

Devonian Old Red Sandstone sedimentation and tectonic history of Billefjorden fault zone, Spitsbergen

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Received 25 July 1986; accepted in revised form 24 April 1987

Abstract

Devonian Old Red Sandstone exposed within and west of the Billefjorden fault zone in Dicksonland, central Spitsbergen, consists of up to 3000 m of conglomerate, sandstone, and mudstone that rapidly thin eastward. The Devonian sediments form a single, large-scale fining upward sequence of fluvial, paludal, and marginal marine origin. Low-sinuosity channel processes dominated the lower portion of the sequence; the middle portion was transitional, probably deposited in meandering channels, and by proximal overbank processes on levees and floodplains. The upper portion of the sequence consists of floodbasin and marginal marine sediments. Nodular calcrete zones suggest prolonged weathering and root mottles indicate plant growth. Trace fossils suggest periods of marine and brackish water conditions within the fluvial-appearing sequence. Current directions and facies distributions indicate gradual wearing down of a source area to the south.

The sedimentation pattern within the Old Red Sandstone adjacent to the Billefjorden fault zone contrasts with that of known strike-slip fault-bounded basins: there is no repetitive stacking of facies, and there are no thick sequences of conglomerates or breccias; none of the units show coarsening near the fault. Units thin to the east and lack evidence of faulting contemporaneous with deposition. The eastern distal edge of the Devonian basin may coincide with the gently sloping edge of a half-graben. The early to middle Devonian passive basin margin, late Devonian reverse slip on the Billefjorden fault zone, and normal faults controlling the western margin of the Carboniferous depositional basin may coincide because all were controlled by a Caledonide zone of weakness along a pre-Old Red Sandstone fault in Hecla Hoek rocks.

Introduction

Devonian Old Red Sandstone rocks (Føyn & Heintz, 1943; Friend, 1961; Murascov & Mokin, 1979) are exposed in a fault-bounded area in north-central Spitsbergen (Fig. 1). On the eastern boundary of the exposure along the Billefjorden fault zone, the Devonian section is faulted against pre-Silurian Caledonide metamorphic rocks of the Hecla Hoek Series (McWhae, 1953; Harland et al., 1974). Relatively undeformed Carboniferous rocks (Cutbill & Challinor, 1965) overlie folded and

faulted Devonian strata, the Balliolbreen strand of the Billefjorden fault zone, and pre-Silurian Hecla Hoek Series.

The Billefjorden fault zone, largely concealed beneath the waters of Wijdefjorden and Austfjorden, and by post-Devonian sediments to the south (Fig. 1), is well exposed only in our area of study in Dicksonland, southwest of Austfjorden (Fig. 2). Friend & Moody-Stuart (1972), Harland et al. (1974), and Harland & Wright (1979) have suggested that the absence of Old Red Sandstone directly east of the Billefjorden fault zone (Fig. 1)

