GEOLOGY AND ORE

EXPLORATION AND MINING IN GREENLAND

Tungsten and tin occurrences in East Greenland

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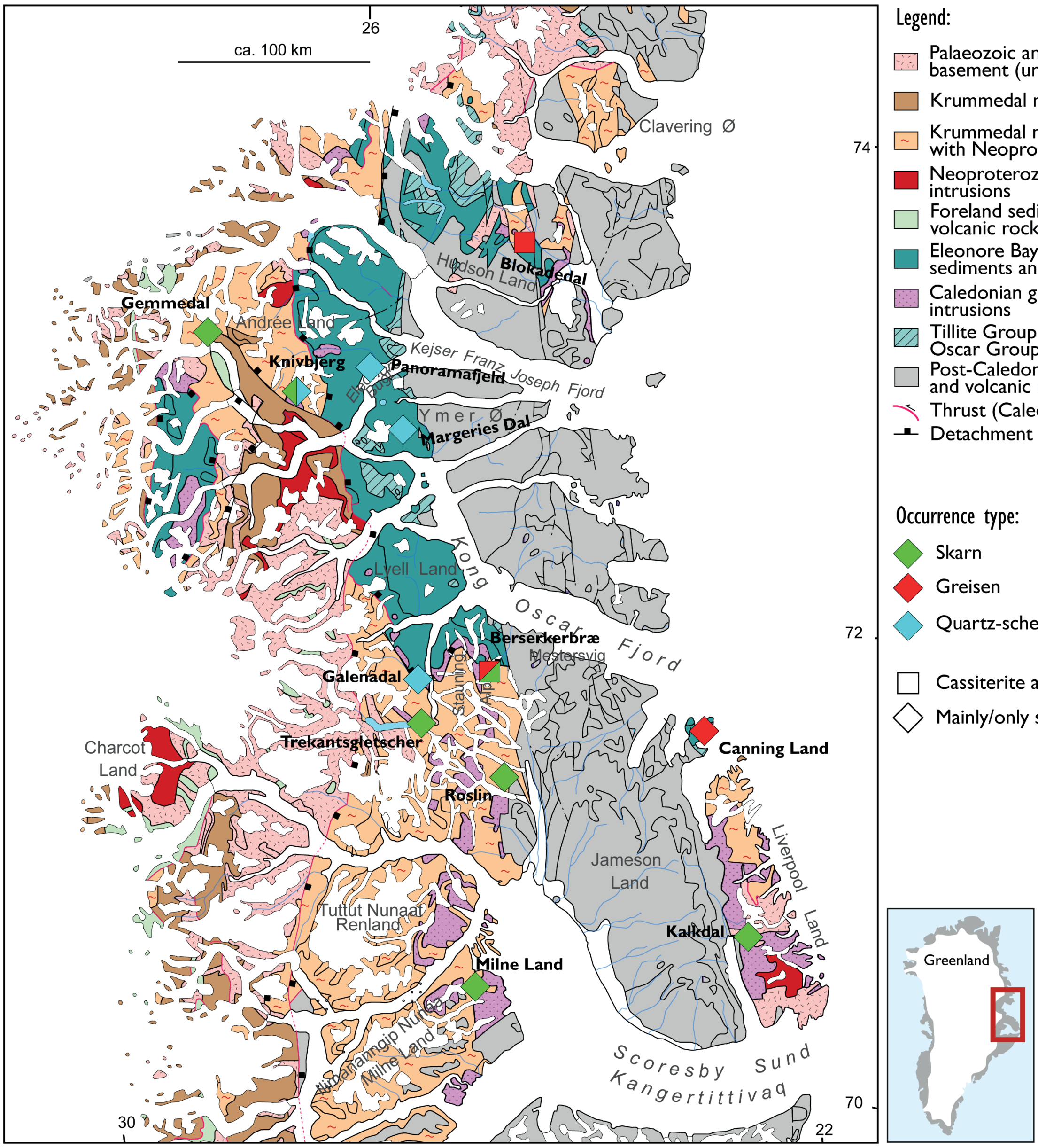
The East Greenland Caledonides host an array of tungsten (W) and tin (Sn) mineral occurrences, representing three different deposit types: skarn, greisen, and quartz-scheelite veins. Tungsten is found in scheelite and tin in cassiterite. The observed deposit types correspond to distinct geological processes driven by magmatic and metamorphic fluids during the Greenlandic Caledonides orogenic evolution. U-Pb dating, carried out at GEUS, of scheelite and cassiterite has led to the identification of three significant mineralisation pulses at ~425 Ma, ~400 Ma, and ~370 Ma. These correspond to the emplacement of S-type granites during thrusting, emplacement of A-type granites during the onset of syn-orogenic extension, and migration of metamorphic fluids released during late-orogenic extension, respectively. The first two pulses, related to magmatic fluids, formed skarn and greisen occurrences, and the latest event triggered the formation of quartz-scheelite veins. Trace element geochemistry on scheelite and cassiterite allows for the differentiation of the three studied deposit types. The geochemical fingerprinting provides a novel tool for identifying and differentiating cassiterite and scheelite deposit types, optimising early-stage exploration strategies in less-accessible terrain. Detailed analysis of mineral assemblages, geochemistry, U-Pb dating and structural controls have enhanced the understanding of the East Greenland mineral occurrences.

Introduction

Exploration efforts by Nordisk Mineselskab (Nordmin) during field campaigns in the 1960s to 1980s targeted scheelite occurrences, guided by stream sediment sampling. These field campaigns identified scheelite-rich skarns typically in Krummedal metasedimentary rocks, Sn-W-bearing greisen mainly formed in the lower part of the Eleonore Bay Supergroup (EBS), and structurally controlled quartz-scheelite veins often seen in the upper EBS, but also in other rock types. Nordmin's initial focus revolved around high-grade W occurrences in skarns, greisen, pegmatites, and especially in quartz-scheelite veins. In Margeries Dal, a resource was delineated, with 82 000 tons with a diluted concentration of 2.3 wt% W, with concentrations up to 24 wt% in drill cores half metre intervals. Subsequent work by GEUS highlighted the potential of cassiterite-bearing systems and their association with greisenised granite. From the 1990s-2000s further

Scheelite and calcite veining from Margeries Dal, Ymer Ø, tungsten occurrence. Photo: 21stNorth.



