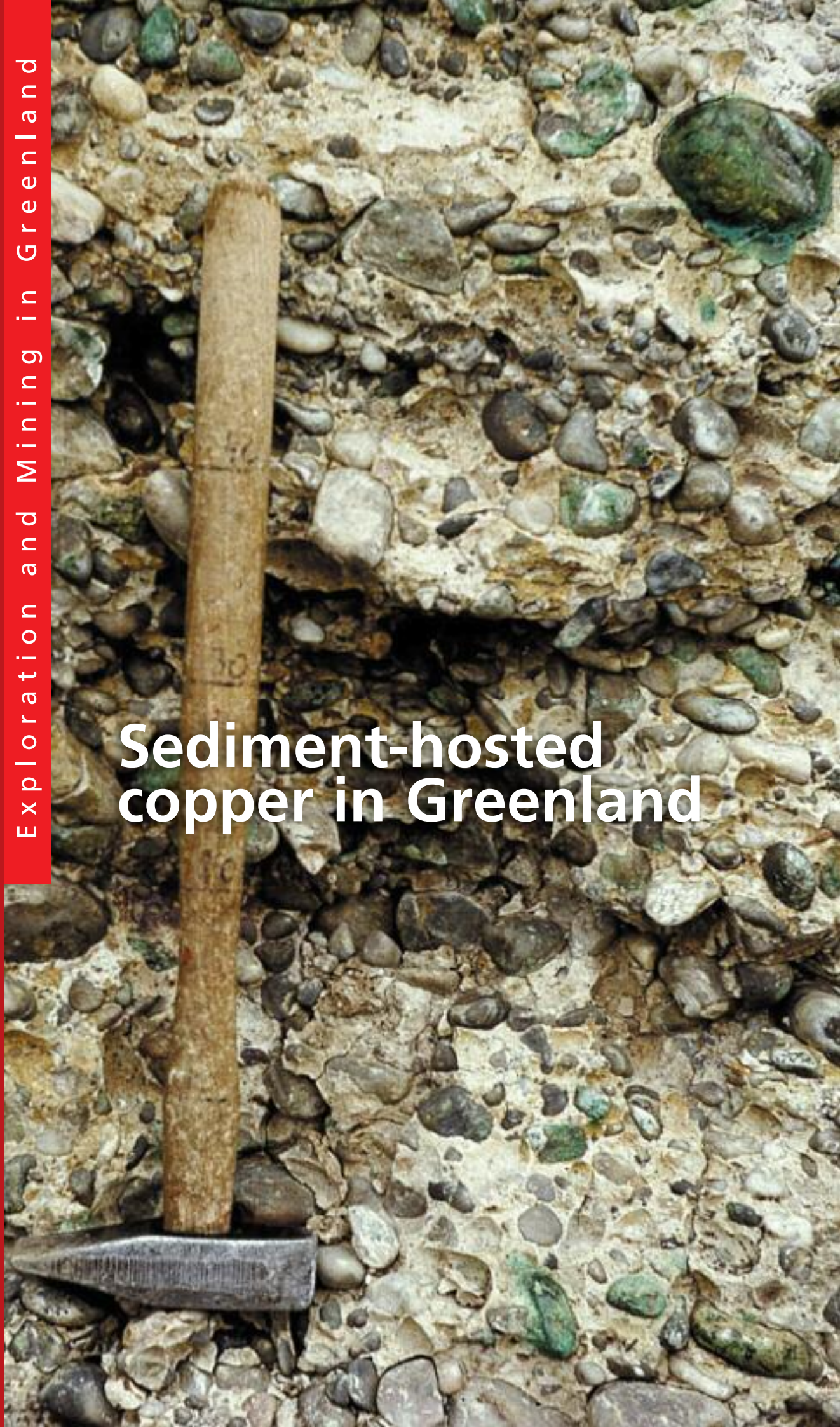
GEOLOGY AND ORE

Exploration and Mining in Greenland

Sediment-hosted copper in Greenland



Sediment-hosted copper in Greenland

- Assessment of potential and undiscovered Cu deposits

With the growing world population and with the ongoing energy transition, copper is expected to strengthen its importance as a key commodity.

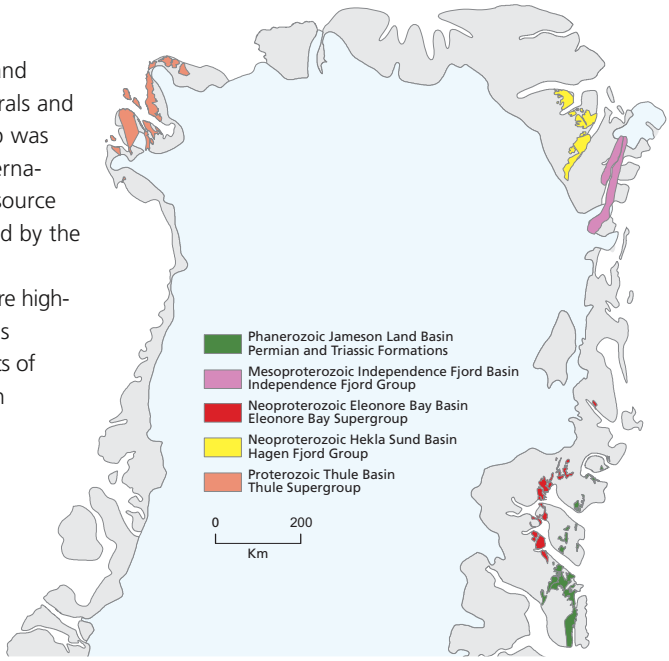
The mineral potential of Greenland is underexplored. However, this edition of Geology and Ore illustrates that Greenland could hold a good potential for undiscovered Cu deposits. The large sedimentary successions in Greenland are particularly favourable for sediment-hosted copper occurrences. Occurrences related to the Reduced-facies (Kupferschiefer) Cu, Redbed Cu, Revett Cu and Volcanic Redbed Cu types have all been discovered in Greenland. While most of the tracts holding potential for hosting sediment-hosted occurrences have only seen limited investigation, the Jameson Land Permian and Triassic formations have attracted significant exploration efforts over the last 15 years.

