been documented in Old Red sequences elsewhere (Miller 1979; Craft & Bridge 1987).

Calcrete deposits of Wood Bay Group (by W.E. Reed).—The persistent calcrete horizon at the base of the Stjørdalen Formation (Fig. 10) occurs over at least 100 km^2. At different locations the calcrete horizon overlies coarse channel sandstones (Fig. 16A), fine levee sandstones and floodbasin mudstones of the Keltiefjellet Formation. Exposures of the calcrete horizon generally are either strongly prismatic, or exhibit a distinctly knobby character (Figs. 16BC). The prismatic outcrop is caused by more or less hexagonally arranged, vertical fractures, spaced so that the

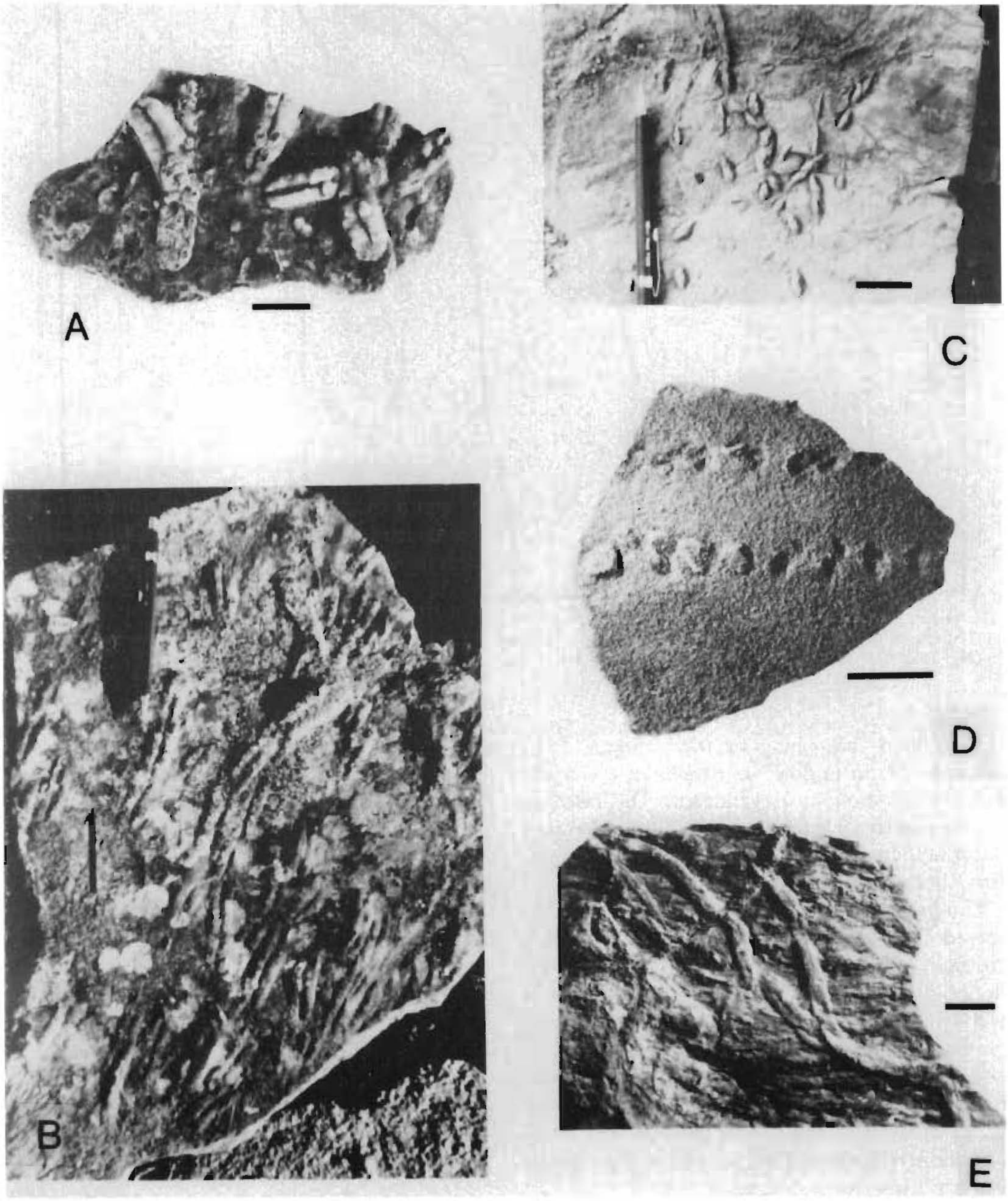


Fig. 14. Photographs of trace fossils from the Wood Bay Group. A. *Rusophycus*, convex hyporeliefs on base of sandstone. Scale bar = 2.0 cm. B. *Cruziana*, convex hyporeliefs on base of sandstone. Scale bar = 5.0 cm. C. *Lockeia*, convex hyporeliefs on base of sandstone. Scale bar = 3.0 cm. D. *Merostomichnites*, convex hyporeliefs on base of siltstone. Scale bar = 3.0 cm. E. *Isopodichnus*, convex hyporeliefs on base of siltstone. Scale bar = 0.5 cm.

prisms are approximately 10 to 15 cm across. The lengths of the prisms vary from a few decimeters to over a meter. Outcrops exhibiting a knobby character are invariably lenticular, and may be bounded above or below by the prismatic calcrete. Knobby calcretes appear to be an accumulation

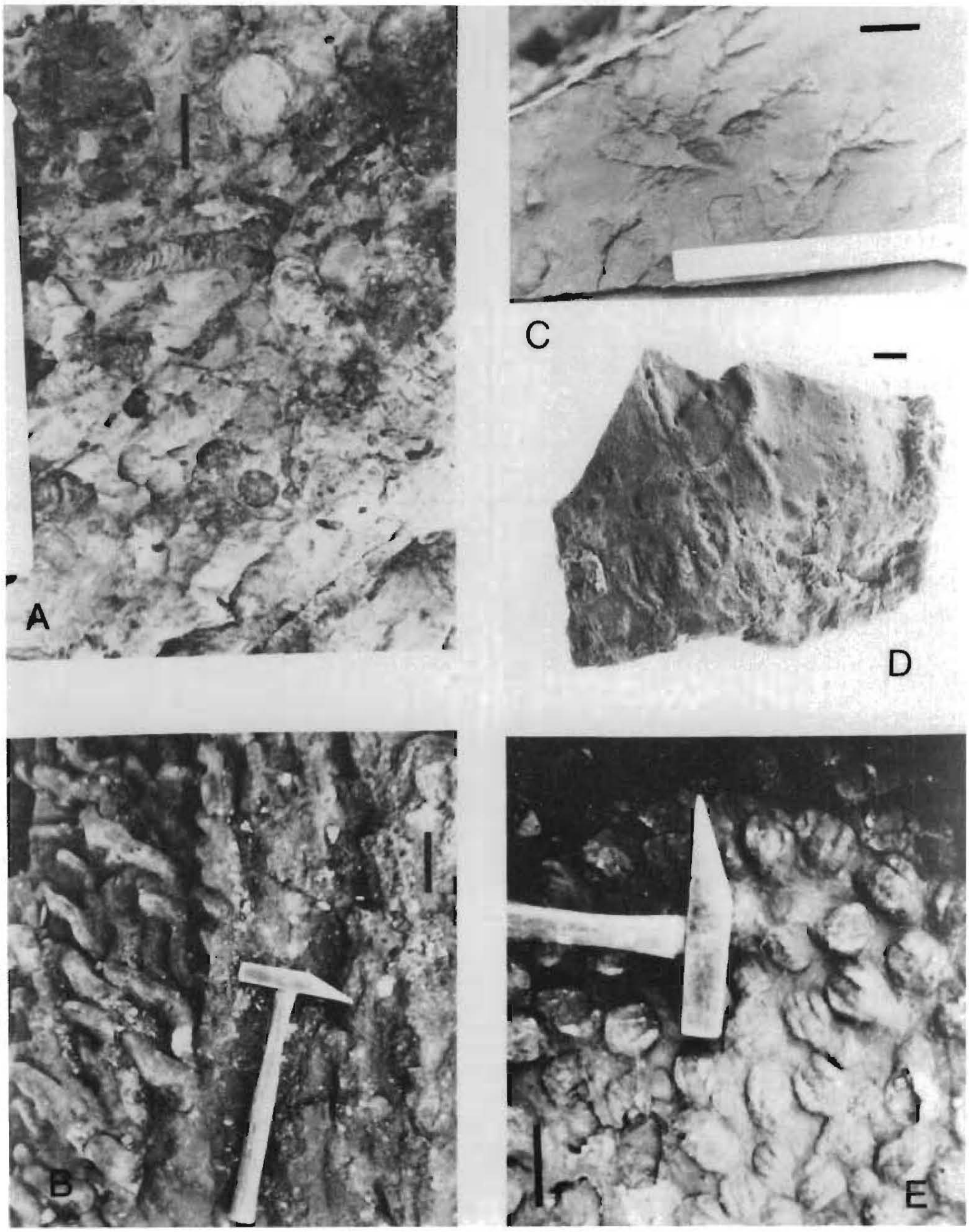


Fig. 15. Photographs of trace fossils from the Wood Bay Group. A. *Taenidium*, cross sections of several horizontal and vertical endichnial burrows, some showing back-filling. Scale bar = 3.0 cm. B. Unidentified "ropy" burrows, preserved as convex hyporeliefs on base of sandstone bed. Scale bar = 6.0 cm. C. Unidentified branching mud-filled endichnial burrows in sandstone. Scale bar = 5.0 cm. D. *Planolites*, concave hyporeliefs on base of sandstone. Scale bar = 1.0 cm. E. Unidentified tri-lobate traces occurring as convex hyporeliefs on base of sandstone. Scale bar = 7.0 cm.

