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The Citronen Fjord massive sulphide deposit, Peary Land, North Greenland: discovery, stratigraphy, mineralization and structural setting

Frank W. van der Stijl and Greg Z. Mosher

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Citronen Fjord, SEDEX deposit, Cambro-Silurian, Franklinian Basin, Peary Land, North Greenland, massive sulphides, gossans, starved basin, carbonate debris flows, sub-basin setting, shelf–trough junction, regional tectonics.

Cover
Low cloud and mist shroud the land on the eve of the discovery of the Citronen Fjord massive sulphide deposit in May 1993. The deposit was found during regional reconnaissance using low-cost logistics, viz. a skidoo–sledge expedition using the fjord ice. Primary targets were the reported gossans and sulphide showings in the Lower Palaeozoic sediments at Citronen Fjord. The scene shows the company Platinova's arrival at the mouth of Citronen Fjord, looking south into the fjord with low-lying marine terraces visible at its head. Massive sulphides were encountered on the first-day of exploration in the low cloud-covered hills of the Discovery area (left background). The height of the mountain on the right is about 850 m. Photo: Stefan Bernstein, 17th May, 1993.

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Contents

Abstract

Van der Stijl, F.W. & Mosher, G.Z. 1998: The Citronen Fjord massive sulphide deposit, Peary Land, North Greenland: discovery, stratigraphy, mineralization and structural setting.
Geology of Greenland Survey Bulletin 179, 40 pp.

The Citronen Fjord massive sulphide deposit in the Lower Palaeozoic of North Greenland is the world's most northerly base metal mineralization. Since discovery in 1993, it has been intensively investigated by geological and geophysical surveys, and by drilling. The deposit is generally flat lying with a thickness up to 50 m; it extends from outcrop level to depths of 300 m.

Three main stratiform sulphide sheets occur within a 200 m thick stratigraphic sequence; these are composed of massive and bedded pyrite with variable amounts of sphalerite and minor galena. The proven mineralization is continuous over a strike length of at least 3 km with a maximum width of 500 m; an additional 5 km of mineralization along the same trend is suggested by geological mapping and gravity surveys. The total tonnage of sulphides is estimated to exceed 350 million tons. The overall base metal resource is estimated at 20 million tons of 7 per cent zinc, with a higher grade core of 7 million tons containing 9 per cent zinc and 1 per cent lead.

The Citronen Fjord deposit is located at the eastern end of the Palaeozoic Franklinian Basin that extends through the Arctic Islands of Canada and across northern Greenland. Its discovery is an example of a successful exploration strategy based on regional evaluation, sparse but telltale surface mineralization observations and low-cost logistics: a skidoo–sledge expedition. The stratiform mineralization is hosted in the dark argillaceous rocks of the Amundsen Land Group of latest Ordovician to Early Silurian age that comprises a starved basin sequence of cherts and shales with siltstones and mudstones, punctuated by carbonate debris flow conglomerates derived from the nearby southern carbonate shelf. The Lower Palaeozoic strata at Citronen Fjord are part of the southern margin of the North Greenland Fold Belt characterized by southerly-facing folds and thrust faults.

A new geological map of the Citronen Fjord area is presented featuring Cambrian, Ordovician and Silurian strata, with two north–south cross-sections illustrating the main structure. Twelve informally-named lithostratigraphic units are recognized and comments given on correlation to the regional stratigraphy. Tectonic contacts separate Lower Cambrian strata from the Ordovician–Silurian part of the succession. It is concluded that the Citronen Fjord stratigraphy could be of local development in a sub-basin controlled by syn-genetic faults.

The lead-zinc deposit is interpreted to be of sedimentary-exhalative origin formed by the precipitation of sulphides from metal-bearing fluids introduced onto the sea-floor through underlying fractures. The significant components of this deposition model include the existence of a tensional tectonic regime, deep-seated fractures and a restricted sub-basin morphology. Massive to dendritic-textured pyrite is interpreted to represent vent-facies deposition while the bedded sulphides are taken to be the corresponding distal facies. The precise tectonic control of the fractures is debatable, as is the role of the so-called Navarana Fjord Escarpment – a palaeo-topographic feature marking the junction between shelf and trough that is assumed to lie immediately to the south of the Citronen Fjord.

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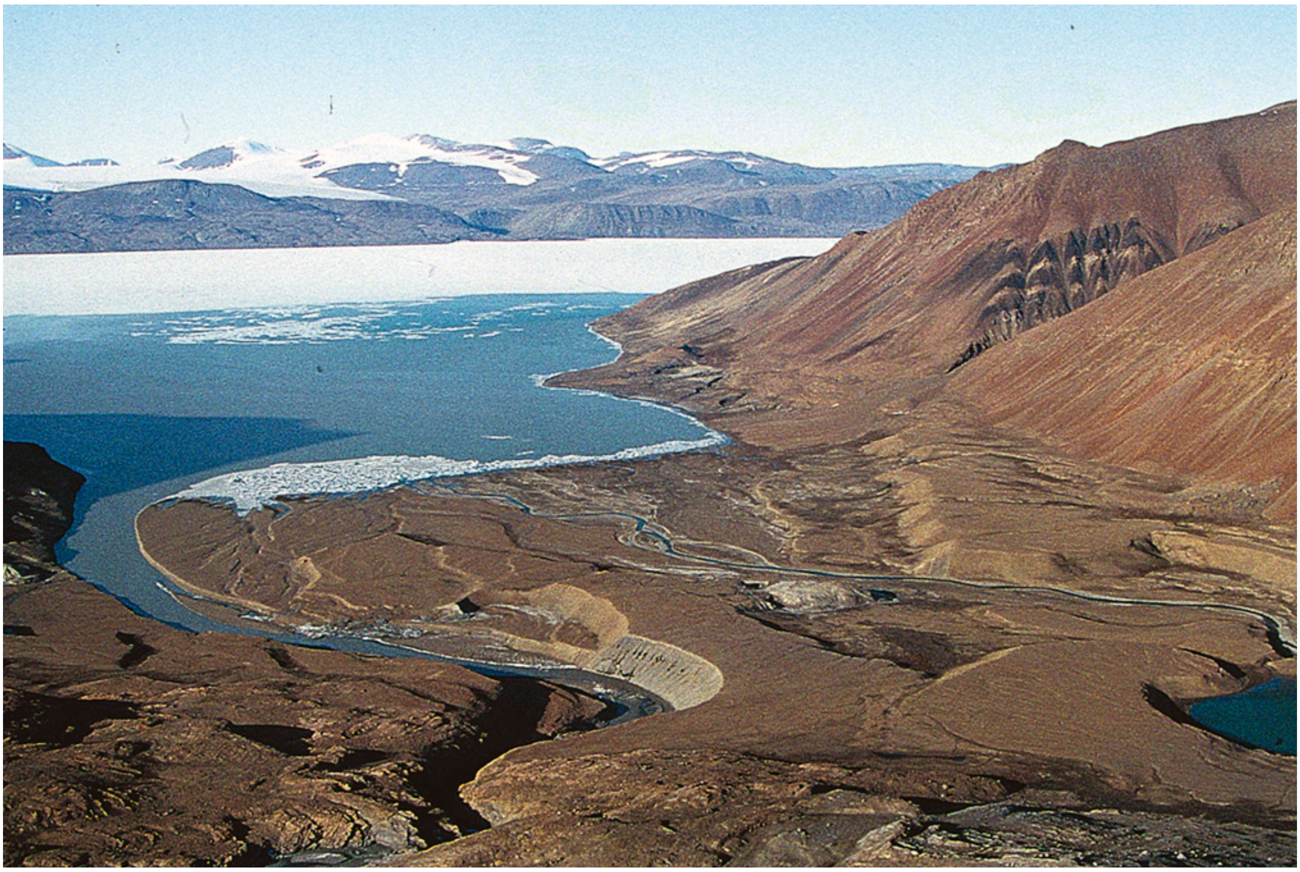