Geological map of East Greenland (ca. 70-76 °N), showing the main geological units, sample localities for Sn and W occurrences with their main mineralisation deposit types.

limited exploration for W or Sn in the East Greenland Caledonides was mainly performed by NunaOil-NunaMinerals A/S, as well as more recently by SRK Exploration and Greenfield Exploration Ltd.

Within the scope of the European Union co-financed EIT-Raw Materials project MinExTarget and the Tin&Tungsten project financed by the Greenlandic Government and GEUS, samples of these occurrences have been studied in detail and the results of these investigations are summarised herein.

Geological Setting

The East Greenland Caledonides (~70°N to ~82°N) formed during the Silurian and early Devonian Laurentia-Baltica collision (~420 Ma). The basement in the area between 70-74°N is composed of Archean or Palaeoproterozoic orthogneiss complexes. The Krummedal supracrustal sequence, a series of high-grade metamorphic metasediments, overlies the orthogneisses and consist of migmatitic metasedimentary rocks derived from sandstone, mudstone, and locally calcareous mudstone and limestone, deposited between 1050 Ma and 950 Ma. The Neoproterozoic EBS was deposited on top, reaches a stratigraphic thickness of 13-16 km, and comprises a sequence of unmetamorphosed to low-grade metamorphosed shallow-marine sediments. The Greenlandic Caledonides consist of two major thrust sheets, and all known W- and Sn-enriched occurrences are found in the Hagar Bjerg thrust sheet and overlying allochthonous sedimentary rocks (EBS). These basement and supracrustal units were intruded by Caledonides granites, including I-type, S-type muscovite-biotite leucogranites (~425 Ma) and A-type nearly undeformed alkaline

Skarn in marble at Knivbjerg, Andrée Land.

peraluminous granites (~400 Ma), and emplacement of the latter two was critical to the region's W-Sn endowment. Subsequently, during the Mid and Late Devonian (~370 Ma), syn- to post-orogenic extensional events and detachment faulting lead to the mobilisation of fluids in the upper crust.

Skarn Deposits

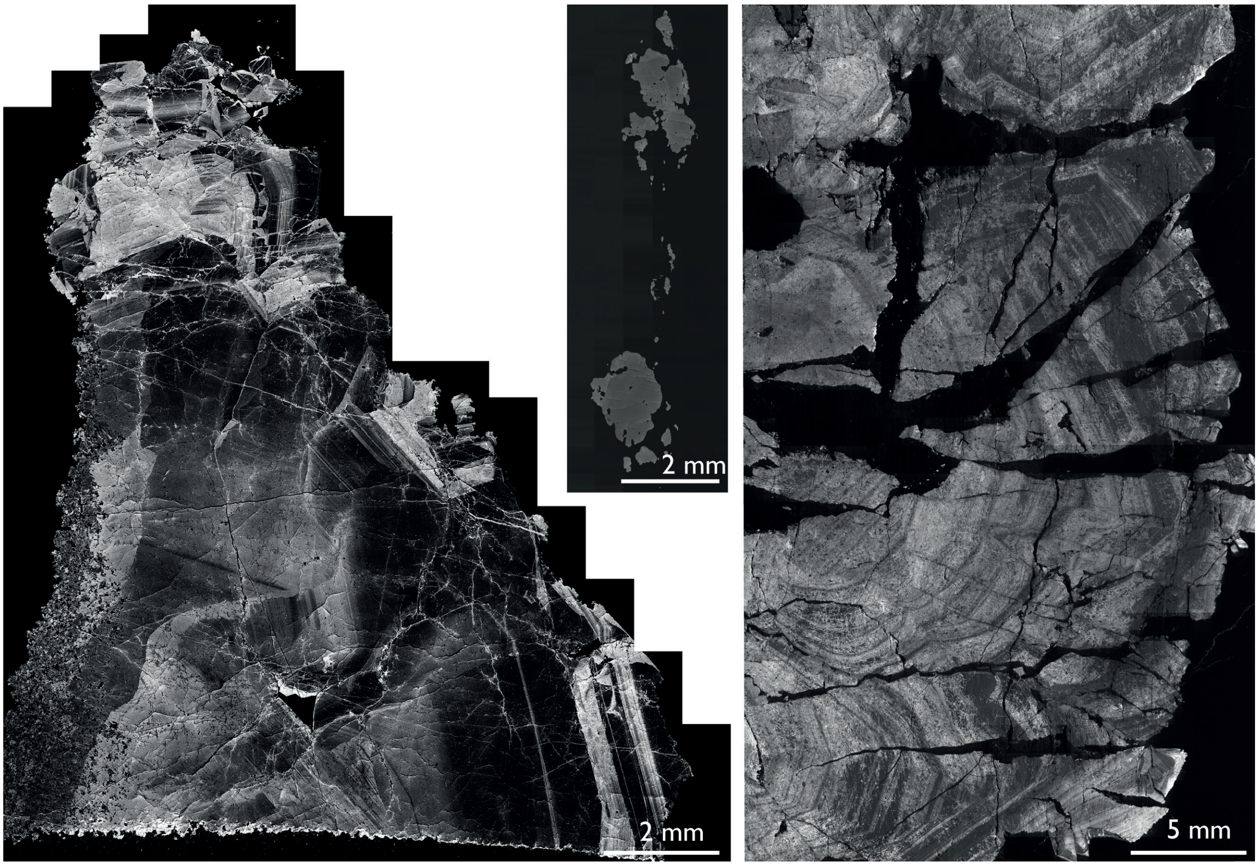
The scheelite-bearing skarn occurrences in the Caledonites occur in marbles or calcium-rich schists in the Krummedal metasedimentary rocks. Skarns are typically coarse-grained rocks with diopside, augite, and wollastonite, often with garnet (grossular or almanditic grossular) or clinozoisite. These minerals form distinct zones, aligning with the host rock's foliation or structural features. Scheelite is commonly associated with these calc-silicate minerals, often growing at mineral zone boundaries. Skarns exhibit high-temperature metamorphic textures, with large pyroxene and garnet crystals, and interstitial calcite with impurities, indicating complex metasomatic interactions.

At **Knivbjerg**, the mineral assemblage includes wollastonite, diopside, clinozoisite, and apatite. Wollastonite grows as small grains following the foliation, whereas clinozoisite and especially diopside are observed as large grains growing across the foliation in a random orientation. Scheelite occurs in zones that bear relict evidence of small intruding veins. U-Pb dating of scheelite yields an age of 410 ± 27 Ma, linking mineralisation to the emplacement of either the S-type granites or the A-type granites.