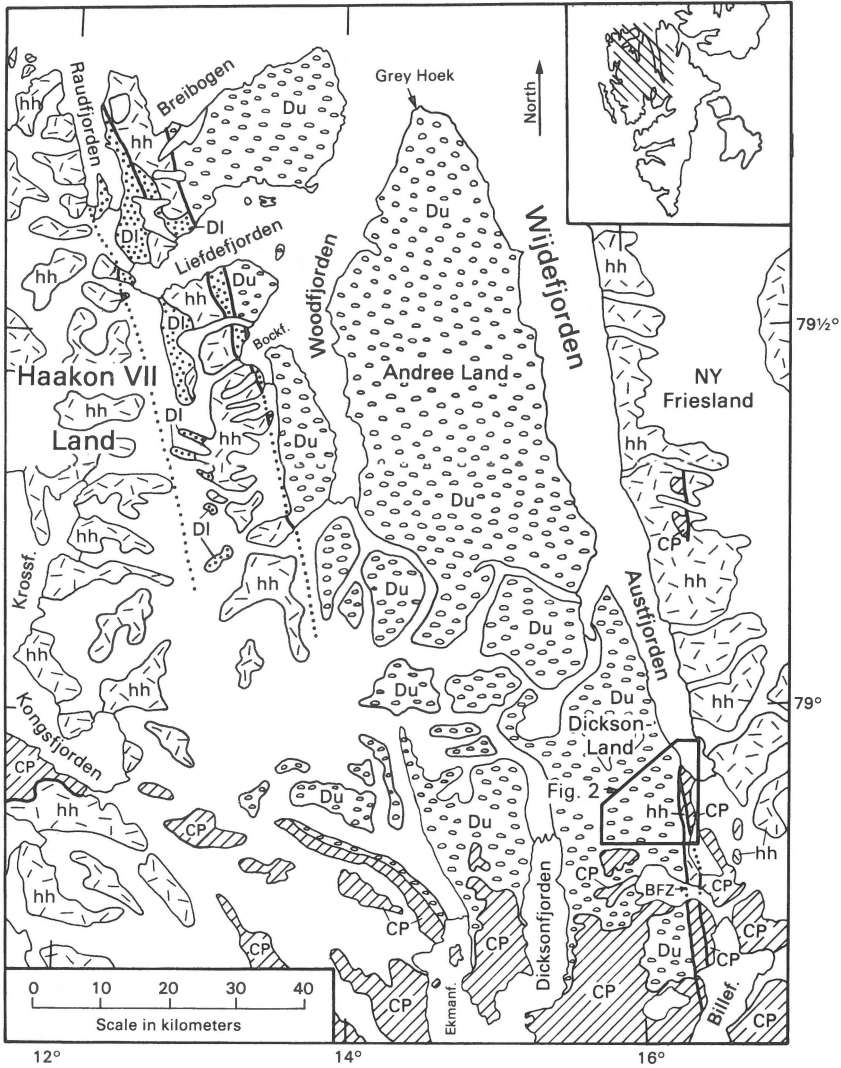


Fig. 1. Geologic map of a portion of Spitsbergen generalized from Hjelle & Lauritzen (1982) showing the Billefjorden fault zone (BFZ), and an outline of the area mapped in detail (Fig. 2). Symbols: CP: undifferentiated Permian and Carboniferous rocks; Du: upper units of Devonian Old Red Sandstone, Mimer Valley Group, Widje Bay Formation, Grey Hoek Group, and Wood Bay Group; DI: lower units of Devonian Old Red Sandstone, Red Bay Group, and Siktefjellet Group; hh: Caledonian basement Hecla Hoek Series.

may be explained by large-scale late Devonian left-slip along the Billefjorden fault zone. However, structures in the Devonian rocks exposed along and within the Billefjorden fault zone in this area (Fig. 2) suggest reverse-slip, rather than major late Devonian strike-slip (McWhae, 1953; Lamar et al., 1986, in prep.). Thus, a major impetus for our work has been to search for sedimentological evidence of the proposed faulting, examine the nature of the eastern margin of the Old Red Sandstone basin,

and explain the apparently abrupt termination of the Old Red Sandstone along the present trace of the Billefjorden fault zone.