Introduction

The Citronen Fjord massive sulphide deposit is located at the fjord of that name on the south side of Frederick E. Hyde Fjord in northern Peary Land, North Greenland (Figs 1–3). Citronen Fjord is situated some 250 km north-west of the Danish military support base Station Nord and 100 km south-east of Kap Morris Jesup, the northern cape of Greenland. The location at 83°05′N and 28°15′W makes it the most northerly base metal mineralization presently known in the world. The mineral deposit was discovered in May 1993 by Platinova A/S during a reconnaissance exploration programme and it has been investigated by mapping, drilling and geophysical surveys during the period 1993–1997.

The distribution of sulphides in the area was initially defined by gravity and electromagnetic surveys and subsequently tested by an extensive programme of core drilling which demonstrated the occurrence of a continuous mineralization over a strike length of three kilometres with a maximum width of about 500 m. Geological mapping and gravity data suggest that the mineralized trend in the area of initial discovery – herein called the Discovery area – continues for an additional five kilometres towards the sulphide exposures near the north-western corner of Citronen Fjord.

Scope of this paper

The massive sulphide deposit occurs within the Lower Palaeozoic strata of the Franklinian Basin that occupies the northernmost part of Greenland and is continuous across the Canadian Arctic Islands to the Beaufort Sea (Fig. 2). Regional geological maps of the Franklinian Basin are part of the 1:500 000 scale 'Geological map of Greenland' and Citronen Fjord appears on the Peary Land sheet (Bengaard & Henriksen 1986a; Henriksen 1992). No detailed geological maps of the Citronen Fjord area have been published and the nearest 1:100 000 scale map is the Nordkronen sheet (Pedersen & Henriksen 1986) covering an area at the head of Frederick E. Hyde Fjord. The north-eastern corner of this sheet is 30 km from Citronen Fjord.

An important part of Platinova's exploration at Citronen Fjord has been the detailed geological mapping of the sulphide body and its immediate environs. This paper presents a simplified edition of the surface geological map, and gives cross-sections to illustrate the general structure (see Figs 5, 6). On the basis of these, the stratigraphy and structural characteristics of the area are discussed. The massive sulphide deposit is described in general terms, including its stratigraphical and regional setting; the various mineralization types are described with comments on their genesis and tectonic control.

As might be imagined, five years of continuous exploration has led to the accumulation of substantial data sets, particularly those gained from the geophysics and drilling programmes. At the time of writing (summer 1997) these data sets are being used in an economic assessment of the exploitation aspects of the deposit, and will not be released to the public. The data are, however, mentioned in this account in so far as the information is relevant to the general descriptions and interpretation. A short description of the main geophysical methods is given and pertinent drill-holes are included on the cross-section (see Fig. 6).

The discovery of the massive suphide deposit at Citronen Fjord is an illustrative example of a successful exploration strategy in the High Arctic, based on regional evaluation of a continental-scale sedimentary basin, sparse but tell-tale mineralization data and on low-cost logistics (MINEX 1993). To illustrate this aspect of the study, a history of exploration in the Citronen Fjord area is given, together with the exploration strat-

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Fig. 1. The location and environs of the Citronen Fjord massive sulphide deposit. **Upper**: view south up the Citronen Fjord valley with Esrum Elv and the gravel terraces of the Beach area in the foreground. The river canyon in the centre is that of 'Citronen Elv' and the gossans of the Discovery area are on the lower mountain slopes in the distance to the east of 'Citronen Elv' (see Fig. 19). The distant mountains are composed of homoclinal Silurian sandstone turbidites of the Peary Land Group with the height of the plateau surface at around 750 m. Photo: August 1995. **Lower**: view north over Esrum Elv, Citronen Fjord (open) and Frederick E. Hyde Fjord (ice covered) to the snow-clad mountains of Johannes V. Jensen Land that are up to 1200 m high. The dark exposures on the north side of the gully 'East Elv' visible on the right are of the Cambrian Buen Formation (pale bands are the Cigar debris flow) in thrust fault contact above and below with units of the Silurian Merqujôq Formation (see Figs 5, 6). The top of the cliff is about 850 m. Photo: late July 1993.

