Structural geology

The pattern of deposition within the Franklinian Basin during Early Palaeozoic time was dominated by the facies boundary of which the latest stage is termed the Navarana Fjord Escarpment. This tectonostratigraphic lineament (also called the Navarana Fjord Lineament, e.g. Higgins *et al.* 1991a; Soper & Higgins 1991) was probably controlled by a deep-seated structure that was active from late Proterozoic until late Silurian time (Surlyk 1991).

Superimposed upon this regional pattern of deposition were two periods of Palaeozoic tectonism, the Caledonian in latest Silurian to Devonian time, and the Ellesmerian in Devonian to Carboniferous time. In addition, there are two dislocations of regional extent that have played an important role in the geological evolution of the Citronen Fjord area, viz. the E–W-trending Harder Fjord Fault Zone (HFFZ) and the NW–SE-trending Trolle Land Fault Zone (TLFZ) that intersect the inferred Navarana Fjord Escarpment in the general region of Citronen Fjord (Fig. 22).

Caledonian Orogeny

Initiation of Caledonian deformation was manifested by the deposition of the Merqujôq Formation sandstone turbidites, the source area for which was the rising Caledonian mountains to the east (Hurst 1980; Hurst & Surlyk 1982; Surlyk & Hurst 1984; Higgins *et al.* 1991a, b; Surlyk 1991). By late Silurian time, progressive uplift led to westerly-directed thrust faulting. This early Caledonian thin-skinned, thrust-fault deformation phase was named the 'Vølvedal orogeny' by Pedersen (1986) and is manifested in the Vølvedal area of Amundsen Land bounded approximately by the Harder Fjord Fault Zone to the north and by the southern shore of Frederick E. Hyde Fjord (Fig. 22). The thrust faults emanate within the Cambrian deep-water mudstone strata (the Frigg Fjord mudstone of the Polkorridoren Group) and displace overlying Ordovician and Silurian sediments.

The main tectonic transport direction was to the west with refraction toward the south-west along the buried Lower Silurian platform margin formed by the Navarana Fjord Escarpment. The west-directed displacement is estimated to be in the order of 80 to 100 km, such that Ordovician sediments, now exposed around the inner reaches of Frederick E. Hyde Fjord, would have originated near the mouth of the fjord. This thrust fault deformation is interpreted as a foreland deformation related to the Caledonian succession of sinistral transport events along an E–W-trending megashear situated at the northern margin of the Franklinian Basin (Håkansson & Pedersen 1982; Pedersen 1986).

The spectacular juxtaposition of the Cambrian and Silurian strata exposed in the north-eastern part of the Citronen Fjord area (Figs 1, 5), which is assumed to be due to low-angle thrusting, is thought most likely to have originated from this early Caledonian thrust-fault deformation.

Ellesmerian Orogeny

In northern Greenland, the Ellesmerian Orogeny caused north-to-south compression during late Devonian to early Carboniferous time producing prominent folds and thrusts and a number of approximately E–W trending tectonic zones (Soper & Higgins 1987, 1991; Higgins *et al.* 1991a). Deformation and metamorphism diminish from north to south and extend as far as the Navarana Fjord Escarpment.

North of the Navarana Fjord Escarpment three tectonic zones have been defined: from south to north, the thin-skinned, fold and thrust zone; the divergence and imbricate zone; and in the north, the orthotectonic zone. The Citronen Fjord area is located at the convergence of the southerly two tectonic zones, while the orthotectonic zone forms the northern coast of Frederick E. Hyde Fjord but 5 km distant on the northern side of the Harder Fjord Fault Zone (Fig. 22; see Higgins *et al.* 1991a, fig. 65). The stable platform to the south of the escarpment remained essentially undeformed during the Ellesmerian Orogeny.

