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Deep section of a Neoproterozoic fossil magma rich rifted margin exposed

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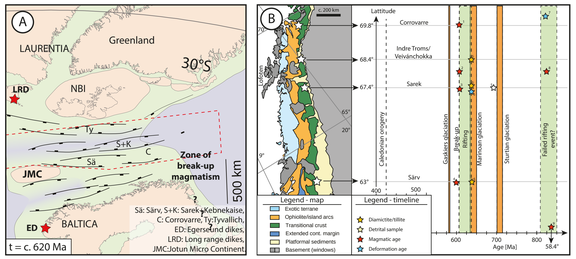
Introduction



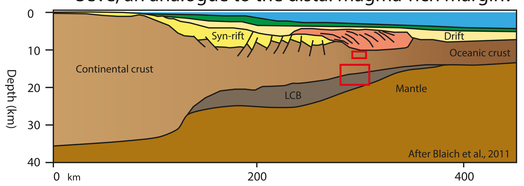
A) Paleogeographic reconstruction of Baltica and Laurentia at c. 620 Ma. Narrow rift basins, developing on a wide margin with localized magmatism in the central part of the incipient rift, whereas the basins developing outside of this zone has little to no evidence for magmatism

B) Tectonostratigraphic map of the north-central part of Caledonides. Green areas represent transitional crust where the rift related assemblages are found. Time line with main events and key features occurring during rifting. Note Iapetus opening at c. 605 Ma. White stars: field areas

The pre-Caledonian rifted margin is preserved and exposed in the Seve Nappe Complex in the Scandinavian Caledonides

1) Kjøll et al., 2019 - Corrovarre dikes; 2) Baird et al., 2014 - Kebnekaise dikes 3) Svenningsen, 2001 - Sarek dikes; 4)Kumpulainen et al., 2016 - Särv dikes; 5) Kjøll, In prep - glaciogenic diamictite, 640Ma deformation age and youngest zircon; 6) Kumpulainen, 1980 - tillite; 7) Kohl et al., 2018 - brittle normal faulting; 8 Paulsson and Andreasson, 2002 - bimodal magmatic complex; 9) Walderhaug et al., 1999 - mafic dikes.

Seve, an analogue to the distal magma-rich margin?

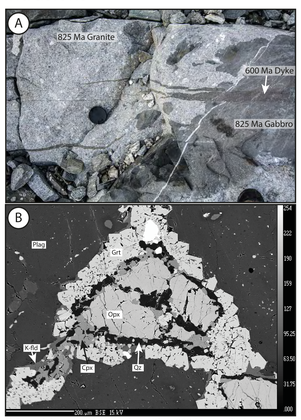


The Walvis margin, offshore Namibia formed during opening of the S. Atlantic and is a classical magma-rich rifted margin. Red squares are the approximate areas possibly representing analogues that can be found within the Scandinavian Caledonides

Distal magma rich rifted margins are generally comprised of three domains: 1) Extrusive domain, 2) Intruded middle crust, and 3) A lower crustal body. The latter two may be found in the Caledonides

A lower crustal body?

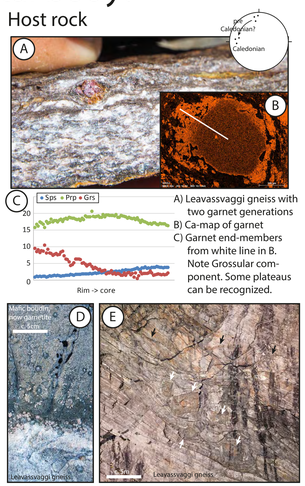
Intrusions



A) Bimodal magmatic complex with c. 832 Ma rapakivi granite and coronitic gabbro cut by 605(?) Ma dykes. Dykes are amphibolite grade whereas gabbro preserves higher metamorphic grades

B) BSE image of corona texture. Plag and opx is reacting to form: grt + cpx + qz ± K-fld.

Host rock

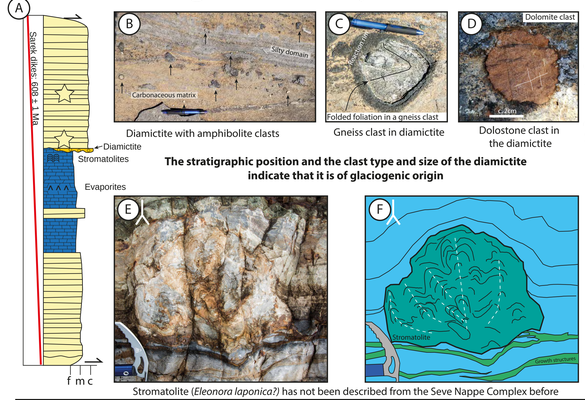


A) Leavassvaggi gneiss with two garnet generations
B) Ca-map of garnet
C) Garnet end-members from white line in B. Note Grossular component. Some plateaus can be recognized.

