Ore geological studies of the Citronen Fjord zinc deposit, North Greenland: project 'Resources of the sedimentary basins of North and East Greenland'

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The multidisciplinary research project 'Resources of the sedimentary basins of North and East Greenland' was initiated in 1995 with financial support from the Danish Research Councils (Stemmerik *et al.*, 1996). In the 1996 field season, ore geological studies continued on the shale-hosted Citronen Fjord zinc-lead prospect in North Greenland (Figs 1, 2). Platinova A/S discovered the deposit in 1993, and has subsequently explored the area by means of geological mapping, gravity surveys and diamond drilling. About 30 km of diamond drilling have been completed, and a resource of over 20 million tons of stratiform ore with 7 % zinc and 1 % lead has been estimated (Platinova A/S, 1996a, b). An additional fault-controlled, high-grade zinc-mineralised zone was encountered in the north-western part of the 'Discovery Zone' in 1996 (Platinova A/S, 1996b).

Mineralisation

The Citronen Fjord zinc-lead deposit, located in sediments of the Lower Palaeozoic Franklinian Basin (Figs 1, 2), is interpreted to be of sedimentary-exhalative type. Stratiform sulphides are hosted by the Upper Ordovician – Lower Silurian Amundsen Land Group, which comprises black mudstones and chert, interbedded in places with dark grey calcarenitic turbidites and thick carbonate conglomerates of inferred debris flow origin

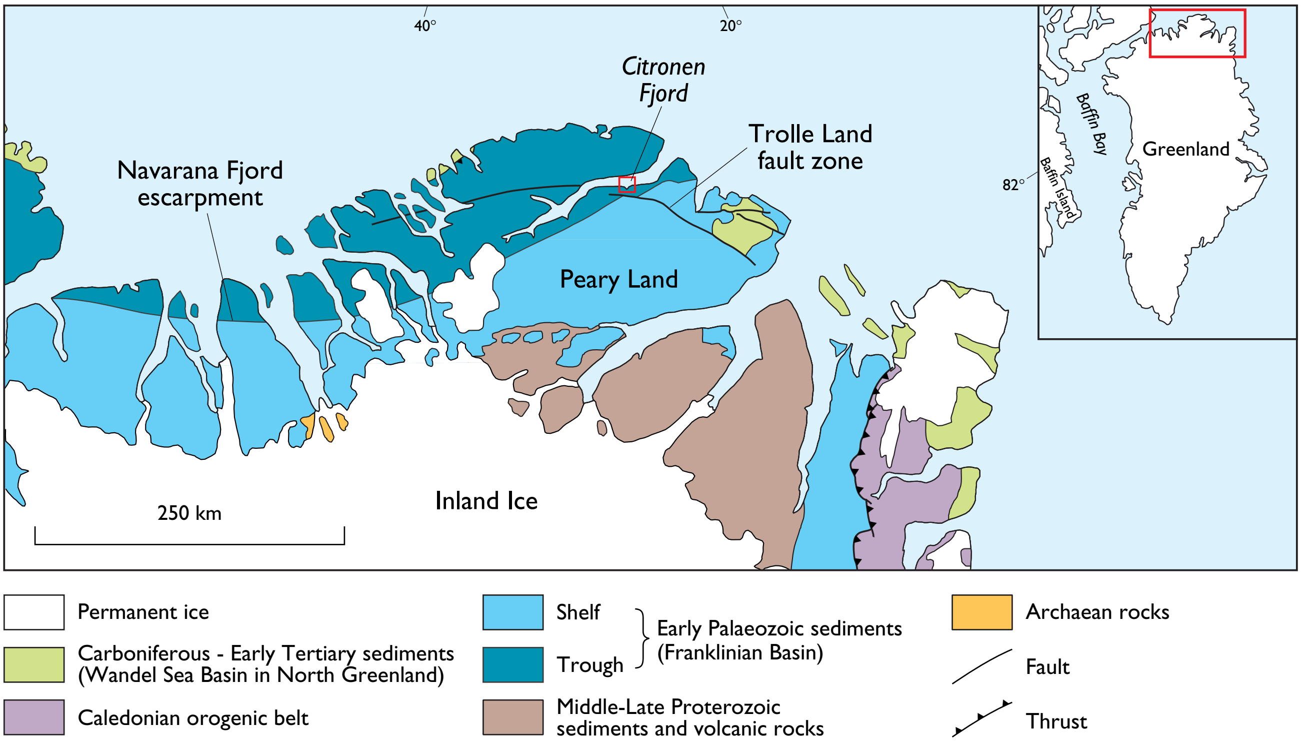

Fig. 1. Geological map of North Greenland. Modified from Stemmerik *et al.* (1996).