Harder Fjord Fault Zone

The Harder Fjord Fault Zone seems to have been a significant structural feature during both Caledonian and Ellesmerian deformation, and was presumably repeatedly active up to Tertiary or even Recent times. Dextral strike-slip movement of a few tens of kilometres associated with dyke emplacement and volcanic

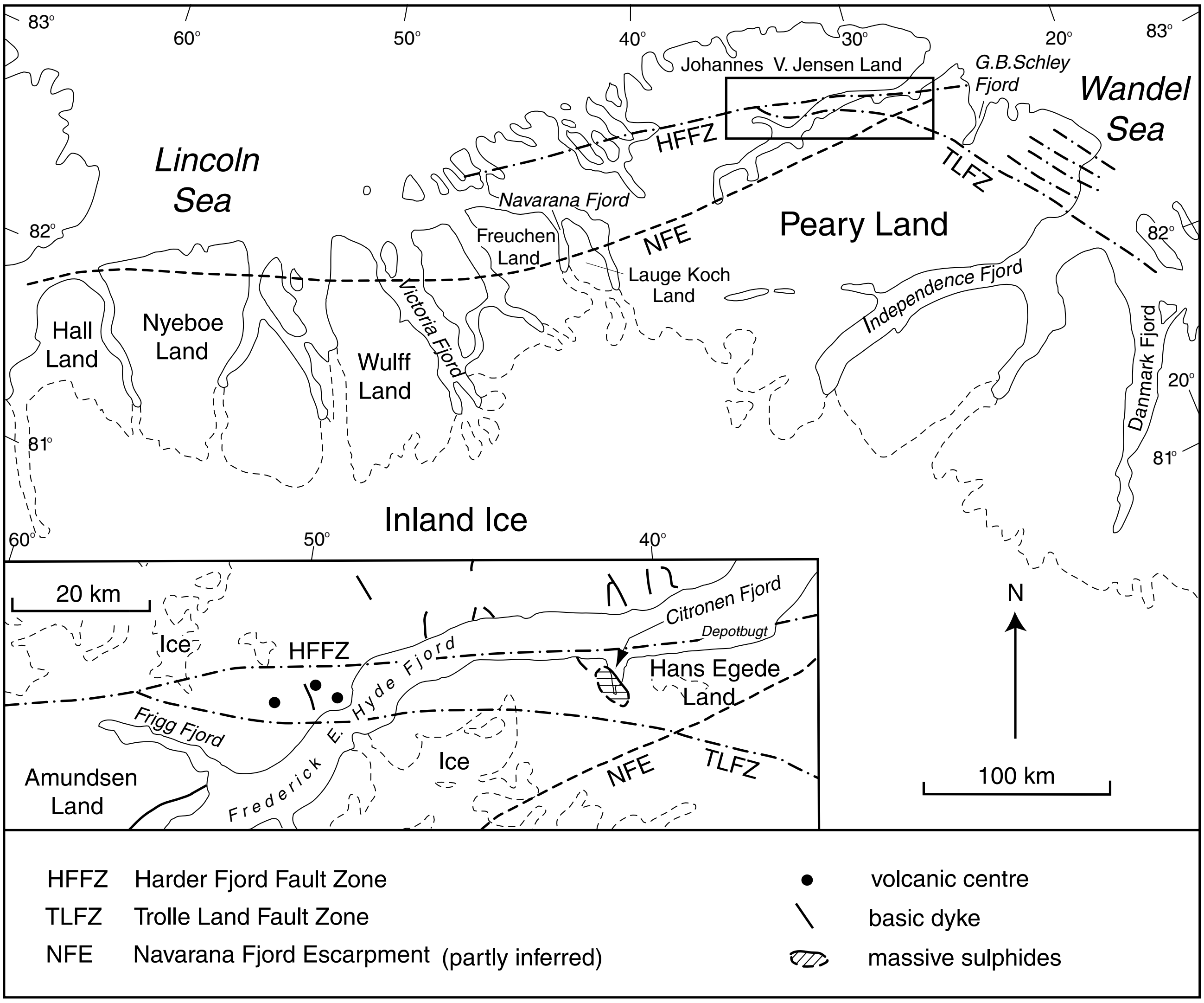

Fig. 22. Map of northern Greenland showing the structural setting of the Citronen Fjord sulphide deposit north of the Navarana Fjord Escarpment and at the junction of important fault zones. Data taken from various published papers by the Geological Survey of Greenland. **Midtkap** is the cape on Frederick E. Hyde Fjord containing the easternmost volcanic centre.

activity is interpreted to have taken place during the Cretaceous–Tertiary, with later Tertiary vertical uplift of possibly as much as 1–2 km on the north side of the fault (Soper & Higgins 1987).