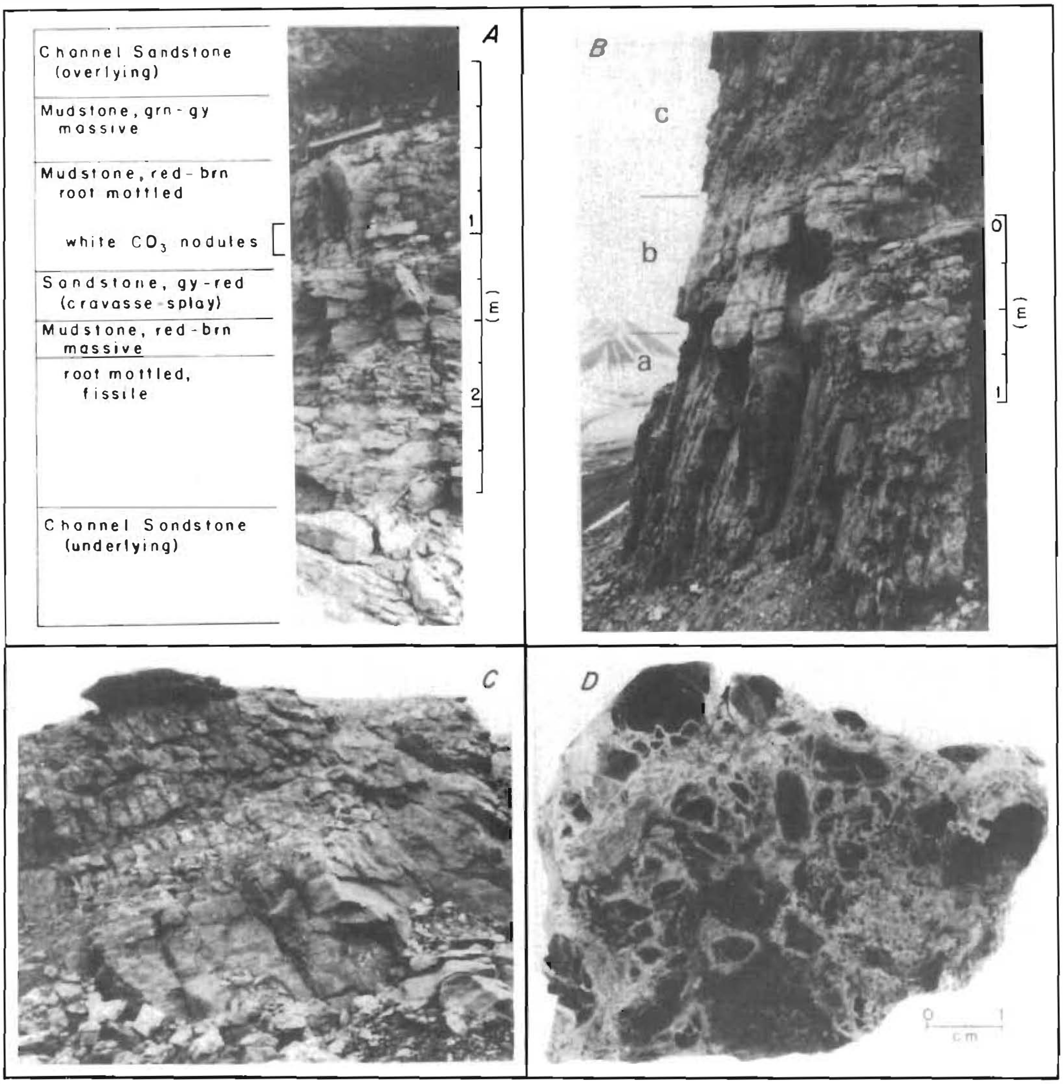


Fig. 16. Photographs of calcretes and preserved soil zones. A. Detailed stratigraphy within the Keltiefjellet Formation, showing a preserved soil. The A-horizon is interpreted as the massive and the root mottled zones and the B-horizon is the carbonate nodule interval. B. Photograph of the lower portion of calcrete illustrating the lower prismatic zone, overlain by an intervening 0.75 m of sandstones and mudstones, overlain in turn by knobby calcrete. The brecciated texture of the calcrete is visible in the lower right corner of the photograph; the dark material is low ferroan calcite, and the light is dolomite. C. Prismatic calcrete in gradational contact with the underlying sandstones of the Keltiefjellet Formation. The hammer, near the center of the photograph, is 50 cm long. D. Slabbed section of the calcrete, stained with an acidic solution of alizarin red S and potassium ferricyanide. The dark material is mostly low ferroan calcite, which stains purple, and a few lithoclasts of ferroan dolomite, which stain turquoise; the unstained light carbonate is dolomite. Note the dolomitic coatings on several of the lithoclasts.

of eroded and redeposited calcrete cobbles with no preferred orientation.

Soil profiles without calcrete are common (Fig. 16A). These appear as partially to completely root mottled zones, normally exhibiting a gradational decrease in the intensity of bioturbation downward in the bed. Zones of carbonate nodules or glaebular calcretes (Netterberg 1980) also occur in the Wood Bay Group and are most commonly found in sediments deposited in levee or floodbasin environments (Moody-Stuart 1966). These depositional environments and glaebular calcretes occur infrequently in the upper part of the Kapp Kjeldsen Formation, more commonly in the Keltiefjellet Formation, and abundantly in the Stjørdalen Formation. Glaebular calcretes vary from a single layer of nodules (Fig. 16A) to zones several meters thick. The zones may occur singly or grouped together. Nodules may be widely separated or closely packed.

The calcretes were studied in standard petrographic thin sections, stained and unstained, and by inspection of hand samples and stained slabs with the dissecting microscope. Thin sections and slabs were stained according to the method of Dickson (1965). In this technique, calcite, ferroan calcite, dolomite, and ferroan dolomite may be distinguished (Fig. 16D). The calcrete horizon is a low ferroan calcite breccia with occasional fragments of high ferroan calcite and rarely ferroan dolomite bound together with dolomite. Nodules from glaebular calcretes are invariably low ferroan calcite. The calcretes are similar to those described by Allen (1974, 1987). The petrology and a fossil soil (pedogenic) origin of the calcrete beds and nodules of the Wood Bay Group are discussed in greater detail by Reed et al. (in prep.).

Soft sediment deformation structures of Wood Bay Group (by W.E. Reed).—Soft-sediment deformation structures occur within channel, levee and crevasse-splay deposits of the Kapp Kjeldsen and Keltiefjellet Formations. Flame structures, convolute folding, clastic dikes and sandblows (Fig. 17), and structureless zones which we believe represent liquefied beds were observed within the map area, although none of the structures were observed in the measured sections (Figs. 6, 7, 9 and 10). The maximum amplitude of flame structures is 20 centimeters, and amplitudes of convolute folds range from a few centimeters to over a meter; every gradation between the distinctive flame structures and convolute folds occurs.

There is no consistent fold orientation or overturn direction within convolute folded beds. Liquefied sedimentary layers tens of centimeters

Fig. 17. Sandblow structure resulting from rapid dewatering of liquefied underlying sandstone bed (at base of outcrop); intrusion cuts through levee deposits of the Keltiefjellet Formation and is truncated by horizontal beds above the hammer. Amplitude of structures is 2.6 m; scale is shown by 50 cm long hammer.

in thickness occur, often with several liquefied zones grouped closely. Clastic intrusions with cross-cutting relationships greater than 2 meters were observed at several localities, particularly within the Keltiefjellet Formation. Dineley (1960) and Friend (1965) suggest that these structures formed as a result of earthquake shaking.

Grey Hoek Group

Skamdalen Member of Gjelsvikfjellet Formation.—Holtedahl (1914ab) originally named strata exposed on Grey Hoek (Fig. 1), north of the study area, the Grey Hoek Series. Friend et al. (1966) renamed the Grey Hoek Series the Grey Hoek Formation, and more recently Murashov & Mokin (1979) redefined the Grey Hoek Group to include the Gjelsvikfjellet, Tavlefjellet and Forkdalen Formations. According to Murashov & Mokin (1979), only the Skamdalen Member of the Gjelsvikfjellet Formation may be recognized in Dicksonland. We have designated strata overlying the Stjørdalen Formation as the Skamdalen Member of the Gjelsvikfjellet Formation on the basis of the lithologic description of this unit given by Murashov & Mokin (1979).

Although they do not give specific locations, Murashov & Mokin (1979) report a thickness of 250 m for the entire Gjelsvikfjellet Formation and 150 m for the Skamdalen Member of the Gjelsvikfjellet Formation. We measured 67.5 m of the Skamdalen Member on the ridge 1.4 km southwest of Bulmanfjellet (Fig. 18) and a 400 m thick section is exposed on Watsontoppen (Fig. 19). The top of the Skamdalen is not exposed within the study area.

The Skamdalen Member consists of interbedded mudstone and siltstone (90%) and thin-bedded sandstone (10%). Sandstones are more prominent in the Watsontoppen sequence (Fig. 19) than in the section measured on Bulmanfjellet (Fig. 18); sandstones and mudstones form regular cycles. The mudstones and siltstones are predominately greenish gray and gray with occasional grayish red to brown layers, and contain rare carbonate nodules. The sandstones are greenish-gray, fine- to medium-grained lithic arkosic wackes containing abundant plant debris. The lithologies and sedimentary structures are consistent with Worsley's (1972) interpretation of brackish water lagoonal deposition.

Old Red Sandstone deposition and basin tectonics

Depositional dnvironment.—Rocks of the Wood Bay Group comprise fluvial, and possibly brackish water-marine lithofacies. Friend & Moody-Stuart (1972) examined regional variations in paleocurrents, grain size, sand distribution and cyclothem thickness of the Wood Bay Group. Their work suggests a high-gradient, proximal system of streams in the west, contemporaneous with larger magnitude, lower gradient stream systems in the central and eastern part of the basin. Lower Wood Bay Group drainage in the west was generally eastward towards the center of the present outcrop area; paleocurrent directions in the east were almost exclusively northward, parallel to the basin axis (Friend & Moody-Stuart 1972). Based on the alluvial basin infilling models of Miall (1981) the Spitsbergen Old Red Sandstone basin represents a transverse fan-river system. This system drains into a longitudinal trunk stream running north along the basin axis and emptying into an estuarine marine system. During deposition of the upper Wood Bay Group nearly all paleocurrents throughout the basin were flowing north parallel to the western boundary of the present Old Red Sandstone outcrop. This suggests the wearing down of a local source area to the west, and transition from local to regionally controlled drainage directions (Friend & Moody-Stuart 1972).

Within our study area the Wood Bay Group (Figs. 6, 7, 9 and 10) comprises a single large-scale fining-upwards (Fig. 8) sequence of fluvial origin (Allen 1965; Miall 1978; Hempton 1983; Bluck 1986) which thins rapidly to the east (Figs. 11 and 13). The lower part of the sequence is predominately low sinuosity channel deposits; the middle portion consists of meandering channel, proximal overbank (levee), crevasse splay and distal overbank (floodplain) deposits; the upper part of the sequence is predominately floodplain deposits and includes pedogenic calcretes (Fig. 16). This fining upward trend is also indicated by the decrease in the sandstone component of fluvial cyclothems recognized by Friend & Moody-Stuart (1972, Fig. 18). Terrestrial conditions ceased with deposition of the overlying Grey Hoek Group in a marginal marine environment (Worsley 1972). Sediments of the Wood Bay—Grey Hoek Group sequence reflect a progressive decrease in stream gradient, and therefore increasing geomorphic maturity which is consistent with the wearing down of highland sediment sources to the west and possibly to the south.

Character of basin margins.—Spitsbergen Old Red Sandstone rocks crop out in an elongate basin bounded on the east and west by basement-cutting faults. The southernmost Wood Bay—Grey Hoek Group sediments exhibit distal source facies and have north-directed paleocurrents; thus, a large part of the original sedimentary basin probably extends south under younger deposits (Friend & Moody-Stuart 1972). The eastern boundary of the Old Red Sandstone exposure is formed by the Billefjorden fault zone, considered to be a major tectonic lineament with repeated episodes of activity (Harland et al. 1974; Reed et al. 1987). Friend & Moody-Stuart (1972) see no sedimentological or paleocurrent evidence for the existence of the Billefjorden fault zone or an

