Mafic igneous rocks and mineralisation in the Palaeoproterozoic Ketilidian orogen, South-East Greenland: project SUPRASYD 1996

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The multidisciplinary SUPRASYD project (1992–96) focused on a regional investigation of the Palaeo-proterozoic Ketilidian orogenic belt which crosses the southern tip of Greenland. Apart from a broad range of geological and structural studies (Nielsen *et al.*, 1993; Garde & Schønwandt, 1994, 1995; Garde *et al.,* 1997), the project included a mineral resource evaluation of the supracrustal sequences associated with the Ketilidian orogen (e.g. Mosher, 1995).

The Ketilidian orogen of southern Greenland can be divided from north-west to south-east into: (1) a border zone in which the crystalline rocks of the Archaean craton are unconformably overlain by Ketilidian supracrustal rocks; (2) a major polyphase pluton, referred to as the Julianehåb batholith; and (3) extensive areas of Ketilidian supracrustal rocks, divided into psammitic and pelitic rocks with subordinate inter-stratified mafic volcanic rocks (Fig. 1). The Julianehåb batholith is viewed as emplaced in a magmatic arc setting; the supracrustal sequences south of the batholith have been interpreted as either (1) deposited in an intra-arc and fore-arc basin (Chadwick & Garde, 1996),
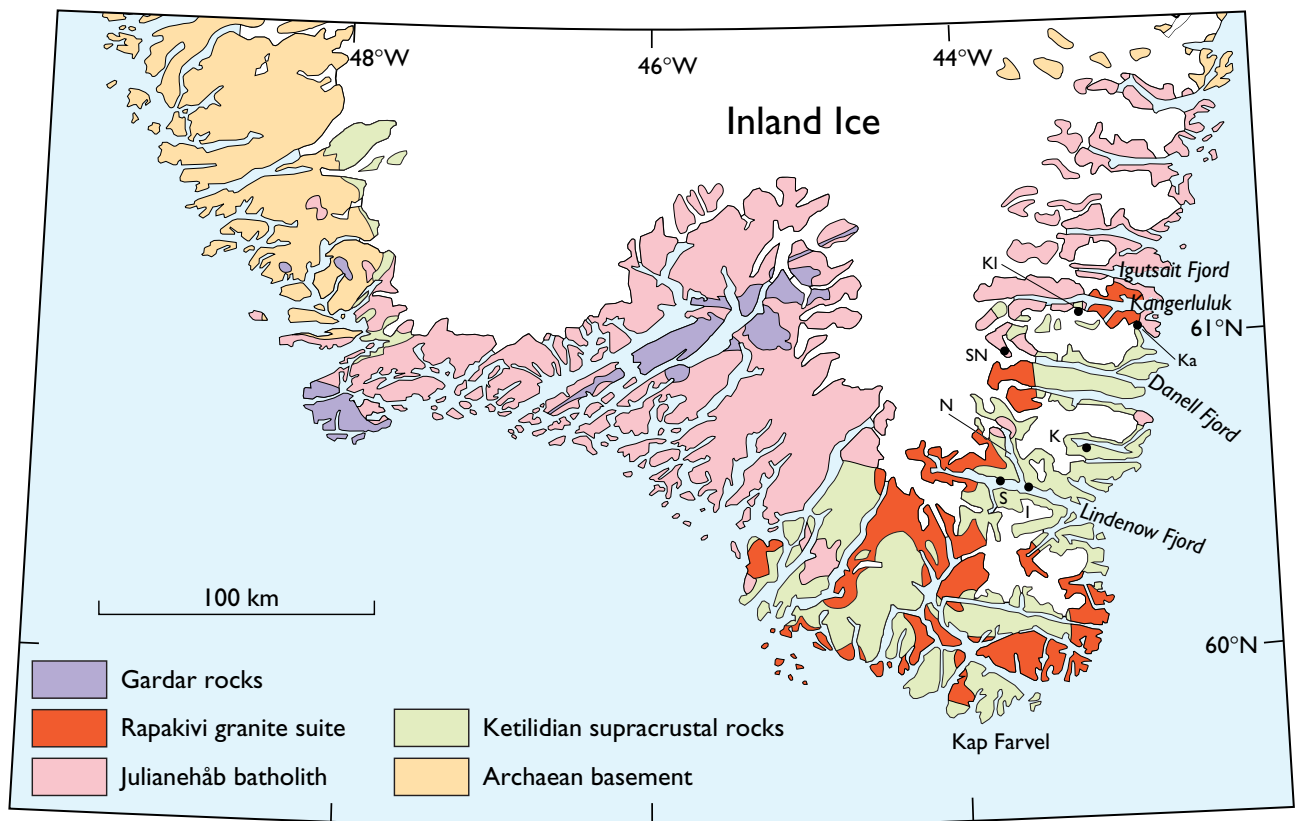