Introduction

Sedimentary basin environments younger than 1600 million years (Ma) constitute c. 40% of Greenland's 410 000 km^2 ice-free land. Of this, the Phanerozoic basins (<400 Ma) accounts for c. 20% (31 570 km^2), the Lower Palaeozoic and the Neoproterozoic basins for c. 50% (85 280 km^2) and the Mesoproterozoic basins for c. 30% (47 970 km^2). These basins are well-known for several mineralisation types of which sediment-hosted copper, especially in the form of Reduced-facies and Redbed copper types, are some of the more common types. However, only limited exploration has been carried out on copper deposits hosted in the sedimentary successions.

A 'Workshop on the Potential for Undiscovered Sedimentary Hosted Copper Deposits in Greenland' was held in 2009. The purpose of the workshop was to assist the mineral sector in their planning of new exploration targets and provide the sector with the scientific background and necessary data to make qualified decisions. The workshop was arranged by the Geological Survey of Denmark and Greenland (GEUS) and the Bureau of Minerals and Petroleum (BMP). The workshop was also part of the cooperative international effort 'Global Mineral Resource Assessment Project' (GMRAP) led by the U.S. Geological Survey.

This edition of Geology and Ore highlights some of the results from this workshop, including characteristics of the main sedimentary provinces in Greenland, their known Cu deposits and the resulting potential for undiscovered Cu deposits within these provinces.



Distribution of tracts with sedimentary successions that are regarded as having potential for sediment-hosted copper deposits in Greenland.

How to evaluate undiscovered Cu deposits?

During the workshop, an evaluation of the potential for undiscovered sedimentary hosted Cu deposits in Greenland was carried out according to the standardised process utilised in the GMRAP. In this process, an assessment panel of experts discusses all available knowledge and data according to the mineralisation type about a specific area (tract) and assesses the possibility of finding deposits within this tract. The expert panel consists of geologists, geophysicists, ore geologists, etc. with specialist knowledge about the geology, mineralisation or mineral deposit model considered; both from academia and industry. Each tract is defined down to 1 km depth below surface. The members of the assessment team make their individual, anonymous estimates (*bids*) of the number of deposits of a specific size and grade they believe can be found and mined in a specific tract, under the best of circumstances. This is done at different confidence levels. A panel discussion of the bids leads to a *consensus bid*, which is used as input to a statistical simulation. The result is an estimate (prediction) of the size of undiscovered tonnage of ore and number of tonnes of the commodity in question the tract contains. The statistical simulation includes global inventories/curves of tonnage and grades about known deposits/mines of the mineral deposit model in question. The deposit size and grades that the members of the assessment panel give their bids on are defined by the median of the grade-tonnage curves.

Copper deposit types covered

Sediment-hosted Cu deposits account for c. 23% of the world's Cu production and known reserves. They are also important sources of Ag and Co, and some deposits also produce other metals such as Pb, Zn, U, Au and PGE.

Sediment-hosted copper deposits are stratabound epigenetic and diagenetic deposits formed independently of igneous processes. They occur most commonly in sedimentary basins that contain marine or large-scale, lacustrine rocks with evaporites that immediately overlie continental redbeds and in isolated nonred units within the redbed successions themselves. In general, they are formed within 30° of the palaeoequator in arid environments and in sedimentary successions associated with intracratonic, long-lived rift or passive margin settings.

Fact Box — General characteristics of sediment-hosted copper deposits

Mineral deposit subtype	Synonyms	General description	Mineralisation	Depositional environment	Ore control	Host rock types	Ore tonnage and grade	Global examples
Reduced-facies Cu	Copper-shale, stratiform copper hosted by low-energy sediments, marine paralic, Kupferschiefer type, Central African type	Stratabound, disseminated copper sulphide deposits in reduced-facies sedimentary rocks overlying or interbedded with redbed sequences or subaerial basalt flows.	Copper mobilised by oxidised brines; the reducing suphide-bearing fluids are derived from reduction of sulphate in marine or lacustrine, organic-rich, fine-grained sediments. Sabkhas, evaporates, or other sources of brines are important.	Formed in continental clastic sedimentary basins succeeded by epicontinental shallow marine or lacustrine basin. Within 30° of the palaeo-equator.	Pyritic shales, algal mats or reef colonies are important as reducing environments. Late orogenic development of fracture-permeability and hydrologic setting to drive the process of fluid mixing is important.	Shale, siltstone, mudstone, clay (reduced facies marine or lacustrine rocks). Organic carbon and disseminated pyrite common constituents.	Median ore tonnage of 33 Mt and a median copper grade of 2.3 %.	Kupfershiefer (Poland), Zambia deposits (African Copperbelt, Zambia).
Redbed Cu	Redbed-hosted Cu, sandstone-hosted Cu, continental redbed	Stratabound, disseminated copper and copper sulphides occurring in reduced zones of redbed sequences.	Copper mobilised by oxidised brines; the reducers are formed by the presence of plant debris. In some cases local evaporate beds are present.	Found within host rocks deposited by alluvial systems entering closed-basin playas or coastal environments, shallow seas and evaporate basins. Within 30° of the palaeo-equator.	Permeable sandstone beds are a controlling factor. Pyrite can be a significant local reducer if present. Redox fronts (roll fronts) in ore-forming fluids and disequilibrium conditions are important chemical controls.	Redbed sequence containing white- or grey-bleached zones in sandstone and/or black, grey or green, reduced beds of shale and siltstone.	Median ore tonnage of 2 Mt and a median copper grade of 1.6 %.	Corocoro (Bolivia), Nacimiento and Stauber (New Mexico, US).
Revett Cu	None	Stratabound, disseminated copper and lead-zinc sulphides occurring in broad redox boundaries.	Copper mobilised by oxidised brines; the reducer is a broadly distributed and diffuse fluid, typically a hydrocarbon liquid or gas, or sulphide-rich sour gas.	Deposited as fan deltas entering closed-basin playas or coastal enviroments, shallow seas and evaporate basins. Within 30° of the palaeoequator.	Permeable beds are important. Redox front (roll front) controls copper deposition. Nearby marine basins with deposits of hydrocarbon are sources for the formation of reducing fluids.	Sandstone, quartzite, arkose and conglomerate.	Median ore tonnage of 14 Mt and a median copper grade of 0.8 %.	Spar Lake and Montanore-Rock Creek (Montana, US), Cashin Mine (Colorado, US), Dzhekazgan (Kazakhstan)
Volcanic Redbed Cu	Basaltic Cu, Andean manto Cu.	Disseminated, native copper and copper sulfide veins and infilling amygdules, fractures and flowtop breccias in the upper parts of thick sequences of subaerial basalt, and copper sulfides in overlying sedimentary beds.	Copper mobilised from volcanic rocks during diagenesis or early-stage metamorphism; precipitation in permeable locations under favourable chemical, pressure, and temperature conditions.	Copper-rich continental to shallow marine basalt interlayered with redbeds in arid to semi-arid environments formed near palaeo-equator.	Flow-top breccias, amygdules, fractures in basalt; organic shale, limestone in overlying sequence. Associated reduced, carbonaceous sedimentary rocks may play a role. Syn-sedimentary faulting may be important.	Shallow marine basalt flows, breccias and tuffs, redbed sandstone, tuffaceous sandstone, conglomerate.	Not applicable. (USGS grade-tonnage curves have not been established). Kirkham(1996): 28 deposits with an ore tonnage from 0.85 Mt to 220 Mt and a copper grade from 0.8% to 12.8% Cu.	Keweenaw and Calumet (Michigan, US), Kennicott and Denali (Alaska, US), Boleo (Mexico), Buena Esperanza (Chile), Redstone and Sustut (Canada).

