Magmas, metasomatism, and melting – the Svecofennian orogeny in southernmost Finland

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The evolution of the Svecofennian crust in the Hanko-Ekenäs area in southernmost Finland was a nearly 100 myr-long process involving metamorphic, metasomatic, and magmatic processes. Supracrustal rocks deposited during the early Svecofennian were deformed, intruded by granitoids, and significantly altered by fluids. Both the supracrustals and the intrusive granitoids were partially melted during the late Svecofennian.

Keywords: Svecofennian orogeny, granite, migmatite, metasomatic alteration

1. Introduction

The Svecofennian orogeny at *ca* 1.9-1.8 Ga formed or modified most of the crust in southern and western Finland. In southern Finland, evidence of partial melting is abundant in the Late Svecofennian granite-migmatite (LSGM) zone, a WSW-ENE belt of psammopelitic, metapelitic, and metavolcanic migmatites and anatectic granites (Ehlers et al., 1993). Edelman and Jaanus-Järkkälä (1983) proposed that a tectonic boundary separates the southernmost directly observable part of the Svecofennian domain from the rest of Southern Finland. Thus, the Hanko-Ekenäs coast and archipelago may have formed in a different setting than the LSGM zone and contribute to a more detailed picture of the Svecofennian orogeny.

2. Methods and lithological materials

To investigate the crustal evolution in the study area we combine field observations, petrographic examination, major and trace element whole-rock geochemistry, and U-Pb in zircon radiometric dating. We have also identified shear zones in the field and in pre-existing aeromagnetic and bathymetric data to discuss the petrological data in a tectonic context.

The study area rock types are supracrustal metatexites, granitic metatexites, even-grained granodiorites, and different kinds of leucogranites. *The supracrustal metatexites* are compositionally varied migmatised metavolcanic and metasedimentary rocks, some of which contain conspicuous non-primary K-feldspar megacrysts. The megacryst-bearing supracrustal metatexites resemble deformed granites. *The granitic metatexites* also contain K-feldspar megacrysts and were migmatised, but in contrast to the protolith of the supracrustal metatexites, they were originally plutonic granitoids. They are near-parallel to the schistosity of the supracrustal metatexites but crosscut them in places. In both types of metatexites, leucosomes have diffuse boundaries to the host rocks and melanosomes are absent.

The even-grained granodiorites are deformed grey granodiorites that display preferred mineral orientation. At some locations, the grey granodiorite gradually transitions into pink, granitic stripes of varying width. In contrast, *the leucogranites* of the area are non-oriented granites containing partially assimilated paleosome rafts. The leucogranites appear as the major rock type in the central part of the study area, but similar granite also appears as leucosomes among the metatexites. The leucogranites vary in appearance between predominantly red and predominantly grey variants with inconclusive relative ages. At one location, an *altered leucogranite* contains quartz-poor and K-feldspar rich altered stripes.