The eastern continuation of the Harder Fjord Fault Zone along Frederick E. Hyde Fjord between Midtkap and Depotbugt is inferred by the sharp outline of the southern shoreline. Furthermore, as suggested in this paper, the effects of the fault zone are also seen by the somewhat unusual lithological and textural characteristics of the Ordovician strata (i.e. Unit 7: Middle debris flow) that are exposed in the West gossan area (see section 'Stratigraphy of the Citronen Fjord area', p. 19).

Trolle Land Fault Zone

The Trolle Land Fault Zone is a prominent NW–SW-trending structure that cuts across the eastern end of Peary Land and forms the western border of the Wandel Sea Basin, which contains sediments of Carboniferous to Tertiary age (Håkansson & Pedersen 1982). The fault zone appears in the Citronen Fjord area as a prominent lineament that on aerial photographs can be traced in a west to north-west direction as far as the area opposite Midtkap along Frederick E. Hyde Fjord (Fig. 22). Across the fjord immediately west of Midtkap the structure continues until it eventually merges with the Harder Fjord Fault Zone at a point north of Frigg Fjord

Fig. 23. Tightly folded calcareous siltstones of the Citronens Fjord Member in the hinge zone of the recumbent fold structure shown in Figure 4 on the west side of Citronen Fjord. Slaty cleavage is visible. The hammer is 40 cm long.

(Pedersen 1980; Fig. 22). This suggests that the Trolle Land Fault Zone originally developed as a splay of the Harder Fjord Fault Zone.

Within the structural wedge formed by the Harder Fjord Fault Zone and the Trolle Land Fault Zone, a number of volcanic centres occur (Pedersen 1980; Parsons 1981; Fig. 22). A Middle Devonian K/Ar age of 380 ± 5 Ma has been obtained from a sample taken from one of the intrusive bodies, suggesting an origin that is time-related to the Vølvedal orogeny (Pedersen & Holm 1983). Although more investigations of the genesis and age of these intrusives are clearly warranted, it does seem likely that their emplacement was controlled by the convergence of the two fault zones. However, the apparent discrepancy in timing between the intrusive events and the genesis of the massive sulphides at Citronen Fjord does not lend support to a direct genetical relationship.

Structural elements in the Citronen Fjord area

As described in the section 'Regional geology' (p. 13), the Citronen Fjord area is located at the southern margin of the North Greenland Fold Belt. In the northern part of the area around Frederick E. Hyde Fjord, strata are recumbently folded and thrusted; to the south folding is less intense, and homoclinal strata occur just south of the map area (see Fig. 1).

General fold style

The structural style in the northern part of the Citronen Fjord area is characterized by the occurrence of large-scale, approximately E–W-trending moderately inclined to recumbent, close to tight folds with north-dipping axial planes and sub-horizontal fold axes. A well-exposed example of a south-verging recumbent fold pair is seen in exposures of the Hangingwall debris flow (Unit 9) on the western side of Citronen Fjord (Dawes & Soper 1979, fig. 12; Figs 4, 23). Drill hole information as well as field observations confirm that this structure is persistent in both the underlying Footwall shale (Unit 8) and the overlying Calcareous siltstone (Unit 10, see Fig. 6).