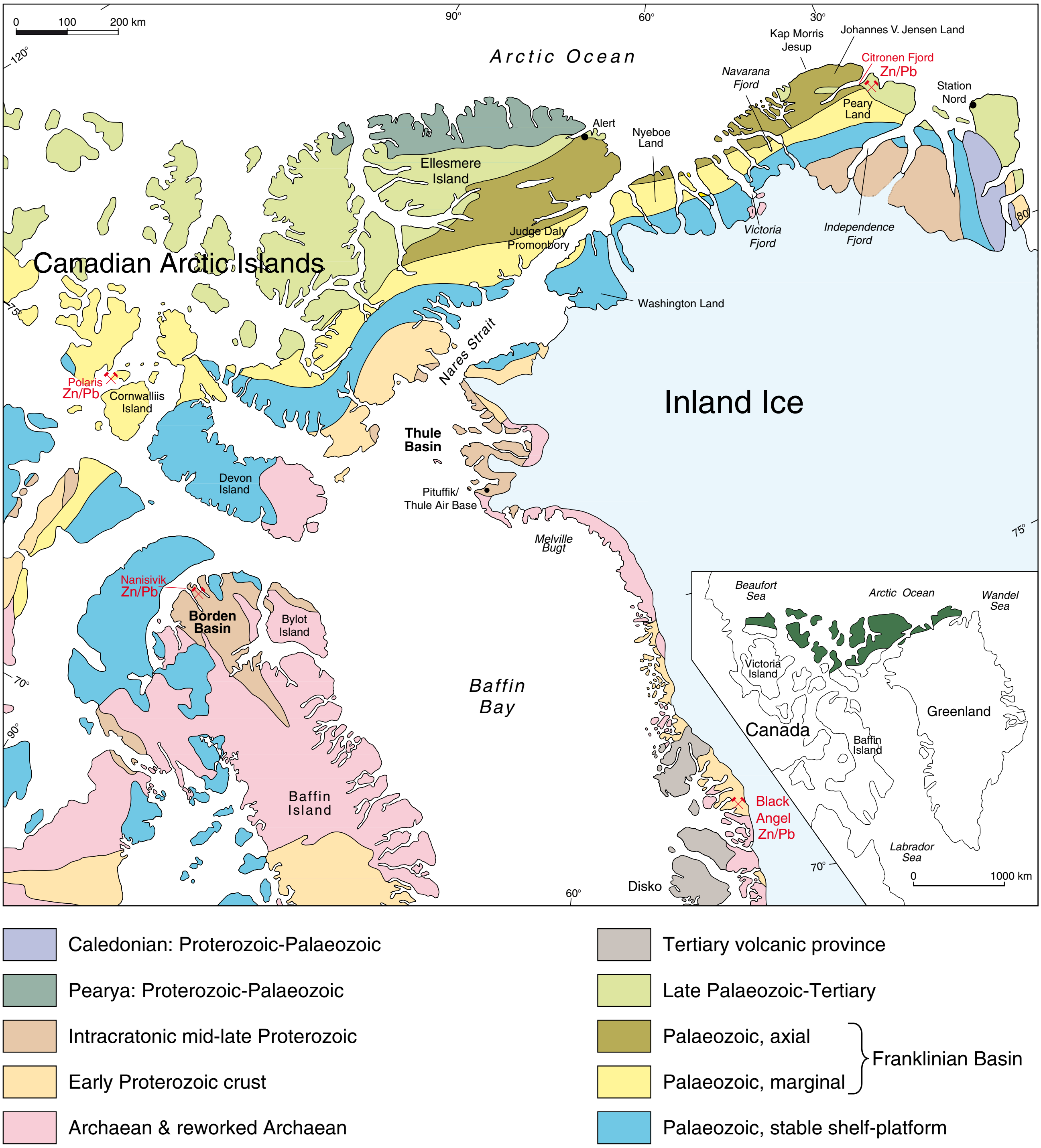


Fig. 2. Geological map of northern Greenland and adjacent parts of the Canadian Arctic Islands showing the location of Citronen Fjord in north-eastern Peary Land. The zinc-lead mines of Nanisivik and Polaris in Canada – in the Proterozoic Borden Basin and Palaeozoic Franklinian Basin respectively – and the abandoned Black Angel mine in the Precambrian shield of West Greenland, are also shown. The Citronen Fjord massive sulphide deposit is situated at the boundary between the southern platform and shelf (marked 'marginal') and northern deep water trough (marked 'axial') of the Franklinian Basin. The inset map shows in green colour the extent of the Franklinian Basin stretching for 2500 km from the Beaufort Sea to the Wandel Sea. Modified from Dawes (1994).

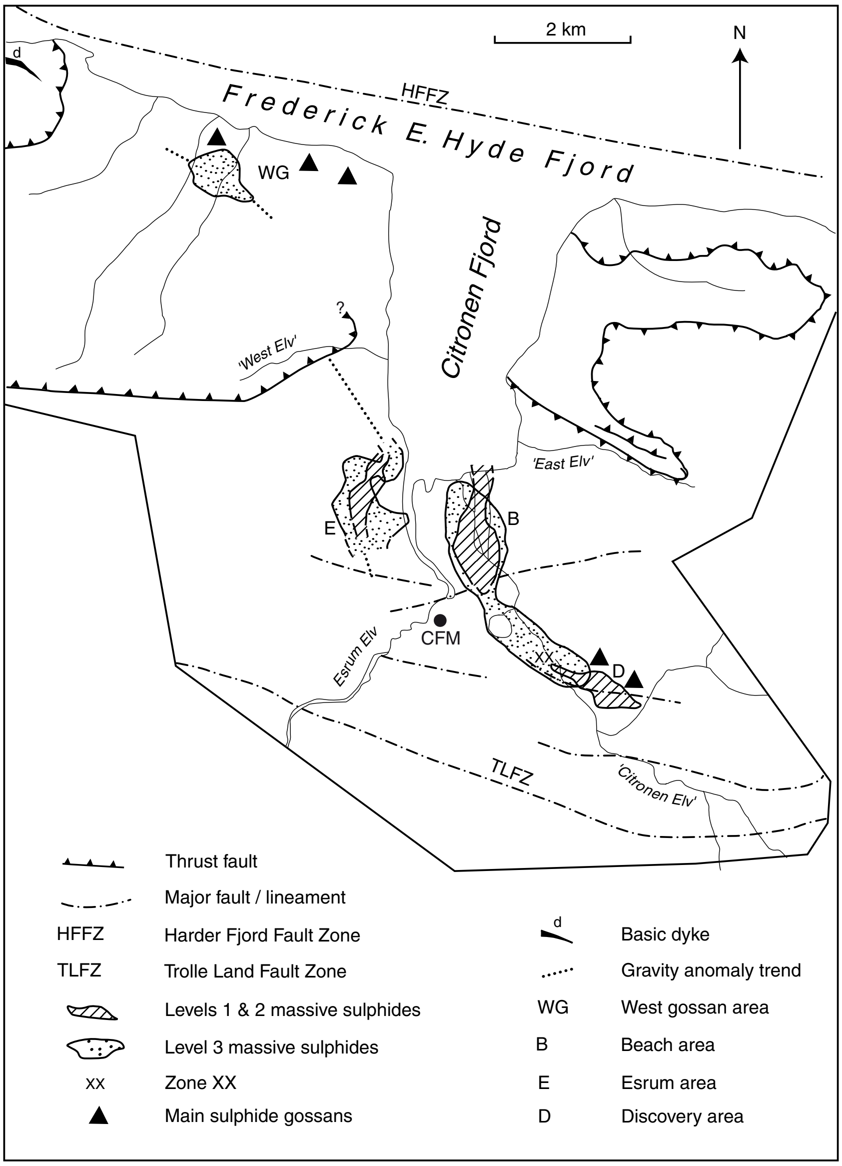


Fig. 3. Location map of the Citronen Fjord area showing the outline of the mineralization levels, main gossans, gravity anomaly trends, and the mineralized zone XX. **CFM** marks the type locality of the Citronens Fjord Member of Hurst & Surlyk (1982). A geological map of the same area is given in Fig. 5.

egy that, combined, led to the discovery of the massive sulphide deposit in 1993.