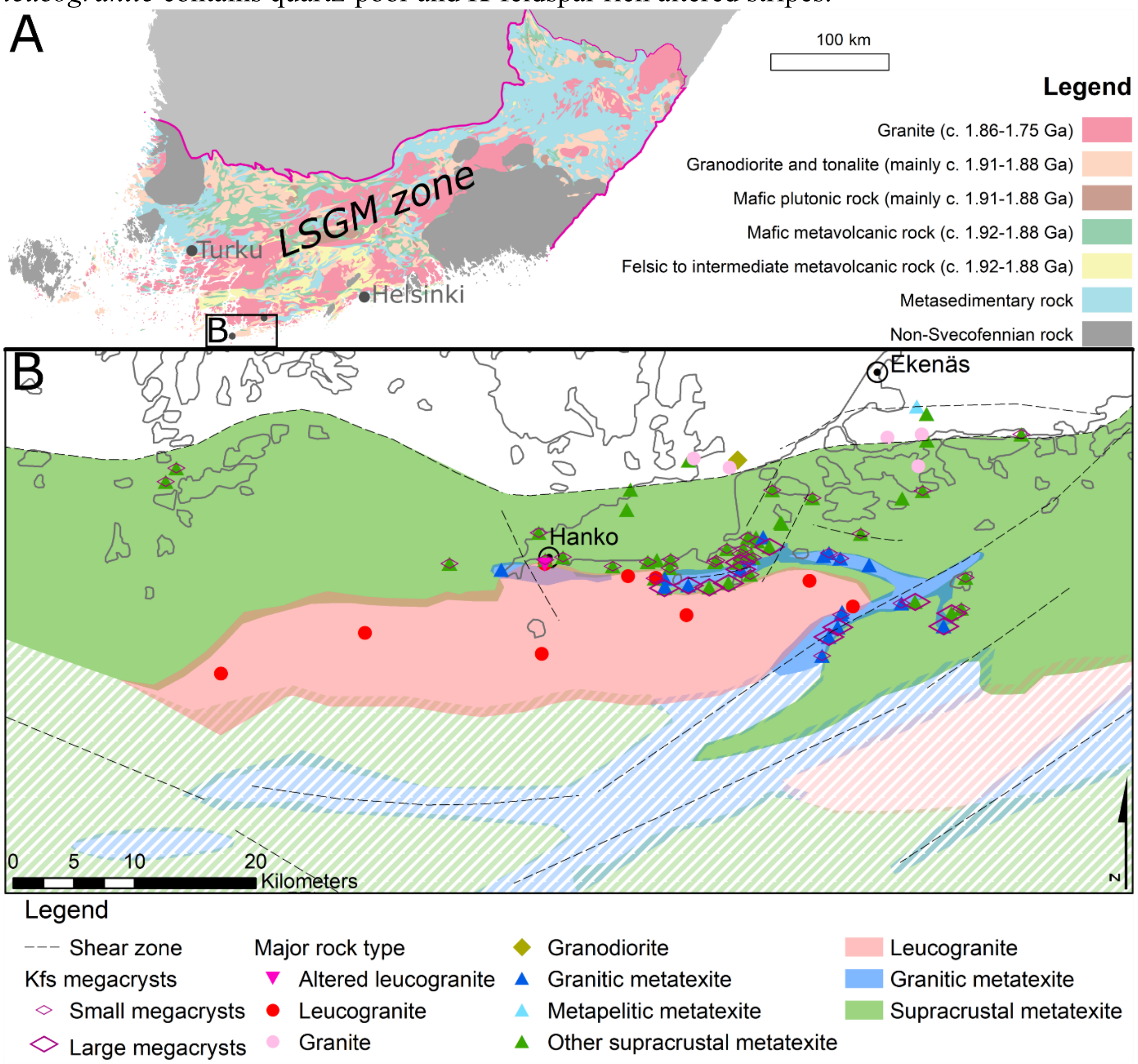

Figure 1. A) The Southern Svecofennian Subprovince. B) Map of the study area based on field observations, aeromagnetic maps, and previous lithological maps. To the North, the study area is bordered by the proposed tectonic boundary (Edelman & Jaanus-Järkkälä, 1983). The hatched filling indicates areas lacking any outcrops above the sea level.

3. Results

The U-Pb in zircon dating of migmatite samples reveals both protolith and migmatisation ages. The megacryst-bearing supracrustal metatexite source ages are around 1.89 Ga, whereas the granitic metatexite crystallisation ages are *ca.* 1.88 Ga. Leucosome crystallisation ages in both types of migmatites are *ca.* 1.82 Ga. The best estimate for the even-grained granodiorite crystallisation age is 1.87 Ga, although this age is only tentative due to large errors and small sample size. The leucogranite ages range from 1.85 to 1.82 Ga.

Geochemically, the granitic metatexites and leucogranites are mainly ferroan and calc-alkalic to alkali-calcic, whereas the even-grained granodiorites are mostly magnesian and distinctly calcic. The altered leucogranite is significantly more alkalic than any other rocks.

Apart from some of the even-grained granodiorites, which are metaluminous, all our analysed samples are weakly peraluminous. Even the leucogranites are only weakly peraluminous. Notably, the megacryst-bearing supracrustal metatexites are similar to the granitic metatexites in major element composition except for a wider variation in SiO_2-content.

The REE slopes of the even-grained granodiorites and granitic metatexites display similar basic shapes, but the granitic metatexites are more enriched in REE than the granodiorites. Compared to the even-grained granodiorites, the leucogranites are enriched in LREE but contain similar amounts of HREE. The altered leucogranite is heavily enriched in all REE except Eu and the heaviest REE (Er-Lu). The analysed supracrustal metatexites are different from each other and display different REE slopes than any of the granitoids.

P_2O_5, Zr, and Hf are mostly depleted in the leucogranites in comparison to the metatexites. These elements are significant constituents of apatite and zircon, the accessory minerals usually found as inclusions within biotite in our study area. As the leucogranites contain very little biotite compared to the migmatites, these mineral phases and elements are also depleted in them. Monazite is prevalent in leucogranites as well as in migmatites, and its compatible trace elements Rb, Th, U, and light REE are present in roughly similar quantities in these rock types, although the variation is a little higher among the leucogranites than among the metatexites.

