Metamorphosed plutonic rocks of the Scandian Upper Allochthon, coastal mid-Norway: Intrusive roots of an Ordovician-earliest Silurian calc-alkaline arc

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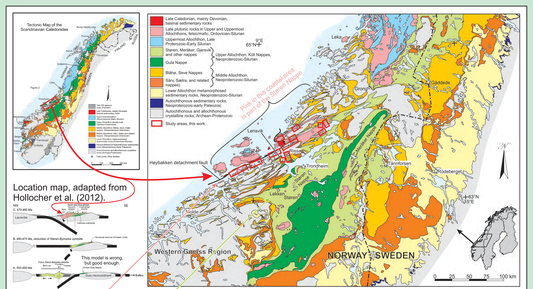
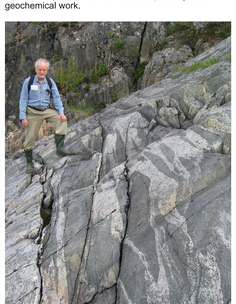
Abstract

The Støren Nappe of the Upper Allochthon of Mid-Norway has four major parts. The Støren Group (1) consists of overwhelmingly basaltic Late Cambrian-Early Ordovician oceanic ophiolite complexes. These were obducted onto the peri-continental Gula Group (2) in the Iapetus Ocean. On these an Ordovician-Silurian arc was built, beginning in the back-arc region with strata of the Hovin Group (3) that has fossils of the Laurentian Toquima-Table Head fauna. NW of (3) and intruding it and the ophiolites are plutonic rocks (4) of an Ordovician - Early Silurian magmatic arc with U-Pb zircon ages of 482-442 Ma. Thrusting of (1-4) onto Baltica occurred in the Silurian-Devonian Scandian Orogeny. Much work has been done on (1), (2), (3). Here we report 153 new analyses of samples of (4) from near the coast SW, W, and NW of Trondheim. They are apparently derived from the plutonic arc roots, with rare recognizable volcanics. SE of the Høybakken brittle detachment most are strongly deformed gneisses, but to the NW on the islands of Hitra and Smøla they are almost undeformed. They span a continuous composition range of 45-77% SiO_2, and from hornblendite to granite, with no bimodal tendency as is seen in volcanic rocks in the Støren Group (1). Most mafic rocks are tholeiitic, some calc-alkaline, one alkaline, but rocks with >57% SiO_2 are overwhelmingly calc-alkaline. There are two distinct geochemical domains: In the Lensvik Synform, and its extension along strike to the NE, these rocks are dominated by tonalitic gneisses with flat, or slightly REE-enriched or -depleted patterns that closely resemble oceanic 'plagiogranites; weak to strong negative Nb-Ta anomalies indicating arc affinity, resembling anomalies in Støren Group mafic volcanics (1); and small negative to no Eu anomalies. The larger domain, across strike to the NW, is dominated by tonalites with strongly enriched LREE and variably depleted HREE patterns, suggesting variable residual garnet and plagioclase in the magma source regions; uniformly large negative Nb-Ta anomalies; and small Eu anomalies (~half), no Eu anomalies (a few). Excluding cumulates, mafic rocks range from LREE-depleted to strongly LREE-enriched. Metamorphic mineral assemblages indicate peak epidote-amphibolite-facies metamorphism, with no evidence for partial melting.



Location map, adapted from Hollocher et al. (2012).

Slightly deformed granite containing pink microcline phenocrysts. Follafoss area.



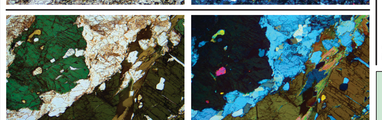
Hornblende-biotite tonalite near Rissa, with numerous, somewhat deformed hornblende diorite xenoliths.

Deformed hornblendite block in hornblende diorite, Kopparen. This is interpreted to be a cumulate rock.

Undeformed Granite, image widths are 4 mm. Blocky plagioclase, quartz, and alkali feldspar, with hornblende, biotite, epidote, and dark titanite.