Characteristics of the three first subtypes of sediment-hosted copper deposits are extracted from Cox et al. 2007. The cited medians of the ore tonnage and the copper grade are extracted from the established grade-tonnage curves. The characteristics of the genetically related Volcanic Redbed Cu deposit type are mainly extracted from Cox 1984 and Kirkham 1996.

SEDIMENT-HOSTED COPPER IN GREENLAND

Spectacular outcrops of the Neoproterozoic Eleonore Bay Supergroup which hosts several known Cu occurrences of the Reduced Facies Cu type along the coastal cliffs (height up to 1000 m) of Geologfjord, North-East Greenland. Photo: Martin Sønderholm.

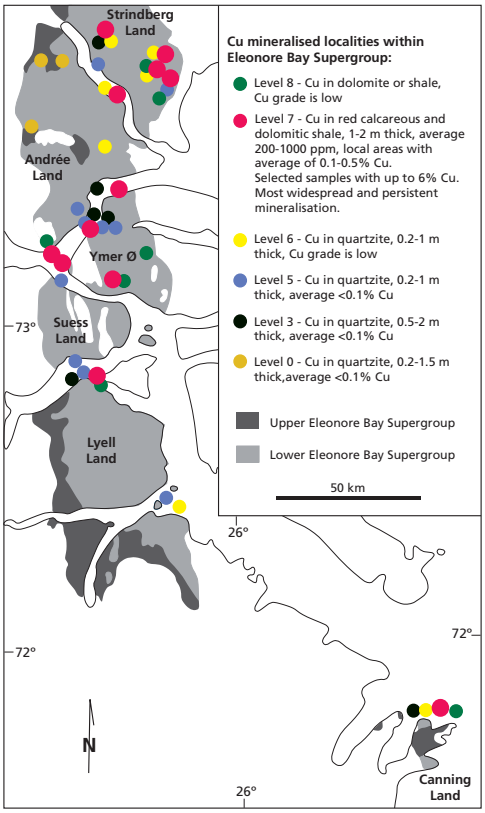
Malachite-stained outcrop of quartzitic sandstone from the Brogetdal copper occurrence in the uppermost Lyell Land Group of the Neoproterozoic Eleonore Bay Supergroup in Strindberg Land, North-East Greenland. Photo: Henrik Stendal.

Genetically, sediment-hosted copper deposits form as a result of fluid mixing in permeable sedimentary and (more rarely) volcanic rocks. Two fluids are involved, an oxidizing brine that carries copper and a reduced fluid, commonly formed in the presence of anaerobic, sulphate-reducing bacteria. Mineralisation in the sedimentary Cu systems can occur from early diagenesis to basin inversion and metamorphism. Overall, to form a sediment-hosted copper deposit, four conditions are required:

1. An oxidizing source rock that is hematite-stable and must contain ferromagnesian minerals or mafic rock fragments, from which the copper can be leached.
2. A source of a basinal brine that mobilises the copper.
3. A source of reduced fluid to precipitate the copper and (in many cases) to supply sulphur.
4. A structural and stratigraphic setting favourable for fluid mixing between the Cu-bearing brine and the reducing fluid and subsequent sulphide deposition.

According to Cox *et al.* (2007) sediment-hosted copper can be divided into three descriptive mineral deposit models: Reduced-facies Cu, Redbed Cu and Revett Cu. The three types differ in the strength and efficiency of the reducer at the site of deposition. Furthermore, the genetically related fourth type, Volcanic Redbed Cu, is included in the assessment.

Occurrences of sediment-hosted Cu are relatively frequent within sedimentary successions regarded as fertile for this type of mineralisation. However, the vast majority