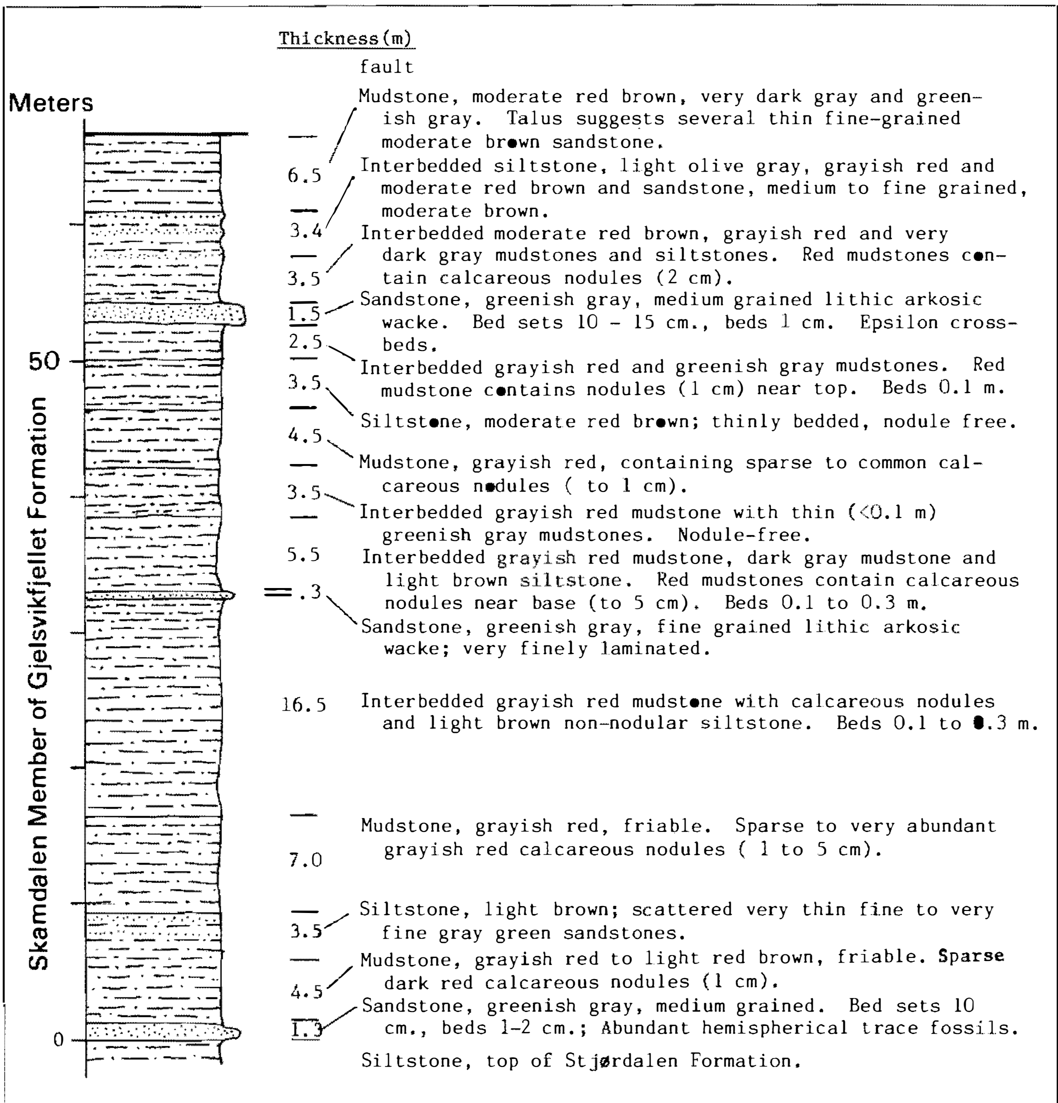


Fig. 18. Columnar section of Skamdalen member of Gjelsvikfjellet Formation exposed on ridge 1400 m southwest of Bulmanfjellet, map coordinates: N8760700, E525440. Based on brief visit, descriptions are not complete. See Fig. 19 for location of section.

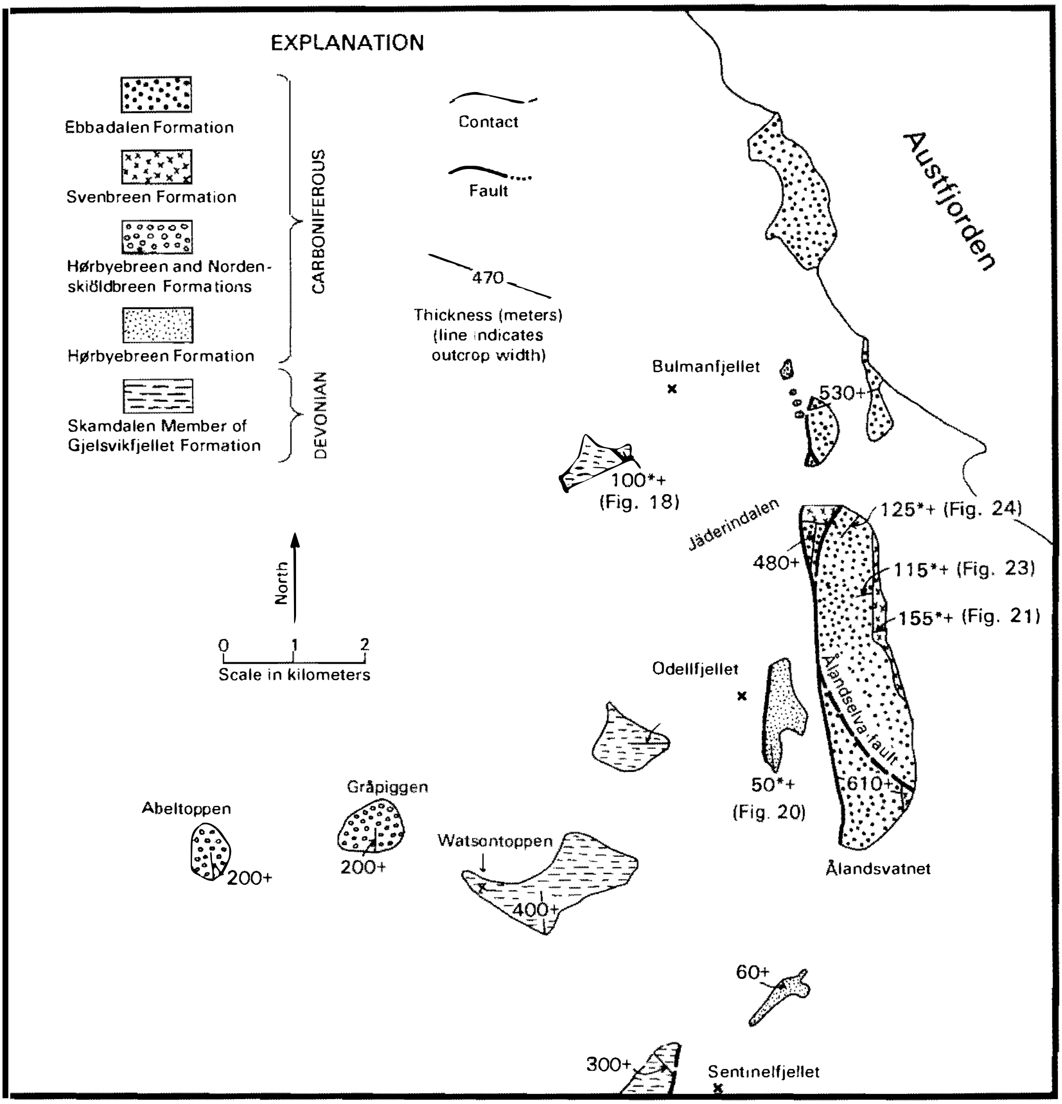


Fig. 19. Distribution and thicknesses of Skamdalen member of Gjelsvikfjellet Formation (Devonian) and Carboniferous units scaled from geologic map (Fig. 3) and measured sections (*) (Figs. 18, 20, 21, 23 and 24).

eastern source area during Wood Bay Group deposition. We also found none of the characteristics reported for previously documented active fault-bounded basins within our study area: repetitive stacking of facies or thick conglomerate or breccia sequences of limited lateral extent typical of fault bounded basins (Crowell 1974; Miall 1978; Ballance 1980) were not observed along the eastern margin of the Wood Bay Group exposure (Reed et al. 1987).

The rapid eastward thinning of the Wood Bay Group and lack of evidence for an eastern source area suggests that the eastern basin margin was gently sloping to the west and tectonically inactive during deposition of the Wood Bay Group; because of rapid eastward thinning, the original Wood Bay Group basin margin need not have been much farther east than the present outcrop edge.

As noted above, the western margin of the

Wood Bay Group exposure exhibits evidence of tectonic activity; the lower Wood Bay Group had a western source area and easterly directed paleocurrents; the source area was worn down and paleocurrents were directed northward during upper Wood Bay Group deposition. The pre-Wood Bay Group, late Silurian to early Devonian, Siktefjellet and Red Bay Groups consist of conglomerate, sandstone and siltstone exposed along the western margin of the Old Red Sandstone outcrop 70 to 120 km northwest of the area studied (Friend 1961; Gee & Moody-Stuart 1966). Siktefjellet and Red Bay Group lithologies suggest alluvial fan and source proximal fluvial deposition and an uplifted, possibly fault bounded source area. Molluscan fossils in the Red Bay Group (Allen et al. 1967) indicate local marginal marine deposition.

Origin of Old Red Sandstone Basin.—Basin asymmetry is revealed by evidence for fault activity during deposition of Old Red Sandstone units along the western margin of the basin while the eastern margin of the basin was inactive. The basin asymmetry may be explained best by a half-graben with an active faulted western margin and passive eastern margin (Reed et al. 1986). Extensional origins also have been proposed for other post-Caledonian Old Red Sandstone basins (Norton 1986; Friend 1986; McClay et al. 1986). Birkenmajer (1975) has suggested that the Spitsbergen Old Red Sandstone rifted basin may represent the failed arm of a plate triple junction (alaucogen), which coincided with the opening of a proto-Arctic Ocean.

Mimerbukta Sandstone

An elongated, fault-bounded outcrop of interbedded quartzite and shale in east Dicksonland (Fig. 5) has been named the Mimerbukta Sandstone by Friend (1961). This unit occurs directly west of the "high-angle thrust" (i.e., Billefjorden fault zone) and contains fossils which suggest correlation with the Wood Bay and Mimer Valley Groups (Friend 1961). More recently, Friend et al. (1966) abandoned the term Mimerbukta Sandstone and indicated "that these rocks should be considered highly deformed eastern parts of both the Wood Bay and Mimer Valley Formations." We found these rocks to be lithologically distinct from the Wood Bay Group rocks within the study area. Therefore, we have retained the name Mimerbukta Sandstone because of the distinctive nature of this unit.

Within the study area, the Mimerbukta Sandstone consists of interbedded fine- to medium-grained, massive, well-cemented light gray and olive gray quartzite and dark green, red, and black siltstone and shale. These rocks occur as highly deformed slices and slivers within the Billefjorden fault zone. Because of the complex structure and poor exposure, the total thickness cannot be determined but may be as much as 1000 m.

Carboniferous System

Sedimentary rocks of Carboniferous age within the area are the Hørbyebreen and Svenbreen Formations of the Billefjorden Group overlain by the Ebbadalen and Nordenskiöldbreen Formations of the Gipsdalen Group (Fig.5). These rocks range in age from early to middle Carboniferous (Tournaisian to Sakmarian; Cutbill & Challinor 1965).

Billefjorden Group

The Billefjorden Group consists of the Hørbyebreen Formation overlain by the Svenbreen Formation (Cutbill & Challinor 1965, Gjelberg & Steel 1981).

Hørbyebreen Formation.—The Hørbyebreen Formation is exposed in Dicksonland along and west of the Billefjorden fault zone (Harland et al. 1974, Fig. 8). Within the mapped area, patches of the Hørbyebreen Formation on Odellfjellet, Bulmanfjellet and the north end of Sentinelfjellet rest on Hecla Hoek and Mimerbukta Sandstone, whereas on Gråpiggen and Abeltoppen they rest on Stjørdalen and Keltiefjellet Formations (Fig. 3). These relationships indicate an unconformity at the base of the Hørbyebreen Formation.

On the slope southeast of Odellfjellet (Fig. 19) a 50 m thick section of Hørbyebreen Formation was measured (Fig. 20); the unit consists of light gray, pebble-cobble conglomerate overlain by interbedded gray to tan sandstone, black, red and purple siltstone and shale, and conglomerate beds similar to the basal conglomerate. Clasts within the conglomerate layers are almost entirely quartz and pale orange quartzite. No clasts of amphibolite, the most common Hecla Hoek metamorphic rock in the area, were observed in the conglomerate. According to Gjelberg & Steel (1981) the Hørbyebreen Formation was deposited by west flowing braided streams derived from a Hecla Hoek source area.