Granite

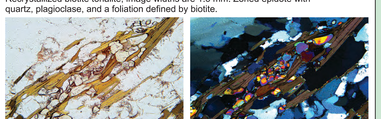
Mostly recrystallized granite, image widths are 4 mm. Fine-grained quartz, plagioclase, and alkali feldspar, with biotite and epidote.

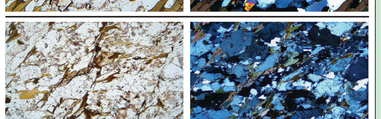


Relatively undeformed hornblende-biotite tonalite, image widths are 4 mm. Large hornblendes in a matrix of biotite, quartz, plagioclase, and epidote.

Tonalite

Recrystallized biotite tonalite, image widths are 1.6 mm. Zoned epidote with quartz, plagioclase, and a foliation defined by biotite.

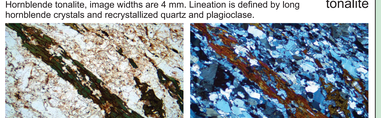


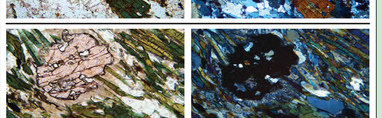


Biotite tonalite, image widths are 4 mm. Foliation is defined by biotite and a trail of titanite, with variably recrystallized quartz and plagioclase.

Hornblende tonalite, image widths are 4 mm. Lineation is defined by long hornblende crystals and recrystallized quartz and plagioclase.

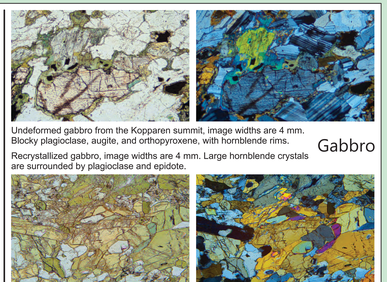
More tonalite





Diorite, image widths are 1.6 mm. Undeformed garnet crystal in a matrix of hornblende, quartz, and plagioclase, which is partly replaced by sericite.

Diorite



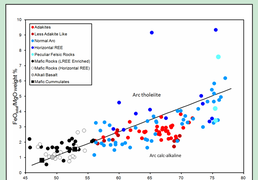
Undeformed gabbro from the Kopparen summit, image widths are 4 mm. Blocky plagioclase, augite, and orthopyroxene, with hornblende rims.

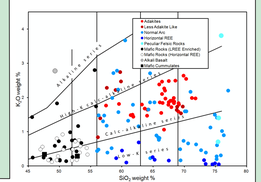
Recrystallized gabbro, image widths are 4 mm. Large hornblende crystals are surrounded by plagioclase and epidote.

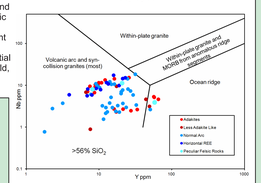
Gabbro

Petrology

These plutonic rocks have all been metamorphosed to epidote amphibolite facies, based on mineral assemblages. Deformation varies from essentially none, for rocks having intact igneous textures and even igneous pyroxenes, to completely recrystallized.