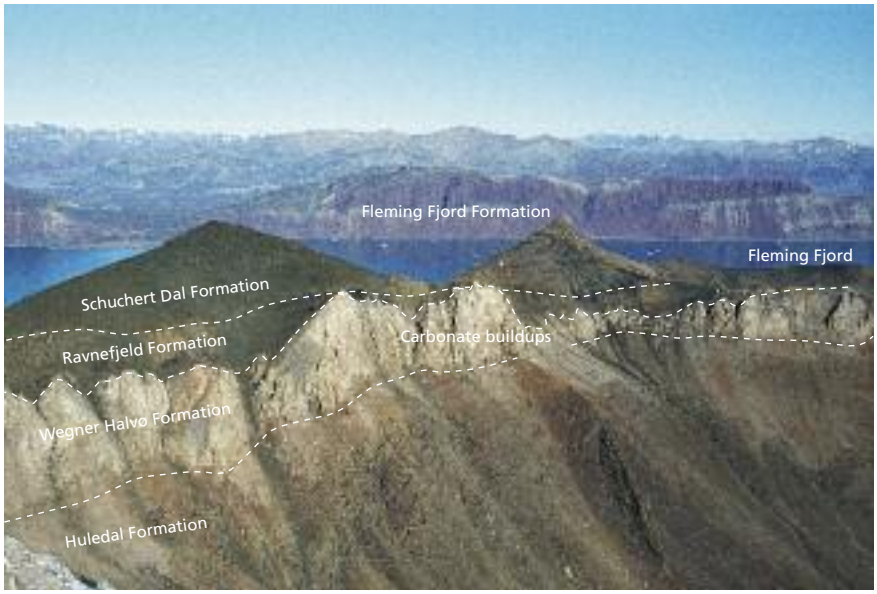


Distribution of known Cu mineralisation within the Eleonore Bay Supergroup, central East Greenland. The different symbols refer to different mineralised levels in the Ymer Ø, Lyell Land and Nathorst Land Groups. Mineralised level number 7 is regarded as being the most widespread and persistent mineralisation. Modified after Harpøth et al. 1986.

of sediment-hosted Cu mineralising systems produce small, mostly subeconomic occurrences. Nevertheless, large deposits of all of the above Cu mineral deposit types are also found. Especially the Reduced-facies Cu type can form very large mineralising

Most important known sediment-hosted copper occurrences in Greenland

Type of Cu mineralisation	Location	Host rock	Name of deposit/ occurrence	Grades and size
Reduced-facies Cu	Central East Greenland, Jameson Land Basin	Black shales of the Upper Permian Ravnefjeld Formation	Vimmelskaftet	Cu mineralisations are widespread in this area. Chip samples (n=39) over 20 m contain 200–850 ppm Cu, 1300–7000 ppm Pb and 350–1260 ppm Zn. 1–3 cm thick mineralised beds are known from several localities and contain 10% combined Zn and Pb.
			Devondal	Cu mineralisations are widespread in this area. A chip sample over 2.5 m averages 200 ppm Cu, 200 ppm Pb and <500 ppm Zn.
		Silty mudstone of the Upper Triassic Pingel Dal Beds of the Edderfugledal Member, Fleming Fjord Formation	Pingel Dal Beds	A widespread and laterally persistent Cu mineralisation is known over an area of 1000 km². Thickness of mineralised horizons is between 0.2–2 m. 29 chip samples yield averages of 2000 ppm Cu over 1.1 m with a range of 200–5000 ppm Cu over 0.3–1.9 m.
	North-East Greenland, Eleonore Bay Supergroup	Calcareous and dolomitic shales of the uppermost part of the Neoproterozoic Ymer Ø Group	Ymer Ø Group	Widespread and persistent Cu mineralisation extends for more than 275 km from north to south. Thickness of mineralised horizons is from a few cm to a few m. Average Cu content ranges from 2500 ppm to 15000 ppm with an average content of 7000 ppm. Selected samples yield up to 6% Cu. The average Ag content is low with a Cu/Ag ratio of 1000–1500.
Redbed Cu	Central East Greenland, Jameson Land Basin	Grey and red intercalated mudstones of playa flat origin of the Upper Triassic Fleming Fjord Formation	Nordenskiøld Fleming Fjord Formation	Cu mineralisations have been recorded in 0.1-1 m thich sandstone beds throughout an area of 100 km². Chip samples from 21 sections (650 m laterally) show an average content of 500 ppm Cu (from 27 to 3500 ppm) and 1.3 ppm Ag (from 0.8 to 4.8 ppm) over a thickness of 0.38 m (from 0.25 to 0.6 m). Maximum values stem from a selected grab sample with 27.5% Cu, 787 ppm Ag.
	North-West Greenland, Thule Basin	Pale sandstones of the Meso- to Neoproterozoic Qaanaaq Formation of the Baffin Bay Group	Olrik Fjord	The Cu mineralisation is restricted to a 100 m² area. A composite grab sample shows 4000 ppm Cu.
			'Red Cliffs'	Isolated outcrops of copper mineralised sandstone. Grab samples yields up to 1.5% Cu.
Revett Cu	Central East Greenland, Jameson Land Basin	Braided alluvial plain conglomerate consisting of well-rounded quartzite, carbonate, granite pebbles/cobbles in sand and carbonate matrixes of Upper Permian Huledal Formation	Rubjerg Knude	In some areas the Cu mineralisation extends over 20 m in thickness but in average the thickness is between 5 m and 10 m. For an area of 1.3×2.5 km a resource of 5 Mt with 3000 ppm Cu can be estimated (based on 13 chip samples).
			Ladderbjerg	Thickness of the Cu mineralisation is 10 m. A resource of 2.5 Mt with an estimated grade of 1500 ppm Cu has been estimated for an area of 1×4 km. An associated Pb mineralisation with an average thickness of 8 m is estimated to contain 1.5 Mt with an estimated grade of 1% Pb (based on eight chip samples from the area).
Volcanic Redbed Cu	North-East Greenland, Hekla Sund Basin	Shallow shelf sediments of the Jyske Ås Formation of the Neoproterozoic Hagen Fjord Group	Jyske Ås Formation	Composite grab samples from the Jyske Ås Formation contain up to 3% Cu and 100 ppm Ag.



The carbonate buildups of the Wegner Halvø Formation and the overlying black shales of the Ravnefjeld Formation, central East Greenland. Photo towards north-west, with Fleming Fjord in the background and the western part of the peninsula Wegner Halvø in the foreground. The cliff face is c. 400 m high. Photo: Mikael Pedersen.

systems as illustrated by the Kupferschiefer-related Cu deposits in the Permian Zechstein basin of Europe and the African Copper Belt deposits in the Neoproterozoic Katangan basin. Also the Volcanic Redbed Cu type can produce large deposits.

Sedimentary environments in Greenland

During the Proterozoic and throughout the Phanerozoic, major intercontinental-rift-related sedimentary basins formed in North and North-East Greenland with sedimentary successions reaching up to 18 km in thickness.

Within Meso- to Neoproterozoic basins, the most important sedimentary successions for copper deposits are the sediment-volcanic succession of the Thule Supergroup of the Thule Basin in North-West Greenland and the allochtonous, siliciclastic shelf and carbonate platform successions of the Eleonore Bay Supergroup in North-East Greenland.