Wood Bay Group

Previous work

Strata of Siegenian and Emsian age exposed adja-

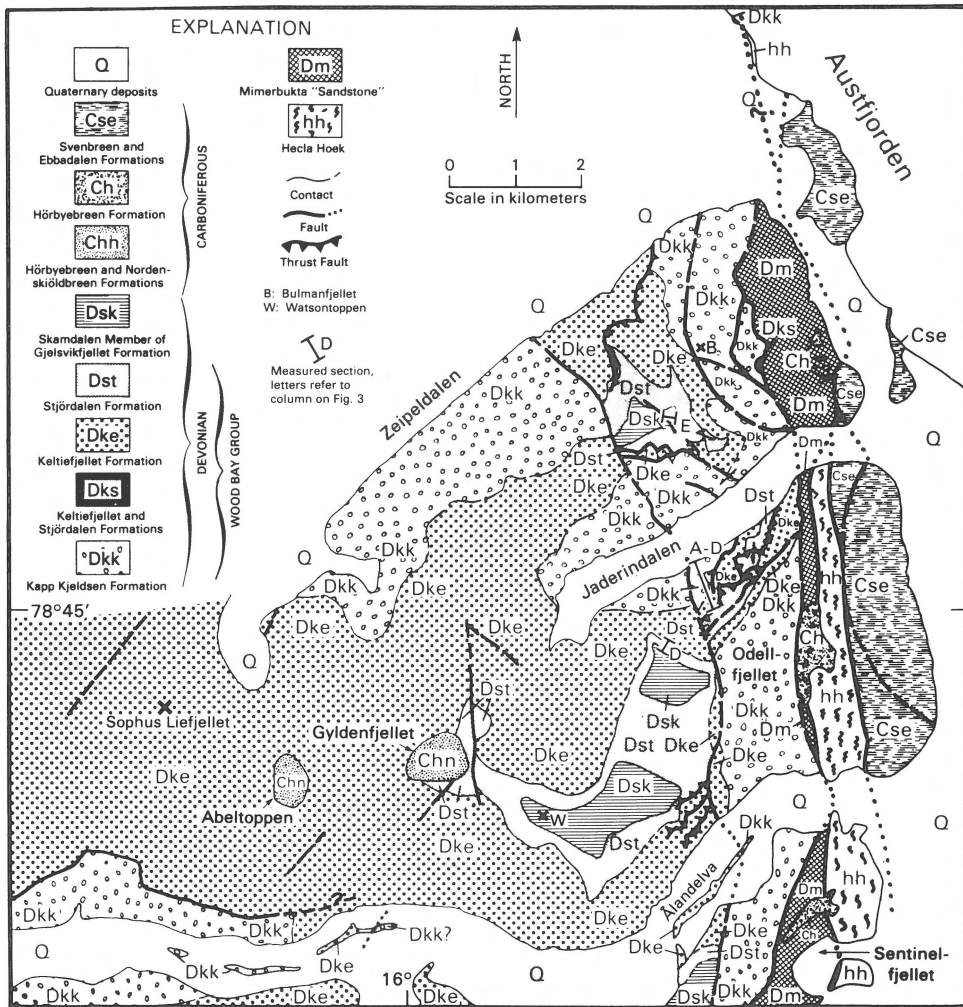


Fig. 2. Geologic map of area along Billefjorden fault zone showing locations of measured sections.

cent to Woodfjorden in northern Spitsbergen (Fig. 1) were originally named the Wood Bay Series by Holtedahl (1914a, b) and have been redefined by Føyn & Heintz (1943), Friend (1961) and Friend et al. (1966). Most recently, Murascov & Mokin (1979) and Lamar et al. (1986, in prep.) have included the Kapp Kjeldsen, Keltiefjellet, and Stjør-dalen Formations in the Wood Bay Group. Friend (1965), Moody-Stuart (1966), and Friend & Moody-Stuart (1972) described the sedimentary structures found in the Wood Bay Group.

Kapp Kjeldsen Formation

The base of this formation is not exposed in the area studied. We measured 210 m of Kapp Kjeldsen Formation (Fig. 3AB) on the south side of Jaderindalen (Fig. 2). The maximum thickness of 710 m within the mapped area is found on the south side of Ålandelva directly northwest of Sentinel-fjellet (Fig. 2). Our measured section consists of lithic arkosic wackes (72%), and mudstones (28%). The predominantly fine- to coarse-grained, yellow-gray wackes are usually carbonate cemented, and contain layers and channel fillings of

pebble and mud clast conglomerate. The mudstones are fissile, predominantly grayish-red; some are root mottled.

Keltiefjellet Formation

We measured 158 m of Keltiefjellet Formation (Fig. 3CD, 4) south of Jaderindalen (Fig. 2). The unit thickens to the west and consists of mudstones (61%) and sandstones (39%). The mudstones are fissile, light gray to reddish-brown and grayish-red. The predominantly greenish-gray quartz wackes, arkosic wackes, and lithic arkosic wackes are fine- to medium-grained, and are usually carbonate cemented; they contain rare pebble and mud-clast conglomerate layers.

Stjørdalen Formation

We measured 42 m of Stjørdalen Formation south of Jaderindalen (Fig. 3E, 5). Similar to the Keltiefjellet Formation, thickness increases to the west. The Stjørdalen Formation consists of interbedded mudstone (79%) and sandstone (21%), sandstone proportion within the Stjørdalen succession decreases northward. The mudstones are moderate brown, grayish-brown, and pale red-brown and exhibit abundant zones of carbonate nodules. Most of the sandstones, concentrated in the lower half of the sequence, are very fine- to medium-grained, grayish-red arkosic wackes, and lithic arkosic wackes.