A) Mafic boudins in the Leavassvaggi gneiss, almost completely replaced by garnet
B) Several generations of mafic dykes in the Leavassvaggi gneiss

Locally, the lower part of the Seve Nappe Complex may represent an analogue to a Lower Crustal Body (LCB) More work is needed to constrain timing of metamorphism and deformation

Age of the dykes and sedimentary sucession



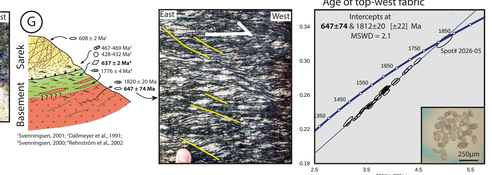
Diamictite with amphibolite clasts

Gneiss clast in diamictite

Dolostone clast in the diamictite

The stratigraphic position and the clast type and size of the diamictite indicate that it is of glaciogenic origin

Stromatolite (*Eleonora laponica?*) has not been described from the Seve Nappe Complex before



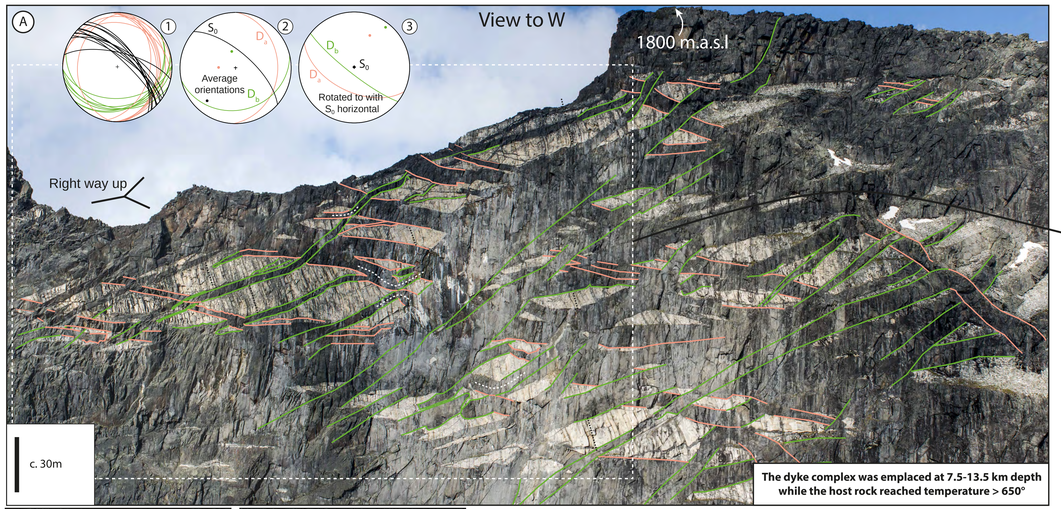
G) U-Pb zircon ages from an extensional shear zone below Sarek indicate that thinning of the basement had commenced at 637 Ma, presumably making space for the syn-rift sedimentary succession

H) All the sediments are cut by 597-608 Ma mafic dykes, dated by U-Pb in zircon and baddeleyite

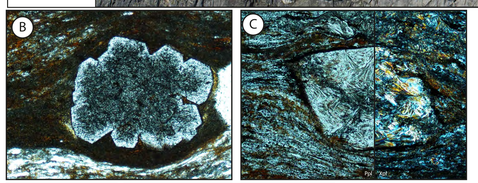
The deposition of the glaciogenic diamictite can be constrained to be between 637 and 605 Ma and thus, likely related to the Marinoan glaciation

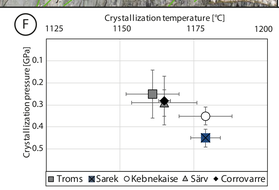
The magmatism, which peaked around 605 Ma, was a relatively late feature in the rifting process

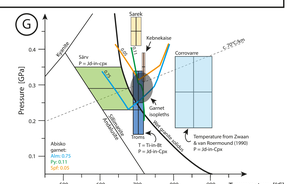
Dyke complex - depth of emplacement



The dyke complex was emplaced at 7.5-13.5 km depth while the host rock reached temperature > 650°







A) Cliff from Sarek, national park that shows the well exposed and preserved 608 Ma dyke swarm. Different dyke orientations are color coded. Dark rocks are dykes, light rocks are sediments. Note that dykes are mutually cross-cutting and abruptly change directions (white dashed lines).