Svenbreen Formation.—In Dicksonland the Svenbreen Formation is exposed along and east of the Billefjorden fault zone (Harland et al. 1974, Fig. 8). The Svenbreen Formation is exposed on steep slopes and cliffs on Trikolorfjellet directly west of Mittag-Lefflerbreen and between Ålandsvatnet and Jäderindalen (Fig. 19), where 155 m of section was measured (Fig. 21). The base of the Svenbreen Formation is not exposed in the mapped area. Steel & Worsley (1984) recognize a change in sedimentation from alluvial fan deposition characteristic of the Hørbyebreen Formation to meandering stream and floodplain deposition characteristic of the Svenbreen Formation as a regional trend throughout Svalbard.

Svenbreen Formation sediments range from coarse pebble conglomerates through mudstones, generally occurring in a series of fining upward sedimentary cycles. Colors vary from light olive-gray to gray-red; tones of red and brown predominate, giving the outcrop characteristic red-bed coloration. Sandstone beds are often moderately to poorly sorted, and most are wackes. Detrital grains range from subangular to well rounded, and most beds consist of moderately rounded grains. Clasts in Svenbreen Formation sandstones and conglomerates include red, pink, and green quartzite, vein (polymict) quartz, with minor concentrations of dark lithic fragments (metamorphic?). Mud clasts and coal fragments are common. Bedding plane surfaces show abundant mica. Cements are most commonly clay or ferruginous clay, which accounts for the red coloration; some beds exhibit fine-grained calcite in the matrix.

The lower 50 meters of the Svenbreen Formation exposure (Fig. 21) consists of a series of fining-upward cycles characterized by medium to fine grained sandstones with discontinuous pebble or cobble zones. These beds exhibit abundant cut-and-fill structures which are often overlain by sandstones with large-scale (>1 m) epsilon cross-beds. These features suggest deposition by channel-dominated high-gradient, low-sinuosity streams (Allen 1963). The Svenbreen Formation paleogeographic reconstruction of Steel &

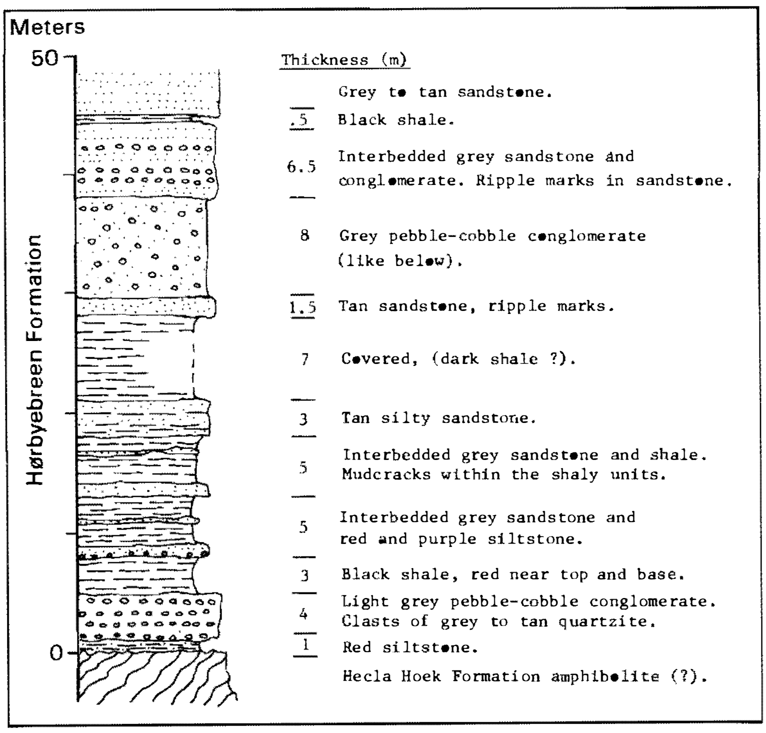
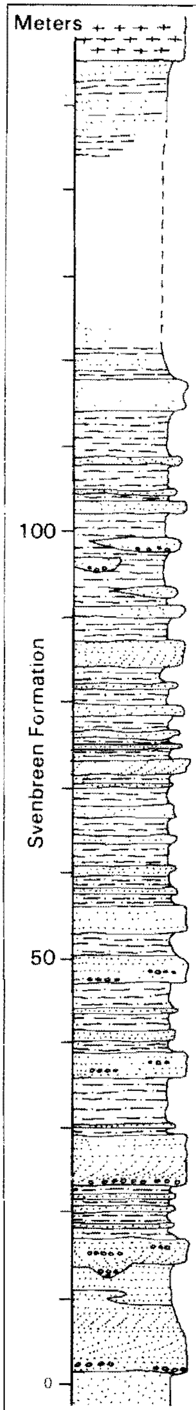


Fig. 20. Columnar section of Hørbyebreen Formation exposed on slope 700 m northeast of Odellfjellet. Descriptions based on brief visit. See Fig. 19 for location of section.



Thickness (m)	
	Anhydrite, base of Ebbadalen Formation.
37.5	Covered. Outcrops to south indicate interbedded mudstone, moderate brown (5YR 3/4) and sandstone (medium to fine), pale red (5YR 3/4) quartz wacke.
3.5	Sandstone (fine to medium) pale red (5YR 3/4) quartz wacke. Massive.
12.1	Interbedded sandstone (medium to fine), pale red (5R 6/2 to 10R 6/2) to light olive gray (5Y 5/2) quartz wacke and mudstone, olive black (5Y 2/1 to 5Y 5/2) to moderate brown (5YR 3/4) fissile, abundant mica, silty. One sandstone bed has wavy bedding and "birds-eye" structure.
12.0	Interbedded mudstone, moderate brown (5YR 3/4) with lenticular sandstone (medium) grayish orange (10YR 7/4) to light olive gray (5Y 5/2) quartz wacke. Sandstones exhibit distinct channel forms, some show pebble lags at base.
2.7	Mudstone, moderate brown (5YR 3/4), abundant root mottles.
3.2	Sandstone (medium to coarse), greenish gray (5GY 6/1) quartz arenite. Abundant cut-and-fill structures, epsilon cross-beds.
12.4	Interbedded mudstone, grayish red (10R 4/2), abundant root mottles; and sandstone (medium), grayish orange (10YR 7/4) quartz wacke. Bed sets average 0.3 m. Sandstone at base has lenticular plane laminations and ripple cross-laminations and mud cracks on bedding surfaces. One lenticular sandstone (coarse) greenish gray (5GY 6/1) with pebble conglomerate at base; pebbles to 3 cm., dominantly pink and red quartzite.
15.5	Interbedded sandstone (fine to medium) grayish red (5R 4/2) quartz wacke, very thinly laminated, weather flaggy; and siltstone, yellow gray (5Y 7/2).
3.2	Sandstone (medium), grayish red (5R 4/2) quartz wacke, and yellow gray (5Y 7/2) quartz wacke; up to 10% pink and red quartzite grains.
6.0	Sandstone (medium), grayish orange (10YR 7/4) quartz wacke. Grades upward into mudstone, reddish brown (10R 4/6). Base of unit shows discontinuous lenses of granules.
8.3	Interbedded siltstone, light brown (5YR 6/2 to 5YR 6/4) with minor sandstone (fine to medium) reddish brown (10R 5/4); thinly laminated, bed sets 0.2 to 0.3 m.
3.0	Sandstone (medium) grayish orange (10YR 7/4), quartz arenite; lenses of pebble conglomerate in channels.
6.7	Mudstone, reddish brown (10R 4/6) to greenish gray (5GY 6/1), finely laminated, bed sets 0.1 to 0.2 m. Irregularly mottled near top. Sandstone near base, fine-grained reddish brown (10R 5/4) quartz wacke.
6.0	Sandstone (medium), grayish orange (10YR 7/4) quartz wacke. Thin lenses of rounded quartzite pebbles. Burrowed.
6.2	Interbedded mudstone, greenish gray (5GY 6/1) and sandstone (fine to medium), reddish brown (10R 5/4) quartz wacke. Bed sets range from 0.01 to 0.2 m for mudstones and 0.1 to 0.5 m for sandstones.
3.0	Sandstone (medium), olive gray (5Y 4/1) quartz arenite; 10% pebbles of quartzite as stringers along cross-beds. Bed sets 0.3 to 1 m.
4.4	Sandstone (medium to fine), olive gray (5Y 4/1) quartz arenite; ca. 1% pink quartzite grains.
8.0	Sandstone (fine to medium), grayish red (10R 4/2) quartz wacke, ferruginous matrix; 5-10% pebbles of rounded quartzite and vein quartz. Dominantly cross-bedded with abundant cut-and-fill structures; discontinuous lenses of pebble conglomerate in lower 2 m.
1.7	Sandstone (fine), grayish red (10R 4/2) quartz wacke, ferruginous matrix; massive, blotchy weathering. Base covered with alluvium.

Fig. 21.– Columnar section of upper portion Svenbreen Formation exposed on slope 2.2 km east-northeast of Odellfjellet; map coordinates: N8758370, E529100 to N8758480, E528930. See Fig. 19 for location of section.

Worsley (1984) suggests flow from north to south.

The interval from approximately 50 to 80 m above the base of the Svenbreen Formation exposure consists of conformable sandstone-mudstone beds with smaller scale epsilon cross-beds (<1 m) (paleocurrent directions were not determined), small-scale cut-and-fill features, mudcracks and root mottling. These characteristics suggest more extensive levee development and less prominent channel processes.

The interval above approximately 80 m in the measured section has a higher content of mudstones and continues to show small scale cut-and-fill structures, root mottled sands, mud cracks on bedding surfaces, and small (<1 m) lensoid sand bodies encased in mudstone. These features suggest floodplain, minor channel, crevasse-splay, low-gradient and high-sinuosity fluvial deposition.

Gipsdalen Group

The Nordenskiöldbreen and Ebbadalen Formations of the Gipsdalen Group are exposed within the area studied.

Ebbadalen Formation.—The Ebbadalen Formation is exposed over south Dicksonland east of the Billefjorden fault zone (Holliday & Cutbill, 1972, Fig. 2; Harland et al. 1974, Fig. 8). Within the area of interest, the Ebbadalen Formation is exposed east of the Billefjorden fault zone on the coastal plain north of Jäderindalen, on the east slope of Odellfjellet and on Trikolorfjellet (Fig. 3). The contact between the Svenbreen Formation and the overlying Ebbadalen Formation is marked by a change from predominately pale red and red-brown mudstone and sandstone of the Svenbreen Formation to yellow sandstone, gray shales and anhydrite beds of the Ebbadalen Formation. The contact is well exposed on Trikolorfjellet and where we measured section 2.0 km northeast of Odellfjellet (Figs. 19, 23 and 24). For mapping purposes we subdivided the Ebbadalen Formation into three informal members a, b and c from bottom to top.