Grey Hoek group

Skamdalen Member of Gjelsvikfjellet Formation

Holtedahl (1914a, b) originally named strata overlying the Wood Bay Group on Grey Hoek (Fig. 1) the Grey Hoek Series. Murascov & Mokin (1979) redefined the Grey Hoek Group to include the Gjelsvikfjellet Formation. We have designated strata overlying the Stjørdalen Formation as the Skamdalen Member of the Gjelsvikfjellet Forma-

tion (Fig. 2) on the basis of the lithologic description given by Murascov & Mokin (1979, p. 256).

In the area we studied, the top of the Skamdalen Member is not exposed. On the ridge 1400 m southwest of Bulmanfjellet, we measured 67.5 m of Skamdalen (Fig. 3E), and a 400 m-thick section is exposed on Watsontoppen (Fig. 2). This unit (Fig. 3E) consists of interbedded mudstone and siltstone (90%) and sandstone (10%). The mudstones and siltstones are predominantly greenish gray and gray with occasional grayish red to brown layers, and contain rare calcareous nodules. The sandstones are greenish-gray fine- to medium-grained lithic arkosic wackes, containing abundant plant debris.

Tectonics implications

Sedimentation patterns in fault-bounded basins

Rapid uplift and subsidence, induced by fault movement, results in thick sedimentary successions and high sedimentation rates adjacent to active faults (Miall, 1978). Facies distributions of sediments in fault-bounded basins may be similar, whether the bounding faults show strike-slip or dip-slip. However, basins formed by strike-slip along basin margin faults exhibit several common sedimentation features (Ballance, 1980; Reading, 1980) produced by the relative position of sediment source and depocenter with respect to the bounding fault. Individual facies commonly show a limited lateral extent, and evidence for an active source area nearby is frequently indicated by restricted deposition of locally-derived conglomerates and breccias (Crowell, 1974).

The Hornelen Basin of Norway (Steel et al., 1977; Steel & Gloppen, 1980) and the Ridge Basin of California (Crowell, 1974, 1982; Link & Osborne, 1978) are well-documented examples of basins with strike-slip margins. Recent work (Norton, 1986; McClay et al., 1986) suggests that the margins of the Hornelen Basin are local strike-slip segments of a major detachment fault. The Hornelen and Ridge Basins exhibit similar characteristics: they are elongate parallel to the strike-slip