The Thule Supergroup reaches a total thickness of at least 6 km, possibly 8 km and was deposited in an intracratonic fracture basin with block faulting and basin sagging formed in a divergent plate region. The base of the basin is defined by an unconformity with underlying peneplained basement rocks. The sediments consist of multicoloured, mainly shallow-water, siliciclastic sediments with one interval of volcanic rocks with basic sills at several levels. The depositional environment is continental (intertidal to subtidal) to lacustrine and shallow marine with cratonic basaltic magmatism.

The Eleonore Bay Supergroup comprises a more than 14 km thick succession of shallow-water sedimentary rocks, which accumulated in a major sedimentary basin that evolved through a rapidly subsiding, siliciclastic shelf, a stable, siliciclastic shelf, carbonate platform development and glaciogenic deposition. The basin is exposed north-south for *c.* 450 km and east-west for *c.* 200 km. The early part of the succession probably started out at palaolatitude c. 30°, whereas the late part of the succession ended at *c.* 40°.

The post-rift, thermal subsidence, sedimentary successions of the Neoproterozoic fluvial to shallow marine sag deposits of the Hagen Fjord Group of the Hekla Sund Basin in North-East Greenland may also have copper potential. This succession overlies the up to 1350 m thick well-preserved Mesoproterozoic flood basalts of the Zig-Zag Dal Formation.

Late Palaeozoic and Mesozoic sedimentary basins related to continental break-up with formation of rift basins developed along the continent-ocean margin in North, East and West Greenland. Most interesting for sediment-hosted copper deposits are the Permian and Triassic successions of the Jameson Land Basin in East Greenland. The Upper Permian rocks of the Jameson Land Basin consist of an up to 180 m thick succession of non-marine conglomerate, marine sandstone and shale and carbonate platform sediments including evaporites and algal-laminated gypsum. The shales have attracted considerable attention due to their

View of the Ladderbjerg Cu deposit within the Huledal Formation, central East Greenland. Photo: Bjørn Thomassen.

high potential as hydrocarbon source rock. The Triassic succession consists of a c. 1700 m thick sequence of shallow marine to continental and lacustrine clastics with intercalations of evaporites and thin carbonates.

Known sedimentary hosted copper occurrences

Limited exploration for sediment-hosted copper mineralisation has been carried out in Greenland. Only a few occurrences have been investigated in detail to a level which allows for qualified estimates of overall tonnage and grade.

Reduced-Facies Cu occurrences

In central East Greenland, within the Jameson Land Basin, Reduced-facies Cu occurrences are known from both Upper Permian and Upper Triassic strata. The copper mineralisation within the black shales of the Ravnefjeld Formation is widespread and has been compared with the European Kupferschiefer type. Copper mineralisation within the Triassic strata of the Jameson Land Basin is known from several levels. The most pronounced and promising occurrences is the Reduced-facies Cu-type mineralisation found within cyclically bedded sandstone, siltstone and mudstone of the Upper Triassic Pingel Dal Formation of the Edderfugledal Member, Fleming Fjord Formation.

In North-East Greenland, within the Neoproterozoic Eleonore Bay Supergroup (EBS) eight levels of stratiform and stratabound Cu mineralisation have been observed. This observation has been made within a 3 km thick stratigraphical pile of the uppermost three stratigraphical groups of the four groups that make up the EBS. The most widespread and persistent level of mineralisation occurs within the lowermost part of the Ymer Ø Group. Genetically, the mineralisation is interpreted to be syn-sedimenentary to early diagenetic in origin and probably best represents a Reduced-facies Cu-type mineralisation. Algal mounds and pseudomorphed evaporites adjacent to the mineralised Cu level within the lowermost Ymer Ø Group may have played an important role in the formation of reduced brines.

Geologist inspecting the mineralised conglomerate of the Ladderbjerg Cu deposit in the Huledal Formation, central East Greenland. A resource of 2.5 Mt with a grade of 1500 ppm Cu has been estimated for an area of 1×4 km (based on eight chip-sampled sections of the 8–10 m thick conglomerate). Photo: Bjørn Thomassen.

Also, the lowermost part of this Group was formed by a major transgressive event, possibly accompanied by a shift to more arid climate. Most Reduced-facies Cu deposits are formed during such trangressions of reduced marine sediments over redbed deposits. The mineralisation shows similarities with part of the Zambian copper belt and the Precambrian Belt Supergroup in Idaho and Montana. The mineralisation also displays similarities with Cu deposits in the Neoproterozoic Adelaidean Sequence of the Stuart Shelf, South Australia.