Of the 480 m of Ebbadalen Formation estimated to be present on the northeast slope of Odellfjellet (Fig. 22) we were able to measure 239 m (Figs. 23 and 24). Gjelberg & Steel (1981)

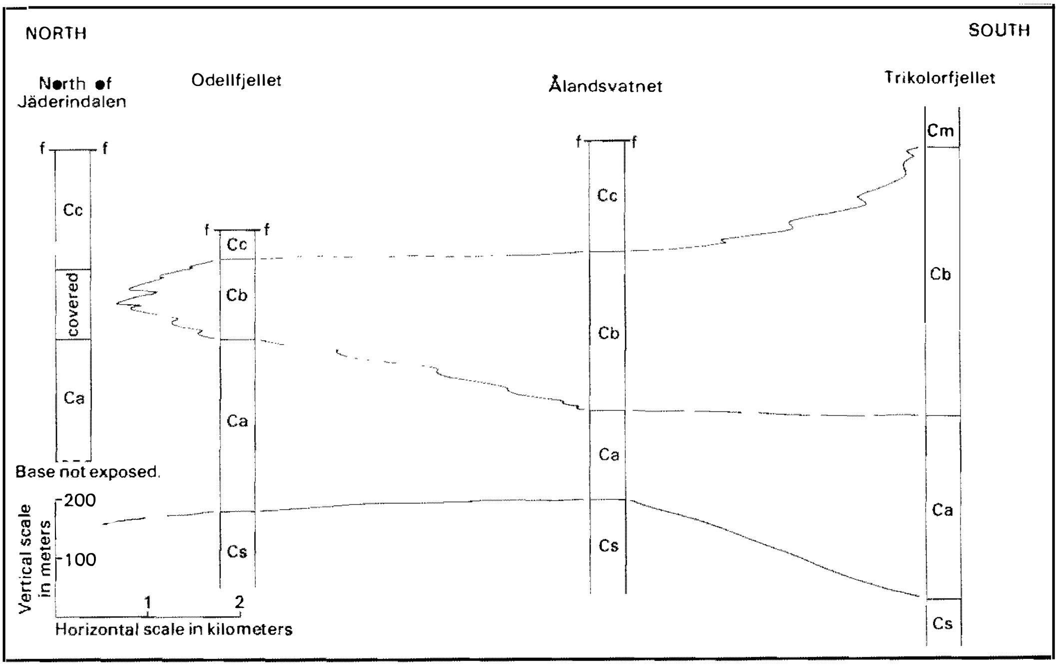


Fig. 22. Diagram of variations in thickness of members of Ebbadalen Formation. See text for nature of measurements and Fig. 19 for locations. Abbreviations: Cs, Svenbreen Formation; Ca, Cb, Cc, Members a-c of Ebbadalen Formation; Cm, Minkinfjellet Member of Nordenskiöldbreen Formation (exposed south of map area, Fig. 3); f-f, fault.

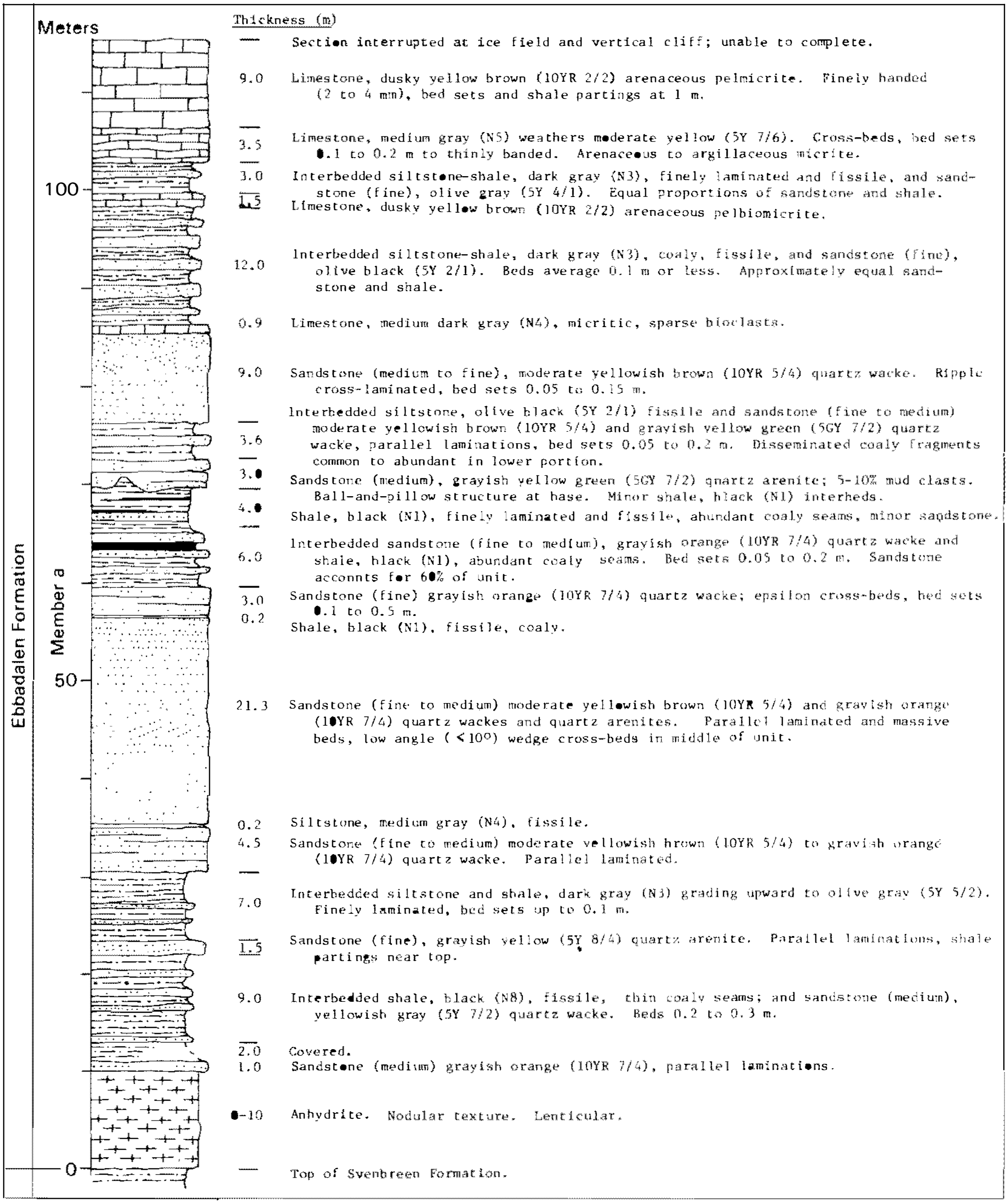


Fig. 23. Columnar section of lower portion of member a of Ebbadalen Formation exposed on slope 2.6 km northeast of Odellfjellet; map coordinates: N8759240, E528870 to N8759260, E528830. See Fig. 19 for location of section.

present a detailed section of Ebbadalen Formation measured on Odellfjellet and Holliday & Cutbill (1972) present a measured section on Trikolorfjellet south of our area. Figure 22 illustrates the approximate thicknesses of the members of the Ebbadalen Formation at the following locations: north end of Trikolorfjellet; south-facing slope directly north of Ålandsvatnet; north-

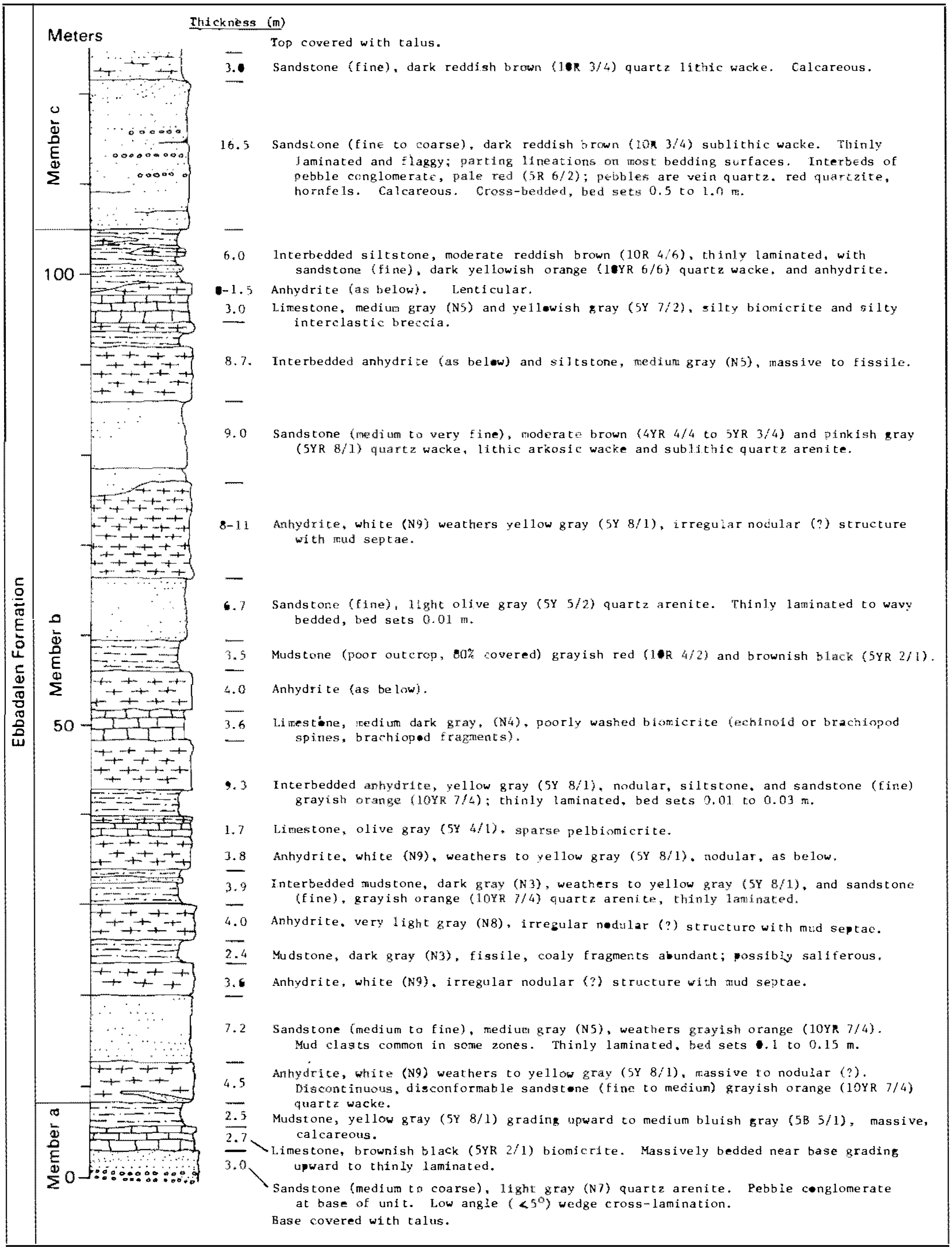


Fig. 24. Columnar section of middle portion of Ebbadalen Formation exposed directly south of Jäderindalen; map coordinates: N8760030, E528540 to N8759720, E528340. See Fig. 19 for location of section.

east slope of Odellfjellet, west of Ålandsvatnet fault; on the coastal plain directly north of Jäderindalen (Fig. 19). The thickness of member b on the northeast slope of Odellfjellet was measured (Fig. 24), and the other thicknesses were scaled from the geologic map (Fig. 3).

The total thickness of the Ebbadalen Formation ranges from 540 to 780 m. The thickness of the formation and the middle member in particular, thin northward from Trikolorfjellet across the area (Fig. 22), suggesting that, of the Ebbadalen Formation localities studied, Trikolorfjellet is closest to the depocenter. From Ålandsvatnet to the northeast slope of Odellfjellet the lower member thickens as the middle member thins (Fig. 22), thus, thinning of the anhydritic middle member may be due to depositional topography.

