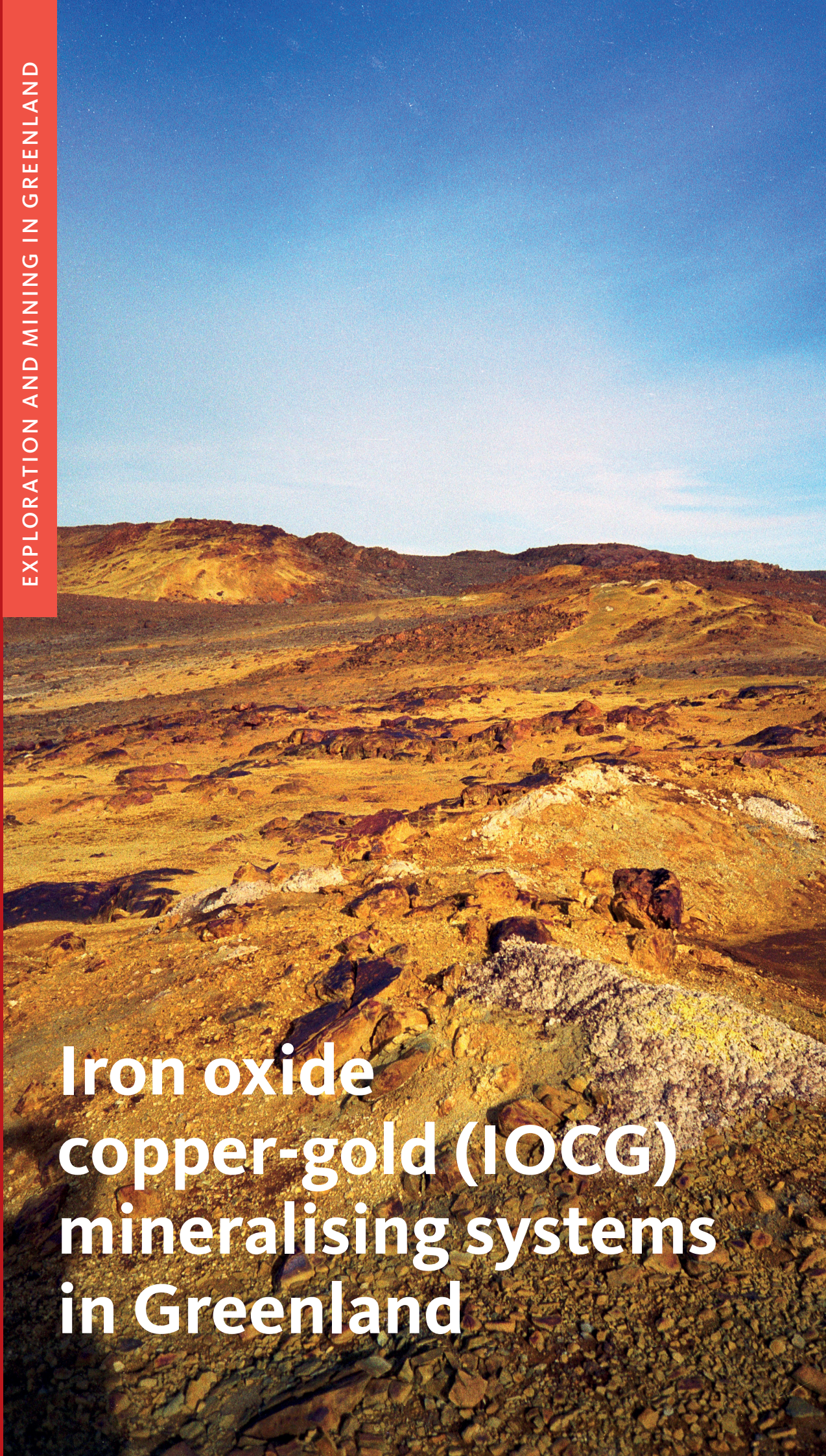


GEOLOGY AND ORE



EXPLORATION AND MINING IN GREENLAND

**Iron oxide
copper-gold (IOCG)
mineralising systems
in Greenland**



Iron oxide copper-gold (IOCG) mineralising systems in Greenland

In the wake of the discovery of the giant Olympic Dam Cu-U-Au-Ag-REE deposit in South Australia in 1975, a conception developed of an important class of ore deposits not previously recognised as such. Subsequent realisation of its significance by the discovery of new deposits of this type attracted keen interest both from academic institutions and exploration companies worldwide.

