# MID-PROTEROZOIC EVOLUTION OF THE FENNOSCANDIAN SHIELD

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**Summary**
Recent geological, geochemical, and geophysical data on the Fennoscandian Shield are reviewed and combined into an assessment of the mid-Proterozoic (~1.7–1.3 Ga) evolution of the shield.

**Introduction**
During the last decade, the Fennoscandian (or Baltic) Shield of northern Europe (Fig. 1) has been at the focus of active geological and geophysical research and new data has been acquired especially on its central, Proterozoic part, the Svecofennian Orogen (e.g., Haapala and Rämö 1990; Luosto *et al.* 1990; Korja *et al.*, 1993; Korja and Heikkinen 1995; Vaasjoki 1996; Lahtinen and Huhma 1997; Nironen 1997; Ahl *et al.* 1997; Korsman *et al.* 1999).

The Svecofennian Orogen constitutes a complex segment of Paleoproterozoic crust that was differentiated from the mantle ~2.1–1.8 Ga ago. This involved accretion of several arc complexes to the Neoarchean craton in the eastern part of the shield at ~1.91–1.89 Ga and subsequent extensional collapse and mafic underplating. After a ~0.2 Ga period of quiescence, a major tectonothermal event commenced and is recorded by the 1.67–1.47 Ga rapakivi granites and related mafic rocks that formed as the Svecofennian crust was reorganized in response to mantle upwelling and extension. This was followed by continental sedimentation and, at ~1.3 Ga, by extensive CFB-type magmatism that involved partial melting of the upper mantle but not coeval silicic magmatism. In this paper, we review geological, geochemical, and geophysical data recently acquired on the 1.7–1.3 Ga magmatic events and discuss the evolution of the Fennoscandian Shield in this time period.

**Geology**
The 1.67–1.47 Ga (or Subjotnian) rapakivi granites are found as five large batholiths and several smaller batholiths and stocks that sharply cut the surrounding metamorphic bedrock (Fig. 1). They are spatially and temporally associated with mafic rocks that include gabbroids, anorthosite, and diabase dikes (e.g., Haapala and Rämö 1990); volumetrically, the mafic rocks are inferior.

During the last decade, the rapakivi complexes have been the subject of extensive U-Pb chronological work (see Table 1 for citations) and fall into four zones that delineate a gross east-west pattern (Fig. 1, Table 1). The classic Wiborg batholith and associated plutons in southeastern Finland and Estonia are 1.67–1.62 Ga old whereas those in southwestern Finland, Latvia (the huge Riga batholith), and west-central Sweden (Nordingrå) are slightly younger, 1.59–1.54 Ga. The rapakivi granites in central Sweden (west of Nordingrå) have been dated at 1.53–1.47 Ga and those in