In **Gemmedal**, scheelite occurs both in skarnified marbles and mica-schists. The garnet-rich skarns (grossular, diopside, wollastonite, clinozoisite) dominate. The formation of garnet rather than diopside suggest a more aluminous host rock composition. Scheelite occurs in oscillatory-zoned (in CL) irregularly dispatched crystals, reflecting episodic fluid influx, where scheelite formed interstitially between wollastonite, calcite and quartz. The scheelite in the skarn samples could not be dated.

The **Trekantsgletscher** skarns consist of grossular, augite, anorthite, and quartz, locally intergrown with scheelite. Other samples have a mineral assemblage including muscovite or sericite, fluorite, apatite suggesting the presences of hydrothermal fluids. Absolute dating of scheelite of 410 ± 21 Ma, aligns temporally with the intrusion age of the Devonian A-type granites.

At **Roslin**, the mineral assemblage in the scheelite-bearing skarn consists of augite, wollastonite, anorthite, muscovite, and pyrite. Scheelite grains are homogeneous in CL, some show a dispersed array of small grains in thin section. Estimated scheelite U-Pb dates



Cathodoluminescence (CL) images of cassiterite from a greisen sample from Berserkerbræ (right) and scheelite skarn from Knivbjerg (centre) and a vein (Margeries Dal; left). CL shows the growth phases in crystals in different shades of grey. Skarn grains typically show no internal structure while cassiterite and scheelite formed in magmatic or metamorphic veins can show a clear oscillatory zonation.

(397 ± 42 Ma) suggest a possible link to Devonian granitic intrusions.

The **Kalkdal** scheelite skarns are mainly formed in dolomitic marbles. The occurrences contain augite, diopside, actinolite, wollastonite, clinozoisite, grossular. Calcite in these assemblages contains significant silica impurities, possibly reflecting the inclusion of clay particles during intense metasomatic activity. Scheelite formation in Kalkdal is well dated at 394 ± 4 Ma, consistent with the age of magmatic activity around 400 Ma.

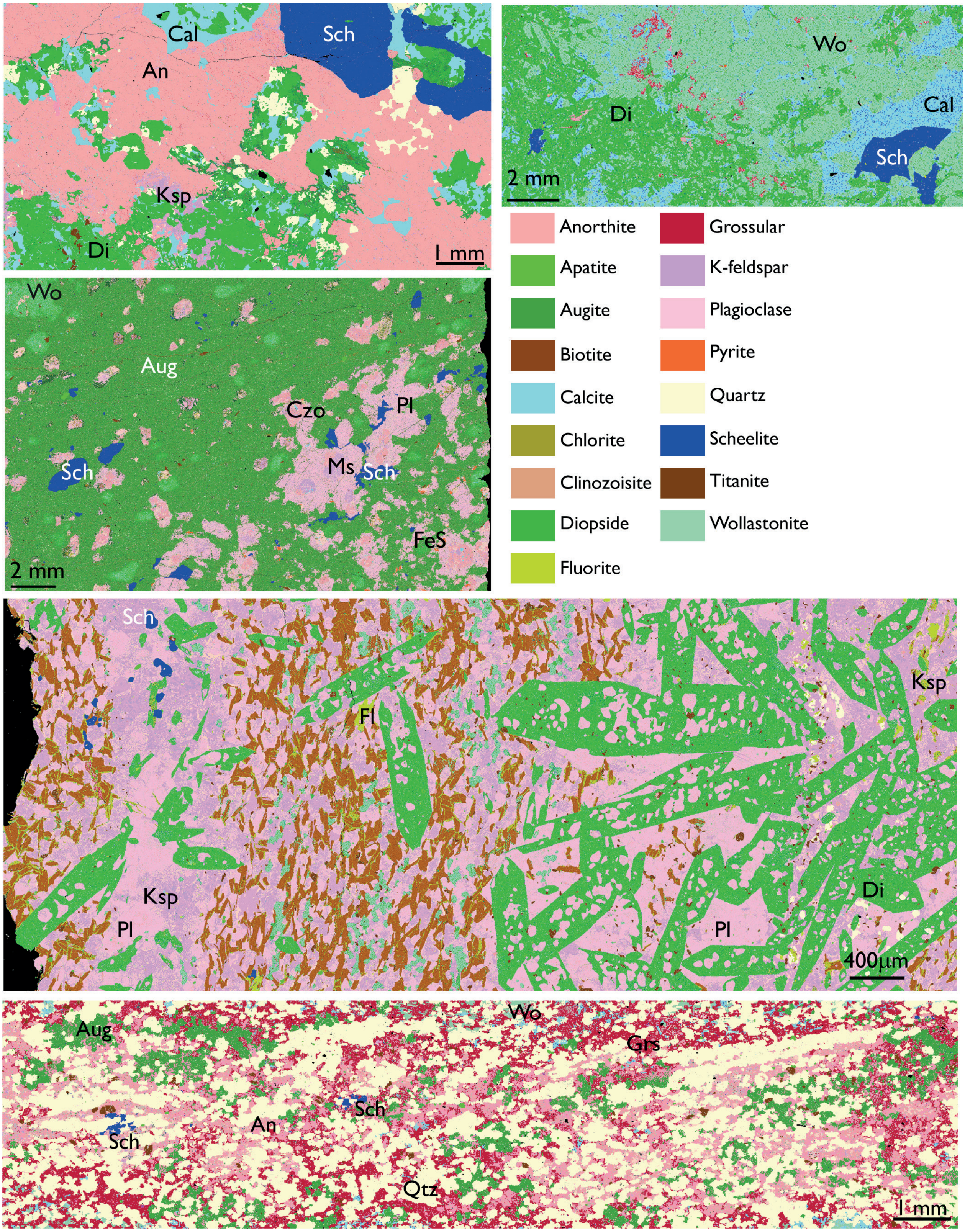
On **Milne Land**, the scheelite skarns are formed in marbles and are characterised by grossular, tremolite or diopside, anorthite, abundant calcite and quartz, and with minor amounts of cassiterite in some samples. The formation age of scheelite (421 ± 21 Ma) probably aligns with the S-type granite emplacement.