Due to its economic importance, over the last two decades, the so-called iron oxide copper-gold (IOCG or FeOx-Cu-Au) class of deposits has become a prime target for exploration. Since the first definition and description of the IOCG deposit, new discoveries, re-classification and increasing worldwide research have shown that IOCG deposits encompass a wide spectrum of hydrothermal ore deposits.

Introduction

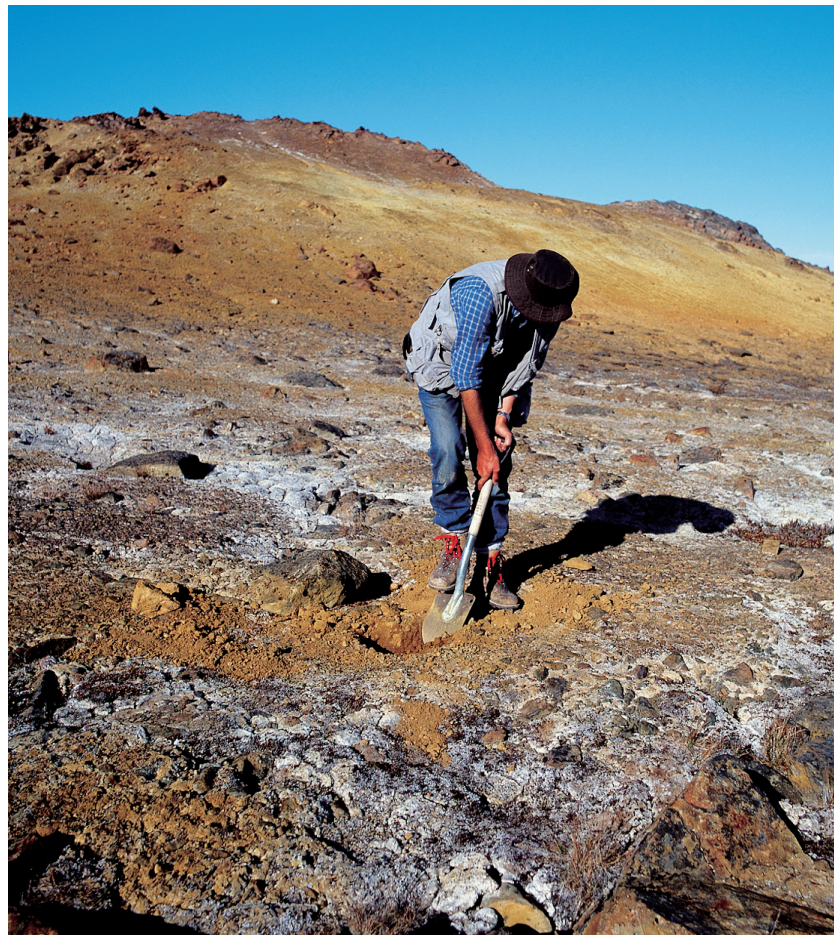
It is understood now that the IOCG class represents a family of related mineral deposits that share a number of distinguishing features:

- low-Ti magnetite and/or hematite (< 2.0 wt % TiO₂)
- extensive Na-K (-Ca) alteration
- REE, Co, Ag ± U, P
- generally coeval magmatism

The current inadequate state of knowledge about this deposit class is reflected in the lack of comprehensive genetic models. Consequently, a genetic classification appears to be an unnecessary limitation when identifying new deposits. Therefore, the classification for the World Minerals Geoscience's Database Project (Geological Survey of Canada), defining six types of IOCG deposits, is used in the fact box. The characteristics of these IOCG deposit types can be directly compared to geological features recognised in Greenland.

Mineral resources characteristics

IOCG deposits may have enormous resources of a wide spectrum of raw materials. They may comprise Fe, Cu, Au, U, REE, F, vermiculite and minor



Soil sampling in a rusty zone of a gneiss sequence in Marshall Bugt, central Inglefield Land.