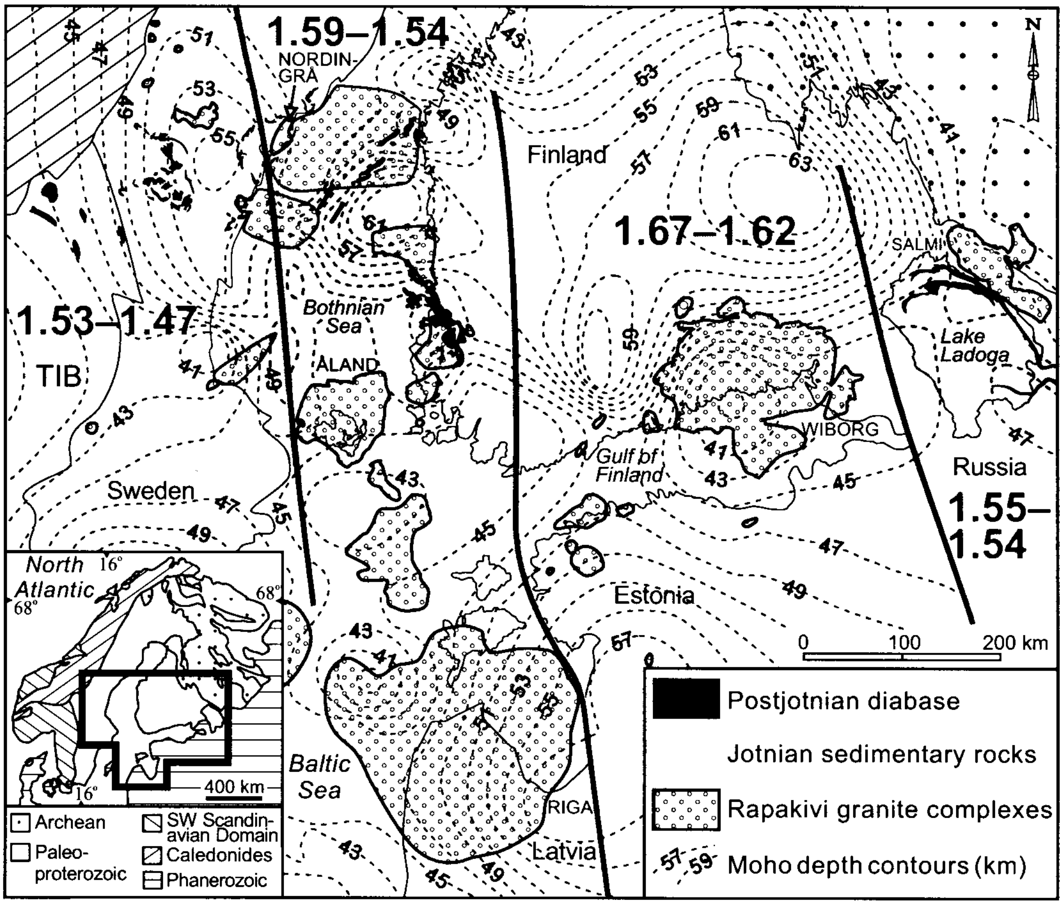


Fig. 1. Map showing the mid-Proterozoic (~1.7–1.3 Ga) lithologic units and crustal thickness in the south-central part of the Fennoscandian Shield. Thick subvertical lines outline four rapakivi granite age zones (1.53–1.47, 1.59–1.54, 1.67–1.62, and 1.55–1.54 Ga; see Table 1). Inset shows area relative to the major crustal domains of the shield. TIB is the 1.85–1.7 Ga Transscandinavian Igneous Belt. Note that the area south of the Gulf of Finland and Lake Ladoga (see inset) is covered by Phanerozoic sedimentary rocks and that the volumetrically minor rapakivi-age mafic rocks are not shown (for the latter, see fig. 2 in Rämö *et al.* 1996). Compiled mainly after Koistinen (1994), Patchett *et al.* (1994), Andersson (1997a), Korja and Heikkinen (1999), Korsman *et al.* (1999), and Persson (1999).

Russian Karelia (Salmi) at 1.55–1.54 Ga.

In terms of their petrography, mineral chemistry, geochemistry, and magmatic association, the Fennoscandian rapakivi granites are typical subalkaline A-type granites (e.g., Haapala and Rämö 1992; Rämö *et al.* 1996; Ahl *et al.* 1997) and their petrogenesis has been associated with mafic underplating and crustal anatexis in an extensional tectonic regime (e.g., Haapala and Rämö 1990; Rämö 1991; Korja and Heikkinen 1995).

The ~1.3 Ga Postjotnian diabases are found as extensive, subhorizontal dikes intruding continental (Jotnian) redbeds that are often spatially associated with the rapakivi granite intrusions. Major occurrences are present in southwestern Finland (Bothnian Sea), central Sweden, and the Lake Ladoga region in Russian Karelia (Fig. 1). The dikes in southwestern Finland have been dated at 1.265 Ga (U-Pb on zircon and baddeleyite; Suominen 1991) and a K-Ar age of 1.22 Ga on the dikes in central Sweden (Welin and Lundqvist 1975; Claesson 1987; see also Patchett *et al.* 1994) and a paleomagnetic age of ~1.28 Ga on a dike in Lake Ladoga (Pesonen 1998) suggest that the Postjotnian magmatism may have been coeval across the southern part of the shield. The Postjotnian magmatism in southern Finland (transitional basalts) and Lake Ladoga region (alkaline basalts) was compositionally variable, presumably due to different mantle source regions (Upton *et al.* 1998; see also Patchett *et al.* 1994).