Topography and exposure

Physiographically, the Citronen Fjord area is part of the 'foreland ranges' of Davies (1972) being composed of heavily glaciated, dissected plateau and rolling hill landscape, with widespread glacial and glaciofluvial deposits. Mountains around Citronen Fjord are between 700 and 1000 m high, and these, particularly to the south where the rocks are homoclinal, show a well-developed plateau surface (Fig. 1).

The area at the head of Citronen Fjord is characterized by a broad delta formed by two major rivers which transect an extensive sequence of raised beaches that border the delta (Fig. 1; see also section 'Geographical and stratigraphical names', p. 10). The delta valley itself is several kilometres wide and surrounded by high mountains; most of the area in which the mineralization occurs is between sea level and *c.* 150 m. The northerly limit of the Inland Ice is about 150 km to the south (Fig. 2) but small ice-fields and ice-caps are common in the highest parts of the area. Frederick E. Hyde Fjord and adjoining fjords are frozen most of the year but for a short period in the summer (up to 6 weeks), Citronen Fjord and the inner part of Frederick E. Hyde Fjord open up (Fig. 1). However, drifting ice can occur until the fjords freeze again in September.

Geographical and stratigraphical names

There are few authorized names for geographic features in this part of North Greenland and, since the region is uninhabited, there are no Greenlandic place names. Hans Egede Land is the land area south of Frederick E. Hyde Fjord, in which Citronen Fjord is located (see Fig. 22). Apart from these three names, the only other feature formally named in our study area is Esrum Elv, the western of the two rivers reaching the head of Citronen Fjord (Figs 1, 3). Thus for convenience of description in this paper, the three other rivers entering Citronen Fjord are informally named, viz. 'Citronen Elv', 'West Elv' and 'East Elv'; the inverted commas indicate the informal status of these names (Fig. 3).

The authorized name of the small fjord forming the location of this study is Citronen Fjord. The fjord was named by the Danish Peary Land Expedition (1947–50) and it was originally authorized as Citronens Fjord (Laursen 1972). This form was in use in the 1970s when the fjord's name was adopted in a formal stratigraphic sense, in the name Citronens Fjord Member (Hurst & Surlyk 1982; see p. 11). In accordance with the Code of Stratigraphic Nomenclature (Hedberg 1976; Salvador 1994), in such cases the original name form must be retained in geological usage and thus, the type section of the Citronens Fjord Member is at Citronen Fjord (Fig. 3).

History of exploration

Early geological investigations

The early knowledge of the geology of the area around Frederick E. Hyde Fjord is derived from information and samples collected by the Danmark Expedition in 1906–1907 (Bøggild 1917), the Danish Peary Land Expedition 1947–1950 (Ellitsgaard-Rasmussen 1955) and an expedition organized by Lauge Koch in 1953 (Fränkl 1955). Although the precise locality in Frederick E. Hyde Fjord is not known, it should be noted in this, the first published exploration history of the Citronen Fjord area, that one crushed shale sample with veins of quartz and calcite collected by Eigil Knuth in 1950, was reported to contain "centimetre-large polycrystalline pyrite balls" (Ellitsgaard-Rasmussen 1955, p. 44). This is the first mention in the literature of sulphides in the Frederick E. Hyde Fjord area.

The first indication of actual mineralization in the Frederick E. Hyde Fjord region was reported in 1960. It was made by W.E. Davies of the U.S. Geological Survey, who, during the first helicopter operation in Peary Land, noted gossans to the south of Frederick E. Hyde Fjord, referring specifically to Depotbugt (20 km east of Citronen Fjord, see Fig. 22) where "there are extreme plays of color and every appearance of mineralisation" (personal and written communications to the Geological Survey of Greenland 1969).

In 1969, during the British Joint Services Expedition, a multi-disciplinary, spring–summer skidoo expedition to Johannes V. Jensen Land (northernmost part of Peary Land; Fig. 2), the Depotbugt gossan, noted from the air by Davies, was checked (Dawes 1969). In addition several gossans on the shore of Frederick E. Hyde Fjord just west of Citronen Fjord were observed (marked 'West gossan area' on Fig. 3). One of these was investigated and found to be hosted in a carbonate breccio-conglomerate with sulphide mineralization associated with intense calcite veining. Other conspicuous limestone breccio-conglomerate beds were noted in cliffs on the western coast of Citronen Fjord. One recumbently folded unit within dark shales and siltstones and overlain by a thick succession of calcareous sandstones was sampled and subsequently dated from its shelly fauna as early Silurian in age (Dawes 1969; Bjerreskov & Poulsen 1973; Dawes & Soper 1979; Fig. 4).

The two limestone breccio-conglomerate units noted in 1969, interpreted as platform-shelf edge debris flows, are the Middle debris flow (Unit 7) and Hangingwall debris flow (Unit 9) of this paper (see under 'Stratigraphy of the Citronen Fjord area', p. 17). The gossans at Depotbugt and Citronen Fjord were sampled but no indications of significant mineralization were recorded (P.R. Dawes, personal communication 1993).

Fig. 4. Typical, brown to rusty-weathered bedrock exposure at Citronen Fjord showing resistent and recumbently-folded, limestone debris flow conglomerate – the Hangingwall debris flow of this paper – within calcareous siltstones on the west side of Citronen Fjord. These fossiliferous Silurian beds and the south-facing structure, described by Dawes & Soper (1979), are part of the Citronens Fjord Member of Hurst & Surlyk (1982). Annotation: 8, Footwall shale; 9, Hangingwall debris flow; 10, Calcareous siltstone. Height of sea cliff to left is about 100 m; height of mountain is about 950 m.

Regional geological mapping

A decade later the Frederick E. Hyde Fjord region was revisited in the period 1978–1980 during helicopter-supported regional systematic mapping by the Geological Survey of Greenland (Henriksen & Higgins 1991). The Citronen Fjord area is included on the 1:500 000 Peary Land map sheet (Bengaard & Henriksen 1986a; Henriksen 1992). Hurst & Surlyk (1982) visited the area during their regional study of the Silurian turbidites (Peary Land Group). They referred all strata at Citronen Fjord to the Merqujôq Formation (the basal part of the Peary Land Group) illustrating the geology by an aerial photograph (Hurst & Surlyk 1982, fig. 58; Hurst 1984). This interpretation was shown on the geological map in Friderichsen *et al.* (1982).