Greisen Deposits

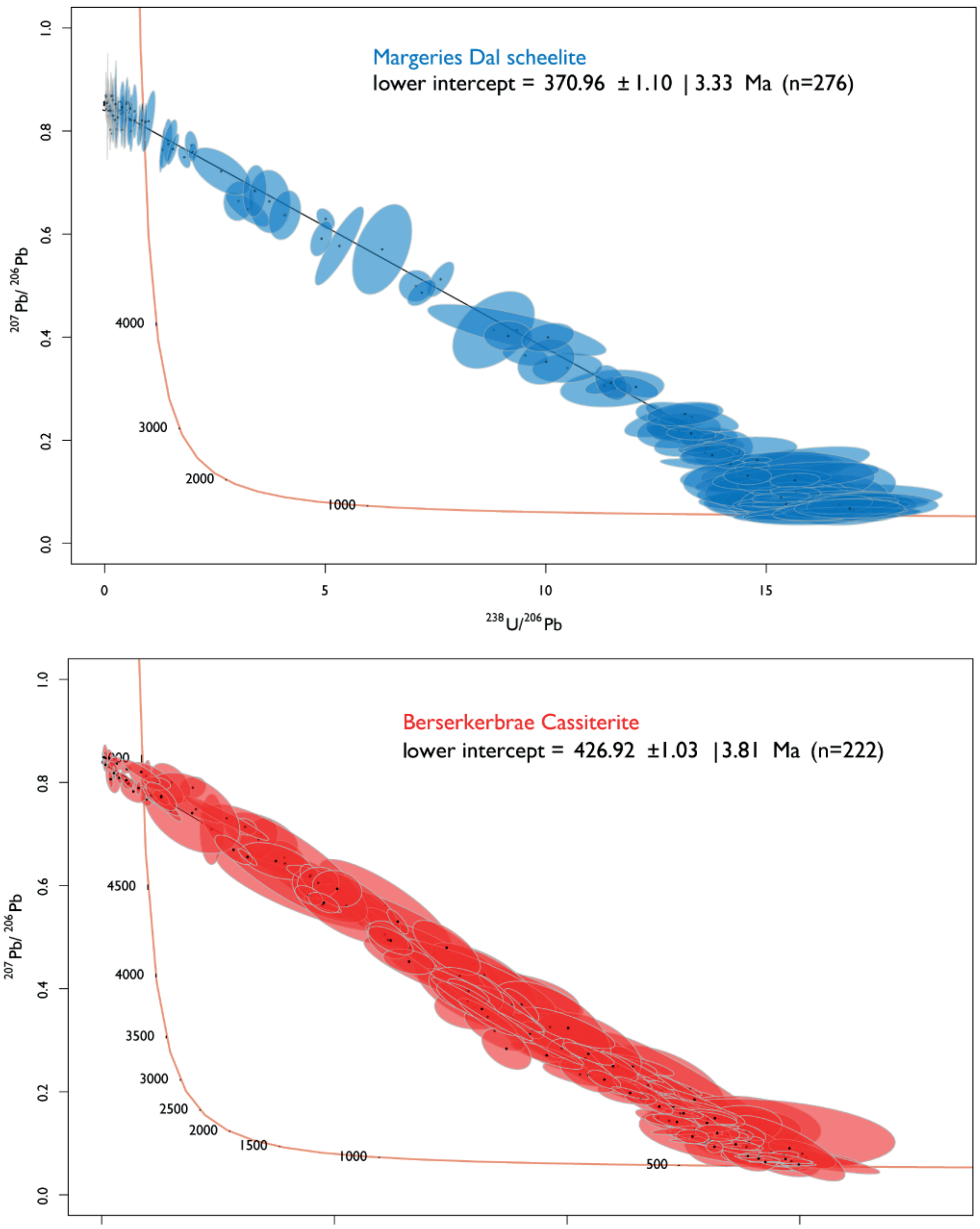
The greisen occurrences in East Greenland host cassiterite, scheelite or both. The greisen zones are characterised by a fine-grained texture with abundant muscovite, quartz, chlorite, and albite. These minerals replace earlier feldspar-bearing rocks, creating a highly altered matrix with varying amounts of cassiterite and scheelite crystals. Fluorite appears as small grains and larger veins, either contemporary with or cutting through the greisen assemblage. Greisen occurrences seem to prevail in the lower EBS sediments.

Mineralisation in **Blokadedal** is only observed in floats within glacier moraine. Higher in the valley, an outcropping fertile A-type granite may be linked to this mineralisation. Cassiterite is found

Hand specimen of garnet-bearing skarn.



Mineral maps of skarn samples from Kalkdal (two at the top), Roslin, Knivbjerg and Trekantsgletscher. Mineral maps are created with a Scanning Electron Microscope with Automated Quantitative Mineralogy (AQM) software.