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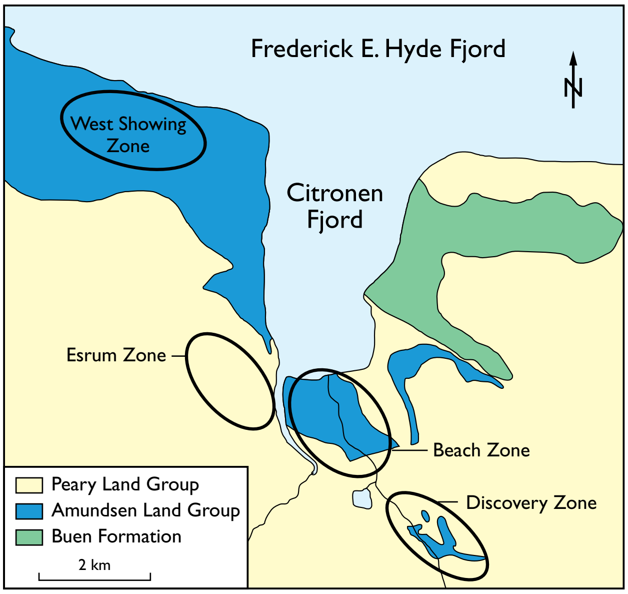

Fig. 2. Geological map of the Citronen Fjord area. Gravity anomalies outline the 'Discovery', 'Beach', 'Esrum' and 'West Showing' zones, and coincide with sub-surface occurrences of sulphide mounds. Simplified after Platinova A/S (1996a) and unpublished Platinova A/S maps.

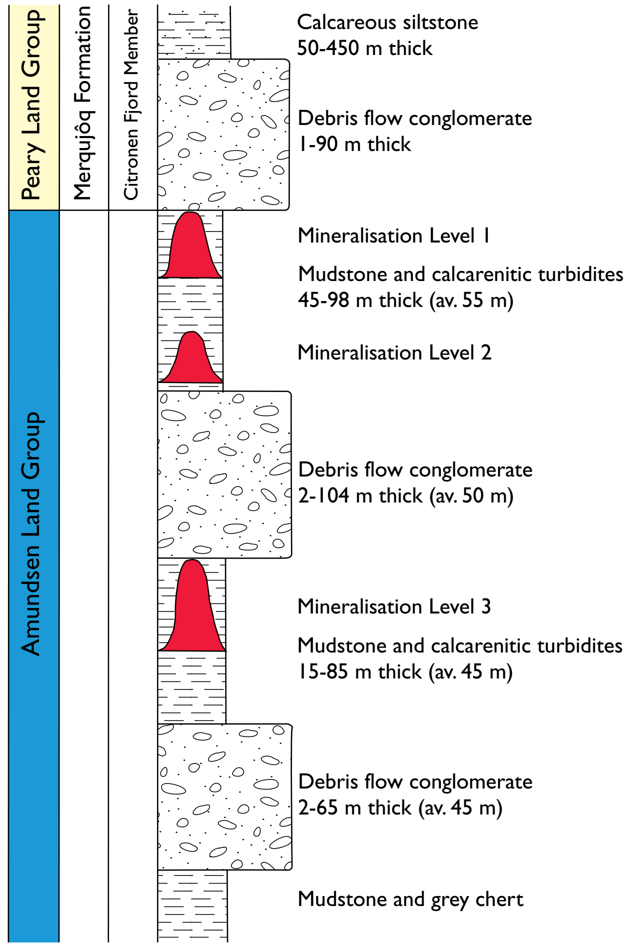

Fig. 3. Simplified stratigraphic column showing mineralisation levels (red) in the 'Beach' and 'Discovery' zones in the Citronen Fjord area. Unit thicknesses from unpublished Platinova A/S reports.