Fig. 1. Locality and geological map of South Greenland, modified after Garde & Schønwandt (1994). The Ketilidian orogenic belt is dominated by the intrusive complex of the Julianehåb batholith. The black dots indicate localities discussed in the text: I= Illukulik; N = Nørrearm; S = Stendalen; K = Kutseq; Ka = Kangerluk; Kl = south side Kangerluluk (see Fig. 4); SN = 'Sorte Nunatak'.

Fig. 2. Rust zones in the Stendalen gabbro, which forms the upper part of the mountain. Approximately 1400 m of relief is shown. Photo: B. Thomassen.

or (2) deposited in a back-arc or intra-arc setting (Stendal & Swager, 1995; Swager, 1995). Both possibilities are plausible and infer subduction-related processes.

Regional compilations of geological, geochemical and geophysical data for southern Greenland have been presented by Thorning *et al.* (1994). Mosher (1995) has recently reviewed the mineral exploration potential of the region. The commercial company Nunaoil A/S has been engaged in gold prospecting in South Greenland since 1990 (e.g. Gowen *et al.,* 1993).

A principal goal of the SUPRASYD project was to test the mineral potential of the Ketilidian supracrustal sequences and define the gold potential in the shear zones in the Julianehåb batholith. Previous work has substantiated a gold potential in amphibolitic rocks in the south-west coastal areas (Gowen *et al.,* 1993.), and in the amphibolitic rocks of the Kutseq area (Swager *et al.,* 1995). Field work in 1996 was focused on prospective gold-bearing sites in mafic rocks in South-East Greenland. Three M.Sc. students mapped showings under the supervision of the H. S., while an area on the south side of Kangerluluk fjord was mapped by H. S. and W. M. (Fig. 4).

Study areas

The areas investigated in 1996 were Illukulik, Stendalen, Kutseq, Kangerluk and Kangerluluk, all located in the coastal areas of South-East Greenland (Fig. 1)**.** The field studies concentrated on volcanic and volcaniclastic sequences containing mafic or ultramafic rocks, which form parts of the widespread supracrustal

sequences south of the Julianehåb batholith. Analytical data from samples collected in 1996 are not yet available; the analytical data presented below result from previous mapping, but can be considered representative of certain study areas. The term amphibolite is used here for rocks consisting mainly of crystalloblastic textures of amphibole and plagioclase with little or no quartz. These rock types are presumed to have originated as extrusive basaltic units; locally primary features such as pillow structure and brecciation can still be recognised. Relict gabbroic textures may indicate that some units were emplaced as sills.

Illukulik and Stendalen

The Illukulik area in Lindenow Fjord contains mainly amphibolite facies psammitic and pelitic rocks. Several phases of minor folds can be recognised, and at least one major, flat-lying E–W trending fold structure is present. The rocks have typical mineral associations of quartz, feldspar, biotite and amphibole with garnet in metapelites and diopside and minor cordierite in carbonate-bearing psammites. Banded carbonate-bearing psammites have been found at three localities in the area, and may represent a single carbonate-rich horizon with a thickness of about 40 m. Amphibolite occurs sporadically within the metasedimentary sequences of the area as lenses 1–10 m thick and tens of metres in length. East of Nørrearm, four ultramafic bodies varying in size from a few metres to 50 m in length occur within a sequence of psammitic and pelitic rocks characterised by rusty alteration.

Rust-coloured cherty horizons 1–10 m in width are often associated with the amphibolites in the Illukulik area, and contain up to a few vol. percent disseminated pyrrhotite, pyrite and minor graphite. The graphite is often concentrated in minor shear-zones (centimetre scale).