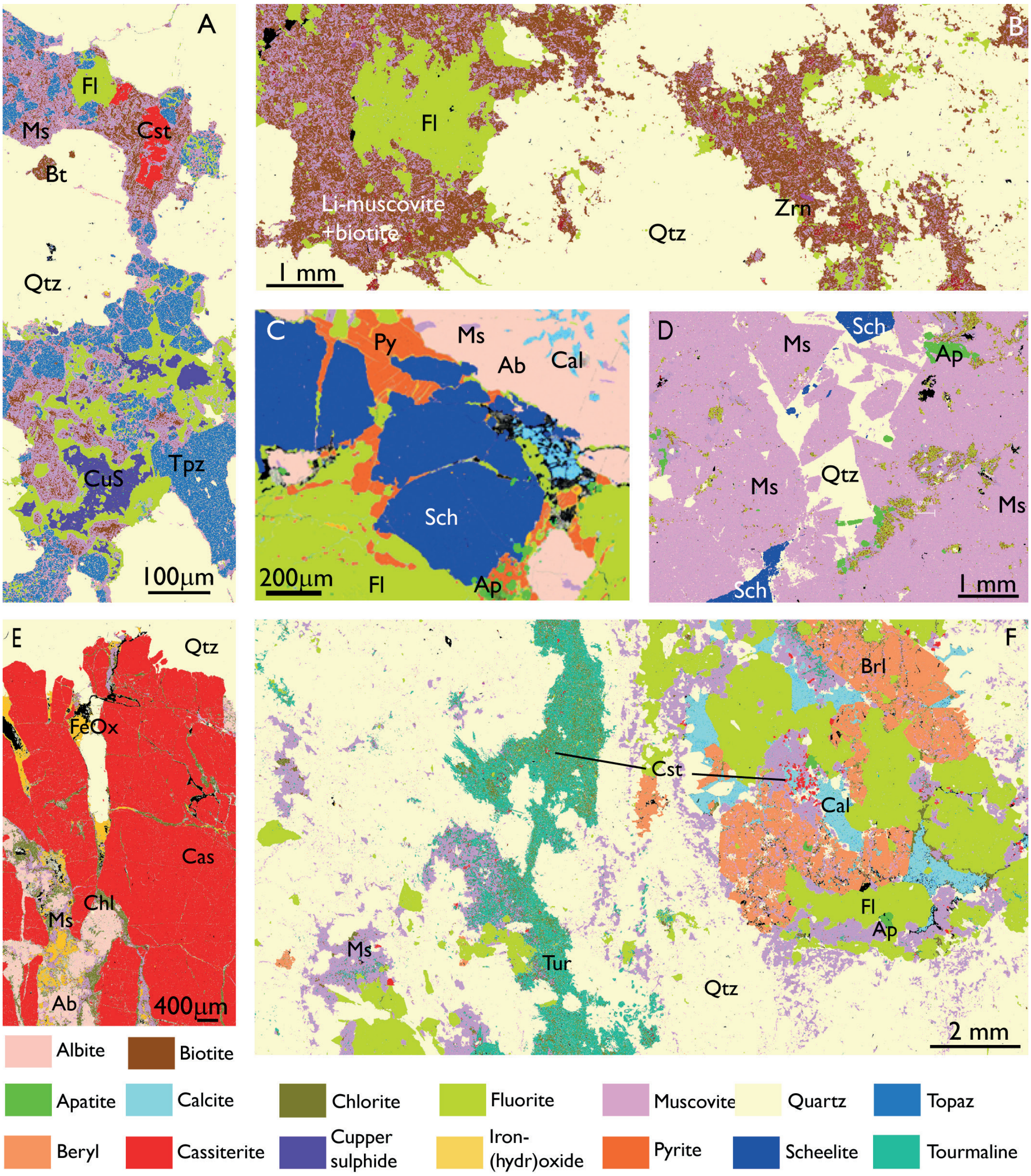


Examples of U-Pb age plots for scheelite (above) and cassiterite (below). Samples were dated with Laser ablation-ICPMS.

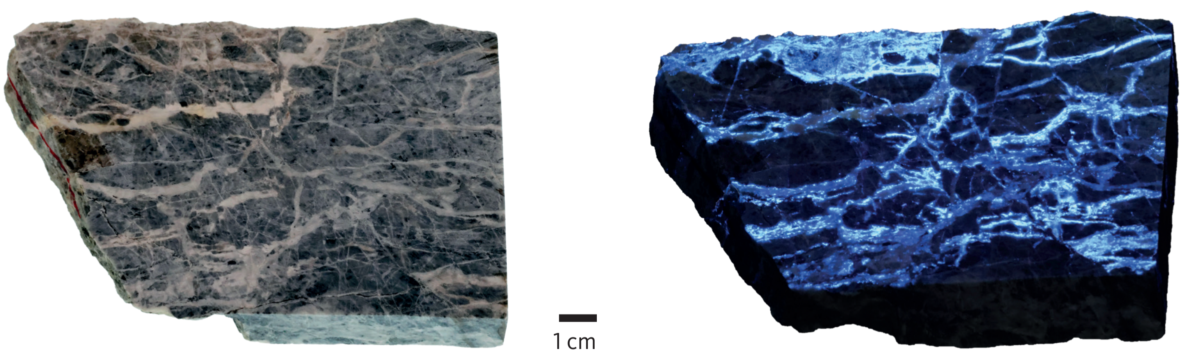
in quartz-rich veins with Li-bearing muscovite, biotite, tourmaline, fluorite, topaz, and beryl. It is finely dispersed in muscovite or tourmaline and associated with aluminosilicates. The samples appear to represent different parts of the greisen system varying from greisenised granite (endogreisen) to country rock affected by greisenisation and cross-cutting tourmaline-fluorite-quartz-cassiterite-bearing hydrothermal veins (exogreisen). Cassiterite U-Pb dating indicates two distinct phases of mineralisation: 387 ± 7 Ma for the exogreisen and 369 ± 3 Ma in the endogreisen, suggesting that the mineralisation within the granites cooled more slowly than that hosted in the country rock.

The **Berserkerbræ** greisen hosts cassiterite in quartz-muscovite veins, with scheelite occasionally found in the same mineral assemblages. Additionally, the samples contain muscovite (lepidolite), fluorite, apatite, albite and a range of sulphide minerals including arsenopyrite. Cassiterite shows both complex sector zoning and oscillatory zonations in different samples in CL, whilst fractures are filled in with secondary pyrite and muscovite. Dating yields 427 ± 1 Ma for cassiterite and 430 ± 37 Ma for scheelite in the greisen.