**Nd isotope geochemistry**

The Sm-Nd isotopic system is an invaluable indicator of the overall age and character of the protoliths involved in rapakivi granite genesis (e.g., Rämö and Haapala 1996). The initial Nd isotopic compositions of the rapakivi granites show important variations (Table 1). The Finnish, Estonian, and Latvian rapakivi granites and the Nordingrå pluton of Sweden have $\varepsilon_{Nd}$ values between –3 and 0. This suggest derivation from the ~1.9 Ga Svecofennian crust (e.g., Haapala and Rämö 1990) and that, in this area, the 1.9 Ga crust is quite homogeneous in terms of mantle separation age. The Riga batholith of Latvia, however, has a slightly higher $\varepsilon_{Nd}$ value than the remainder of these plutons which suggest that the lithosphere may be slightly more juvenile in the south (Rämö *et al.* 1996). Compared to the Finnish occurrences, the Salmi batholith of Russian Karelia is quite different in having more negative $\varepsilon_{Nd}$ values (–9 to –5.5). This indicates a substantial (~50 %; Rämö 1991) Neoarchean component in the protolith of the batholith which is not surprising as it is situated between Paleoproterozoic and Archean domains (Fig. 1). Similar, yet far more surprising, Nd isotopic composition is registered by the rapakivi granites of central Sweden with $\varepsilon_{Nd}$ values between –7.5 and –4.5. No exposed Archean crust is known in central Sweden but the rapakivi granites show that, in the deep parts of the crust, a significant Archean component is present (Andersson 1997a).

The mafic rocks associated with the rapakivi granites show Nd isotopic compositions that differ from those of the granites only marginally (Table 1). They show, however, traits that can be related to mantle source compositions and magmatic evolution. The mafic rocks associated with the Finnish rapakivi granites show $\varepsilon_{Nd}$ values that range from slightly positive (+1.5) to slightly negative (–3). This variation has been ascribed to a slightly depleted mantle protolith ($\varepsilon_{Nd}$ +1 to +2; Rämö 1991; Fröjdö *et al.* 1997) and contamination of the mantle-derived melts by the Svecofennian crust. The mafic rocks associated with the Russian Karelian and central Swedish rapakivi granites ($\varepsilon_{Nd}$ –8 to –6.5 and –10 to –4.5, respectively) are indicative of an enriched mantle protolith and/or contamination by a crust with an Archean component (see Neymark *et al.* 1994; Andersson 1997a). The fact that the Swedish mafic rocks have, on average, slightly more negative $\varepsilon_{Nd}$ values than the associated granites (–10 to –4.5 vs. –7.5 to –4.5) suggests that the upper mantle in this area may have a slightly larger Archean component than the deep crust. Thus the Nd isotopic composition of some of these mafic rocks may rather reflect mantle source characteristics than crustal contamination.

The Nd isotopic composition of the Postjotnian diabases (Table 1) shows less variation than that of the mafic rocks of the rapakivi association, but allows a clear distinction between the Russian Karelian and Finnish (as well as Swedish) suites. The Finnish occurrences have moderately positive initial $\varepsilon_{Nd}$ values (+1.5 to +3) which shows that they were derived from a slightly depleted subcontinental mantle source and were affected by only minor (if