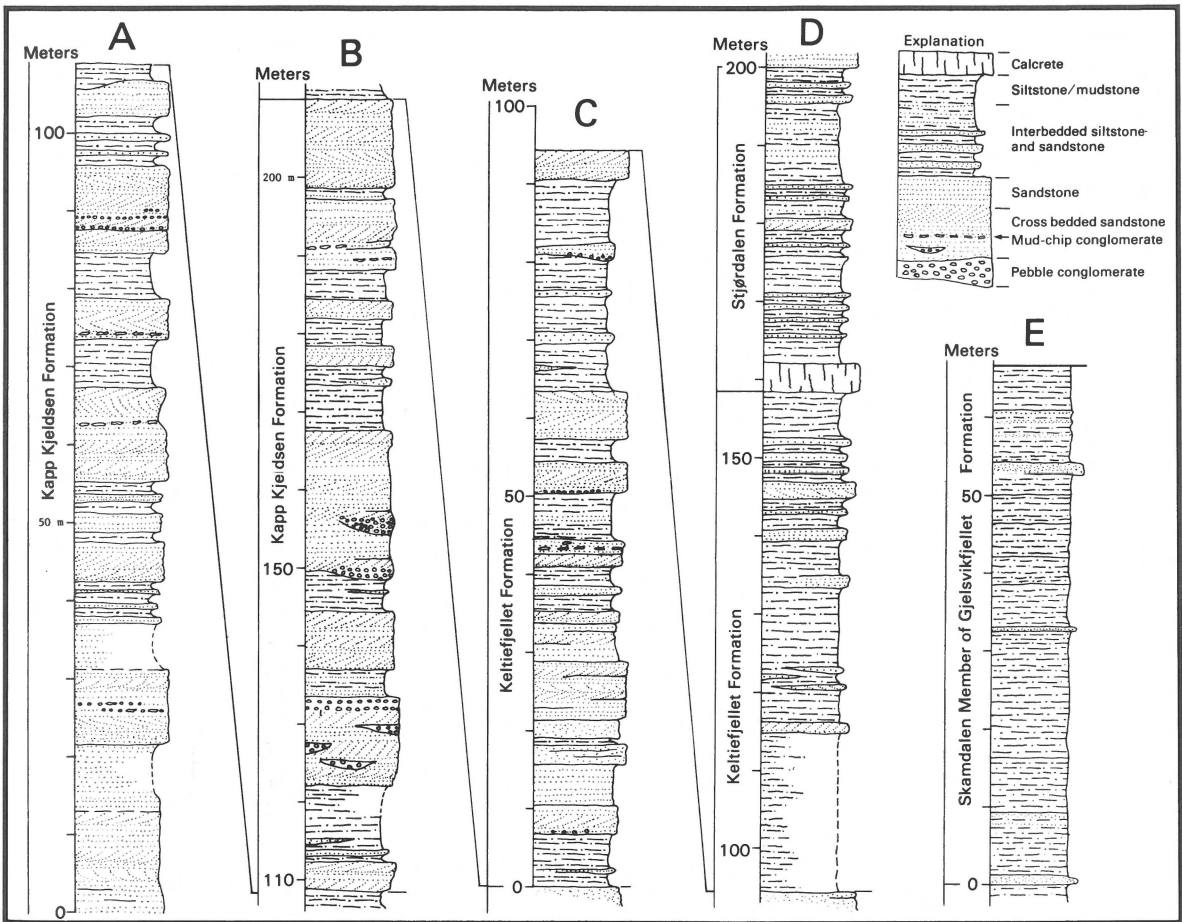


Fig. 3. Stratigraphic sequence of Wood Bay Group sediments measured in Austfjorden area. The base of the measured section of Kapp Kjeldsen Formation (Columns A and B) was located approximately 1250 m N 50° W of Odellfjellet; the base of the measured section of Keltiefjellet Formation (Columns C and lower D) was located 1200 m N 41° W of Odellfjellet; the base of the Stjørdaalen Formation (Column upper D) was located 1840 m N 88° W of Odellfjellet, and the Skamdalen member of the Gjelsvikfjellet Formation (Column E) was measured 1350 m S 40° W of Bulmanfjellet. Geographic locations are shown on Fig. 2.

faults, deep in relation to their width, and asymmetrical because of unequal movement on the two margins of the basin. Sedimentary sequences representing prograding alluvial fans and fan deltas are commonly characterized by upward coarsening, or coarsening- then fining-upward sediment packages tens to hundreds of metres in thickness (Crowell, 1974; Steel et al., 1977; Link & Osborne, 1978; Hempton, 1983).

Marginal fan conglomerates of the Hornelen Basin, and the Violin Breccia, the marginal deposits of the Ridge Basin (Crowell, 1974, 1982), are similar. Each shows coarsening-upward mesocycles tens to

hundreds of metres in thickness, extending outward into basinal sedimentary sequences.

Depositional environments of Old Red Sandstone

Formations within the Old Red Sandstone represent different facies. The change from the Kapp Kjeldsen to the Keltiefjellet Formation reflects a transition from sedimentation in sandy braided stream regimes, dominated by channel processes (Walker & Cant, 1984), to meandering fluvial systems dominated by distal floodplain muds (Moody-