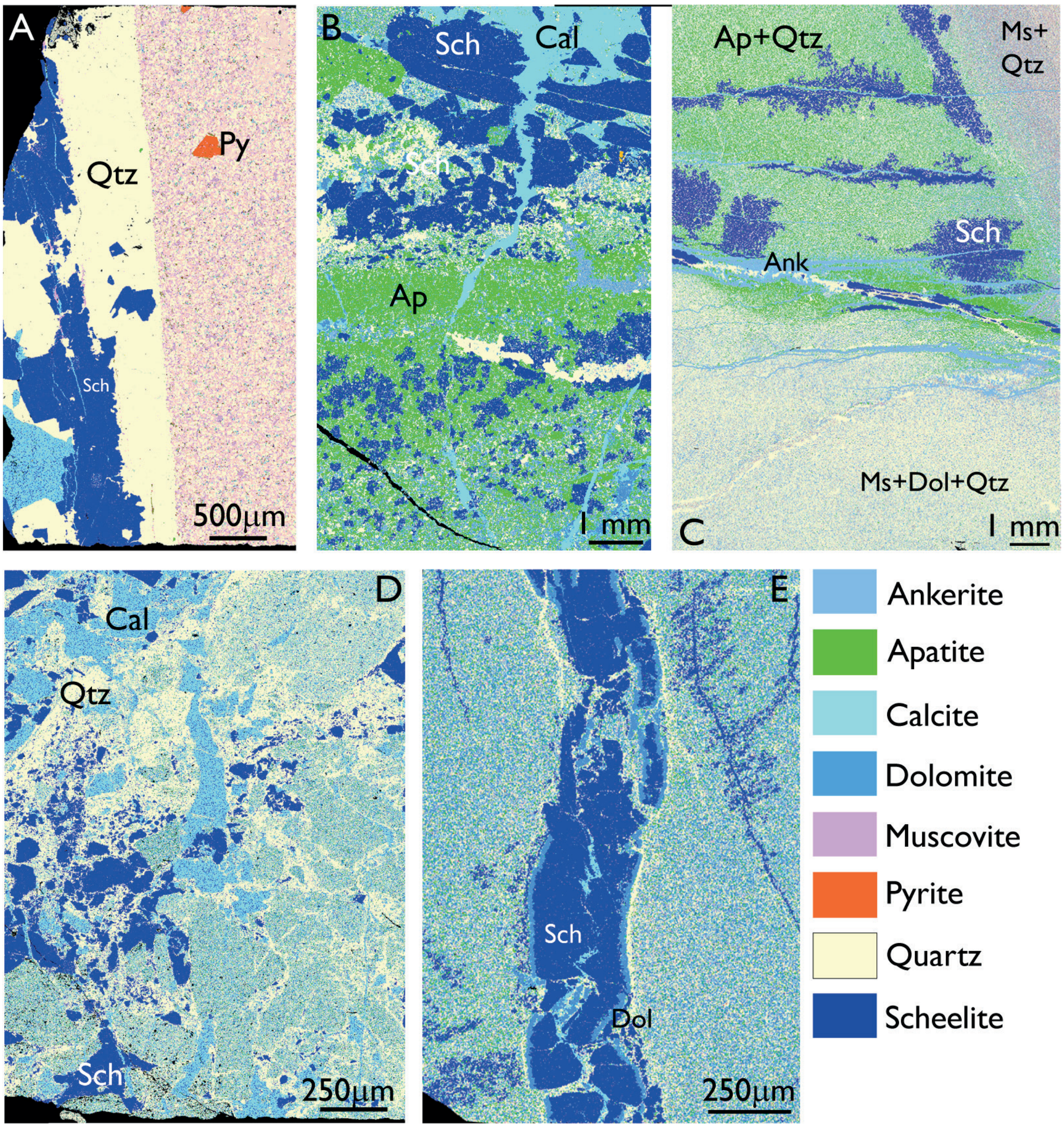
The **Canning Land** greisen, features scheelite associated with quartz, muscovite, chlorite and albite. Minor amounts of cassiterite are observed in samples collected from greisen too. None of the minerals in the samples could be dated with U-Pb.



AQM Mineral maps of greisen samples with either cassiterite and scheelite from Blokadedal (A,B, F) Berserkerbræ (C,E) and Canning Land (D).



Hand specimen of brecciated veins from Margeries Dal or Panoramafjeld in visible light (left) and UV light (right).



AQM Mineral maps of quartz-scheelite veins samples from Galenadal (A), Margeries Dal (B,C) and Panoramafjeld (D,E).

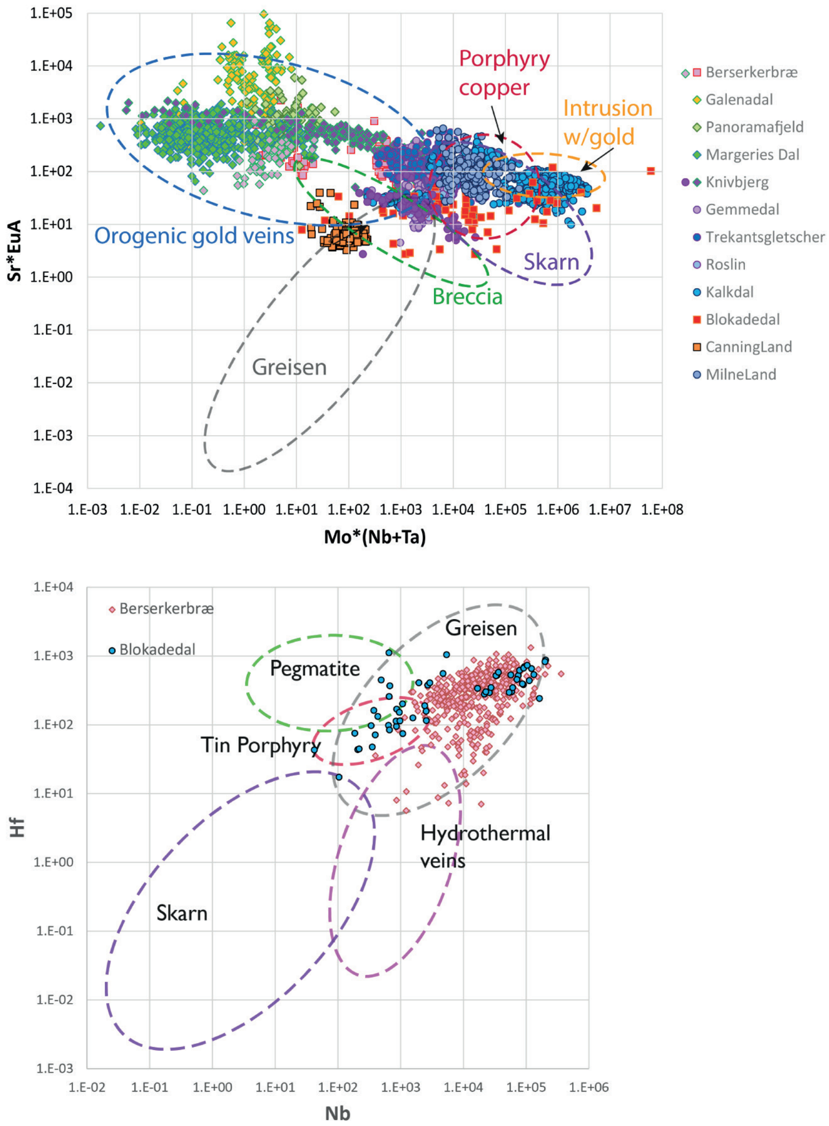
Quartz-Scheelite Veins

The quartz-scheelite veins often occur in brecciated host rocks that consist of fine-grained sediments rich in dolomite, quartz, and apatite. Quartz-scheelite veins are usually intersected by dolomite bands, pyrite-rich layers, and calcite veins. In CL, the scheelite often shows zonation, indicating multiple fluid influx phases. These veins cut through various fractured host rocks, mostly through upper EBS rocks, but for instance in superposed occurrences, also in Krum-medal and lower EBS.