A discordance in attitudes (Fig. 3) suggests an angular unconformity between Ebbadalen Formation, member a and the underlying Svenbreen Formation. Member a contains sandstones, siltstones, coaly shales and fossiliferous limestones. From a distance, the lower Ebbadalen Formation appears prominently on hillsides as distinct buff and black bands because of the color contrast between the interbedded yellow-gray sandstones (50%), black coaly shales and siltstones (35%) and gray fossiliferous limestones and anhydrite (15%).

The lower Ebbadalen Formation sands are unlike those of the Svenbreen Formation below and consist of fine- to medium- grained, moderately to poorly sorted quartz wackes. The Ebbadalen Formation sandstones are white or light gray to pale yellow, and do not exhibit the red-brown ferruginous cement common to the Svenbreen Formation. Fine pebble conglomerates are rare; the clasts are intraformational and almost exclusively buff colored very fine sandstone or siltstone. Colored quartzite grains, prominent in the Svenbreen Formation, are absent or present in only trace amounts in lower Ebbadalen Formation sands. Megascopic examination revealed that mica, feldspar, minor dark lithic grains (metamorphic?), and coal fragments are the major non-quartz constituents of these rocks. Most of the lower Ebbadalen Formation sandstones have a clay matrix; some of the better sorted sandstones lack any significant matrix and are cemented with calcite.

Sandstones within the lower Ebbadalen Formation exhibit fine parallel laminations, ripple cross-lamination, low-angle wedge, and small-scale (<1 m) epsilon cross-bedding. The sandstones are interbedded with black to medium gray, olive gray, fissile, organic-rich siltstone-shale beds (Fig. 23). Fossiliferous marine limestones about 85 m above the base of the Ebbadalen Formation (Fig. 23) are yellow gray, yellow brown and medium dark gray arenaceous pelmicrites and argillaceous micrites.

This sedimentary sequence displays characteristics of a low relief fluvial to paludal regime with shallow, low-gradient, levee-bound distributaries or tidal channels meandering over delta-plains or coastal marshes (cf. Dickinson et al. 1972; Howard & Reineck 1972). Gjelberg & Steel (1981) suggest that the lower Ebbadalen Formation is characterized by shallow marine sandstones and delta deposits.

Member b, middle Ebbadalen Formation is predominantly anhydrite (50%) and saliferous mudstone (20%) with subordinate sandstone (20%) and limestone (10%) (Fig. 24). The top and bottom of the anhydrite beds are generally smooth and regular, but internal lamination within these zones is irregular to chaotic forming "birds-eye" structures. Surface weathering has altered the anhydrite to punky, brownish-gray gypsum.

Clastic rocks of the middle member tend to be dark gray when fresh, weathering to orange. Mineralogic composition, texture and sorting of the sandstones and siltstones is similar to the lower Ebbadalen Formation, except the middle member has a higher percentage of carbonate, gypsum or anhydrite. Mudstones in the middle member are dark gray to brownish black and reddish brown to grayish red; some appear to be saliferous.

Marine limestones in the middle Ebbadalen Formation vary from dark gray, very fine-grained (micritic) limestones having a distinct petroliferous odor when freshly broken, to light gray, richly fossiliferous biomicrites or biosparites (Folk 1959). These limestones contain brachiopod spines and fragments, and are commonly poorly-washed, suggesting a lack of current winnowing of the organic detritus. The anhydrites may represent supratidal sabkha deposits (Kendall & Skipwith 1969; Kinsman 1969) and the interbedded sandstones and mudstones also may be of subtidal to intertidal origin. Gjelberg & Steel (1981) suggest that the upper part of the Ebbadalen Formation is dominated by alluvial fan, sabkha and lagoonal deposition with periodic marine transgressions.

Member c, upper Ebbadalen Formation outcrops (Fig. 24) are pale red pebble conglomerates with well-rounded clasts of vein quartz, red quartzite and dark lithic grains, interbedded with very fine- to coarse-grained sandstones. The sandstone beds and the sandstone matrix of the conglomerates are dark reddish brown quartz wackes with subrounded to rounded, fine to coarse grains. The matrix material is ferruginous to calcareous clay. Member c (Pyramiden Conglomerate of McWhae 1953, Fig. 1) grades south (Fig. 22) into the upper part of member b (Passage Beds of McWhae 1953). Gjelberg & Steel (1981) suggest that the upper portion of the Ebbadalen Formation was deposited as alluvial fans.

Nordenskiöldbreen Formation.—The Nordenskiöldbreen Formation is exposed over much of Dicksonland on both sides of the Billefjorden fault zone south of the area of interest (Harland et al. 1974, Fig. 8). Marine limestone of the Nordenskiöldbreen Formation rests on the Ebbadalen Formation on Trikolorfjellet directly southwest of the area studied and on the Hørbyebreen Formation on Abeltoppen and Gråpiggen within the area studied (Fig. 19) (Harland et al. 1974, Fig. 8) which indicates a major unconformity at the base of the Nordenskiöldbreen Formation. The small exposures of Nordenskiöldbreen Formation on the summits of Abeltoppen and Gråpiggen were not visited during the present investigation.

Quaternary deposits—geomorphology

Active glaciers and the position of the area on the coast of Austfjorden have led to a complex Quaternary history reflected in glacial, lacustrine, alluvial, and marine deposits.

Marine sands and wave cut terraces

Dissected gravel, sand, and silt which contain pelecypod and gastropod shells are exposed near the mouths of Zeipeldalen and Jäderindalen (Fig. 3). These marine deposits and wave-cut terraces are most prominent on the coast directly south of Zeipeldalen and mark previously higher sea levels. The younger marine deposits below an elevation of about 40 m are differentiated from older deposits at elevations of 40 to 90 m. The most obvious raised beach in our area occurs at an average elevation of 40 m near the contact between the upper and lower marine deposits directly south of Zeipeldalen.

This may correspond to 11,000 year old raised beachs on the north coast of Spitsbergen (Salvigsen & Österholm 1982) and 10,000 to 13,000 year old late Weichselian marine limit raised beaches on the west coast of Spitsbergen (Forman 1990). Other radiocarbon dates from beach deposits in northern Spitsbergen below the 40 m level range from 7530 to 10,050 years, whereas the highest beach ridge terrace occurs at an elevation of about 80 m and was dated at 43,340 ± 1600 years (Salvigsen & Österholm 1982).

Glacial Deposits and Landforms

The elongate low hill of sand and gravel where Overgangshytta is situated (Fig. 3) is a recent terminal moraine of Mittag-Lefflerbreen located about 400 m beyond the present edge of the glacier. This advance and a period when Mittag-Lefflerbreen was thicker are marked by fresh exposures of Carboniferous bedrock in steep cliffs on the east slope of Odellfjellet. These exposures of bedrock, formed by glacial scouring of talus, occur as far north as a line extending southwest along the axis of the moraine to the mountain front. The moraine at Overgangshytta must postdate previous high stands of sea level, because the moraine only has been modified by surf action at present sea level. Based on the age determinations reported by Salvigsen & Österholm (1982), the high stands may be as much as 7530 years old. The maximum advance of Mittag-Lefflerbreen marked by the Overgangshytta moraine may correspond to the maximum Holocene extension for Svalbard glaciers at about 1900 A.D. described by Salvigsen & Österholm (1982).

Other glaciers occur at the south edge of the area. Isolated patches of glacial moraine occur within tributary canyons where there are no active glaciers. The U-shaped valleys, and glacial striae and chattermarks on bedrock exposed in these valleys and on the coastal plain north of Jäderindalen also indicate that glaciers were previously more extensive. Salvigsen & Österholm (1982) describe the history, extent and direction of movement of glaciers in northern Spitsbergen, 70 km north of the area studied.

Lake and delta deposits

Ålandsvatnet is dammed by Mittag-Lefflerbreen; strand lines to an elevation of 150 m around Ålandsvatnet mark previously higher levels of the lake formed when Mittag-Lefflerbreen was thicker and formed a higher dam. This higher lake level also is represented by extensive dissected lake and delta gravel, sand and silt exposed on the margins of Ålandsvatnet (Figs. 3 and 25). According to Liestøl (1956) the levels of glacier dammed lakes are usually unstable.

Talus deposits and landslide debris

At many locations bedding planes in apparently *in situ* bedrock have been deformed by creep so that reliable attitudes are difficult to obtain; contacts between *in situ* bedrock affected by creep and talus are often difficult to locate. Talus deposits obscure bedrock exposure over about 30% of the area studied. Actively forming talus cones occur on the east slope of Odellfjellet, where the previous advance of Mittag-Lefflerbreen removed older talus and cut a steep slope. Talus cones with a peculiar stepped morphology similar to rock glaciers described by Swett et al. (1980) occur within the area studied. These stepped talus cones only occur around Ålandsvatnet (Fig. 25) and may be related to variations in lake level. A landslide involving the Skamdalen Member of the Gjelsvikfjellet Formation and the Stjørdalen Formation occurs on the northwest side of Ålandselva (Fig. 3).

Alluvium

Older, dissected alluvium which consists of fine sand and silt occurs on the margins of the major valleys and on the coastal plain north of Jäderindalen. Holocene alluvium, comprised of sand and gravel, overlies older alluvium in active alluvial fans and occurs in major stream channels dissecting the older alluvium.

Beach and tidal flat deposits

Beach deposits on the coast of Austfjorden consist of sand and gravel. Tidal flat deposits composed of silt and clay occur in estuaries at the mouths of Jäderindalen and Zeipeldalen.

Structural geology

The geologic structure consists of faults and folds (Figs. 3 and 26) described from west to east in the following general sequence: 1. structures only in Devonian Old Red Sandstone rocks, 2. structures in both Devonian Old Red Sandstone and Carboniferous rocks, 3. structures in only Carboniferous rocks.

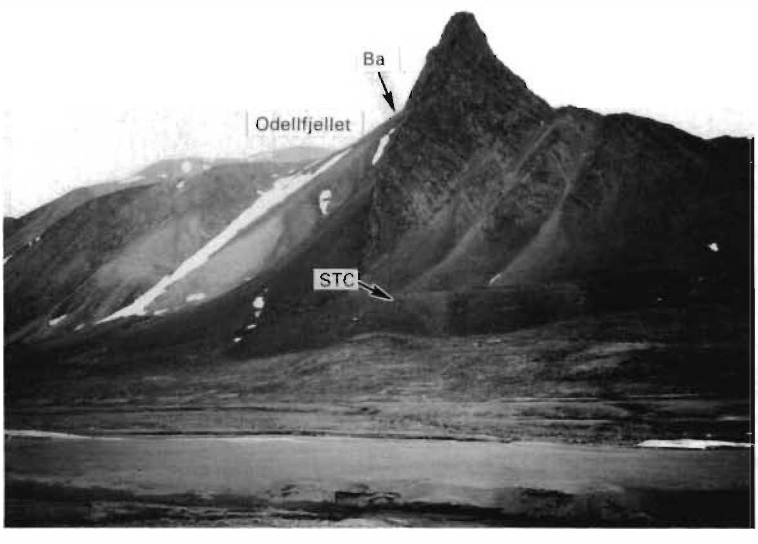


Fig. 25. View of Balliolbreen fault (Ba) west of Odellfjellet from Ålandselva. Hecla Hoek gneiss on right (east) against old Red Sandstone on left (west). Stepped talus cones (STC) in middle right; dissected Quaternary lacustrine sediments in foreground.

Faults

Tromma Fault

The Tromma fault (Fig. 26) trends northeast in the western portion of the area, dips 82° NW and shows 100 m of reverse separation on the Kapp Kjeldsen-Keltiefjellet Formation contact exposed on the north slope of Tromma.