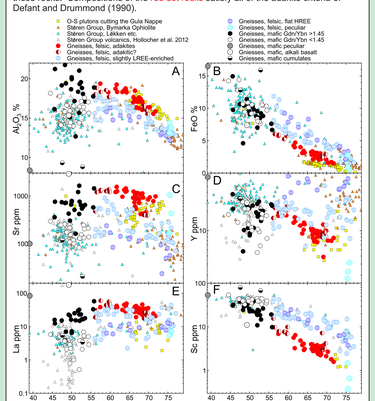


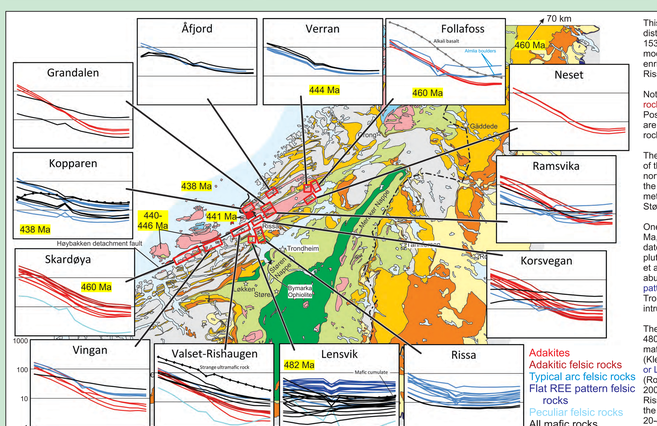




To the upper-right are the two igneous series discriminant diagrams of Miyashiro (1974) and Ewart (1982). As a group, these rocks are largely calc-alkaline, with about half of the mafic and a quarter of the felsic rocks being tholeiitic. One alkali basalt is found as a metamorphosed dike, cutting relatively undeformed granite, at Follafoss. To the lower-right is a tectonic setting discriminant diagram for felsic rocks (Pearce et al., 1984). The rocks plot solidly in the arc field, apparently in two elongate, parallel groups, separated by a partial gap. The diagonal trends of the two groups leads the lower group into the ocean ridge field, possibly the result of crystal fractionation, which would progressively increase the concentration of incompatible elements like Y and Nb.

The metamorphosed igneous rocks analyzed here span a wide compositional range for most analyzed elements. The mafic rocks (<56% SiO_2) include LREE-enriched varieties (**black dots**) that are also rich in Al_2O_3, Sr, and La, and relatively poor in Sc, compared to the others (white dots). The felsic rocks (>56% SiO_2) have LREE-enriched varieties too (red dots, interpreted to be adakites), that are also rich in Al_2O_3, Sr, and La, and poor in FeO, Y, and Sc (consistent with a garnet-pyroxene, e.g., eclogitic, source). Felsic rocks with flat HREE patterns are the reverse (medium-blue dots, normal arc-type, and especially dark-blue dots, possibly oceanic "plagiogranite"-type), consistent with a plagioclase-rich source. This suggests distinct sources for these rocks. Compositions of the red dot rocks satisfy all of the adakite criteria of Defant and Drummond (1990).





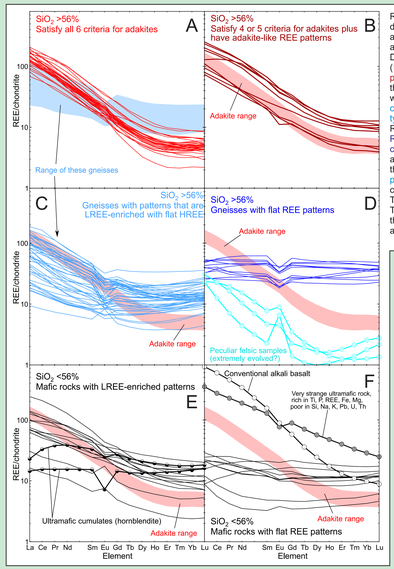
This shows the geographic distribution and REE patterns of all 153 samples. All areas have moderately to strongly LREE-enriched rocks, except Lensvik and Rissa, with adakites in most places.

Notice that adakites and similar rocks have almost no Eu anomalies. Positive or negative Eu anomalies are almost universal for the other rock types.

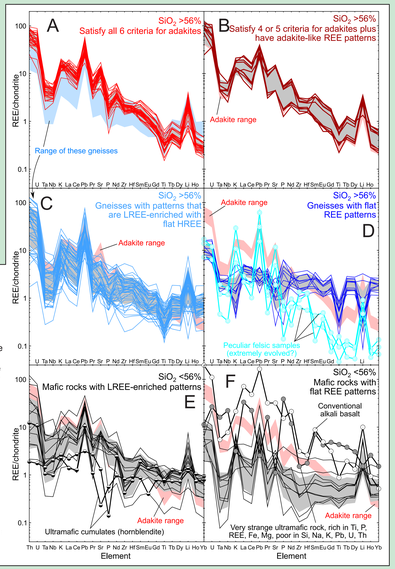
The present geographic distribution of the plutonic rocks is largely northwest of the Støren Group, and the plutonic rocks seem to intrude metamorphosed volcanics of the Støren Group in the Rissa area.

One age date from Lensvik is 482 Ma, much older than the other 13 dates available for these and related plutonic rocks (438-461 Ma; Tucker et al., 2004). At Lensvik are the abundant rocks with flat REE patterns, rather like those across Trondheimsfjord at Rissa where the intrusive relations are seen.