Table 1. Crystallization age and initial Nd isotopic composition (expressed as $\varepsilon_{Nd}$ (T) values relative to the Chondritic Uniform Reservoir; DePaolo and Wasserburg 1976) of major mid-Proterozoic silicic and mafic rocks in the Fennoscandian Shield and its southern continuation

| Area | Central Sweden (W of Nordingrå)[1)] | SW Finland (and Nordingrå), Latvia[2)] | SE Finland, Estonia[3)] | Russian Karelia[4)] |
|---|---|---|---|---|
| RAPAKIVI GRANITES AND CONTEMPORANEOUS MAFIC ROCKS | | | | |
| Age (Ga) | 1.53 to 1.47 | 1.59 to 1.54 | 1.67 to 1.62 | 1.55 to 1.54 |
| $\varepsilon_{Nd}$ (T), granites | – 7.5 to – 4.5 | – 3 to 0 | – 3 to 0 | – 9 to – 5.5 |
| $\varepsilon_{Nd}$ (T), mafic rocks | – 10 to – 4.5 | – 3 to + 1.5 | – 1 to + 1.5 | – 8 to – 6.5 |
| POSTJOTNIAN DIABASES | | | | |
| Age (Ga) | ~ 1.26 | 1.26 | — | ~ 1.28 |
| $\varepsilon_{Nd}$ (T) | – 0.5 to + 3.5 | + 1.5 to + 3 | — | – 10.5 |

Data sources (also including some additional papers mentioned in the listed articles):

[1)] Ahl *et al.* (1997), Andersson (1997a, b), Claesson (1987), Claesson and Kresten (1997), Patchett et al. (1994), Persson (1999)

[2)] Ahl *et al.* (1997); Fröjdö *et al.* (1997), Rämö (1990, 1991), Rämö *et al.* (1996), Suominen (1991), Upton *et al.* (1998)

[3)] Alviola *et al.* (1999), Rämö (1991), Rämö *et al.* (1996), Vaasjoki *et al.* (1991)

[4)] Amelin *et al.* (1997), Neymark *et al.* (1994), Pesonen (1998), Rämö (1991), Suominen (1991), Upton *et al.* (1998)

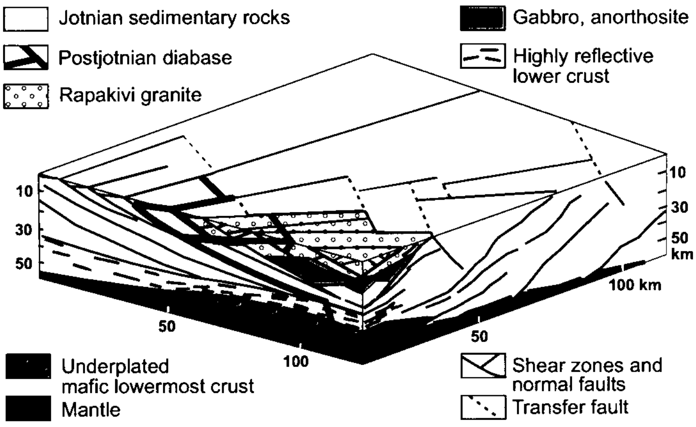


Fig. 2. A schematic model for the emplacement of the rapakivi granites and Postjotnian diabase dikes in an extensional tectonic setting. A system of listric shear zones and conjugate transfer faults gowern the spatial and temporal relationships of the Subjotnian rapakivi granites and gabbroic and anorthositic rocks, Jotnian sandstones, and Postjotnian diabases. After Korja and Heikkinen (1995, 1999).

any) crustal contamination. The $\varepsilon_{Nd}$ values of the Swedish Postjotnian diabases (–0.5 to +3.5) show that the Archean component (that shows in the rapakivi-age mafic rocks of the area) probably did not have much effect on them. In contrast, the Postjotnian diabases of Lake Ladoga have an initial $\varepsilon_{Nd}$ of –10.5 and probably tapped a Neoarchean lithospheric mantle protolith. Lithospheric mantle associated with the Archean crust in Russian Karelia thus probably continues under Lake Ladoga (cf. Upton *et al.* 1998).

**Geophysics**

Extensive seismic, gravimetric, and magnetic studies have been performed in order to reveal the deep structure of the Fennoscandian Shield (see Korsman *et al.* 1999 for review). Deep seismic soundings along several lines have yielded a comprehensive picture of the deep structure of the Svecofennian Orogen. Figure 1 shows the variation of crustal thickness (Moho depth) across the central and southern part of the Fennoscandian Shield as well as its southern continuation.