At **Margeries Dal**, scheelite occurs in cross-cutting quartz veins alongside dolomite, pyrite, and locally stibnite, sphalerite, galena and chalcopyrite. Scheelite is only found where these veins cut through bituminous lime-stone. Zonation in scheelite under CL reflects episodic fluid pulses, whilst U-Pb dating places mineralisation at 371 ± 1 Ma. These veins are interpreted as forming during late-orogenic extension.

Scheelite at **Panoramafjeld** is found in calcite-rich limestones, associated with dolomite, quartz, and late-stage calcite veins. It is texturally linked to quartz veins and dolomite formation, with later calcite veins intersecting earlier mineral assemblages. The setting is very similar to Margeries Dal, and both occurrences also have the same scheelite U-Pb date, 370 ± 4 Ma for Panoramafjeld. In some samples, scheelite appears as small, dis-persed grains without quartz, suggest-ing simpler mineralogical associations.

At **Galenadal**, scheelite is found in calc-silicate layers within metamorphosed sediments, often in quartz-scheelite veins or as dispersed grains in calcite-rich lenses. The mineral assemblage includes quartz, calcite, and pyrite. Scheelite shows oscillatory zoning in CL, especially in the upper calc-silicate



Trace element distributions in scheelite (above) and cassiterite (below) for samples from East Greenland compared to literature data (in ellipses) analysed with LA-ICPMS. Elemental concentrations are in µg/g.

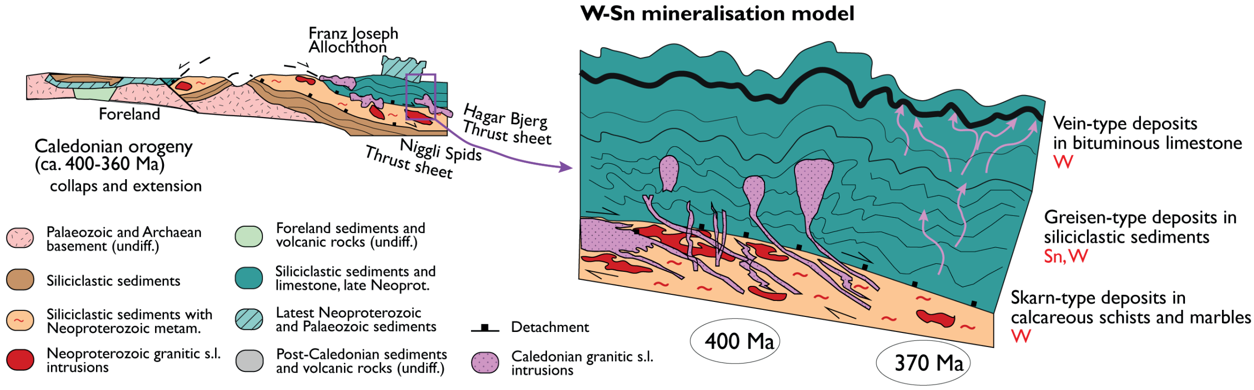
layers, and is texturally linked to reaction zones between quartz and calcite. The younger scheelite age of 352 ± 4 Ma aligns with the waning stages of regional tectonic activity.

At **Knivbjerg**, described above for its scheelite in skarn, a second generation of scheelite observed in quartz-scheelite veins, mainly formed in the schists in the area. Scheelite typically forms near the outer rims of the quartz veins. Scheelite shows an oscillatory zonation when observed with the CL detector in the SEM. The U-Pb date for this scheelite generation is significantly younger at 332 ± 34 Ma.

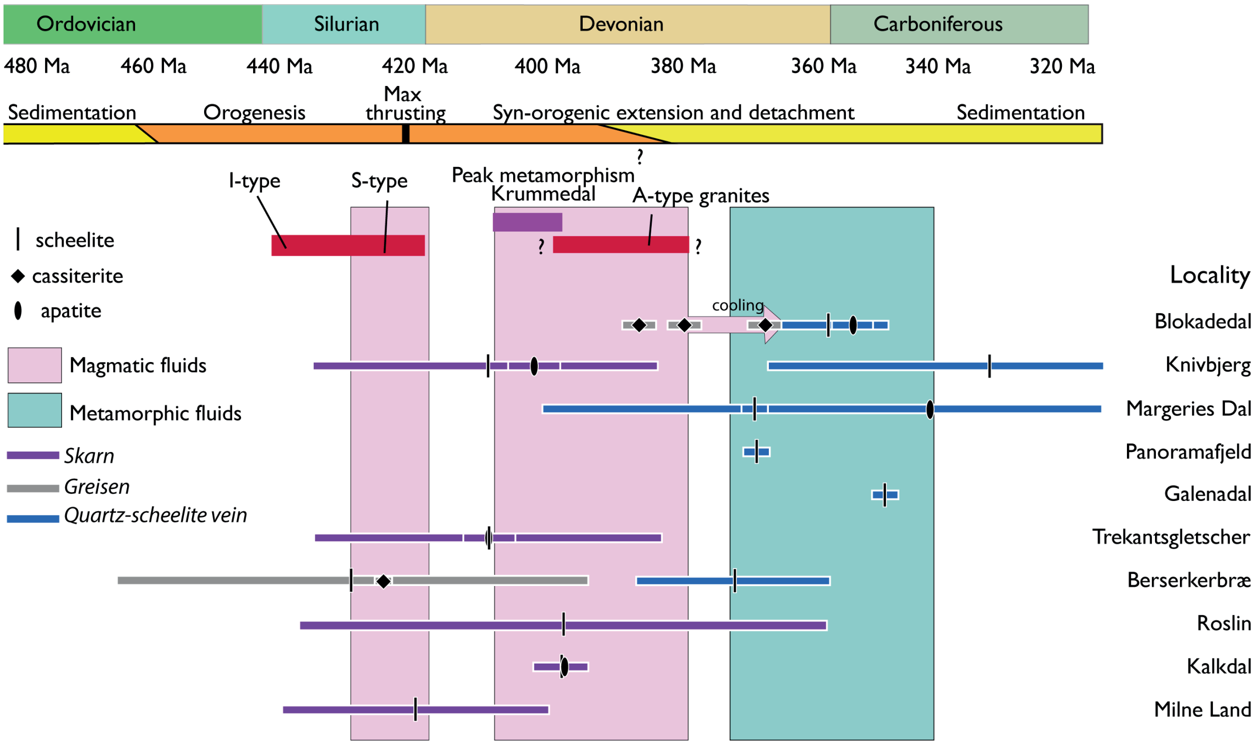
Also, in **Berserkerbræ** quartz-scheelite veins cut across the earlier greisen generation. The quartz-scheelite veins cut discordantly through the wall-rock and dispersed scheelite grains are seen in the matrix of the garnet-bearing host-rock. The age of these scheelite grains was dated to 375 ± 16 Ma.