The mountain complex immediately west of the fjord is framed by a series of very large reclined, south-verging anticlinal/synclinal fold structures (Figs 6, 24). A major hinge area with associated thrust faults strikes parallel to the trend of 'West Elv' and explains a well-developed linear feature that is visible on aerial photographs. It is assumed that these fold structures continue eastwards to correlate directly with fold structures observed along the valley of 'East Elv'.

In the north-eastern map quadrant, some large-scale reclined fold structures were recognized by detailed mapping of the relatively easily traceable Cigar debris flow (Unit 2) and the overlying Calcareous siltstone (Unit 10; see Fig. 6).

In the less-deformed southern part of the area, moderately inclined to recumbent, open to tight folds with predominantly north-dipping axial planes and sub-horizontal, E–W-trending fold axes occur in more restricted areas (Fig. 25).

A stereographic projection of poles to bedding (Fig. 27a) indicates folding along flat-lying, ESE-trending fold axes (azimuth 107°).

A slaty cleavage (S_1) is often well developed in areas of more intense folding (Figs 23, 26) but is weak

Fig. 24. Large-scale recumbent south-verging pair of tight folds in sandstone turbidites (Unit 12) at the south-western end of Citronen Fjord. The height of the mountain is about 950 m a.s.l. with the shoreline just visible

or absent in less disturbed areas. A π-diagram of S_1 measurements (Fig. 27b) shows a preferred dip and dip direction of approximately 70° towards 217°. The zone axis of the cleavage trends 127°, indicating a minor deviation of about 20° with the constructed F_1 fold axis (cf. Fig. 27a).

These results correspond well with the structural analysis of the fold belt in the north-western part of Hans Egede Land by Pedersen (1979) who explained the deviation in direction between the zone axis of the cleavage and the constructed fold axis by a model of changing deformational parameters during the structural evolution of the fold belt.

Thrust faults

Large-scale fold structures and regional thrust faults occurring in the northern area along Frederick E. Hyde Fjord reflect the regional geometry of the North Greenland Fold Belt. In the north-eastern part of the study area, Cambrian and Silurian sediments are in direct paraconformable contact. In spite of the absence of categoric tectonic textures in rock exposures along this contact (see discusssion under 'Stratigraphy of the Citronen Fjord area', p. 17), the boundary is interpreted as a thrusted contact because of the age of the strata involved, and the presence of Ordovician strata nearby.

Fig. 25. Gentle to open folds in sandstone turbidites of Unit 12 north of Esrum Elv. Carbonate debris flow conglomerates of the Upper debris flow (Unit 11) outcrop in the lower right corner. West of the mouth of Esrum Elv; the stretch of river shown is *c.* 100 m.

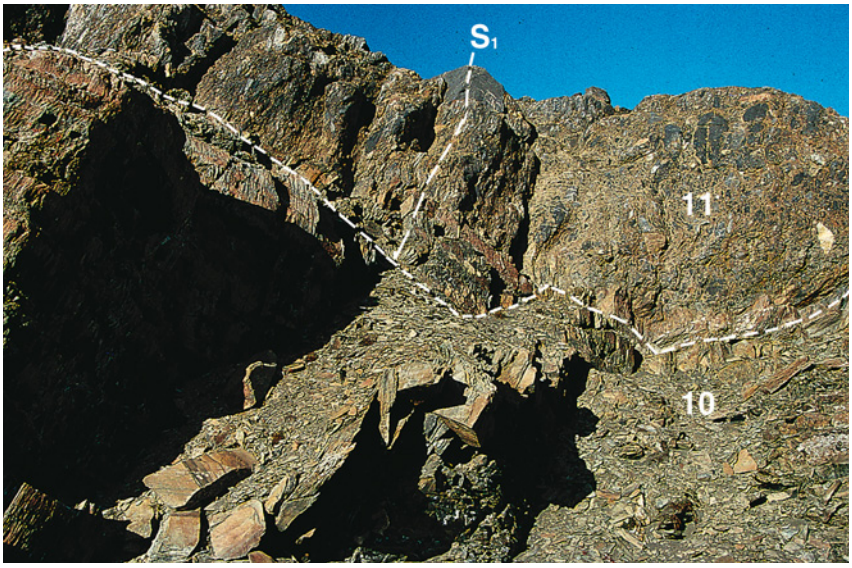

Fig. 26. Well-developed slaty cleavage (S_1) in calcareous siltstones (Unit 10) and overlying carbonate debris flow conglomerates of the Upper debris flow (Unit 11). Thickness of the debris flow is about 8 m. South-east of type locality of the Citronens Fjord Member; for location, see Fig. 3.