Stendalen is situated about 4 km west of Illukulik in Lindenow Fjord. The mafic rocks here make up a gabbroic to leucogabbroic sequence (Fig. 2), locally with primary magmatic banding and with magnetite-bearing bands up to 2 m thick. Five raft-like rusty-coloured horizons 1–15 m thick occur in the lower part of the gabbroic sequence and are probably of sedimentary origin. These rusty-coloured horizons can be traced eastwards for 2 km along Lindenow Fjord until they become discontinuous. They consist lithologically of a quartz-feldspar-biotite schist characterised by varying amounts of disseminated sulphides (pyrrhotite, minor pyrite and chalcopyrite) and graphite. Graphite is common in some horizons and is semi-massive in associated shear-zones. Granitic and mafic dykes, containing abundant epidote, intrude the gabbroic body and its host rocks.

The metasedimentary rocks underlying the gabbroic body in Stendalen contain a semi-massive pyrite-bearing pelitic layer with up to 10 wt % graphite. Samples from this unit yielded maximum trace element values of Au (161 ppb), Cu (0.14 %), Zn (0.24 %), Ni (0.08 %), Mo (97 ppm), Se (43 ppm) and V (1160 ppm).

Kutseq

Mafic rocks crop out on the south side of Kutseq Fjord (Fig. 1) as amphibolitic layers within a psammitic and semi-pelitic supracrustal sequence. The amphibolites vary from 50 m to about 200 m in thickness, and the alternation of amphibolite and metasediments occurs at all scales from a few centimetres to several metres. Within the amphibolite-dominated sequence three metasedimentary horizons, together making up 10–40% of the total sequence, can be traced over a wide area. The sequence is deformed by a major WNW plunging antiform, such that the amphibolite-bearing sequence is exposed over a 6 km long fjord section. Two types of mafic rocks can be distinguished, a massive amphibolite with wide textural variations (amphibolite 'A'), and a less common feldspar-rich amphibolite (amphibolite 'B'). The two types of rock occur in alternating sequences that are parallel with the main deformation; each sequence is usually several metres thick. Contact relations between the amphibolite types 'A' and 'B' are sharp. Later intrusive events include a slightly mineralised suite of felsic dykes and mafic dykes, as well as common pegmatite veining.

Amphibolite 'A' varies from a fine-grained banded amphibolite to a coarse-grained gabbroic type which locally appears undeformed; textural variations take place over centimetre–decimetre distances. This green-black coloured rock has a well developed schistosity; calc-silicate alteration is generally restricted to minor shear fractures.

Amphibolite 'B' crops out mainly near the closure of the major WNW plunging antiform. It is a fine-grained rock, but with common feldspar porphyroblasts of metamorphic origin; porphyroblasts may constitute up to 30 % of the rock. In some places the rock has a very characteristic banding caused by yellow to brownish carbonate-bearing layers, each from a few centimetres to 20–30 cm thick. This calc-silicate alteration is interpreted as due to pre-deformation hydrothermal processes. A distinct zonation is observed with carbonate minerals in the centre, followed outwards by minerals such as diopside, hornblende, K-feldspar and rarely garnet.

Three types of mineralisations have been recorded within the Kutseq area:

1) Distinct stratiform rust-zones a few metres wide occur within the amphibolite layers, or at the contact between amphibolite and metasedimentary layers. One major rust zone in the central part of the amphibolite-bearing sequence is more than 75 metres across, and contains a few vol. percent of iron sulphides.

2) Felsic dykes, although usually thin (10–40 cm), contain a greater concentration of ore minerals than the more extensive rust zones. The slightly discordant felsic dykes are composed of assemblages of quartz–albite–hornblende–biotite and ore minerals such as pyrrhotite and arsenopyrite. Anomalous elements in analysed samples of the felsic rocks include arsenic (up to 1.7 %) and minor gold (up to 200 ppb) (Swager *et al.,* 1995).

3) Mineralisation in quartz veins in minor shear zones, from a few centimetres to 1 m in width and up to tens of metres long, includes disseminated arsenopyrite, pyrrhotite and small amounts of magnetite and ilmenite. Graphite is found as minor massive layers.