(Fig. 3). The Amundsen Land Group was deposited in a sediment-starved trough a few kilometres basinward of the up to 1 km high, E–W trending Navarana Fjord escarpment that formed the outer margin of a wide carbonate platform (Fig. 1; Higgins *et al.*, 1991; Surlyk & Ineson, 1992). Carbonate debris flow conglomerates derived from this platform are useful stratigraphic markers in the area. At Citronen Fjord, the Amundsen Land Group is overlain by the Citronen Fjord Member, one of four major carbonate gravity flow units in the Merqujôq Formation (Peary Land Group). The Merqujôq Formation is a thick sandstone turbidite sequence that was laid down in the Franklinian Basin over much of North Greenland during the Silurian (Hurst & Surlyk, 1982; Surlyk & Ineson, 1992). The lowermost unit in the Citronen Fjord Member in the type area is a massive carbonate boulder conglomerate, which forms the upper limit for known stratiform mineralisation (Fig. 3).

Platinova A/S has recovered trilobites from a succession of greenish black and black mudstone on the east side of Citronen Fjord, which have been determined to be of *Olenellus*-type (F. W. van der Stijl & A. T. Nielsen, personal communications, 1997); this indicates an Early Cambrian age, and the succession is tentatively referred to the Buen Formation (Fig. 2). The contacts between this unit and the Amundsen Land and Peary Land Groups are tectonic.

The Citronen Fjord ore deposit comprises at least five major, massive sulphide mounds that form a 10 km long NW–SE trending lineament (Fig. 2). It is noteworthy that this trend is roughly parallel to the Late Palaeozoic – Mesozoic Trolle Land fault zone (Håkansson & Pedersen, 1982; Birkelund & Håkansson, 1983). Although no evidence of pre-Carboniferous activity along this fault zone has been documented to date, one can speculate that the Trolle Land fault zone is a reactivated Early Palaeozoic structure. The distances between the mounds vary from a few hundred metres to 4 km, and the mounds occur at several different stratigraphic levels within the mudstone sequences between three thick debris flow conglomerate units. The stratigraphic positions of three sulphide mounds in the 'Beach' and 'Discovery' zones are indicated in Figure 3.