Hurst & Surlyk (1982) defined the carbonate breccio-conglomerates interbedded with mudstones and siltstone turbidites, conspicuous in the western part of the area along Citronen Fjord and west of Esrum Elv, as the Citronens Fjord Member of the Merqujôq Formation. The type section (Hurst & Surlyk 1982, section 33; Fig. 3) contains two main intervals of conglomeratic rocks, with the lower and thickest interval containing a conglomerate unit about 80 m thick. The resedimented limestone conglomerate beds, interpreted as base-of-slope debris flows by Hurst & Surlyk (1982), correspond to Units 9 and 11 of this paper (see Fig. 7).

The Citronen Fjord area is part of the region mapped by Pedersen (1979, 1980, 1982). In mapping the carbonate conglomerate units as markers in a fairly uniform sedimentary succession (Units 9 and 11 of this paper), Pedersen (1982) in an unpublished thesis recognized the existence of argillaceous rocks stratigraphically lower than the Citronens Fjord Member referring the strata to the Ordovician Amundsen Land Group. The map in Pedersen (1982), showing a narrow, NW–SE striking inlier of Amundsen Land Group (Nordpasset Formation) on the east side of Citronen Fjord following 'East Elv', that continues on the western side of the fjord at its mouth, is the outcrop pattern adopted on recent maps of the area, e.g. Bengaard & Henriksen (1986a, b).

Sulphide mineralization within limestone conglomerates south of Citronen Fjord in association with fault splays of the NW–SE-trending Trolle Land Fault Zone was also reported by Pedersen (1982; Fig. 3). Fracture-filling copper-zinc mineralization was noted with quartz-calcite veining; the main mineral assemblage being pyrite, sphalerite, chalcopyrite and trace galena. The mineralization is stratabound and it has an epigenetic appearance (Pedersen 1982). Laboratory investigations on Pedersen's samples during a mineral assessment programme were reported by Lind (1993) who concluded that the sulphides were probably deposited in the permeable conglomerates from hydrothermal solutions rising through the fault zone.

The gossans and mineralization noted in 1979 are on the western side of 'Citronen Elv', actually within sight of the massive sulphides discovered more than a decade later by Platinova A/S on the eastern side of the river (i.e. Discovery area on Fig. 3). Drilling has proved that the showings observed in 1979 are part of the narrow zone of post-sedimentary mineralization

(Zone XX) occurring in the Middle and Hangingwall debris flows (Units 7 and 9; see section 'Stratigraphy of the Citronen Fjord area', p. 17).

Commercial exploration strategy

Although mineral exploration in the High Arctic has been naturally hampered by its remoteness and climatic conditions, there have been operative mines in the Canadian Arctic Islands for many years and one, the Polaris zinc-lead mine, is within the Franklinian Basin (Fig. 2). The nearest mines to northern Greenland are zinc-lead operations; Nanisivik in the Borden Basin of northern Baffin Island has been in production since 1976 and the Polaris mine farther north has been operative since 1982. These two underground operations are presently the world's most northerly metal mines. The geological provinces housing these two mineral deposits – Proterozoic in the case of Nanisivik, Palaeozoic in the case of Polaris – have direct geological counterparts on the opposite side of the Baffin Bay – Nares Strait seaway, in northern Greenland (Dawes 1994; Fig. 2).

A glance at a metallogenic map of this part of the Arctic, for example that given by Gibbon (1991), shows several prospective areas for economic minerals in the Canadian Arctic Islands. One of these is the Franklinian Basin that stretches for 2500 km from the Beaufort Sea to the Wandel Sea (Fig. 2). Present geological knowledge defines that the two major provinces of this basin – a southern or south-eastern platform and shelf and a northern deep-water trough – existed throughout Lower Palaeozoic time and that these provinces stretch across the Arctic Islands and continue into North Greenland (Dawes & Kerr 1982; Trettin 1991).

In the 1970s and 1980s several base metal discoveries were made in the Arctic Islands within the Palaeozoic rocks of the Franklinian Basin, with a main target being zinc-lead mineralization within carbonates and in the off-shelf shale facies. Apart from Polaris, one discovery to the east was made by Great Plains Development Ltd. in Judge Daly Promontory, just 30 km from the Greenland coast, within Lower Palaeozoic shelf rocks bordering the deep-water sediments of the Hazen Formation (Fig. 2; see Gibbon 1991). These carbonate shelf formations and the argillaceous Hazen Formation have direct stratigraphical counterparts to the east in western North Greenland and yet that region in the early 1980s had only been subjected to sporadic commercial investigations.

Discovery of the massive sulphides

In 1992 Platinova A/S participated in a joint venture program with Nanisivik Mines Ltd. to explore for base metals in the Franklinian Basin, in western North Greenland (Hall Land – Freuchen Land region, see Figs 2, 22). The primary focus of this work was an assessment of the deep-water clastic sediments of the Amundsen Land Group, the stratigraphic equivalent of the Hazen Formation of Arctic Canada. This group occurs in the Nyeboe Land – Freuchen Land region as a narrow east–west striking belt over a distance of about 300 kilometres (Higgins *et al.* 1992). Numerous, minor occurrences of zinc and lead sulphides in various settings were found throughout the belt during helicopter reconnaissance. Although none of these occurrences had apparent economic potential, it was obvious that the Amundsen Land Group is highly prospective and that a similar evaluation of the eastern portion of the belt was warranted. In Peary Land to the east, exposures of Amundsen Land Group sediments are largely confined to the lands bordering Frederick E. Hyde Fjord where there are discontinuous outcrops over a distance of about 125 km (Friderichsen *et al.* 1982; Bengaard & Henriksen 1986a; Higgins *et al.* 1991a, b).

Thus, after the initial investigations in western North Greenland in 1992, Platinova A/S continued the study into the following year with a prospecting programme in the Frederick E. Hyde Fjord area. Field work was based on the low-cost logistics of skidoo transport using the fjord-ice in spring and early summer as main access through the region. This program began in May and had as one of its primary objectives the investigation of the reported gossans and sulphide occurrences in the Citronen Fjord area that had been observed in 1969 and 1979. Massive, outcropping sulphides were encountered on the first day of exploration at Citronen Fjord in the inland gossan area now termed the Discovery area (Figs 1, 3, 19). The discovery was so promising that a full-scale exploration programme that included drilling was organized and executed the same summer (MINEX 1993).

The Discovery area is close, but not obviously related, to the fracture-controlled mineralization sampled by the Geological Survey of Greenland in 1979 and it is about eight kilometres south-east of the outcropping sulphides first observed and sampled in 1969 on the south shore of Frederick E. Hyde Fjord (Fig. 3). Our exploration suggests that sulphide mineralization may be continuous between these two areas outlining a major NW-trending mineralization zone.

The geological, geophysical and drilling work started in 1993 by Platinova A/S has continued each year to include summer 1997. Until then, 143 exploration holes have been completed, totalling 32 400 m.