The thrusting event leading to the juxtaposition of these Cambrian and Silurian strata must have pre-dated the deformation phase that resulted in the large-scale reclined fold structures since these clearly overprint this contact. This indicates a corresponding structural origin as described for the Early to Middle Devonian thrust faults in the Vølvedal region, Amundsen Land, some 100 km to the west of Citronen Fjord (Fig. 22; Pedersen 1986).

On the western side of Citronen Fjord, the Cambrian siltstones have not been identified and, although exposures are not particularly good, the strata are assumed absent. This suggests that the tectonic slice does not extend across Citronen Fjord or, alternatively, it may have a more northerly strike and be indicative of a westerly-directed thrust faulting.

The southern limit of this structural wedge involving Cambrian strata is defined by an approximately NW–SE-trending, sub-vertical fault structure which is exposed along 'East Elv'. We have the impression that this important fault in reality is the down-folded continuation of the above thrust fault contact (Fig. 6). This gains support from the lack of any indications of faulting in exposures of Merqujôq Formation siltstones and sandstones on the mountain slope at the eastern end of the valley. On the contrary, there is in this area evidence of intense folding with axial directions parallel to the trend of this E–W valley (see section 'General fold style', p. 34).

In the north-western part of the study area in the West gossan area (Fig. 3), intraformational thrusts and thrust faults, generally associated with flat-lying recumbent folds, are common within Amundsen Land Group mudstones and carbonate debris flows. Together with the abundance of different kinds of brecciation textures and observed facies changes (see section 'Stratigraphy of the Citronen Fjord area', p. 17), these features seem to confirm the inferred proximity of the Harder Fjord Fault Zone.

Block faulting

As evidenced by field observations and the drill hole information, the sub-surface stratigraphy is off-set by some major normal faults. The most important of these is detected approximately 600 m north of the small lake, *c.* 2 km to the south of Citronen Fjord, causing a southern downthrow of the stratigraphy in the order of 150 m (Fig. 5). The fault outcrops at the mouth of the Esrum Elv and in a gully in the cliff face north-west of the lake.

Most of the faults recognized in the map area have an ENE–WSW strike and they are clearly post-Ellesmerian in age. Faults with an observed strike-slip component generally have a strike of 105° which corresponds to the orientation of both the Harder Fjord (105°) and Trolle Land (105–120°) Fault Zones. This direction also corresponds to the general strike of the stratigraphic units and fold axes of the area. It is assumed that most fractures exposed in the Citronen Fjord area are the product of interaction between these two fault systems during different stages of the structural geological history.