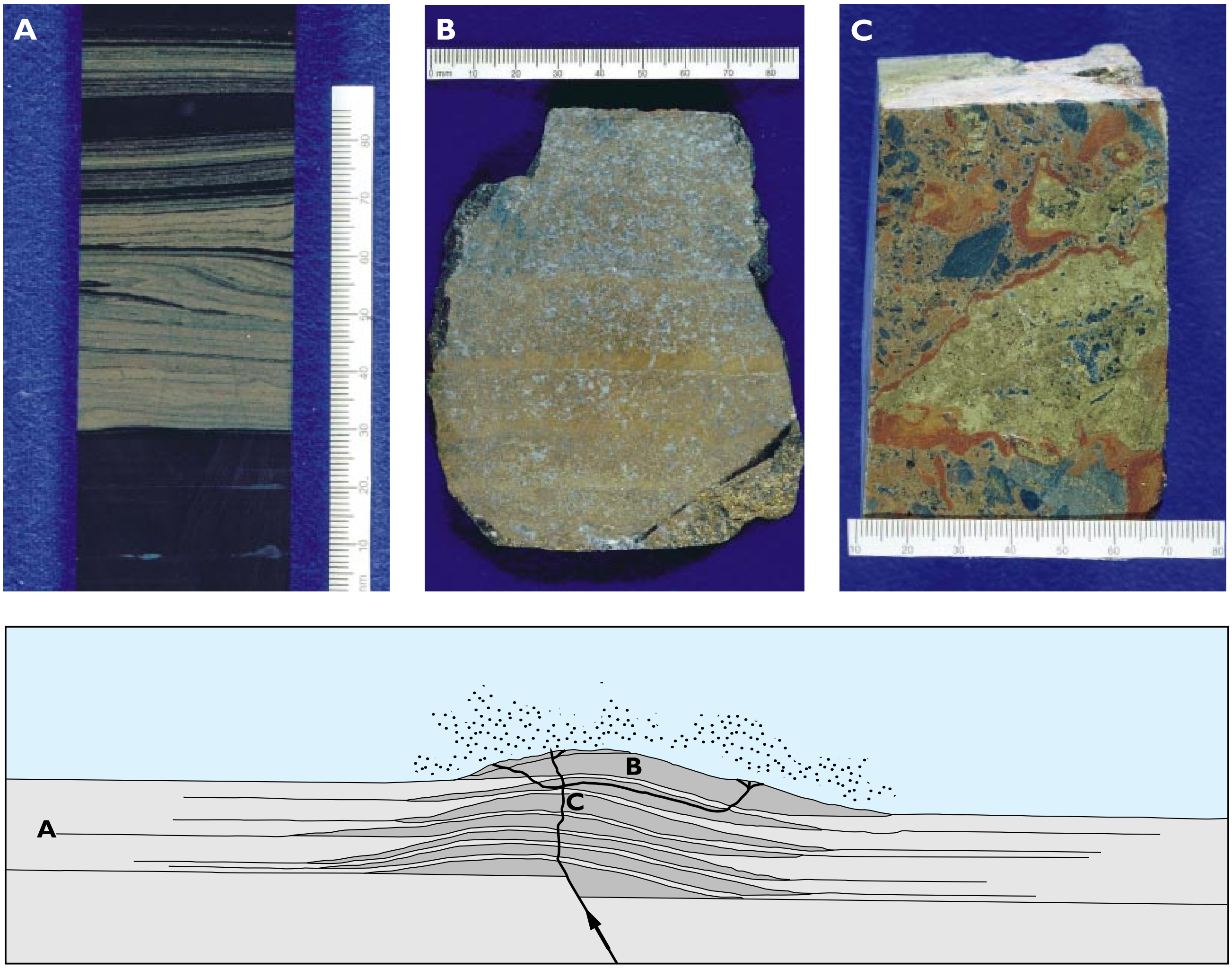

Fig. 4. Schematic cross-section through a sulphide mound formed on the sea floor, and three typical styles of mineralisation. **A**: Mudstone interbedded with laminated framboidal sulphides showing primary sedimentary and diagenetic structures. **B**: Massive and semi-massive sulphide beds with net-like textures and pyrite laminae. **C**: Vein with brecciated mudstone and sulphide with overgrowth and replacement textures. The sulphide clasts are overgrown by sphalerite (brown) and the matrix is very rich in fine-grained sphalerite. The ranges of sulphur isotope compositions of sulphides representing the mineralisation styles A, B and C are shown in Figure 5.

The individual sulphide mounds are up to 1500 m long and 600 m wide, and have a maximum thickness of about 25 m. The central parts of the mounds consist of sulphides (pyrite, sphalerite and galena) and carbonates (calcite, dolomite and ankerite). Minor amounts of chalcopyrite and quartz have also been observed. The sulphide content varies from about 25 % to nearly 100 %. The sulphides in the mounds are confined to beds that are normally 30–60 cm thick, but are locally up to *c.* 2 m thick. Interlayered with the sulphide beds are irregular mudstone beds from a few millimetres to 10 cm in thickness.

Within individual beds in the mounds, the sulphides display great textural variation. A characteristic feature is spheroidal intergrowth of two or more of the following phases: carbonate, pyrite, galena, sphalerite and silica. The spheres are massive or have complex radiating textures, and are often overgrown by diagenetic or metasomatic subhedral pyrite (Kragh, 1997). Some of the beds consist of laminated framboidal pyrite, whereas others show recrystallisation and replacement textures and overgrowths by sulphides and carbonates. In general, the upper parts of the sulphide mounds show primary lamination disturbed by replacement or recrystallisation, particularly in those mounds that occur just below debris flow conglomerates. The sulphide mounds grade laterally into laminated framboidal pyrite with interstitial sphalerite and carbonate. In places, the mas-