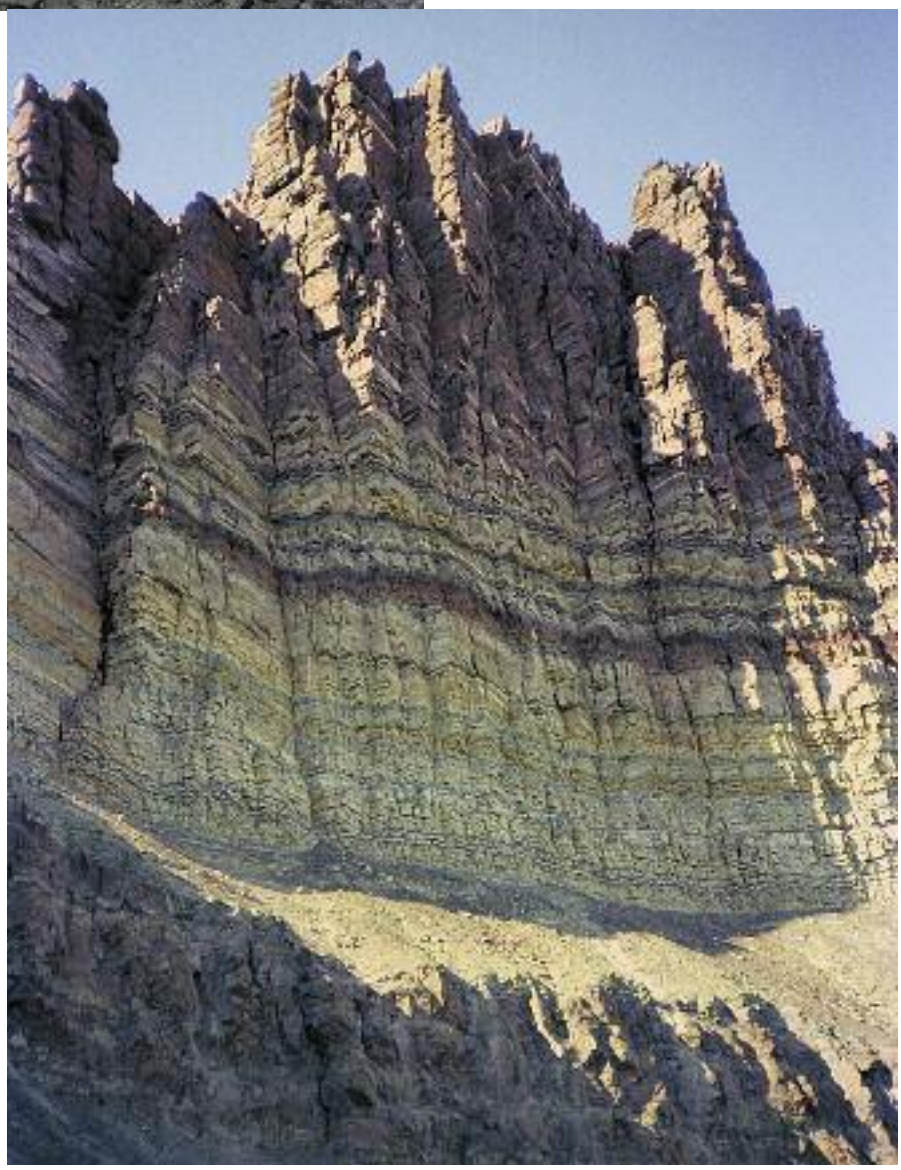
Redbed Cu occurrences

Copper mineralisations are found throughout the Triassic stratum in the Jameson Land Basin, central East Greenland. Redbed Cu-type mineralisations occur within the Ørsted Dal and Malmros Klint members of the Upper Triassic Fleming Fjord Formation. The copper occurrences are hosted in two

The black shale of the Upper Permian Ravnefjeld Formation on Wegener Halvø is a known host of Reduced-facies Cu-type mineralisation in central East Greenland. Maximum values from grab samples show 11.5% Zn, 7.7% Pb and 0.35% Cu. Photo: Bjørn Thomassen.

or more 0.1 to 1 m thick, grey, pale-yellowish weathering beds intercalated with red mudstones. Thin intraformational breccias, septarian nodules and plant fragments up to 30 cm long occur locally.

The entire stratigraphical succession of the Meso- to Neoproterozoic Thule Supergroup hosts redbed units in abundance. It is estimated, that redbed successions form 20 to 55% of the total stratigraphical thickness in four out of the five formations that constitute the Thule Supergroup. This means that redbed successions, depending on their position in the basin, make up from 0.5 to 1.9 km of the total sedimentary package of the basin. There is good evidence for long, extensive fluid/brine activity within the basin; and block faulting associated with half-graben structures may have provided the important fracture-permeability and hydrologic setting to drive the process of fluid mixing needed to form the Redbed Cu-type mineralisation. This is also reflected by the distribution of known Redbed Cu occurrences within the Thule Supergroup, which all are adjacent to the major faults.

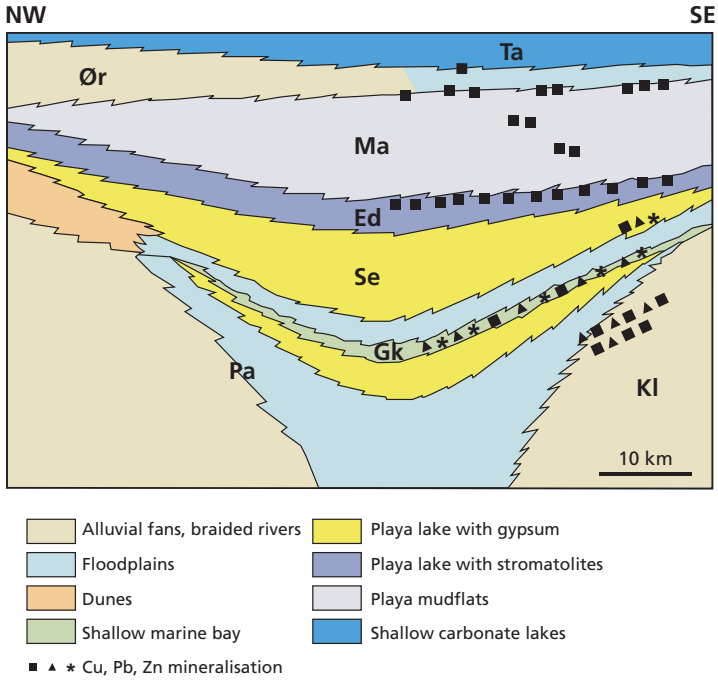


Thick, silty, multicoloured mudstones from the Upper Triassic Pingel Dal Beds of the Edderfugledal Member, Fleming Fjord Formation of the Jameson Land Basin in central East Greenland. The cliff face is 50 m high. Widespread and laterally persistent Reduced-facies Cu-type mineralisation occurs within the beds over at least 1000 km². Photo: Bjørn Thomassen.