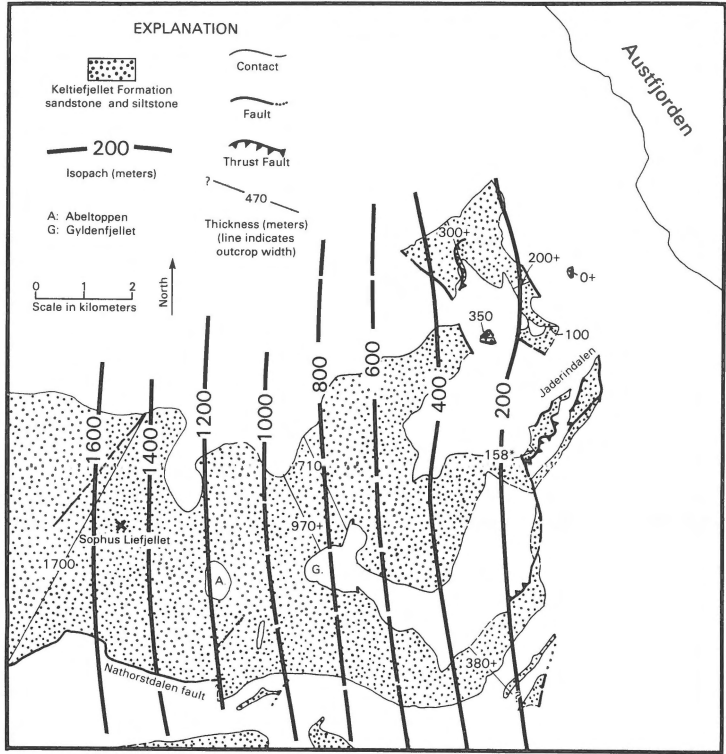


Fig. 4. Isopach map showing distribution and thickness of Keltiefjellet Formation. Thicknesses are scaled from the geologic map (Lamar et al., in prep. Plate I) and measured section (Fig. 3).

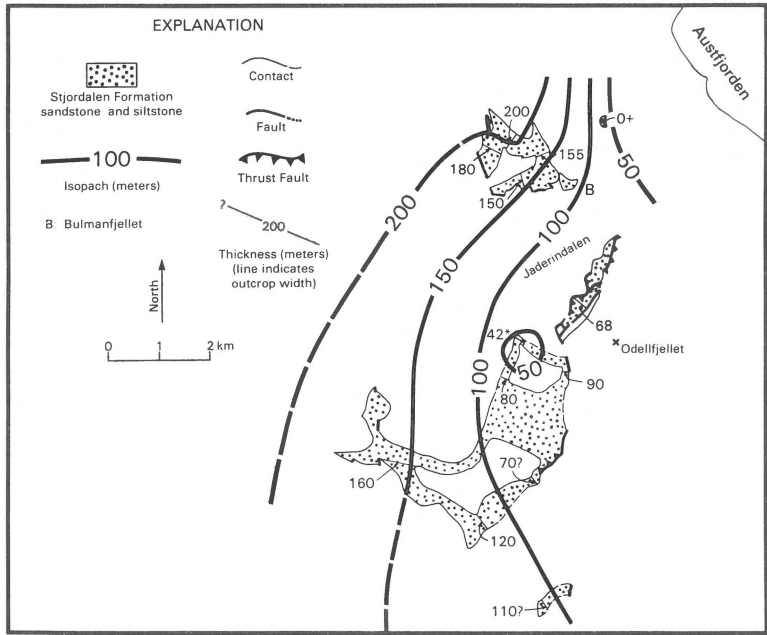


Fig. 5. Isopach map showing distribution and thickness of Stjørdalen Formation. Thickness are scaled from the geologic map (Lamar et al., in prep. Plate I), and measured section (Fig. 3).

Stuart, 1966; Allen, 1983; Walker & Cant, 1984). Finer grained sediments of the Stjørdalen and Keltiefjellet Formations may represent tidal flat, estuarine, paludal, or distal floodplain accumulations, while coarser, sandy sediments within these units represent deposition in subordinate channels, on levees, or in crevasse splays (Allen, 1965). Pebble and mud clast layers most likely represent channel lags (Walker & Cant, 1984; Miall, 1977). Nodular calcrete zones, mostly in the upper Keltiefjellet and throughout the Stjørdalen Formations, suggest prolonged non- or slow deposition with attendant soil development (Reed et al., in prep.), and root mottled intervals indicates abundant plants (Farmer et al., in prep.). Although the Keltiefjellet Formation has the lithologic characteristics of meandering fluvial deposition, alternating marine, non-marine and brackish conditions are suggested by trace fossils (Farmer et al., in prep.): *Cruziana* and *Rusophycus*, which characterize muddy intervals of the upper Keltiefjellet, indicate marine influence; *Merostomichnites*, found on surfaces of thin sandy beds, suggest brackish conditions (Størmer, 1934; Ekdale et al., 1984), while *Iso-podichnus* indicates a freshwater environment (Perch-Nielsen et al., 1972; Trewin, 1976).