FACT Box Classification of IOCG deposits into various types

Type	Giant ore deposit	Mineralisation	Alteration	Commodity	Ore body
Olympic Dam	Olympic Dam, South Australia	magnetite-hematite-bornite-chalcopyrite breccia matrix	potassic	Fe, Cu, Au, Ag, REE, U	pipe-like and irregular breccia
Cloncurry	Osborne, Queensland, Australia	magnetite-hematite-apatite replaced by Cu-Fe sulphides, Au, etc.	potassic	Cu, Au, Ag, Bi, Co, W	stratabound, vein, breccia
Kiruna	Kiirunavaara, Sweden	massive magnetite-apatite-actinolite	sodic	Fe ± Cu, Au	tabular, pipe-like, irregular
Iron skarn	Magnitogorsk, Urals, Russia	massive magnetite-garnet-pyroxene	sodic	Fe ± Cu, Au	stratabound lensoid, irregular
Phalaborwa	Phalaborwa, South Africa	magnetite, apatite, fluorite, Cu sulphides, etc.	sodic + potassic	Cu, Au, Ag, REE, PGE, vermiculite, magnetite, P, U, Zr, Se, Te, Bi	veins, layers, disseminations
Bayan Obo	Bayan Obo, Mongolia Autonomous Region, China	magnetite, hematite, bastnaesite, Fe-Ti-Cr-Nb oxides, fluorite, monazite, etc.	sodic + potassic	Fe, Nb, REE	stratabound, lenses, veins, layers, disseminations

resources of Ag, Nb, P, Bi, Co as well as the less essential resources of PGE, Ni, Se, Te, Zr, As, B, Ba, Cl, Co, Mo, Mn and W. The IOCG classes are generally characterised by high tonnage and low-grade ore. The giant and famous Olympic Dam deposit in South Australia is the world's fourth largest Cu deposit, the fifth largest Au deposit and the largest U deposit. It also contains significant quantities of Ag, according to the 2008 status by the operator BHP Billiton. The Phalaborwa deposit in South Africa is the world's second largest Cu mine and largest vermiculite mine and has by-products of Au, Ag, PGE, magnetite, P, U, Zr, Se, Te and Bi, according to the 2008 status by the operator Rio Tinto Mining and Palabora Mining. The Bayan Obodeposit in the Mongolia Autonomous Region, China is the world's largest rare-earth elements (REE) producer, where also Nb and Fe are mined. IOCG deposits, thus, contain major resources and represent important players on the global raw-material market

Exploration criteria

IOCG deposits are commonly hosted by metamorphic terranes that formed dur-

ing the entire geologic history, from the Archaean to recent times, but mostly in the Proterozoic. In spite of large areas of Proterozoic rocks in Greenland, about 40% of the ice-free area, only very few IOCG occurrences were found. Therefore, Greenland is regarded as a promising grassroots exploration target for IOCG deposits. Geophysical, geochemical and remote-sensing techniques are very useful in this context, and regional data available for large parts of Greenland. Due to the commonly large size of the IOCG-like deposits, such regional exploration methods are well suited in order to outline potential target areas.

The occurrence of magnetite and/or hematite (iron oxide) in the mineralisation is one major unifying feature of IOCG deposits, which can be picked up by airborne as well as ground magnetic and gravity surveys. High density and magnetic response result in common coincident gravity and magnetic anomalies. The mineralisation is also characterised by a well-induced polarisation and resistivity response, whereas iron oxide-rich ore bodies show a good electrical conductivity.

The frequent regional K-alteration

and U-rich mineralisation result in anomalies that are detectable by airborne radiometric surveys. Furthermore, regional geochemical surveys are well suited to identify the often extensive and multi-element mineralisation. IOCG deposits are largely controlled by regional structures and splays of such structures. These features can easily be mapped additionally using remote-sensing techniques. Consequently, there are a number of well-suited exploration methods for 'greenfields' exploration in remote areas such as Greenland. For many of Greenland's ice-free areas these data are already available.

Possible IOCG occurrences in Greenland

No IOCG deposit has up till now been recognised from Greenland. Thus, the potential IOCG localities mentioned here are drawn from the literature and their classification has to remain vague. However, some occurrences have typical features of IOCG-type deposits as listed in the fact box and show the potential for this kind of mineralisation in the areas reported:

Olympic Dam- type deposit

South Greenland with the Proterozoic Ketilidian orogen represents a known metallogenetic province for Cu, Au and U, locally associated with iron oxides. The Au-Bi-Ag-As-W-Cu-Mo multi element mineralisation at Niaqornaarsuk and Qooromiut occurs in quartz veins with a quartz-albite-magnetite alteration halo. The quartz veins are controlled by second-order shear zones to the regional, NE-SW trending sinistral, strike-slip shear zones. The mineralisation is suggested to be related to mid-crustal, calc-alkaline, arc-related intrusions (about 1780 Ma) of the Julianehåb batholith. The mineralised veins are up to 5 m wide, can be followed about 200 m along strike and contain 1-5 ppm Au.