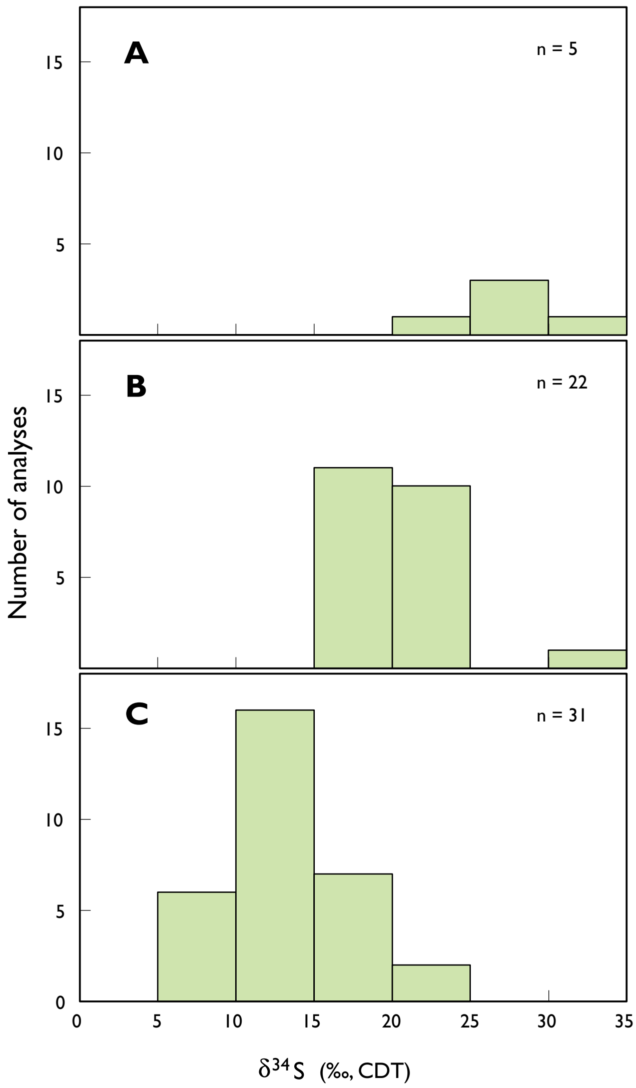

Fig. 5. Sulphur isotope distribution histograms for sulphides from the Citronen Fjord ore deposit. A, B and C refer to the sulphide mineralisation styles shown in Fig. 4 (A in this diagram includes data from disseminated pyrite in unmineralised Amundsen Land Group mudstone). CDT: analyses normalised to the Canyon Diablo troilite standard. Modified from Fougt (1997).

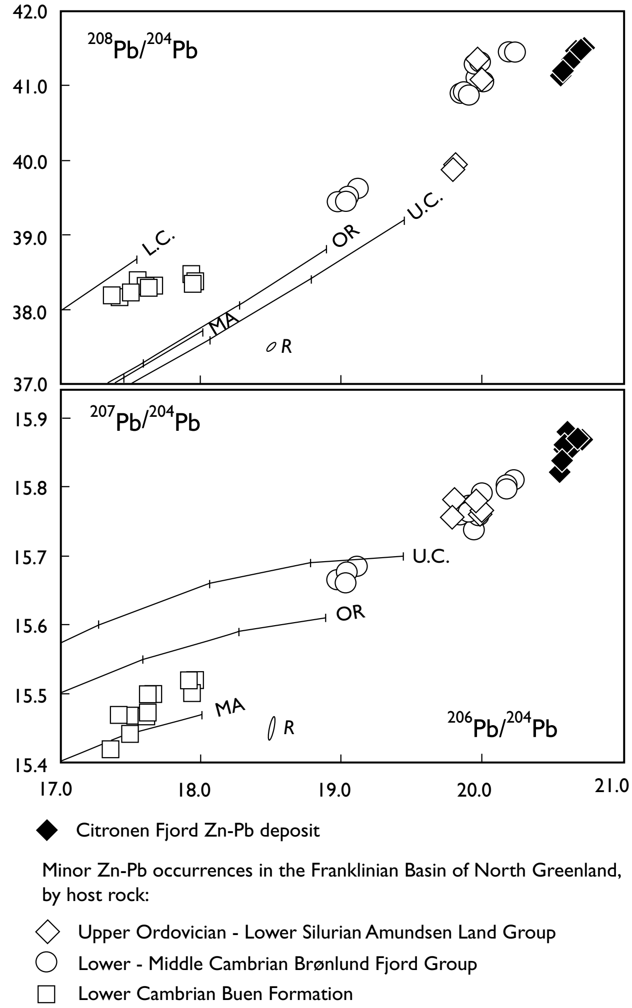

Fig. 6. Lead isotope diagrams for galena from the Citronen Fjord ore deposit and minor sulphide occurrences in North Greenland. R = Typical analytical reproducibility (0.10 %, 2 σ). 'Plumbotectonic' growth curves for reference from Zartman & Doe (1981): MA, mantle; OR, orogen; U.C., upper crust; L.C., lower crust. Modified from Jensen (1997).

sive sulphides are cut by quartz-calcite veins with partly replaced or recrystallised wall rock fragments. The fragments can be either angular or deformed, and are typically overgrown by sphalerite or pyrite. Debris flow conglomerates lying directly above sulphide mounds are often mineralised with pyrite, sphalerite and galena occurring in the matrix and as rims on the clasts (Kragh, 1997).