Geophysical exploration

After the initial discovery of surface outcrops, the evaluation of the Citronen Fjord deposit has been strongly guided by geophysical techniques that were introduced immediately in 1993. Gravity and some time-domain electromagnetic surveys have formed the basis of the geophysical work that was mainly conducted in the summer periods of 1993–1995.

Bouger gravity maps generated from readings at 50 m stations on lines at 100 m apart have proved to be a reliable indicator of the distribution of sub-surface sulphides. Electromagnetic surveys have shown strong responses from the mineralization but barren sulphide units and graphitic host rocks also give conductive responses that are not of economic interest.

Gravity measurements respond to the presence of excess mass and have indicated the presence of thick sections of pyrite but the technique cannot specifically indicate areas of zinc or lead enrichment. However, this has not proven to be a serious limitation, as evaluation of gravity anomalies by drilling is a far more expedient means of locating base metal mineralization than by 'blind' drilling on the basis of geological extrapolation alone.

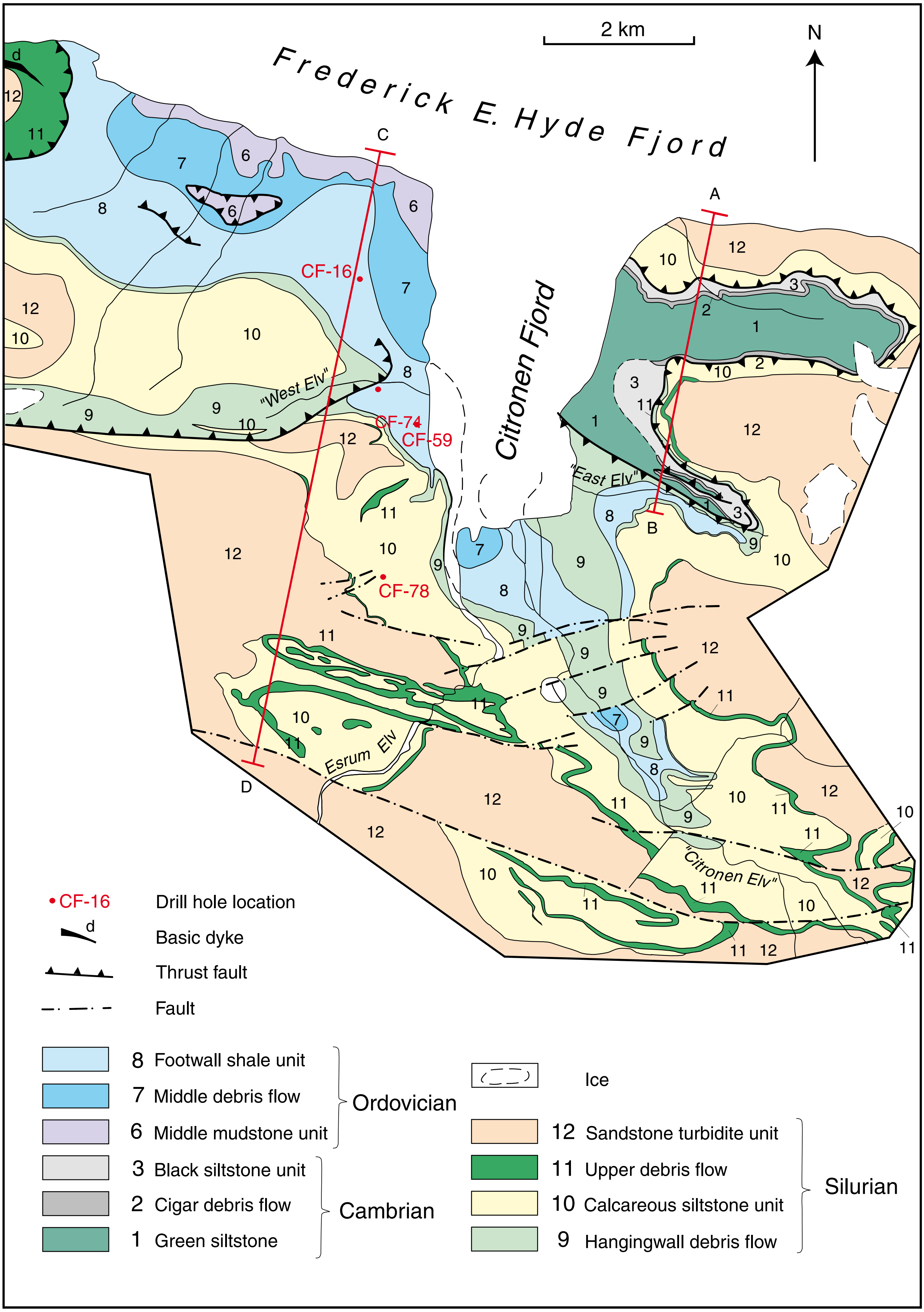
Gravity data have been corrected for elevation, and later terrain corrections were applied to compensate for the rough terrain and the influence of adjacent mountains and fjords. The terrain corrections did not significantly change the position of the gravity anomalies in the main Citronen Fjord valley which were drilled prior to their application.

Regional geology

Citronen Fjord is situated near the eastern end of the Franklinian Basin just north of the facies boundary between the southern carbonate platform and shelf and, a northern deep-water trough (Fig. 2). The basin was deformed in Devonian–Carboniferous time giving rise to a belt of tectonism and metamorphism that now occupies the northern coast of Greenland facing the Arctic Ocean (North Greenland Fold Belt); an orogenic belt that in broad terms coincides with the deep-water trough. The study area around Citronen Fjord lies at the southern margin of the North Greenland Fold Belt that is characterized by southerly-facing folds and thrust faults. Thus, the host strata to the main sulphide mineralization are folded, deep-water Ordovician argillaceous rocks with interbedded carbonate debris flows, derived from the nearby carbonate platform. The overlying Silurian clastic strata form the hinterland of Citronen Fjord (Figs 1, 4, 5).

The most dominant feature of the Franklinian Basin throughout Lower Palaeozoic time was an abrupt facies transition from shallow-water, primarily carbonate sedimentation in the south, to deep-water, dominantly fine clastic sedimentation in the north (Higgins *et al.* 1991a, b: Surlyk 1991). This pattern was established in late Precambrian to early Cambrian time with the initial subsidence of the basin. From early Cambrian to early Silurian time the geographical position of the facies front appears to have been relatively stable. Several widely separated exposures in western North Greenland of this facies front are represented by rocks of late Middle Ordovician to Early Silurian age. The most spectacular exposures are in the fjord walls of Navarana Fjord, between Freuchen Land and Lauge Koch Land (see Fig. 22); a fjord that has given its name to this palaeo-topographic feature, viz. the Navarana Fjord Escarpment (originally named the Navarana Fjord Fault, e.g. Hurst & Surlyk 1984, fig. 5; also called the Navarana Fjord Lineament, e.g. Higgins *et al.* 1991a; Soper & Higgins 1991).