Revett Cu occurrences

Scattered, stratabound copper occurrences are known from the Upper Permian sandy conglomerates of the Huledal Formation of the Jameson Land Basin, central East Greenland. Two of these occurrences are large enough to have been subjected to

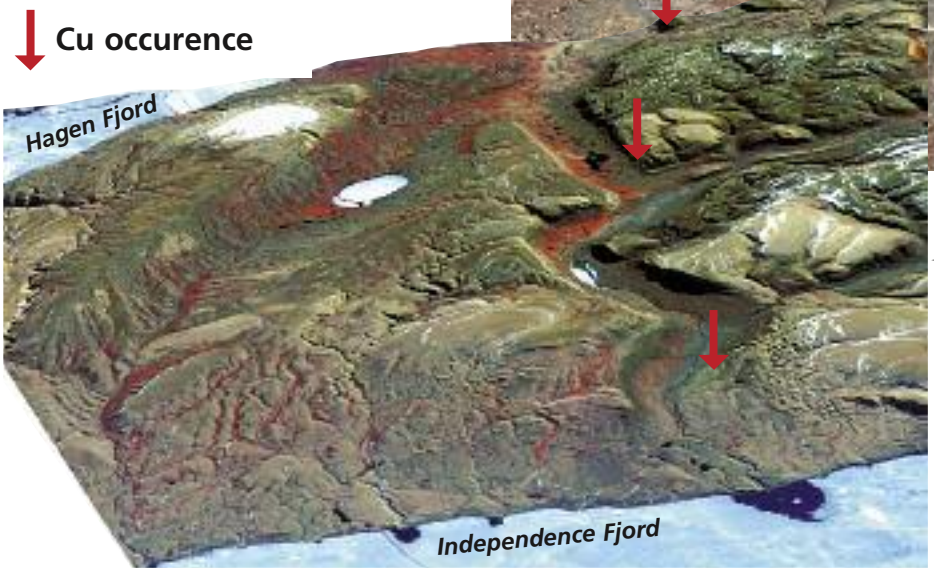
The 700 m high cliff face at Buch Bjerg consisting of Upper Triassic sediments of the Fleming Fjord Formation (red sediments near the top of the cliff), Gipsdalen Formation (the paler red to grey part) and the Pingo Dal Formation (the underlying pinkish sediments) of the Jameson Land basin. The Triassic succession hosts several several known Reduced-facies and Redbed Cu-type mineralisations. Photo: Asger K. Pedersen.



*Generalised facies pattern and mineralisation of the Triassic Pingo Dal, Gipsdalen and Fleming Fjord Formations. **Kl** = Klit Dal Member, **Pa** = Paradigmabjerg Member, **Gk** = Gråklint Beds, **Se** = Kap Seaforth Member, **Ed** = Edderfugledal Member (including Pingel Dal Beds), **Ma** = Malmros Klint Member, **Ør** = Ørsted Dal Member, **Ta** = Tait Bjerg Beds. After Harpøth et al. 1986.*

estimates of tonnage and grades. The Huledal Formation belongs to the marine Foldvik Creek Group which was deposited unconformably mainly on extremely flat Carboniferous – Lower Permian peneplain. The formation is up to 120 m thick with great thickness variation. The formation consists of poorly sorted, immature fluvial conglomerate beds, sandstone sheet deposits and some mudstones. The conglomerate constitutes a high pre-ore permeable bed. Parts of the Upper Permian succession are bituminous-bearing and are regarded as a good source rock for hydrocarbons. At central Trail Ø, the Rubjerg Knude Cu deposit occurs within conglomerates of the Huledal Formation, which is 30–60 m thick here. Central Trail Ø is dominated by block faulting, which may have played an important role as the fluid path-

Stained, elongated zone within pale sandstone surrounded by red sandstone of the Jyske Ås Formation. The zone appears to be structurally controlled. Photo: Bjørn Thomassen, Avannaa Resources Ltd.



Landsat TM colour composite draped on a digital elevation model. Indications of known Cu occurrences within the Neoproterozoic Jyske Ås Formation along the N–S-oriented valley Neergaard Dal on eastern I.C. Christensen Land, North-East Greenland, can be seen on the image. The image is seen from the north. No vertical exaggeration.

Upper Permian dolomitic limestone (Karstryggen Fm) resting on Huledal Fm conglomerate (foreground) at western Wegener Halvø. Massive bornite mineralisation forms along faults transecting the stratigraphic boundary.

way in the formation of the mineralisation. Above the conglomerate unit occurs a 50 m thick sandstone unit, which is overlain by a 10 m thick sabkha unit containing fine-grained gypsiferous sandstones and gypsum beds. This unit is followed by a complex unit that represents the erosional plateau with a variety of sandstones, siltstones, shales and various carbonate rocks. The mineralisation is associated with palaeo-channels within the conglomerate unit. Bitumen content between mineral grains is observed. The mineralisation is believed to be of the Revett Cu type. Still in the Huledal Formation, but farther north, scattered stratabound Cu occurrences are found, where the formation has an average thickness of 10 m. The most significant of these being the Ladderbjerg Cu deposit, which is more than 10 m thick in an area of 1×4 km.

Volcanic Redbed Cu occurrences

No firmly established Volcanic Redbed Cu occurrences are known from Greenland. However, Cu deposits have been found in North-East Greenland that may be candidates for this type of occurrence. These occur within the Neoproterozoic, post-rift, thermal subsidence sediments of the lower part of Hagen Fjord Group of the Hekla Sund Basin, which overlies the well-preserved Mesoproterozoic flood basalts of the Zig-Zag Dal Formation.

The copper occurs both as native copper and copper-sulphides. An elongated nature of the Cu occurrences suggests a relationship with graben faults and structures which may play an important role for the transportation of the mineralising fluids.