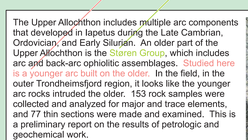
The Bymarka ophiolite in the 500-480 Ma Støren Group also contains mafic (gabbros) and felsic rocks (Klemetsaunet rhyodacite) with flat or LREE-depleted REE patterns (Roberts et al., 2002; Slagstad, 2003). The felsic plutonic rocks from Rissa and Lensvik may be related to the Støren Group, rather than the 20-40 MY younger arc plutonic rocks of this study.



REE diagrams for all samples, divided up by silica content and pattern type. A) Adakites according to the criteria of Defant and Drummond (1990). B) Rocks with similar patterns that satisfy fewer of the adakite criteria. C) Rocks with patterns and other compositional characteristics typical of arc intrusives. D) Rocks having unusual flat REE patterns and high HREE concentrations. These rocks are only found at Lensvik, though samples having patterns nearly as flat (C, but concave up) are found across Trondheimsfjord near Rissa. The mafic rocks have patterns that are LREE-enriched (E) and relatively flat (F).



Spider patterns for all samples, divided up just like the REE patterns to the left. Gray bands are the median, ±1 standard deviation of the mean, for the main group of patterns in each figure. A, B, C, E, and F all have the same anomalies: negative Ta-Nb, Zr-Hf (minor), Ti, and positive K, Pb, Sr, Li, and possibly Th and U. Anomalies like these are typical of arc igneous rocks, and are interpreted to result from progressive replenishment of the mantle melting region by fluids from the subducting slab and sediments. In D the felsic rocks have have flat REE patterns and negative K, Sr, and Li anomalies. This may indicate a more highly depleted source region that was not so well replenished by the subduction zone fluids (though this does not fully explain the anomalies).



The Upper Allochthon includes multiple arc components that developed in Iapetus during the Late Cambrian, Ordovician, and Early Silurian. An older part of the Upper Allochthon is the Støren Group, which includes arc and back-arc ophiolitic assemblages. Studied here is a younger arc built on the older. The field, in the outer Trondheimsfjord region, it looks like the younger arc rocks intruded the older. 153 rock samples were collected and analyzed for major and trace elements, and 77 thin sections were made and examined. This is a preliminary report on the results of petrologic and geochemical work.

Summary

- The rocks described here were apparently emplaced as plutons in an Iapetan volcanic arc that was active in the Ordovician and earliest Silurian.
- The suite is a mix of calc-alkaline and tholeiitic varieties, at first glance resembling a typical mature/continental arc complex.
- Mafic rocks span a range from LREE-depleted to LREE-enriched, more or less forming a continuum.
- Felsic rocks span an even wider range that includes adakitic rocks (LREE-enriched, HREE-depleted), typical calc-alkaline arc rocks (LREE-enriched, flat HREE), and rocks with flat patterns and high HREE concentrations. Composition gaps indicate no continuum.
- Both mafic and felsic rocks* have the same anomalies on spider patterns, including negative Nb-Ta, Zr-Hf, and Ti anomalies, and positive K, Pb, Sr, Li, and possibly Th-U anomalies.
- The presence of such strong anomalies in the adakites indicates that they are not melts from a mid-ocean ridge-derived subducted slab, but instead are from melting normal arc basalt crust at high pressure, leaving a garnet-rich (eclogitic?) restite.
- Tholeiitic series rocks are dominantly in the Lensvik and Rissa areas.
- *Most of the felsic rocks with flat REE patterns are also at Lensvik and Rissa, and these have very different NEGATIVE K, Sr, and Li anomalies.
- The arc was at least partly built on or at the edge of an earlier arc complex represented by the Støren Group, which is dominated by 500-480 Ma tholeiitic intrusive and volcanic rocks.
- The Støren Group is similar in age to at least some rocks at Lensvik and possibly Rissa areas, and also strong compositional similarities. They may therefore be related.
- Rocks from the other areas are younger (438-461 Ma) and chemically distinct.
- This sample set apparently includes rocks from two lapetan arcs.

References

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