Fig. 3. Agglomerate in the volcaniclastic sequence in Kangerluk.

Kangerluk

The supracrustal rocks in Kangerluk fjord (Fig. 1) represent a complex association of volcanic and sedimentary rocks intruded by a feldspar porphyry stock. The rocks have been subjected to several phases of deformation, and a NNW–SSE striking schistosity is prominent. Granitic and mafic intrusions post-date the deformation events.

The main supracrustal rock types present are mica schists with or without hornblende; where present the hornblende occurs as 1–8 mm long phenocrysts. The protolith to the mica schist is uncertain. The volcanic part of the sequence is characterised by well-preserved agglomerates or polymict breccias(?) composed principally of large angular clasts (2–50 cm across) of felsic to intermediate rocks; mafic clasts are less common (Fig. 3). The feldspar porphyry is a fine-grained rock, light to dark grey in colour with 0.5–1 cm phenocrysts of feldspar.

The hornblende mica schists are commonly altered, especially in north-west Kangerluk; the alteration products are generally folded, and alteration thus predates the deformation of the area. Alteration products include calc-silicates such as epidote, diopside, garnet and carbonate. Ankerite, representing the latest phase of alteration, forms veins from a few millimetres to a metre thick that transect the schistosity as well as all rock types. Silicificification is locally observed.

Mineralised zones observed in Kangerluk fjord area vary in size from a few tens of centimetres to several metres in width. Most visible mineralisation comprises pyrrhotite with minor pyrite and chalcopyrite, and disseminated graphite (a few vol. percent). Sheared semi-massive graphitic layers are common in rusty mineralised zones. Two mineralised layers have been traced for one kilometre along strike. A semi-massive graphite body, about 30 m × 9 m in size, occurs on the north shore of Kangerluk fjord within the sheared mica schist.

Kangerluluk

A 200–300 m thick supracrustal sequence on the south side of Kangerluluk comprises a complex association of phenocryst-rich lava flows, pyroclastic deposits, dykes and sedimentary rocks. The sequence dips generally northwards at up to 30°, and is locally deformed by minor tight folds. Metamorphism is low amphibolite facies grade, but sedimentary and volcanic textures are well preserved. Four main facies associations have been recognised (Fig. 4), and make up the Kangerluluk volcano-sedimentary sequence. These are:

1) a conglomorate-sandstone facies association;
2) a pyroclastic facies association;
3) a volcanic facies association;
4) a peperitic facies association.

Feldspar-pyroxene-magnetite-phyric dykes and sills intrude all facies associations. Other dyke phases appear to be penecontemporaneous with effusive volcanism or related to early recumbent folding and late brittle movements. The numerous dyke phases illustrate the complexity of the area.

Volcano-sedimentary sequence

Volcanic facies association

- Feldspar-phyric flow (pyroxene < 5%)
- Feldspar- pyroxene- phyric flow
- Pyroxene-phyric flow (dyke?)

- Peperite facies association
- Pyroclastic facies association
- Conglomerate-sandstone facies association

Volcanic morphology

- Pillowed
- Breccia
- Massive

Intrusive rocks

- Felsic dyke
- Appinite dyke
- Feldspar- magnetite-phyric dyke or sill
- Feldspar-pyroxene-phyric dyke or sill
- Synvolcanic granitoid (Julianehåb batholith)

- Strike and dip with younging direction
- Strike and dip of overturned bed
- Strike and dip of schistosity
- Fault
- Mineralised zone
- Syncline and anticline

Fig. 4. Geological map of the area mapped on the south side of Kangerluluk fjord. For location, see Fig. 1. Modified from Stendal (1997).

Fig. 5. Pillow lava in contact with the pyroclastic facies association, Kangerluluk.

The conglomerate-sandstone facies association is composed of discrete conglomerate and sandstone units; locally the former have an unconformable contact with the Julianehåb batholith. The presence of plutonic clasts in the conglomerate indicates that the Julianehåb batholith was locally a topographic high at the time of sediment deposition. This facies association is considered to represent a subaerial to subaqueous transition zone, based on the occurrence of sedimentary structures such as trough cross-bedding, planar bedding, and a close association with pillowed flows which indicate a subaqueous environment.