Consensus bids on the number of undiscovered Cu deposits per area

Type of Cu mineralisation	Region	Area	Tract name	Areal extent	Number of undiscovered Cu deposits on different confidence levels				
					N90	N50	N10	N05	N01
Reduced-facies Cu	Central East Greenland	Permian Ravnefjeld Formation	CE-2, 4–15	2250 km²	0	0	0	0	2
		Triassic Pingel Dal Beds	CE-1 A	2000 km²	0	0	0	2	4
		Triassic Pingel Dal Beds	CE-1 B	1000 km²	0	0	0	0	2
	North-East Greenland	Neoproterozoic Eleonore Bay Supergroup	CE-1–6, CE-9–16	2111 km²	0	0	0	1	4
		Neoproterozoic Eleonore Bay Supergroup	CE-7–8	1000 km²	0	0	0	2	4
Revett Cu	Central East Greenland	Permian Huledal Formation	CE-2	436 km²	0	0	0	1	2
		Permian Huledal Formation	CE-4–7	882 km²	0	0	0	1	3
		Permian Huledal Formation	CE-8–12	449 km²	0	0	0	2	4
		Permian Huledal Formation	CE-13–14	361 km²	0	0	0	1	3
		Permian Huledal Formation	CE-15	165 km²	0	0	0	0	1
Redbed Cu	Central East Greenland	Triassic Fleming Fjord Form.	CE-1 A	2310 km²	0	0	0	2	4
		Triassic Fleming Fjord Form.	CE-1 B	1150 km²	0	0	0	0	2
	North-West Greenland	Meso- to Neoproterozoic Nares Strait Group	NW-5–10	5680 km²	0	0	1	2	5
		Meso- to Neoproterozoic Baffin Bay Group	NW-1–2, NW-5–10	5740 km²	0	0	0	2	5
		Meso- to Neoproterozoic Narssârssuk Group	NW-3–4	320 km²	0	0	0	0	2
		Meso- to Neoproterozoic Smith Sound Group	NW-11–13	1230 km²	0	0	0	2	4
Volcanic Redbed Cu	North-West Greenland	Meso- to Neoproterozoic Nares Strait Group	NW-5b, 8–10	3000 km²	0	0	0	1	2
		Meso- to Neoproterozoic Nares Strait Group	NW-9	290 km²	0	0	0	1	2
	North-East Greenland	Neoproterozoic Hagen Fjord Group	NE-1–9	15,000 km²	0	0	2	3	6
		Neoproterozoic Independence Fjord Group	NE-10–11	5810 km²	0	0	0	1	3

N90–N01 = confidence level; a measure of how reliable a statistical result is, expressed as a percentage that indicates the probability of the result being correct. A confidence level of 10% means that there is a probability of at least 10% that the result is reliable.

Exploration history

Jiangxi Zhongrun Mining Co. Ltd. (Zhongrun) and Nordic Mining Ltd. carried out an exploration programme targeting the Permian-Triassic, on four blocks in Jameson Land, between 2008 and 2012.

Reconnaissance mapping and sampling, profiling, detailed mapping and channel sampling focused on the blocks between Pingel Dal and Devondal. In 2011 and 2012, thirteen diamond core holes (total of 1,783 m) were drilled. This work confirmed mineralized horizons in: (1) limestone of the Permian Foldvik Creek Group, (2) sandstone and conglomerate of the Triassic Pingo Dal Formation, (3) sandstone and mudstone of the Triassic Gråklint Beds, and (4) shale of Triassic Pingel Dal beds.

The Gråklint Beds and the Pingel Dal Beds were considered to be laterally persistent, but relatively low grade compared to the mineralization identified in the Foldvik Group and Pingo Dal Formation. As a result, work focused on the former, where four mineralized zones were delineated, which were suggested as targets for systematic drilling in subsequent years. However, this follow-up has not been carried out to date (Jan 2020) and the company has since relinquished its license.

Avannaa Resources Ltd., partly under an earn-in agreement with Anglo American Plc., explored other areas of the Permian-Triassic of the Jameson Land basin during the years 2011-2014. The work included extensive stream sediment sampling, prospecting, mapping, airborne magnetic and TEM surveys and one drill campaign.

New, fault-controlled bornite-chalcocite mineralisations were discovered both in the Karstryggen Fm at Wegener Halvø and in fractured basement gneisses at the extreme north of Klitdal, structurally close to the overlying, now eroded Triassic strata. Other chalcocite mineralisations were discovered in the Permian Huledal Fm at Traill Ø and at Wegener Halvø extending the known mineralisations here while new chalcocite mineralisations were found in the Triassic sandstones of the Klitdal Member in Klitdal area scattered over 20km, but all of low grades (<1 wt% Cu). In 2014 a drill program targeting four keys areas in Klitdal retrieved 1,807m of core from eight drill holes, but failed to intersect any copper mineralisations and the licenses were relinquished thereafter.

In 2018, Independence Group NL and Greenfields Exploration have agreed on a joint venture to explore areas covering Neoproterozoic Eleonore Bay Supergroup and Jameson Land Permian and Triassic formations.

Potential areas for undiscovered copper deposits

At the 'Workshop on the Potential for Undiscovered Sedimentary Hosted Copper Deposits in Greenland' the members of the assessment team gave their bids on different confidence levels on how many copper deposits they thought could be discovered under the best circumstances. The distribution of undiscovered copper deposits on the different confidence levels as well as the increase in numbers from one confidence level to another reflect the level of knowledge about the various areas and the overall feeling about the potential within the areas.

In general the assessment team agreed that the biggest potential for large-grade-tonnage deposits of the Reduced-facies Cu type was within the Neoproterozoic Eleonore Bay Supergroup in North-East Green-

Olrik Cu mineralisation within the Qaanaaq Formation in the Thule Basin, North-West Greenland (the green malachite-stained patch in the foreground of the hill). The mineralisation is adjacent to two major faults of the Olrik half-graben structure.The mineralisation covers an area of 100 m². Photo: Bjørn Thomassen.

land and the Upper Triassic Pingel Dal Beds of the Fleming Fjord Formation in central East Greenland. Also the Hagen Fjord Group in North-East Greenland was regarded as having a large potential for deposits of the Volcanic Redbed Cu type.

Concluding remarks

Greenland represents a region for grass-root exploration with great potential for sediment-hosted copper mineralisations. Many sedimentary successions in Greenland are considered favourable and bear evidence of the mineralising processes needed to form a copper deposit. This is also reflected in the many known copper mineralisations discovered in all the sedimentary successions. However, in most cases only limited exploration campaigns have been carried out and only a few occurrences have seen detailed investigations. Especially interesting are the underexplored parts of the successions of the Eleonore Bay Supergroup in North-East Greenland and the Upper Permian and Triassic sediments in central East Greenland. They host known as well as have further potential for the important Reduced-facies Cu-type mineralisations in Greenland.

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Front cover photograph

Cu-mineralised conglomerate of the Revett Cu type at the Ladderbjerg Cu deposit in the Permian Huledal Formation, Jameson Land Basin, central East Greenland. Photo: Bjørn Thomassen.

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Graphic Production
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Printed
January 2020 © GEUS
Update of January 2011 issue

Printers
Rosendahls A/S

ISSN
1602-818x (print)
2246-3372 (online)