About 200 km to the northwest of the above occurrence, copper was mined between 1905 and 1914 from a mineralisation containing up to 5 wt% Cu, 1.5 ppm Au and 250 ppm Ag in the Kobberminebugt area. The mineralisation, mainly bornite and chalcocite, is hosted in veins and breccias that are controlled by a higher-order splay of a regional lineament. The hydrothermal Cu mineralisation comprises magnetite, hematite, chalcopyrite, electrum and native copper. The lineament cuts through rocks of the Julianehåb batholith and metavolcanic schist. Near by, south-west of the hydrothermal mineralisation, alkaline intrusive rocks of the Gardar suite occur. The rocks of the Gardar suite formed during Mesoproterozoic rifting of the Ketilidian Orogen after its formation. The IOCG mineralisation at Kobberminebugt is probably related to this extensional tectonics as indicated by Pb-isotope characteristics of the hydrothermal bornite.

The magnetic expression of the lineament in Kobberminebugt can be followed beneath the ice from the west coast of Greenland to the east coast in aeromagnetic measurements, showing the general potential for structurally controlled, magmatic-hydrothermal mineralisation in the region.

The southern contact zone of the Palaeoproterozoic Ammassalik mobile belt with the Archaean Craton in East Greenland is characterised by a series

of norite intrusions. The roof zones of these intrusions show breccia zones and up to 30 cm wide veins with a pronounced hematite mineralisation and potassic feldspar alteration. This occurrence has only been little explored, so it cannot be said with confidence that this is actually an IOCG deposit.

The Palaeoproterozoic Nagssugtoqidian orogen in West Greenland represents the western extension of the Ammassalik mobile belt to the east. The Arfersiorfik quartz- diorite intruded a crustal-scale shear zone of the orogen and is known to be magnetite-rich in places. A mineralised amphibolite containing 786 ppb Au, 1.7 wt % Cu and 520 ppm Co is known from a find near the southern extension of the Arfersiorfik

quartz-diorite. The close relationship between crustal-scale sequences and calc-alkaline intrusions with magnetite and albite alteration as well as a Cu-Au-Co occurrence is characteristic of IOCG mineralising systems.