B) Fast grown dendritic garnets formed in the micaceous layers next to the dykes

C) Andalusite which has been statically pseudomorphed into fibrous sillimanite

D) Microphotograph of dolerite. White square marks location for photo E

E) Ca EMPA map of the cpx in D. White lines indicate magmatic zonation

F) Pressure-temperature diagram showing estimate for crystallization pressure and temperature from jadeite-in-clinopyroxene geothermobarometry. Each data point is based on several analyses of clinopyroxenes collected from the dykes.

G) Pressure and temperature estimates by various methods from the different field localities. Garnet isopleths are from contact metamorphic garnets that sit with andalusite which has been pseudomorphed by sillimanite. Temperature estimates are derived using Ti-in-biotite. 70°C/km geothermal gradient indicated with dashed line

Conditions during dyke emplacement

Detailed observations of dike emplacement mechanisms

A) "Brittle" dikes show abrupt changes in orientation and transtensional opening vectors

B) Brittle, dyke 1 (white) deformed by dyke 2 (white arrows)

D) "Ductile" dike emplaced in marble. Dyke cross-cut marble foliation. Note complex instabilities at contact with marble (black arrow)

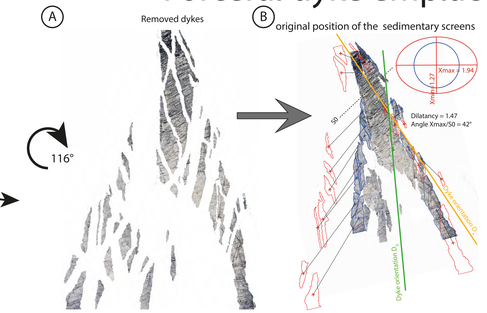
E) Dyke emplaced in migmatitic arkosic host. Note lobate boundaries to host

The introduction of large quantities of mafic magma into the crust led to a shallowing of the brittle-ductile transition

Emplacement of the dykes were not all just brittle, ductile deformation played a major role

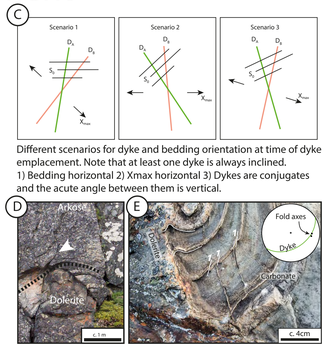
Brittle to ductile conditions

Forceful dyke emplacement



A) Photograph is rotated and dykes are removed from the sedimentary sequence
B) The sedimentary screens are placed back to their original position and anisotropic dilatancy of the rock body is calculated

Dikes accommodated 94% extension and 27% vertical thickening, in the tectonic rift! i.e. tectonic extension rate was less than the magma influx rate Dykes were emplaced in a forceful manner



Different scenarios for dyke and bedding orientation at time of dyke emplacement. Note that at least one dyke is always inclined.
1) Bedding horizontal 2) Xmax horizontal 3) Dykes are conjugates and the acute angle between them is vertical.

In addition to showing brittle-ductile behavior of the host rock these photographs also show that the dyke emplacement was forceful and that the propagating magma deformed their hosts.

D) Emplacement of a visco-elastic finger (dyke with blunt tip) White arrows highlight shear fractures in propagation direction of dyke

E) Calc-silicate layers affected by both brittle and ductile mechanisms

Conclusions

- Parts of the Seve Nappe Complex in the Scandinavian Caledonides represents a fossil analogue to the distal and heavily dyke intruded basement of a magma-rich rifted margin
- Local evidence for high temperature-low pressure magmatic activity could represent an analogue for a lower crustal body, which are often observed at the base of the crust in magma-rich margins, but never in the field
- Magmatism peaked after at least 32 M.yr. of crustal stretching, indicating that it was a relatively late feature in the development of the pre-Caledonian margin
- The exposed level of the dyke complex crystallized at c. 2.5-4.5 kbar, which translates roughly to 7.5-13.5 km depth
- The dikes were emplaced both as: 1) brittle structures, 2) brittle-ductile, and 3) ductile structures at the same level i.e. temperature increased with time lifting the brittle-ductile transition
- Emplacement of the dike swarm accommodated 94% crustal extension and 27% crustal thickening.
  - Magma influx rate > tectonic stretching rate
  - Dykes were emplaced in a forceful manner, deforming their host rock

Whant to learn more? Check out:

Kjøll, Andersen, Corfu, Tegner, Labrousse, Abdelmalak, Planke (2019 - In Press) Timing of break-up and thermal evolution of a pre-Caledonian Neoproterozoic exhumed magma-rich rifted margin. Tectonics
Kjøll, Galland, Labrousse, Andersen (2019 - Submitted) Emplacement mechanisms of a dyke swarm across the Brittle-Ductile transition and the geodynamic implications for magma-rich margins. EPSL