Three typical styles of mineralisation are recognised (Fig. 4). Laminated sulphides may exhibit well-preserved sedimentary structures such as graded bedding and cross-lamination (Fig. 4A), dewatering deformation and diagenetic overgrowths by colloform pyrite. Another common texture is a net-like intergrowth between carbonate and sulphide found in massive and semi-massive sulphides (Fig. 4B). The vein mineralisations vary in composition from sulphide- and carbonate-rich types (Fig. 4C) to nearly pure quartz with scattered aggregates of sphalerite or galena.

Sulphur isotopes

Sulphur isotope compositions have been analysed using conventional sublimation of powdered sulphides (32 analyses) and laser combustion of sulphide grains in polished sections under the microscope (26 analyses). With a beam diameter of about 0.1 mm, the laser combustion technique enables sampling of single small sulphide grains or several domains within larger sulphide grains (Fallick *et al.*, 1992).

The $\delta^{34}S$ values of sulphide minerals from the Citronen Fjord ore deposit range from + 7 to + 35 ‰ (CDT), with the bulk of analyses in the range from + 10 to + 25 ‰ (Fig. 5). As illustrated in Figure 5, the three styles of sulphide occurrence (see Fig. 4) are reflected in the sulphur isotope ratios.

The very heavy sulphur ($\delta^{34}S$ from + 30 to + 35 ‰) of the laminated sulphides (style A) is considered to be inherited from bacteriogenically reduced sea water sulphate. The light sulphur isotope values ($\delta^{34}S$ from + 5 to + 10 ‰) of the vein sulphides (style C) are interpreted as a hydrothermal signature. The intermediate sulphur isotope compositions of the massive sulphides (style B) are preliminarily interpreted as the result of mixing between seawater-derived and hydrothermally-derived sulphur (Fougt, 1997).

Lead isotope characteristics

About 90 lead isotope analyses (all made on galena) constitute the first part of a regional study of sulphide occurrences and potential metal sources in the Franklinian Basin. The objective is to formulate a 'plumbostratigraphic' model that can be used to evaluate the metallogenetic importance of specific lithologies.

The lead in galena from the Citronen Fjord deposit is clearly distinct from the lead in all other galena samples investigated from North Greenland in having very high $^{206}Pb/^{204}Pb$ (uranogenic) ratios (Fig. 6). This difference is fundamental, because the U/Pb ratios of galena are so low that the lead isotopic compositions remain unchanged regardless of the age of mineralisation: the lead from Citronen Fjord thus acquired its distinctive radiogenic signature at the time of mineralisation.

Lead from many of the galena disseminations and minor veinlets in Franklinian Basin sediments in North Greenland is believed to represent mineralising processes on a local scale within the host rock lithologies (Jensen, 1997). Preliminary data for such occurrences indicate that individual lithologies in the sedimentary succession have clearly identifiable lead isotope signatures, and that there are great variations within restricted stratigraphic intervals. There is, however, a general tendency for the lead to become relatively more radiogenic in progressively younger stratigraphic units (Fig. 6).

Analyses of samples considered representative of the host Amundsen Land Group mudstones show distinctly less radiogenic lead than the stratiform ore. This suggests that the metals in the ore may have been mobilised (at least in part) from sources other than the sediments of the Amundsen Land Group, or any other lithology so far analysed in the Franklinian Basin sequence. Underlying basement lithologies are therefore considered to be potential metal source rocks.

Conclusions

The Late Ordovician – Early Silurian shale-hosted Citronen Fjord zinc deposit is interpreted to be of sedimentary-exhalative type (SEDEX), and has remarkably well-preserved sedimentary and diagenetic structures and textures. The ore textures give an excellent insight into syngenetic ore-forming processes and diagenetic and epigenetic modifications.

Sulphur isotope compositions of Citronen Fjord sulphides suggest that the sulphur in the more distal parts of sulphide mounds is mainly derived from seawater. In the recrystallised and veined parts of the mounds, sulphides have a component of hydrothermally transported sulphur.

The Citronen Fjord ore deposit has a distinctive, strongly radiogenic lead isotope signature. None of the lithologies in the Franklinian Basin analysed to date, albeit limited in number, are obvious potential sources for the Citronen Fjord lead, and a significant contribution from underlying basement lithologies cannot be ruled out. The distinctive lead isotope signature of the Citronen Fjord ore may prove useful in determining whether sulphide occurrences found elsewhere in North Greenland are genetically related to this major ore deposit.

Acknowledgements

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