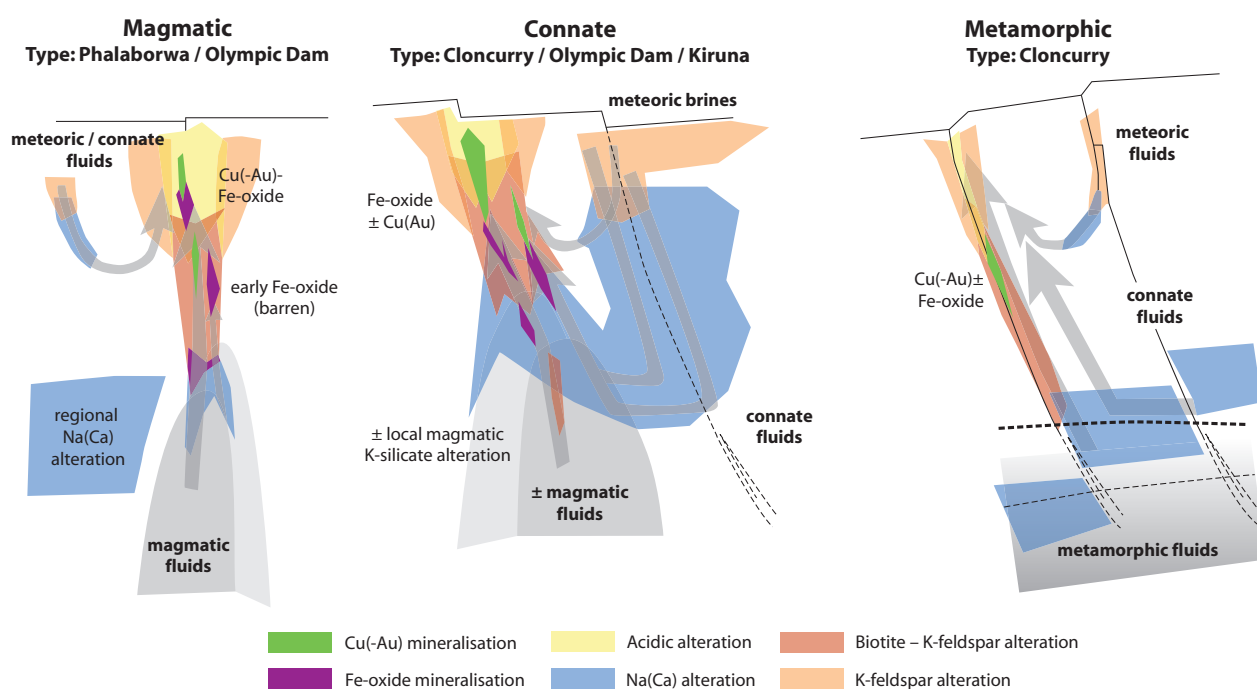
Cloncurry-type deposit

Southern West Greenland is underlain by the North Atlantic craton with several known occurrences of orogenic or lode gold mineralisation (e.g., Storø, Paamiut, Taartoq). In the Paamiut area an amphibolite-hosted breccia contains an iron oxide-Cu-Au mineralisation with a hydrothermal carbonate alteration halo at the Nigerleq Mountain. Further to the south similar occurrences are reported from north of the fjord



Breccia zone with copper mineralisation in Kobberminebugt near the Josva mine in South-West Greenland

Proposed Genetic Models for IOCG Mineralisation



Sermilik. However, the dimension of these mineralisations is rather small.

In North West Greenland, the Palaeoproterozoic Inglefield mobile belt hosts IOCG-like mineralisation in the so-called 'North Inglefield Land gold belt', however, only known from reconnaissance exploration. Gold contents between 0.2 and 12.5 ppm Au and up to 1.28% Cu are reported from a bornite, chalcopyrite, chalcocite, covellite, magnetite, hematite and gold accumulation. Regional east–west-trending fault zones host breccias cemented by hematite that are enriched in Cu and Au as well as a hydrothermal pyrite-barite-hematite alteration within a 4 km by 70 km north–east-striking corridor.

Bayan Obo-type deposit

The Neoproterozoic Sarfartoq carbonatite complex is located at the northern margin of the West Greenland Archaean craton. It forms a conical body of carbonatite and sodic fenite in the core and a marginal potassic hydrothermal alteration zone (75 km²) with hematite and carbonatite dykes. The hydrothermal

Nb, Ta, U and REE mineralisation occurs within this marginal zone in breccia veins associated with the alteration. The mineralisation comprises up to 40 wt % Nb₂O₅, 1 wt % Ta₂O₅ and 1 wt % U.

The Mesozoic Qaqqarsuk carbonatite complex forms a ring-dyke structure with dimensions at the surface of about 15 km². It hosts a Nb, U, REE, Ta and P mineralisation with 3.5 to 6 wt % P₂O₅ and up to 0.5 wt % Nb₂O₅ and < 1 wt % Ta₂O₅. The main Nb mineralisation is hosted by pyrochlore that is associated with sodic alteration and massive magnetite.

The recently discovered Tikiusaaq carbonatite complex is of Mesozoic age and anomalous contents of P, U and REE are reported. The appearance of this complex as a ring complex is very similar to the Qaqqarsuk complex.

IOCG potential in Greenland – the 'greenfields' approach

In the description above, some of the IOCG deposit types listed in the fact box are not discussed. These include the iron skarn-type and the Kiruna-type

both characterised by large-scale, massive magnetite bodies, which are easily recognised by geophysical surveys. Such massive magnetite bodies are not known from Greenland and, therefore, the potential for finding such a deposit is regarded as being low and restricted to the poorly studied areas in East Greenland.

Several carbonatite complexes are known from southern West Greenland but they all lack the distinct Cu mineralisation of the Phalaborwa-type deposits. Therefore the potential for Phalaborwa-type IOCG deposits in Greenland is evaluated as being very low. However, three of the carbonatites are spatially associated with a distal Nb, REE, U, Ta and P mineralisation typified by the Bayan Obo type.