Trace elements

Minerals in ore deposits reflect specific fluid or melt compositions, distinct from those in barren rocks, affecting the trace element concentration of ore minerals and associated phases. Furthermore, each different deposit type can potentially have its own trace elements signature in certain minerals. Therefore, the trace element concentrations in minerals associated with specific mineralisation events can help identifying



W-Sn mineralisation model for the East Greenland Caledonides. Based on Higgins et al. 2004, Hallenstein & Pedersen 1982, and Strachan et al. 2001.



Overview of all obtained mineralisation ages in this study, plotted together with main events in the Caledonian orogenesis.

nearby ore deposits, even those hidden beneath tills, glacial deposits, or located upstream rivers. Scheelite and cassiterite can be linked to skarn, greisen, orogenic gold veins and other deposit types applying multivariate statistics or simply 2D discrimination diagrams.

Timeline for the mineralisation process

The East Greenland Caledonides host Sn-W-greisen, W-bearing skarns, and quartz-scheelite veins. Scheelite and cassiterite occurrences are found, in the Hagar Bjerg thrust sheet, formed during the Upper Silurian to Lower Carboniferous. High-temperature metamorphism or granite emplacement initiated the mineralisation process. S-type granites were emplaced during the latest Silurian (~425 Ma), contemporaneous with main stage thrusting and collision. Heat was transported to the Krummedal sequence metasediments, likely promoting partial melting, and subsequently causing fractionation of Sn and W in the magma and ultimately buildup in magmatic hydrothermal fluids. During the Devonian (~400 Ma), A-type granitic magmatism, resulting from partial melting of the Krummedal sequence metasediments, led to the emplacement of large granite bodies. Magma and magmatic-hydrothermal fluids reacted with the marbles and Ca-rich parts of the metasedimentary rock in the Krummedal metasediments to form skarns. The same magma was also emplaced into the overlying lower EBS, leading to the formation of greisen occurrences in siliciclastic rocks.

Quartz-scheelite veins likely formed from metamorphic fluids during syn-orogenic extension and detachment faulting. These fluids, derived from granulite facies metamorphism at large depth, migrated to shallower depth causing brittle fracturing and metal concentration, precipitating scheelite where meeting reducing bituminous limestone beds.

Implications for exploration

Establishing of the trace element composition of scheelite and cassiterite in stream sediments offers a powerful tool for mineral exploration. For instance, scheelite trace element geochemistry can distinguish skarn, greisen, and vein deposit types based on Mo, Sr, Nb, and Ta. Similarly, cassiterite trace element pairs like Nb/Hf and Ta/Ga provide insights into the typology of its source deposits.

To target scheelite-bearing skarns, exploration should be directed towards A-type or S-type granitic contacts in the Krummedal metasediments or lower EBS units to find scheelite-bearing skarns. A-type or S-type fertile granites with muscovite-albite alteration intruding into EBS should be explored to find greisen with cassiterite or scheelite. Fault zone systems cross-cutting reducing rock types in rocks that were at the brittle-ductile transition temperature condition during the orogenic extension should be investigated to find quartz-scheelite veins.

Parkinson Bjerg with fertile granite intrusion in background, with Blokadedal glacier and moraine with Sn-W mineralised float and Arve river with enhanced trace element concentration in stream sediments in the foreground (looking NW).

Key references

Gilotti, J.A., McClelland, W.C. 2008: Geometry, kinematics, and timing of extensional faulting in the Greenlandic Caledonides – A synthesis. In: Higgins, A.K., Gilotti, J.A. & Smith, M.P. (eds.). The Greenland Caledonides – evolution of the northeast margin of Laurentia. Geological Society of America Memoir 202, 251-271.

Hallenstein, C., Pedersen, J. 1982: Study of Scheelite Mineralization in Central East Greenland. Nordisk Mineselskab A/S, 152pp. GEUS Dodex file report 20688.

Hansen, B.T., Steiger, R.H., Henriksen, N. & Borchardt, B. 1987: U-Pb and Rb-Sr age determinations on Caledonides plutonic rocks in the central part of the Scoresby Sund region, East Greenland: Rapp. Grønl. Geol. U. 162, 139-151.

Higgins, A.K., Elvevold, S., Escher, J.C., Frederiksen, K.S., Gilotti, J.A., Henriksen, N., Jepsen, H.F., Jones, K.A., Kalsbeek, F., Kinny, P.D., Leslie, A.G., Smith, M.P., Thrane, K., Watt, G.R. 2004: The foreland-propagating thrust architecture of the East Greenland Caledonides 72–75 N. Journal of the Geological Society, London, 1661, 1009-1026.

Kalsbeek, F., Higgins, A.K, Jepsen, H.F., Frei, R., Nutman, A.P. 2008: Granites and granites in the East Greenland Caledonides. In: Higgins, A.K., Gilotti, J.A. & Smith, M.P. (eds.). The Greenland Caledonides – evolution of the northeast margin of Laurentia. Geological Society of America Memoir 202, 227-249.

Keulen, N., Heredia, B., Malkki, S.N., Rosa, D., Thomsen, T.B., Whitehead, D. & Hajir Azad, N. 2024: Tin and tungsten occurrences in North-East and central East Greenland (ca. 70-74°N). Final report based on the activities in 2022-2024. GEUS report 2024/32.

Keulen, N., Malkki, S.N., Graham, S. 2020: Automated Quantitative Mineralogy Applied to Metamorphic Rocks. Minerals 10, 47, 29pp. DOI: 10.3390/min10010047

Steenfelt, A. 1982: Uranium and selected trace elements in granites from the Caledonides of East Greenland. Mineralogical Magazine 46, 201-210.

Strachan R.A., Martin M.W., Friderichsen, J.D. 2001: Evidence for contemporaneous yet contrasting styles of granite magmatism during extensional collapse of the northeast Greenland Caledonides. Tectonics 20, 458-473.

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Front cover photograph
Sets of quartz-scheelite veins crosscut the Eleonore Bay Supergroup rocks at Salevebjerg, Hudson Land.

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