Friend & Moody-Stuart (1972) measured south to north paleocurrent directions in the Kapp Kjeldsen and Keltiefjellet Formations. Northward from Jaderindalen (Fig. 2) these formations contain more mudstones; the meandering nature of the fluvial environments increases stratigraphically upward, and also increases toward the north for the entire Wood Bay Group. This apparently reflects a progressively northward decreasing gradient, and therefore increasing geomorphic maturity, consistent with the wearing down of a highland sediment source to the south.

Worsley (1972) studied the Grey Hoek Group in northern Andree Land (Fig. 1) and suggested the sequence was deposited on a broad coastal swamp with shallow lagoons, possibly with prominent barrier island bars on a low relief coast (Worsley, 1972, p. 110). Thus, the lowering of relief initiated in the Wood Bay Group continued through Gjelsvikfjellet Formation deposition.

Conclusions

Devonian sediments exposed adjacent to the Billefjorden fault exhibit none of the characteristics common to the well-documented fault-bounded basins: repetitive stacking of facies, or thick sequences of conglomerates or breccias along the fault trace are absent. West of Austfjorden the Keltiefjellet and Stjørdalen Formations rapidly thin to the east, and none of the Old Red Sandstone sediments coarsen toward the fault trace. Thus, there is no evidence of a highland source area to the east as would be expected if the Billefjorden fault zone was active during or immediately prior to Old Red Sandstone sedimentation. Structural evidence precludes major post-Devonian strike-slip on the Billefjorden fault zone (Lamar et al., 1986, in prep.).

Because of rapid eastward thinning of Devonian units, previously suggested major post-Old Red Sandstone displacement on the Billefjorden fault zone to explain the absence of Old Red Sandstone east of the fault (McWhae, 1953; Friend & Moody-Stuart, 1972; Harland et al., 1974) is not required. The basin margin may have been near the present location of the Billefjorden fault zone. Reed et al. (1986) have suggested normal faulting on the western edge of the Old Red Sandstone basin and that the eastern margin of the basin probably represents the passive side of the resulting half-graben. Recent studies also have suggested an extensional origin for other post-Caledonian Old Red Sandstone basins (Norton, 1986; Friend, 1986; McClay et al., 1986).

Carboniferous sediments unconformably overlie the Old Red Sandstone, and the thickest Carboniferous sediments are interpreted as a graben-fill sequence (McWhae, 1953; Gjelberg & Steel, 1981). The western margin of the graben-fill sequence coincides with normal fault strands of the Billefjorden fault zone active in the Carboniferous and later (McWhae, 1953; Lamar et al., 1986).

In summary, the region adjacent to the Billefjorden fault zone had the following history: 1. Possible major post-Hecla Hoek, pre-Devonian strike-slip (Harland et al., 1974; Harland & Wright, 1979; Lamar et al., 1986); 2. Formation of a depositional

basin by late Caledonide extension and subsequent filling of the basin with the Old Red Sandstone succession; 3. Compression with reverse-slip on the Billefjorden fault zone in late Devonian time (McWhae, 1953; Lamar et al., 1986); 4. Post-Devonian tensional faulting along the Billefjorden fault zone contemporaneous with and following Carboniferous deposition (McWhae, 1953; Gjelberg & Steel, 1981). The earlier, pre-Old Red Sandstone fault in Hecla Hoek rocks may have controlled the location of the late Devonian and Carboniferous faulting, and the eastern edge of the early to middle Devonian depositional basin. Thus, as recognized by Harland et al. (1974), the Billefjorden fault zone has had a remarkably long and varied history of movement which we believe reflects the influence of a Caledonide zone of weakness on later deformation.

Acknowledgments

Funds were provided under National Science Foundation Grants DPP-8200485 and DPP-8306679. L.Z. Valachi was responsible for securing additional funds from Mobil Exploration and Producing Services, Inc., which are also gratefully acknowledged. The idea for this research, as well as valuable information on geology and logistics, came from discussions and correspondence with W.B. Hartland, P.F. Friend, and Mike Hambrey, Cambridge University, and with Y. Ohta, T. Gjelsvik, and T. Siggerud, Norsk Polarinstitutt, Oslo. We also thank Paul Merifield, Mason Hill, Jack Farmer, Eric Hendrix and an unnamed reviewer for reviewing this manuscript.

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