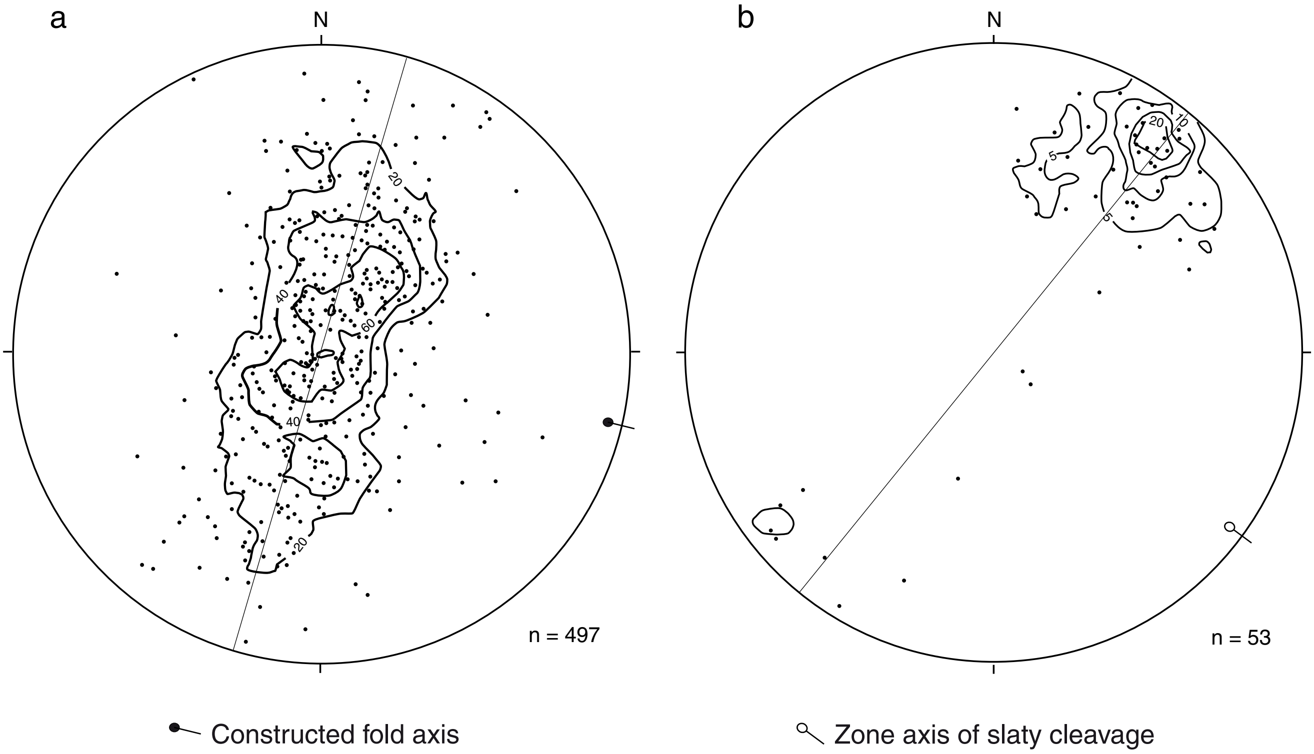

Fig. 27. Stereogram plots from the Citronen Fjord area: **a**, poles to bedding (S_0); **b**, poles to S_1 cleavage. Equal area projection, lower hemisphere. The contours are percentages of the total sample points (497 and 53).

Tectonic control of the massive sulphides

The massive sulphide deposit in the Citronen Fjord area follows an overall trend of approximately 145° azimuth. In places, a well-developed joint system occurs with fillings of coarse-grained calcite (± quartz) and a common strike direction of 140–160°. These di-rections appear to be more northerly trending than the Trolle Land Fault Zone (105–120°), the Harder Fjord Fault Zone (105°) and the trend of the dolerite dyke (120°) that has been described earlier from the north-western quadrant of the map area. This slight difference in orientation may reflect the interaction between the Trolle Land and Harder Fjord Fault Zones. One result of this might be the development of conjugate shear fractures and associated extension and shear joints between these fault zones and this would have provided a maximum opportunity for fluid migration and enhanced heat flow. This tensional tectonic regime could have provided the mechanism for subsidence in which the sulphides eventually became trapped; in this case sub-basin subsidence.

From all the most recent accounts in the literature that have been quoted in this paper, the Navarana Fjord Escarpment can reasonably be projected to be located within 5 km to the south of the mineralization at Citronen Fjord. This palaeo-topographic structure is thought to have been persistent throughout much of Early Palaeozoic time, and is therefore presumed to be a tectonic, rather than a purely depositional feature. However, it is uncertain if the Navarana Fjord Escarpment was responsible in any direct way for the localization of the massive sulphides at Citronen Fjord; an assumption that was considered very likely at the time of the discovery and during the early exploration of the deposit.

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