This escarpment initially had a relief of over 1 km and was so steep that no sediments were deposited on the slope between the shelf and the trough. The in-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7 Middle debris flow
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Ordovician
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2 Cigar debris flow
1 Green siltstone
Cambrian
Ice
12 Sandstone turbidite unit
11 Upper debris flow
10 Calcareous siltstone unit
9 Hangingwall debris flow
Silurian

ferred projection of this carbonate escarpment to the east locates this southern boundary of the basin about 5 km to the south of the outcropping sulphides in the Discovery area (Escher & Larsen 1987; Higgins *et al.* 1991a, b; Surlyk 1991; Surlyk & Ineson 1992).

The mudstones, siltstones, fine-grained sandstones and carbonate debris flows that were deposited regionally in the trough throughout most of the Ordovician and into the Early Silurian have been assigned to three groups – the Vølvedal and Amundsen Land Groups and the lowest part of the Peary Land Group (Friderichsen *et al.* 1982; Higgins *et al.* 1992). Sandstone turbidite deposition in the trough began in late Llandoverian time (middle Early Silurian) in response to the onset of the Caledonian Orogeny in the east (Håkansson & Pedersen 1982; Hurst & Surlyk 1982). By the beginning of Wenlockian time (late Early Silurian) these sediments had buried the Navarana Fjord Escarpment. Filling of the trough by the sandstone turbidites caused the outer margin of the platform to subside and then fail, and the carbonates were transgressed by shales of the Wulff Land Formation (Håkansson & Pedersen 1982; Hurst & Surlyk 1982).

Within the Citronen Fjord map area, the Silurian Peary Land Group comprises Merqujôq Formation sandstone turbidites and calcareous siltstones, with the strata containing carbonate debris flows designated the Citronens Fjord Member (Hurst & Surlyk 1982; Fig. 7). The most recent maps suggest that the nearest exposures of the overlying shales of the Wulff Land Formation are 30 km to the west of Citronen Fjord (Bengaard & Henriksen 1986a, b).

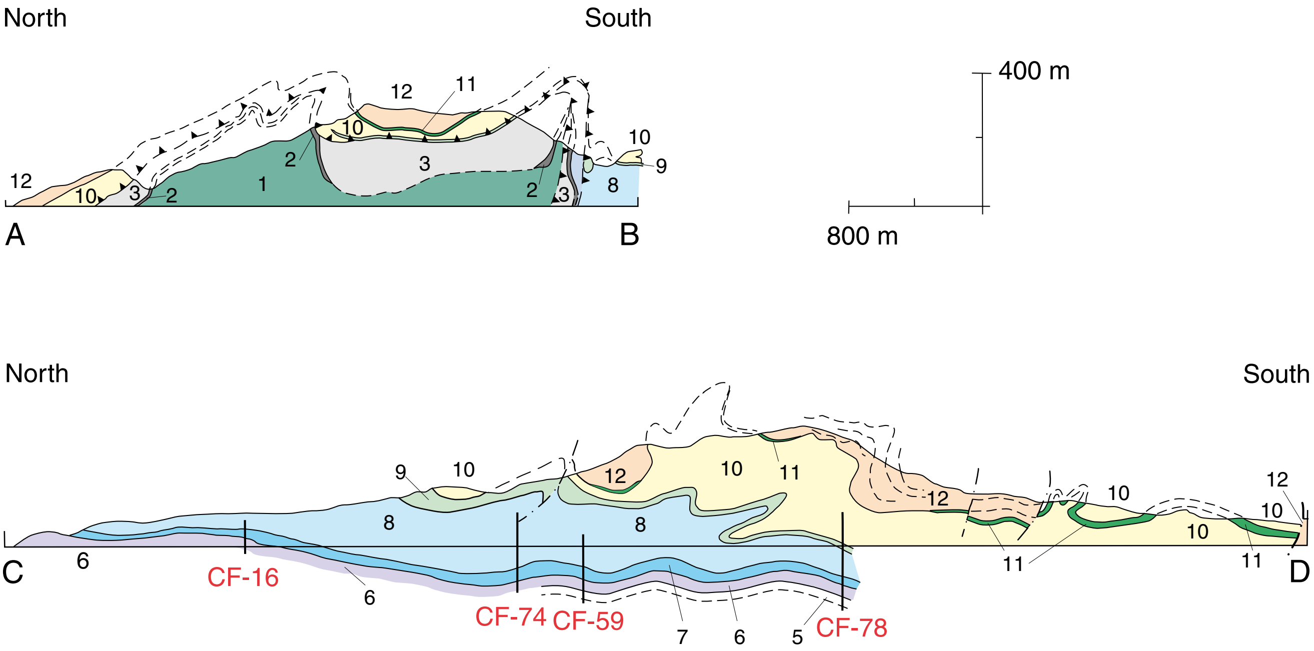

Fig. 6. Two geological cross-sections trending N–S show the structures at the east side (A–B) and west side (C–D) of Citronen Fjord. Eleven lithostratigraphic mapping units are indicated and the locations of drill holes supporting the construction of the profiles are given. Unit 4 was reached by the two most southerly holes. For location and legend, see Fig. 5.

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Fig. 5. Simplified geological map of the Citronen Fjord area. Ordovician Units 4 and 5 are not shown since they are only known from drill cores. Unit 5 is shown on the cross-sections given in Fig. 6. The locations of these cross-sections A–B and C–D are indicated.

Geological map of the Citronen Fjord area

Cambrian–Silurian succession

A geological map of the Citronen Fjord area featuring Cambrian, Ordovician and Silurian sediments is presented here as Figure 5. Based on field observations and drill-core data the succession has been subdivided into twelve lithostratigraphical units that are informally named and numbered consecutively, from oldest to youngest as Units 1 to 12 (see section 'Stratigraphy of the Citronen Fjord area' below). However, parts of the area have an appreciable cover of surficial deposits and two units (4 and 5), consistently present in drill cores, are not known from surface exposures. Hence, on the map only ten units are shown, with the stratal interval of Units 4 and 5 omitted. It is stressed that no stratigraphical hiatus is implied within the Ordovician sequence. Two cross-sections showing all but one (Unit 4) of the lithostratigraphic mapping units are given in Figure 6.

The area west of Citronen Fjord is characterized by the occurrence of large-scale recumbent fold structures and an associated east–west striking thrust fault (see section 'Structural elements in the Citronen Fjord area', p. 34). The recognition and mapping of geological units within the succession of predominantly sandstone turbidites and calcareous siltstones, are also hampered by the obvious intermixture of these rock types, both due to local facies changes and to folding on different scales. As marked on the geological map (Fig. 5), the northern projection of this east–west-striking thrust fault is uncertain.