The major characteristics of the Olympic Dam-type IOCG deposits are:

- craton margin setting
- associated with A-type and/or I-type magmatism



View at the possible IOCG mineralisation in Pariser Bugt, Inglefield Land, North-West Greenland

- two stages of mineralisation, early high-temperature iron oxide, late Cu-Au
- large-scale potassic alteration

Examples of this type in Greenland are occurrences in the numerous Proterozoic orogens and mobile belts surrounding the Archaean craton, namely the Ketilidian orogen and the Ammassalik mobile belt. These areas represent at the same time a craton margin setting. Furthermore, there is a large overlap with areas favourable for hydrothermal Cloncurry-type IOCG mineralisation.

The major characteristics of the Cloncurry-type IOCG deposits are:

- synchronous with regional metamorphism
- associated with I-type magmatism
- formed mainly between 1.8 – 1.4 Ga
- Cu-Au mineralisation overprints a BIF or an earlier hydrothermal iron oxide mineralisation

Small occurrences within the North Atlantic craton and the Cu-Au corridor in

the Inglefield mobile belt are examples of this type in Greenland. Favourable areas in Greenland that fulfil the geological characteristics listed above are located within the numerous Proterozoic orogens and mobile belts surrounding the craton nucleus. One distinguishing feature is that Cu-Au mineralisation overprints earlier iron oxides. Therefore, areas with known BIF and/or hydrothermal iron oxide mineralisation are fertile for IOCG mineralising systems.

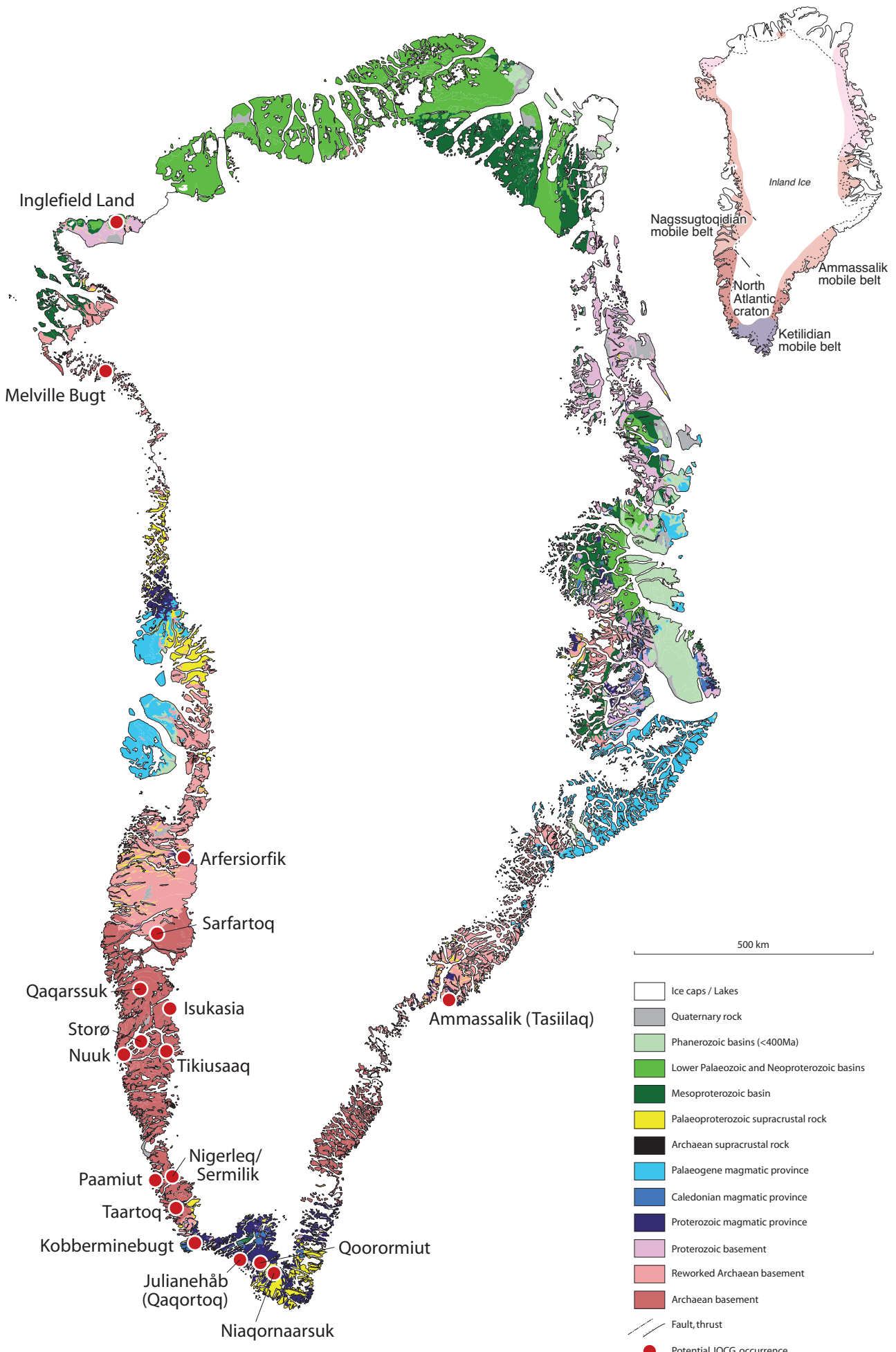
Small BIFs occur in the numerous supra-crustal belts of the craton, with a world class deposit at Isukasia. Sulphide-rich, hydrothermal mineralisation is, e.g., recognised at Isukasia and Taartoq. The genetic association of these occurrences within the IOCG class is, however, unclear. Similarly, numerous sulphide occurrences are identified in North-West Greenland around Melville Bugt, where the entire coastal strip is to a variable extent underlain by BIF horizons. These areas represent, therefore, promising targets for IOCG exploration.