In general, the Svecofennian Orogen is characterized by thick crust (at maximum, 65 km) that has particularly steep and local ovoidal thinnings associated with the mid-Proterozoic rapakivi granites (Fig. 1). The rapakivi granite batholiths are found as relatively thin (~5–10 km) sheet-like bodies in the uppermost part of the crust and are characterized by circular regional Bouguer anomaly minima and smooth magnetic patterns with sharply cutting anomaly contacts (Elo and Korja 1993; Korja *et al.* 1993). The associated gabbroic and anorthositic rocks form local positive anomalies. The large Bouguer gradients result from the combination of the upper crustal rapakivi granites and thinning of the lower crust beneath them.

The upper and middle crust in the southern Svecofennian Orogen are characterized by listric reflectors that flatten out at the depth of 30–35 km (e.g., Korja and Heikkinen 1995). In the seismic profiles the rapakivi granite and related mafic intrusions appear as upper crustal (0–20 km) non-reflective bodies delineated by listric and normal shear zones (Fig. 2). The lower crust is highly reflective and tends to bow up under them. Highly reflective structures within the batholiths are related to contacts between rapakivi granite and associated mafic rocks or Postjotnian diabases. The gabbroic parts have higher velocity, density, and magnetic susceptibility than the surrounding rocks.

The highly reflective lower crust shows upward concave structures that probably result from upward movement of the lower crust as the lithosphere was in a process of overall extension. The high reflectivity is interpreted as having been caused by mafic underplating and intraplating that acted as the thermal energy source for the lower crustal melting that generated the rapakivi granite magmas. The listric shear zones that detach either at the lower crust to middle crust boundary or the Moho boundary probably provided pathways for the ascent of the rapakivi and associated mantle-derived mafic magmas. The space that was created by the extending upper crust was occupied by both the rapakivi granite magmas and the uprising lower crust, and cratonic basins with continental sediments were developed due to thermal contraction of the rift zones (Fig. 2; see also Klein and Hsui 1987). Overall, the Baltic Sea (Fig. 1) has many characteristic features of paleorifts: topographic low (now under water), relatively thin crust with large crustal gradients, and voluminous bimodal magmatism. It should also be noted that the age of the rapakivi granite magmatism across southern Fennoscandia (Fig. 1) does not fit a hot spot track but may rather reflect a spreading plume head underneath the lithosphere (cf. Zeyen et al. 1997). Net strenghtening of thinned crust probably led to cessation of extension and anatexis in any one area and spreading of deformation and magmatism to adjacent areas of weaker (and thicker) crust (Korja and Heikkinen 1995).

The Postjotnian diabase dikes form bright saucer-shaped reflectors in the upper crust. They are spatially nearly always associated with the rapakivi granites which probably reflects the fact that the relatively thin crust hosting the (mechanically ruptured) rapakivi granite batholiths was favourable for the transit of these late mantle-derived basaltic magmas. In contrast to the rapakivi granite event, the Postjotnian basaltic magmatism was not associated with contemporaneous silicic magmas. It may be that, by the Postjotnian time, the Svecofennian Orogen was too cool and infertile to promote further partial melting of the crust (cf. Rämö 1990, 1991).

**Conclusions**

During mid-Proterozoic time (~1.7–1.3 Ga), the Fennoscandian Shield recorded

(1) a prolonged (1.67–1.47 Ga) tectonothermal event that resulted in major lithospheric reorganization associated with mantle upwelling, mafic underplating, crustal extension and thinning, and emplacement of rapakivi granite complexes;
(2) formation of cratonic basins (at ~1.5–1.3 Ga) associated with continental redbeds in areas of major crustal thinning; and
(3) a basaltic event (at ~1.3 Ga) probably shortly following the cessation of redbed sedimentation in any one area.

Nd isotopes of the mid-Proterozoic igneous suites show that the deep crust and upper mantle of the Svecofennian Orogen vary substantially, both in composition and age.

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