The main part of the sequence forms a well-exposed, conformable stratigraphic pile stretching from the upper part of the Upper Ordovician Amundsen Land Group to the Silurian Peary Land Group (Fig. 7). The oldest rocks mapped, siltstones, conglomerate and cherts of Lower Cambrian age, outcrop on the eastern side of Citronen Fjord (referred here to the Buen Formation, see discussion in section 'Cambrian', p. 22 and Fig. 1). They are succeeded by Silurian calcareous siltstones and sandstone turbidites along what is interpreted to be a tectonic boundary rather than a stratigraphic unconformity. Some details of this contact are given below.

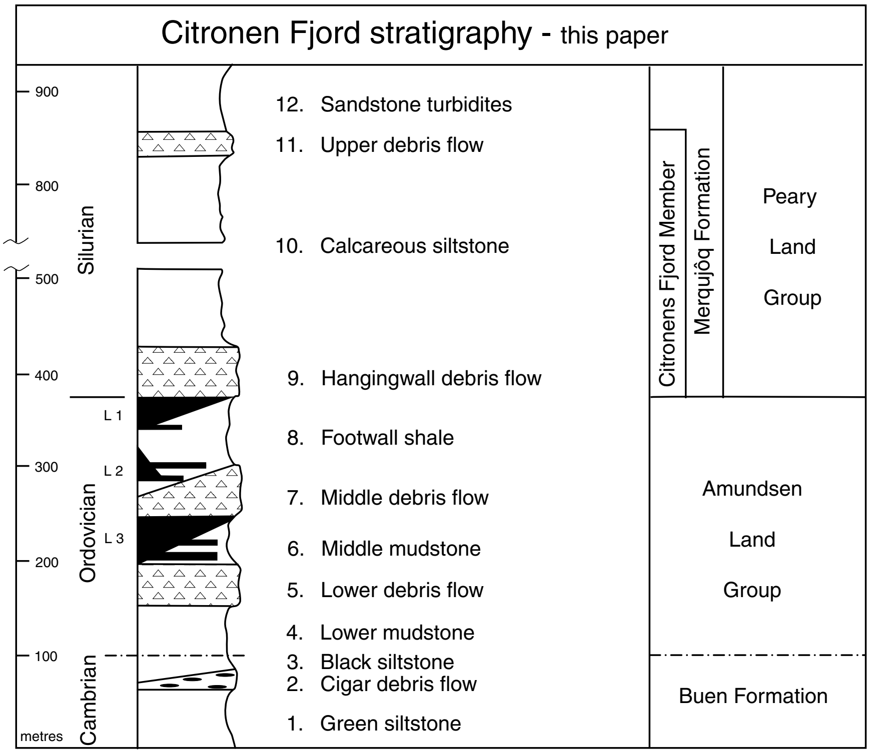

Fig. 7. Generalized stratigraphic section for the Citronen Fjord area showing the twelve informally-named units recognized in this paper, their correlation with the formally defined lithostratigraphy, and the three levels of massive sulphide mineralization (L1, L2 and L3). The geometric characteristics of the sulphide sheets within their respective host rock units is schematically shown by the shape of the black areas. The contact between the Cambrian and overlying succession is shown as tectonic.

Cambrian–Silurian contact

In the cliff exposures both along the northern side of the valley 'East Elv' and on the eastern coast of Citronen Fjord (see Fig. 1), a variably rusty-weathering carbonate conglomerate occurs at the poorly exposed contact between Cambrian and Silurian strata. This is interpreted as a deformed stratigraphic equivalent of the Hangingwall debris flow (Unit 9). The matrix of this conglomerate is locally siliceous and individual clasts are commonly elongated and cigar-shaped and in many respects the conglomerate simulates the conglomerates of Unit 2 (the Cigar debris flow of Cambrian age, see Figs 7, 8).

However, the general chararacteristics of this deformed conglomerate favour a genetic relationship with the actual contact zone which is thus interpreted as a regional low-angle thrust fault. Whatever the precise geometry of this dislocation, it appears from regional comparisons that it represents the absence of an appreciable thickness of Cambro-Ordovician strata. This presumably includes the entire Vølvedal Group (if deposited in this part of the basin) and the entire Amundsen Land Group. The outcrop of Cambrian strata in the north-eastern part of the map area is limited to the south by a steeply-inclined NW–SE-trending thrust fault (Fig. 5).

Basic dyke

Basic dykes of several directions cut the Lower Palaeozoic strata of Johannes V. Jensen Land and the Frederick E. Hyde Fjord region (Soper *et al.* 1982; Henriksen 1992). Some N- to NW-trending dykes are shown in Figure 22. These dykes are regarded as late Phanerozoic (Cretaceous–Tertiary) in age and may reflect extensional events during Late Cretaceous rifting and the formation of the Eurasia basin to the east (cf. Surlyk 1991).

One NW-trending, fine- to medium-grained dolerite dyke is exposed along the south shore of Frederick E. Hyde Fjord just west of Citronen Fjord and shown in the north-western corner of the location and geological maps (Figs 3, 5). It is exposed within a very thick limestone conglomerate and at the contact with overlying and partly intercalated sandstone turbidite beds that are referred to Units 11 and 12 (Upper debris flow and Sandstone turbidites, see Fig. 7). The stratigraphic block of thick debris flows and sandstone turbidites in which the dyke occurs is underlain by black mudstones and siltstones that are referred to Unit 8 (Footwall shale). The major break thus indicated between these two successions is inferred to be a low-lying thrust fault (Fig. 5). The contact between the dyke and this thrust fault is not exposed.

Stratigraphy of the Citronen Fjord area

On the basis of field observations and drill core logging, the main characteristics of the twelve lithostratigraphic units recognized are summarized here in chronostratigraphic order. The stratigraphic contacts between the units are conformable unless otherwise stated. A schematic stratigraphic section, which also shows the positions of the three main levels of mineralization, is shown in Figure 7.

Buen Formation

The three oldest units of the succession mapped at Citronen Fjord are referred to the Buen Formation of Cambrian age (Jepsen 1971; see discussion under 'Lithostratigraphic correlation', p. 22). A discontinuous carbonate debris flow unit separates darker coloured, upper and lower siltstone units (Fig. 1).

Unit 1: Green siltstone

The dominant lithology of this basal unit is fine-grained, thick-bedded to massive, greenish grey siltstone. The unit shows thickness variation that may be in part tectonic. Thus, in the north near Frederick E. Hyde Fjord a vertical thickness of at least 300 m is present while the unit appears to thin to less than 100 m of true thickness to the south along Citronen Fjord. However, the base of the unit is not exposed, neither has it been