Nathorstdalen Fault

The Nathorstdalen fault (Fig. 26) is exposed on the north side of Nathorstdalen and strikes approximately east-west. It displaces Kapp Kjeldsen Formation on the south against Keltiefjellet Formation on the north with a minimum stratigraphic throw of 1700 m, down to the north at the west edge of the area. The fault is not exposed

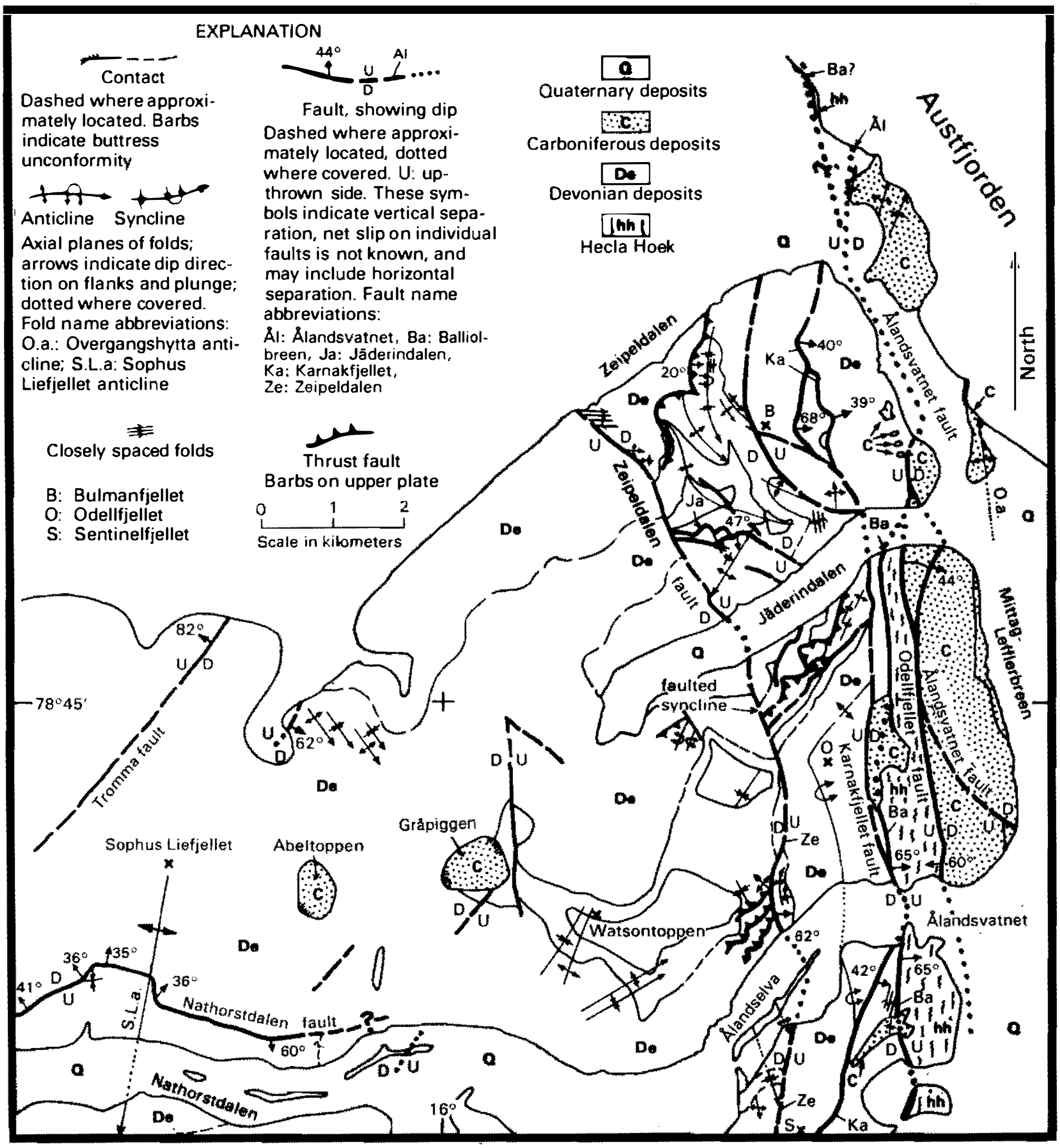


Fig. 26. Structural features in area studied along and west of Billefjorden fault zone. Location is shown on Fig. 2.

east of the canyon which drains the south side of Abeltoppen; the fault may continue east beneath Quaternary deposits. Changes in fault attitude across the Sophus Liefjellet anticline (Fig. 26) indicate the fault has been folded. The western portion of the fault shows normal separation, whereas the eastern end of the fault has reverse separation.

Jäderindalen Fault Zone

The Jäderindalen fault zone consists of an east-west trending zone of parallel and branching faults up to 300 m wide in Old Red Sandstone rocks exposed on the north side of Jäderindalen. Individual fault strands dip 45° to 80°S, and reverse separation varies from about 240 to 420 m. The Jäderindalen fault zone is truncated by the Zeipeldalen fault on the west and is not seen east of the Karnakfjellet fault, and thus appears to predate movement on the Billefjorden fault zone.

Billefjorden Fault Zone

The principal structural feature within the mapped area (Fig. 3) is the Billefjorden fault zone consisting of a 2–4 km wide zone of parallel to branching faults; the average trend of the fault zone is N4°W. The Billefjorden fault zone is best exposed in Ålandselva (Figs. 25, 27 and 28). The names given by Harland et al. (1974, Fig. 8) have been applied to individual fault strands (Figs. 3 and 26). Within the fault zone slivers of Hecla Hoek basement rock occur between the south edge of the area and Jäderindalen, and on the coast north of Zeipeldalen.

Balliolbreen Fault.—The Balliolbreen fault, the major strand of the Billefjorden fault zone, displaces Hecla Hoek basement rocks on the east against Devonian Old Red Sandstone on the west. North of Jäderindalen the Balliolbreen fault may be cut by the younger Ålandsvatnet fault and reappear on the coast north of Zeipeldalen as the western boundary of the Hecla Hoek (Figs. 3 and 26). Well exposed fault surfaces on both sides of Ålandselva (Figs. 25, 27 and 28) dip an average of 65°E.

The trace of the contact between the Hørbyebreen Formation and Hecla Hoek rocks on the ridge northeast of Odellfjellet (Fig. 3) is fairly straight across rugged terrain. Although the Hørbyebreen Formation was deposited there against a scarp in Hecla Hoek rocks along the Balliolbreen fault, no fragments of schist, gneiss or amphibolite typical of the Hecla Hoek occur in the Hørbyebreen Formation. South of this exposure on Odellfjellet the Hørbyebreen Formation lies unconformably across the Balliolbreen fault. The contact between the Hørbyebreen Formation and Hecla Hoek on the north slope of Sentinelfjellet has about 40 m of relief across the Balliolbreen fault; it is not clear whether the Hørbyebreen Formation on Sentinelfjellet is displaced by the Balliolbreen fault. The 6° and 15° dips within the Hørbyebreen Formation on Odellfjellet (Fig. 3) yield apparent dips

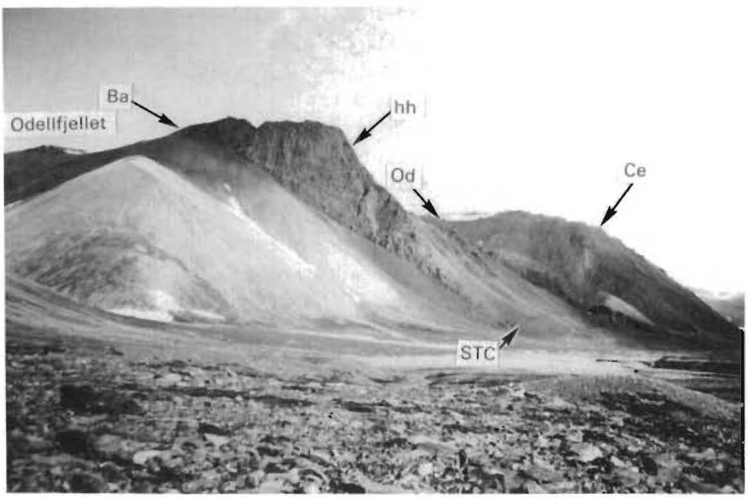


Fig. 27. View of Billefjorden fault zone along north side of Ålandselva. Hecla Hoek gneiss (hh) in center against Old Red Sandstone on left (west) along Balliolbreen fault (Ba). Ebbadalen Formation (Carboniferous) (Ce) on right (east) against Hecla Hoek gneiss along Odellfjellet fault (Od). Light patches are slivers of Mimerbukta Sandstone along Odellfjellet fault. Stepped talus cones (STC) are shown on shore of Ålandsvatnet.

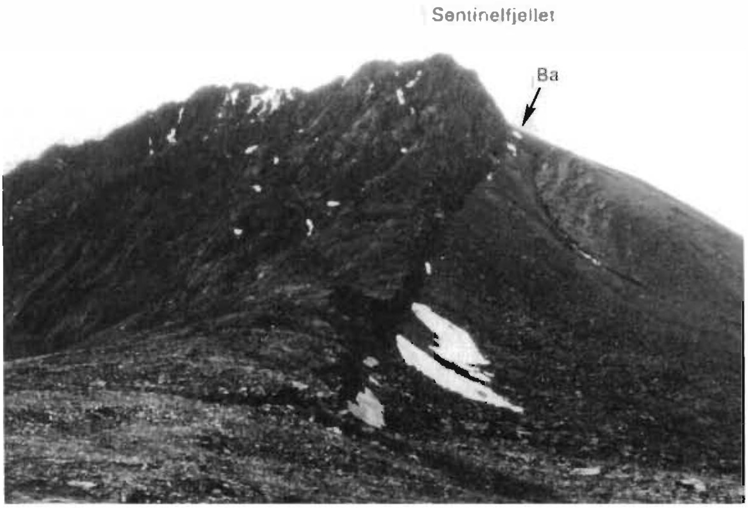


Fig. 28. View of Balliolbreen fault (Ba) on north slope of Sentinelfjellet; Hecla Hoek gneiss on left (east) faulted against Old Red Sandstone on right (west). Displacement vectors listed on Table 1 are from this exposure.

to the east, normal to the Balliolbreen fault of 4° and 2°, respectively. Thus, if the Hørbyebreen Formation was originally horizontal, the Balliolbreen fault would have dipped about 61° to 63°E on Odellfjellet prior to deposition of the Hørbyebreen Formation.

Rocks within the fault zone are easily eroded and not well exposed, and over most of its length the trace of the Balliolbreen fault is covered with talus or is inaccessible on steep slopes partially covered with snow and ice. Thus, the entire width of the fault zone is not available for inspection; exposures of fault gouge consisting of dark gray clay, silt and angular fine- to medium-grained sand occur along the fault. Observations of unfractured rocks on opposite sides of the fault reveal that the maximum width of the fault zone varies from 30 to 100 m.

Table 1 summarizes data on displacement vectors observed on fault surfaces in Hecla Hoek rocks on the south side of Ålandselva in the hanging wall of the Balliolbreen fault (Fig. 28). These were the only displacement vectors seen along the Balliolbreen and other faults, and do not reveal a consistent slip direction.

The base of the Devonian Old Red Sandstone is not exposed within the area and, aside from the slivers of Mimerbukta Sandstone along the Odellfjellet fault, no Devonian rocks are known in the region east of the Balliolbreen fault (Fig. 1). Gravity data suggest a maximum of 4 km of vertical separation on the top of Hecla Hoek basement rock (Harland et al. 1974).