The pyroclastic facies association, up to 30 m thick, comprises 2–50 cm thick beds of tuffs and lapilli tuffs rich in euhedral to broken feldspar and pyroxene crystals. Feldspar crystals locally reach 2 cm in length, and pyroxene crystals are up to 1 cm across. Pyroclastic blocks that distort bedding planes and disrupt wavy beds are interpreted as bombs. Crystal-rich layers 0.5–3 cm thick commonly alternate with 0.2–2 cm thick fine to coarse-grained tuff layers within a bed. Wavy, dune-type bedforms and the abundance of euhedral crystals are suggestive of pyroclastic surge deposits (Fisher & Schminke, 1984).

The 150–200 m thick volcanic facies association is the dominant lithological unit in the Kangerluluk area. Three flow morphologies have been recognised: pillowed, pillow breccia and massive. All flows are characterised by abundant phenocrysts of feldspar (0.5–3 cm) and pyroxene (0.2–2 cm; locally forming up to 5% of the flow). The pillows (Fig. 5), indicative of a subaqueous setting, range from 20 to 300 cm in diameter. The high phenocryst content in all flow types suggests viscous flow.

The peperitic facies association is an unusual 20–30 m thick combination of 2–10 m thick tuff turbidites, fine-grained, aphanitic to grey feldspar-phyric dykes and lava flows. Mixing between magma and sediment is observed, and both sediments and the quenched magma may show chilled margins.

Collectively, the four facies associations are consistent with a volcanic-dominated alluvial fan environment or a braidplain setting adjacent to a sea or lake.

Fig. 6. Pervasive epidote in the hyaloclastite matrix between pillows at Kangerluluk. Pencil as scale.

Shear and fault zones

Three main episodes of shearing or faulting have been recognised in the Kangerluluk area:

1) a complex pattern of décollement folds and associated shearing events;
2) a pronounced set of 060° trending faults which cut the décollement phase; and
3) a prominent set of NE–SW trending shear zones post-dating the 060° trending set.

The first of these episodes comprises three different types of deformation: décollement folds, 100–120° trending faults, and a 010° trending fault. The age relationships between these types are not known, but all pre-date the second episode of deformation. The décollement folds have an amplitude of 2–10 m and are overturned on their south-eastern limb. Fold axes are generally subhorizontal with a NE–SW trend. Shearing is developed parallel to the overturned fold limbs, particularly in contact with more competent sills and dykes. The 100–120° trending faults occur within a pillowed sequence, and generally cannot be traced for more than 50 m. A very pronounced fault trending at 010° follows the boundary between the pyroclastic facies association and the sill and dyke complex. Both the 100–120° faults and the 010° fault exhibit the same type of alteration haloes.

The second faulting episode is represented by pronounced 060° trending faults. In contrast to the first and third episodes, this faulting episode is generally not associated with any significant hydrothermal activity.

The NE–SW trending faults and shear zones of the third episode form a dominant system of steeply dipping structures with sinistral displacements, often associated with hydrothermal alteration.

A system of late 020°–035° trending breccia zones post-date all three phases and occur in both the supracrustal rocks of the Kangerluluk area and within the nearby Julianehåb batholith. These breccia zones, which are up to 2 m wide and can be followed for up to 100 m, are characterised by carbonate alteration.

Mineralisation

The hydrothermal mineralisation spatially associated with the first and third episodes of shearing is clearly epigenetic. The mineral associations developed reflect to a high degree the host rocks: a quartz association is characteristic in the sedimentary rocks and an epidote-garnet association characterises the hydrothermal deposits in the mafic volcanic rocks.

Quartz association

The quartz association is developed in sequences affected by the décollement folds as saddle reefs up to 2 m across containing pyrrhotite and pyrite (up to a few vol. percent). Locally massive pyrrhotite (up to 5 cm thick) occurs at the contacts between the sediments

and the quartz reefs. The saddle reefs are surrounded by silicified alteration halos up to 40 cm wide.

A quartz association is also found within the northeast striking shear zones of the third episode of shearing as *én echelon* sets of quartz veins. These quartz veins occur in the sedimentary rocks and are not generally associated with silicification of the host rock. The quartz veins are 1–2 m wide, 3–10 m long and have normally 1 vol.% of iron sulphides.