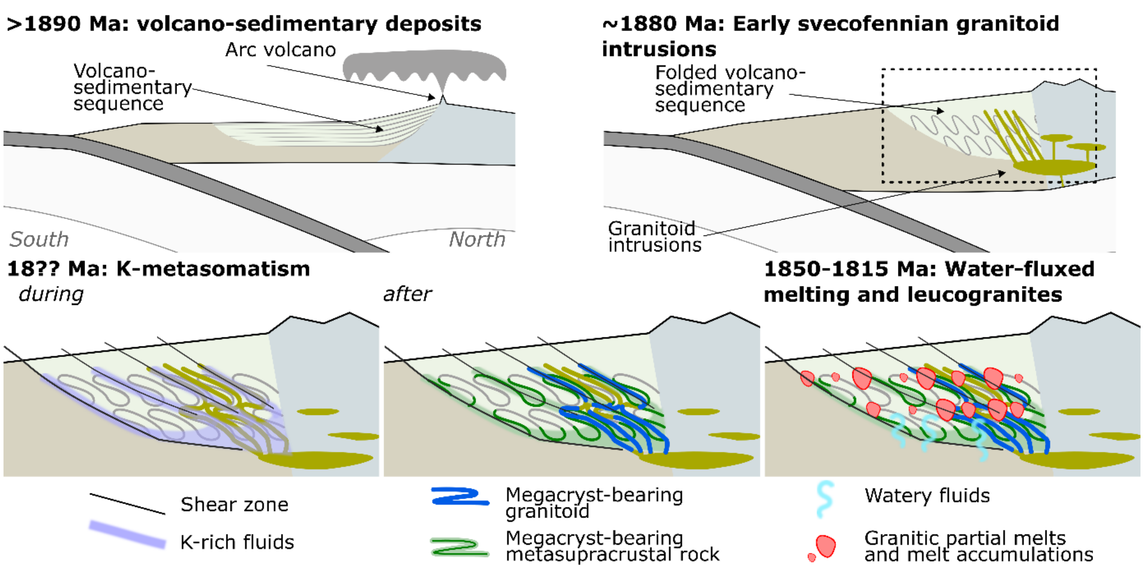

Figure 2. Schematic interpretation of the magmatic evolution in southernmost Finland. Present day north and south marked on the first picture.

4. Crustal evolution stages

I) Until ca 1.89 Ga: Volcano-sedimentary deposits

Supracrustals in the form of volcanic deposits interspersed by limestone and psammitic sediment layers. As pelitic sediments were rare during the deposition phase, and as very few zircons are older than 1.9 Ga, the supracrustal material likely came from the growing magmatic arc rather than an older craton.

II) Ca 1.88 Ga: Early Svecofennian granitoids

The early Svecofennian granitoid magmatism resulted in two different rock types: the even-grained granodiorites and the protolith of the granitic metatexites. As the dating results are not conclusive and no crosscutting relationships between the rock types were found in the field, it is unresolved if they represent two distinct magmatic events with different sources, or if they share a common source but were altered in different ways during later processes. The protolith of the granitic metatexite intruded in folded supracrustal rocks through shear zones.

III) Metasomatic alteration

Non-primary K-feldspar megacrysts in originally supracrustal rocks are associated with the same shear zones where the protolith of the granitic metatexite intruded. The shear zones thus likely carried K-rich fluids that caused megacryst crystallisation in the hosts, resulting in granite-like composition in the originally supracrustal rocks. The timing of this metasomatic event is unclear: the fluids may have either originated in the granitoid magma that crystallized in the shear zones (meaning that the megacrysts in the granitic metatexite were a primary feature), or a later metasomatic event utilizing the same shear zones caused megacryst crystallisation in both the supracrustal and the granitoid rocks.

IV) 1.85-1.81 Ga: Water-fluxed melting and leucogranite formation

Fluid activity continued in the area during the late Svecofennian, as the mineral composition and leucosome morphology in the migmatites indicate water-fluxed melting (Weinberg & Hasalová, 2015). Although the age is concurrent with the migmatisation event in the rest of the southern Finland Subprovince (e.g. Huhma, 1986; Väisänen et al., 2002), dehydration melting was the main anatectic process in the LSGM zone (e.g. Andersen & Rämö, 2021).

The altered leucogranite was enriched in K_2O and depleted in SiO_2 in veinlike patterns. As the dated sample yields two non-overlapping zircon ages, it is possible that the older 1.84 Ga age represents the original crystallisation age of the leucogranite, and the younger 1.82 Ga age a later heat or melt pulse, possibly coinciding with the metasomatic alteration.

In the areas where the leucogranite is the major rock type, largely assimilated paleosome or residuum rafts are noticeably present within the leucogranite. The leucogranites may thus have stalled close to their source rocks rather than risen upwards in the crust. This stalling is consistent with previous work indicating that water-rich granitic magmas are not very mobile (García-Arias et al., 2015).

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