Harland (1969, 1978), Harland et al. (1974) and Harland & Gayer (1972) have suggested that 200–1000 km of left-slip occurred on the Billefjorden fault zone, principally on the Balliolbreen fault (Harland et al. 1974), following deposition of the Devonian Old Red Sandstone. This interpretation is based on the nature and distribution of Hecla Hoek Series in Spitsbergen and equivalent rocks in other portions of the Arctic. Harland et al. (1974) have suggested that this major left-slip explains the absence of Old Red Sandstone east of the fault zone. However, our isopach maps of the Keltiefjellet (Fig. 11) and Stjørdalen Formations (Fig. 13) indicate a rapid west to east thinning of these Old Red Sandstone units such that they may never have been present in western Ny Friesland (Fig. 1). If the other Old Red Sandstone units similarly thin to the east, the absence of Old Red Sandstone in Ny Friesland may be explained without major displacement on the Balliolbreen fault (Reed et al. 1987). As discussed above, the rapid eastward thinning may be the result of pinching out of sedimentary units against the tectonically inactive east margin of the Old Red Sandstone half-graben.

Zeipeldalen Fault.—The Zeipeldalen fault, the westernmost strand of the Billefjorden fault zone, can be traced from southeast of Zeipeldalen to

Table 1. Displacement vectors observed on fault surfaces in Hecla Hoek rocks on hanging wall of Balliobreen fault on south side of Ålandselva (Fig. 27).

Location (distance from fault)	Attitude of surface	Displacement vector	Rake	Inferred slip
20 cm	N17°W 64°E	Polished, slickensides and mullions spaced 4–10 cm.	53°S	left-reverse
		Possible striations.	30°N	right-reverse
20 cm	N1[illegible]°E 59°E	Slickensided surface with striations spaced 1–2 mm.	0°	right or left
1 m	N2°E 68°E	Prominent striations spaced 1–2 mm and mullions spaced 2–4 cm.	85°S	left-reverse
0.5 m	N13°W 54°E	Striations spaced 1 mm, chatter marks perpendicular to striations indicate right-slip.	0°	right
<1 m	N8°W 64°E	Smooth surface with striations spaced 2–4 mm.	80°N	right-reverse
<1 m	N33°E 66°E	Smooth surface with striations.	2°N	right or left
<1 m	N9°E 47°E	Smooth surface with strations spaced 1–2 mm.	58°N	right-reverse
		Striations spaced .5–1 mm	1°S	right or left
<.5 m	N°2W 68°E	Smooth surface with striations spaced 1–3 mm.	72°N	right-reverse

the southern edge of the area. Topographic expression along much of the fault suggests dips of 70°-75°E; a 62°E dip was observed in outcrop directly north of Ålandsvatnet. Vertical separation between equivalent stratigraphic units reverses along the fault, because fault separation is about the same as the amplitude of adjacent folds (Crowell, 1959, discusses this type of relationship).

Karnakfjellet Fault.—On Odellfjellet the Karnakfjellet fault displaces Hørbyebreen Formation on the east against Old Red Sandstone on the west with about 240m of normal separation. The nature of the pre-Hørbyebreen displacement on the Karnakfjellet fault is indeterminate, because the relative ages of the Mimerbukta Sandstone east of the fault and Old Red Sandstone west of the fault are unknown. The curve in the trace of the Karnakfjellet fault as it crosses Ålandselva suggests a dip of about 42°E. Dips of 39° and 40°E were measured on the Karnakfjellet fault on Bulmanfjellet (Fig. 26). Exposures of unbroken rocks on opposite sides of the fault indicate that the maximum width of the fault zone is 100 m.

Odellfjellet Fault.—Carboniferous strata of the Ebbadalen and Svenbreen Formations on Odellfjellet dip an average of 25°W into the Odellfjellet fault. The Odellfjellet fault is poorly exposed, but the slight curve in the fault trace directly north of Ålandsvatnet suggests a dip of about 60°W, and reverse separation. North of Jäderindalen the Odellfjellet fault appears to be cut off by the younger *Ålandsvatnet fault.* Carboniferous strata of similar age are not exposed on opposite sides of the Odellfjellet fault, as the upper portion of the Hørbyebreen and lower portion of the Svenbreen Formations do not crop out; thus, the total stratigraphic separation on these rocks is unknown, but the minimum is approximately 1800 m.

Ålandsvatnet Fault.—Carboniferous strata are downdropped 450 to 550 m along the Ålandsvatnet fault, which dips 44°E and has normal separation. North of Jäderindalen the Ålandsvatnet fault is inferred to be the contact between Old Red Sandstone and Carboniferous rocks on the coast east of Bulmanfjellet.

Folds and Minor Thrust Faults

Dips are steep to overturned and folds are closely spaced in Devonian strata directly west of the Billefjorden fault zone; farther west the folds are more widely spaced and beds are not overturned.

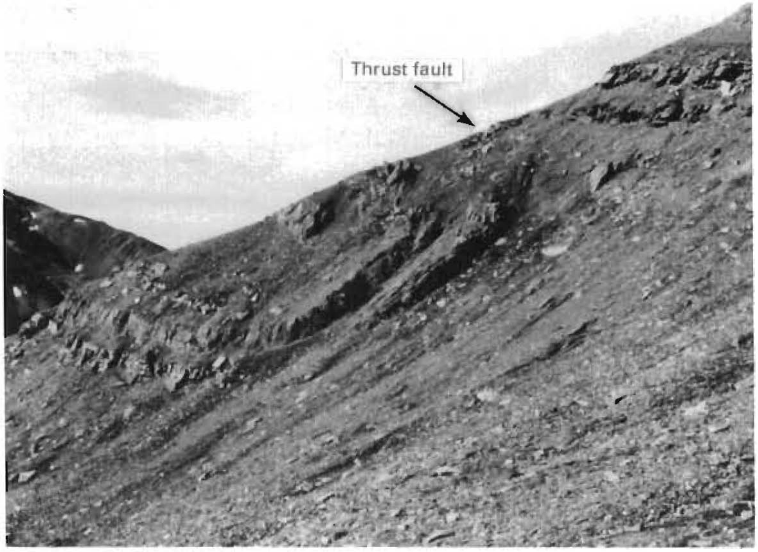


Fig. 29. View of syncline and faulted anticline in area of faulted and folded Stjørdalen and Keltiefjellet Formations of Devonian Wood Bay Group along south side of Jäderindalen.

Old Red Sandstone strata in the area bounded by the Karnakfjellet, Zeipeldalen and Jäderindalen faults are folded into two anticlines and a faulted syncline (Figs. 3, 26 and 29). The fold axes trend N30°E to N40°E and intersect the Billefjorden fault zone at 30° to 40° (Fig. 26). South of Odellfjellet the overturned anticline in the Kapp Kjeldsen Formation parallels the Billefjorden fault zone. The trend of fold axes abruptly changes north of the Jäderindalen fault on Bulmanfjellet, where axes trend N5°E to N45°W and either parallel or intersect a strand of the Billefjorden fault zone at angles of up to 35°.

Strata in the faulted syncline exposed on the south side of Jäderindalen (Fig. 3) are cut by thrust faults with separations not exceeding a few hundred meters. In this area the calcrete horizon at the base of the Stjørdalen Formation defines several complex, overturned folds; these subsidiary folds parallel the synclinal axis, whereas the structure of the adjacent anticlines is less complex. The flanks of the anticlines are steeply dipping to overturned; minor thrust faults were not observed, and minor folds similar to those within the synclinal area are less common. Minor thrust faults, trending N15°E to N50°E, also occur in the Stjørdalen and Keltiefjellet Formations along the Zeipeldalen fault, whereas thrusts were not seen in the Kapp Kjeldsen Formation. Contrasts in the competency of the rocks may explain these different structural styles.

Folds along the Zeipeldalen fault and in the western portion of the area have variable trends (Fig. 26). The Sophus Liefjellet anticline trends N12°E and plunges 6° to 14°S from the south slope of Sophus Liefjellet to the south side of Nathorstdalen. The Overgangshytta anticline trends N5°W, subparallel to the Billefjorden fault zone, and plunges an average of 15°N in the Ebbadalen Formation exposed on the coastal plain north of Jäderindalen. Open folds in the Ebbadalen Formation on the coast directly south of Zeipeldalen trend N5°E to N25°E. Structures in this area are difficult to define because of relatively flat dips and low angle cross-beds.

Tectonic history

Our detailed mapping and stratigraphic studies (Reed et al. 1986, 1987) lead to the following tectonic history:

1. Distribution of lithofacies and thicknesses suggest that the Old Red Sandstone was deposited in a half-graben with a tectonically active west margin and inactive eastern margin (Reed et al. 1986).

2. Large horizontal or vertical displacement on the Billefjorden fault zone is not required to explain the absence of Devonian rocks on Ny Friesland east of the Billefjorden fault zone

because of rapid eastward pinchout of Devonian Old Red Sandstone units against the west sloping inactive half-graben margin (Reed et al. 1987).

3. Structural relationships indicate that the east-west trending Jäderindalen fault and most likely the Nathorstdalen fault were active prior to formation of the north-south trending Billefjorden fault zone and Sophus Liefjellet anticline.

4. The relatively shallow (39°-68°) dip of individual fault strands and the 61° to 63° dip of the Balliolbreen fault prior to deposition of the Carboniferous Hørbyebreen Formation are more characteristic of reverse-slip than strike-slip. Fold axes and thrust faults with maximum separations of a few hundred meters trend from N40°E to N45°W. This nonuniform, arcuate orientation of fold axes and minor thrust faults along the Billefjorden fault zone (Fig. 26) also suggests compression rather than major strike-slip (Lamar et al. 1986). Structures in Mesozoic strata along the Billefjorden fault zone south of Sassenfjorden (Fig. 1) also indicate compression normal to the fault zone (Haremo et al. 1990).

5. Reverse-slip on the Balliolbreen fault and associated folding in Old Red Sandstone rocks, occurred prior to deposition of the Carboniferous Hørbyebreen Formation.

6. Following deposition of Carboniferous strata, reverse separation occurred on the Odellfjellet fault and the Ebbadalen Formation on the coast north of Jäderindalen was folded. This was followed by normal separation on the Ålandsvatnet and Karnakfjellet faults.

The principal evidence for the major sinistral strike-slip proposed by Harland (1969, 1978) and Harland & Gayer (1972) is the character and distribution of pre-Old Red Sandstone Hecla Hoek and equivalent rocks. Thus, major Devonian and post-Devonian sinistral strike-slip are not required; our investigation of structural and stratigraphic relations do not indicate major Devonian and post-Devonian sinistral strike-slip. On the west coast, 100 km west of the Billefjorden fault zone, Ratliff et al. (1987) report evidence for dextral strike-slip in Ordovician rocks which is also inconsistent with previous models of large-scale sinistral strike-slip in western Spitsbergen (Harland & Wright 1979). Although evidence for Devonian and post Devonian strike-slip is not convincing, the long straight trace of the Billefjorden fault zone and severe shattering of Hecla Hoek rocks along the west coast of Ny Friesland (Harland et al. 1974) could be explained by *post*-Hecla Hoek, *pre*-Old Red Sandstone strike-slip (Lamar et al. 1986; MacWhae, 1986; Reed et al. 1987). This faulting could have formed a zone of weakness that controlled the location of the late Devonian and post Carboniferous faulting along the Billefjorden fault zone and the eastern edge of the early to middle Devonian half-graben depositional basin (Reed et al. 1986, 1987). Although we disagree with Harland et al. (1974) on some aspects of the timing and sense of movement, we agree that the Billefjorden fault zone has had a remarkably long and varied history of movement.

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Fig. 3. Geologic map of a portion of Dicksonland, Spitsbergen, Svalbard.