Epidote-garnet association

An epidote-garnet mineral association occurs in the 100–120° faults as alteration zones up to 50 cm containing pyrite and chalcopyrite. The pronounced 010° trending fault in the centre of the area, contains an alteration zone up to one metre wide characterised by epidote, garnet, and minor chalcopyrite.

Mineralisation not spatially related to any shear or fault movements occurs in sedimentary infillings between the pillows of the lava flows (Fig. 6). Alteration is dominated by pistachio-green epidote with subordinate garnet, minor pyrite and pyrrhotite, and copper minerals such as chalcopyrite, bornite and chalcocite.

Late carbonate mineralisation was recorded at two localities on the north side of the head of Kangerluluk fjord, one in supracrustal rocks and the other in rocks of the Julianehåb batholith. Mineralisation at both localities follows steep NNE–SSW trending zones 20–200 cm in width, which can be followed up to 100 m along strike. The zones are silicified and carbonatised, locally with calcite breccias; those in the supracrustal rocks contain hematite veinlets, while the carbonatised zones in the Julianehåb batholith contain iron and copper sulphides, disseminated galena and sphalerite.

'Sorte Nunatak'

The supracrustal sequence at 'Sorte Nunatak' (Fig. 1) is dominated by feldspar-phyric, amygdaloidal metabasalts and andesites interbedded with semipelites, psammites and polymict conglomerates (Chadwick & Garde, 1996). Boulder samples from 'Sorte Nunatak' have yielded anomalous values (up to 9 ppm gold and 4 % copper), contained in narrow mineralised quartz or carbonate veins in weakly deformed meta-basalt (Swager *et al.*, 1995).

Discussion and concluding remarks

The mafic rocks found in the supracrustal sequences of the Kangerluk, Kangerluluk and 'Sorte Nunatak' areas show general similarities in rock types and provenance, and suggest the different areas preserve parts of the same volcano-sedimentary succession. However, those in the Kutseq area probably belong to a different volcanic-sedimentary suite perhaps related to the amphibolite and ultramafic rocks in the Illukulik area. The geological relationships of the gabbro body in Stendalen are not yet clarified.

The Kangerluluk volcano-sedimentary sequence is a complex association of phenocryst-rich lava flows, fluvial to shoreface sediments, and primary pyroclastic deposits. The transition from subaerial to subaqueous sedimentation with effusive volcanism and related pyroclastic deposits, is a common feature of modern (Sigurdsson *et al.*, 1980) and ancient arc systems (Cole & DeCelles, 1991). The inferred fluvial to shallow water setting is broadly in line with the interpretation of a convergent arc environment (Chadwick & Garde, 1996). Local calc-alkaline volcanism, as in the Kangerluluk area, may be indicative of an unroofed magmatic arc. The presence of clasts from a batholithic provenance indicates that volcanism continued as the arc was dissected, the mixture of both plutonic and volcanic detritus suggesting a mature arc stage rather than an incipient arc. The local preservation of an unconformity between the sedimentary rocks and the Julianehåb batholith supports this hypothesis.

Hydrothermal alteration in the intermediate to mafic rocks shows general similarities in all the areas studied where alteration predates deformation. Sulphide mineralisation so far recorded is minor and associated with copper and arsenic. Mineralisation related to the quartz association includes disseminated iron sulphides, locally arsenopyrite and chalcopyrite. The epidote-garnet association at Kangerluluk comprises disseminated iron sulphides and chalcopyrite.

The carbonatised zones are silicified and contain hematite in the mafic volcanic rocks; this is in contrast to mineralised zones in the Julianehåb batholith which have fugacities low in oxygen and high in sulphur, resulting in disseminated iron and copper sulphides, galena and sphalerite.

Along the southern rim of the Julianehåb batholith on the east coast of South Greenland mineralisation is now known in a NE–SW striking zone extending from 'Sorte Nunatak' to Kangerluk. This zone includes the copper-gold mineralisation at 'Sorte Nunatak' and exten-

sive hydrothermal altered zones at the head of Danell Fjord, Kangerluluk and Kangerluk.

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