In particular, the Ketilidian orogen in

South Greenland is regarded as being fertile for IOCG mineralisation, because it combines several of the important characteristics:

- craton margin setting
- associated with A-type and/or I-type magmatism: the Julianehåb batholith
- formation between 1.85-1.65 Ga
- numerous crustal-scale structures
- regional extension: the Gardar suite (ca. 1.35-1.15 Ga) with alkaline intrusions and sediment basins

Also the Nagssugtoqidian, Rinkian, Ammassalik and Inglefield orogenic systems are prospective for IOCG deposits. Crustal-scale structures, associated with alkaline, I-type intrusive rocks, host hydrothermal albite and iron oxide alteration as well as localised, small Cu-Au occurrences.



Potential IOCG occurrences in Greenland					
Locality	Type	Mineralisation	Alteration	Commodity	Ore body
Niaqornaarsuk/ Qoorormiut	Olympic Dam,	Fe-Cu sulphides with Au, magnetite	Sodic	Au, Bi, Ag, As, W, Cu, Mo	Veins, shear zones
Kobberminebugt	Olympic Dam	Cu sulphides with Au, magnetite, hematite	Epidote, fluorite, potassic	Cu, Au, Ag	Veins, brecciasa
Ammassalik	Olympic Dam	Iron oxide, sulphides ?	potassic	Cu ?	Breccias
Arfersiorfik	Olympic Dam	Iron oxide, sulphides ?	Carbonate	Cu, Au, Co	?
Paamiut/ Nigerleq	Cloncurry	Fe-Cu sulphides with Au, magnetite	Carbonate	Cu, Au	Veins, brecciasa
Inglefield Land	Cloncurry	Fe-Cu sulphides with Au, magnetite, hematite	Sodic, barite	Cu, Au	Veins, breccias, shear zones
Sarfartoq	Bayan Obo	Hematite, magnetite, apatite	Potassic (proximal); sodic (distal)	Nb, U, Ta, REE, P	Veins, layers
Qaqarssuk	Bayan Obo	Magnetite, apatite	Sodic	Nb, U, REE, P	Veins, layers
Tikiusaaq	Bayan Obo	Magnetite, apatite	Sodic	REE, P	Veins, layers

Concluding remarks

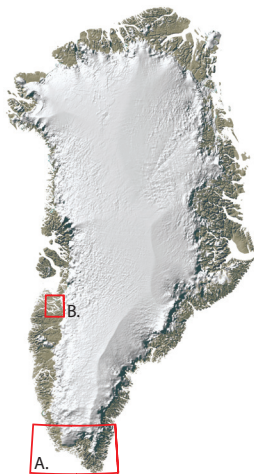
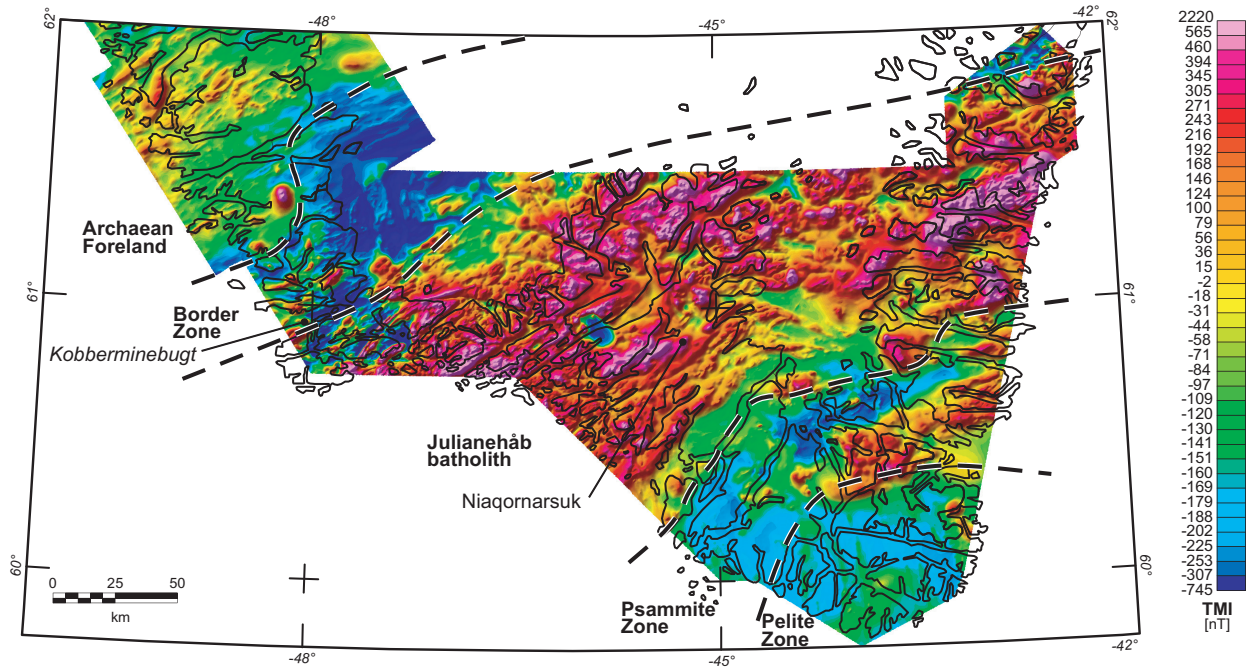
Greenland represents an area for grass-roots exploration posing a challenge to material and logistics and, therefore, also has a large potential for successful 'greenfields' exploration. Greenland has a long tradition of geological exploration and research and its south-western area is widely covered by measurements from geochemical and geophysical programmes, but in the north and the east only local areas are covered.

Although no definite IOCG deposit are recognised in Greenland to this date, some IOCG-like occurrences are suggested and favourable geological environments are observed. This indicates that the ice-free area in Greenland is generally fertile for IOCG deposits and that target-oriented 'greenfields' exploration has a good potential to locate IOCG occurrences or even deposits.

Gully with potassic / iron oxide alteration in the radioactive shear zone located marginally to the Sarfartoq carbonatite complex, southern West Greenland



A.



A. Total magnetic intensity field from regional aeromagnetic data for the Ketilidian orogen. The different segments of the orogen are clearly distinguishable from the magnetics, with the Julianehåb batholith reflected as high magnetic anomaly.

B. Total magnetic intensity field from regional aeromagnetic data covering the Arfersiorfik fjord. The central magnetite-bearing part of the Arfersiorfik quartz diorite shows up a highly magnetic anomaly that can be followed to the east. A Cu-Co-Au-bearing rock sample has been collected just south of the diorite near the Inland Ice. North and south of the diorite is the Nordre Strømfjord shear zone and Nordre Isortoq steep belt located; both crustal-scale structures of the Nagssugtoqidian orogen.



Brecciation near the Cu-Fe mineralisation at the coast north of Rødtop mountain, Kobberminebugt, South Greenland



Fault zone in paragneiss south of Arfersiorfik with malachite staining. Lenses with iron and copper-sulphides occur within the fault zones in this area, southern West Greenland.



View to the core area of the Sarfartoq carbonatite complex.

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Front cover photograph
Gossan zone, anomalous in Au, As, Cu and Zn, hosted by Palaeoproterozoic paragneiss, 10 km south of Marshall Bugt, central Inglefield Land.

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