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ORIGINAL PAPER

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Emplacement mechanisms of late-orogenic granites: structural and geochemical evidence from southern Finland

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Abstract The country rock in southern Finland formed mainly during the Svecofennian orogeny ca. 1.9 Ga ago. The middle and lower crust was partially melted 1.83 Ga ago due to crustal thickening and subsequent extension. During this event, S-type migmatites and granites were formed along a 100×500 km zone. This Late Svecofennian Granite–Migmatite zone (LSGM zone) is a large crustal segment characterised by roughly E–W trending sub-horizontal migmatites and granites. Combined ductile E–W shear movements and NNW–SSE compressional movements defined a transpressional tectonic regime during the emplacement. Partial melts that moved through the crust pooled as granite sheets or froze as migmatites. Major transpressive shear zones border the LSGM zone, which forms a tectonic and metamorphic zone that crosscuts the earlier Svecofennian granitoids. Based on field observations and geochemical data from two sets of outcrops, we show that the great volumes of late-orogenic granites and migmatites in southern Finland were transported and emplaced as small chemically variable batches, possibly extracted from different protoliths. These melt batches were transported along repeatedly activated channels and collected at some horizontal level in the crust. In the Nagu area, the melt batches were trapped under a roof-layer of amphibolite and the whole complex was synchronously folded into open folds with steep axial surfaces and E–W trending fold axes. The sheets of microcline granite are, in places, strongly sheared; the microcline phenocrysts are imbricated and subsequent deformation of the microcline phenocrysts indicates syntectonic movements of the layers as well as a syn-tectonic mechanism for the late-magmatic fractionation. Depending on the degree of crystallisation of the individual melt batches during shearing at different intensities, the granites have slightly different appearances. Some sheared zones show a cumulate-like trace element geochemistry, indicating that melt fractions were expelled from the system, producing layers of deformation enhanced fractionated granites and cumulate layers. Our interpretation is that the Nagu area shows shear-assisted fractionation mechanisms in granitic melts, and that similar processes are responsible for the fractionation trends seen in the sub-horizontal sheeted granites in Hämeenlinna at higher levels in the crust.

Key words Granites · Emplacement · Fractionation · Geochemistry · Partial melts

Introduction

The country rock in southern Finland was formed during the Palaeoproterozoic Early Svecofennian orogeny about 1.9 Ga ago (Nironen 1997). The late Svecofennian Granite–Migmatite zone (LSGM zone, Ehlers et al. 1993), in southern Finland is a large crustal segment, formed along a 100×500 km zone and characterised by roughly E–W trending sub-horizontal migmatites and S-type granites (Fig. 1). These potassium granites have U-Pb zircon ages between 1,840–1,830 Ma (Korsman et al. 1984; Huhma 1986; Suominen 1991). The maximum metamorphic temperature and pressure range during that event is estimated to around 800–850°C and 4–6 kbars, respectively (Väisänen and Hölttä 1999). The granites occur as coarse-grained porphyritic sheets as well as even-grained rounded intrusions. Combined ductile E–W directed dextral shear movements and NNW–SSE horizontal shortening defined a transpressional tectonic regime during the emplacement (Ehlers et al. 1993).

The LSGM zone extends from the archipelago in southwestern Finland to southeastern Finland and transects and overprints earlier Svecofennian granitoids, metasediments and volcanic rocks. It was intruded later by (~1.6 Ga) rapakivi granites (Fig. 1), and major

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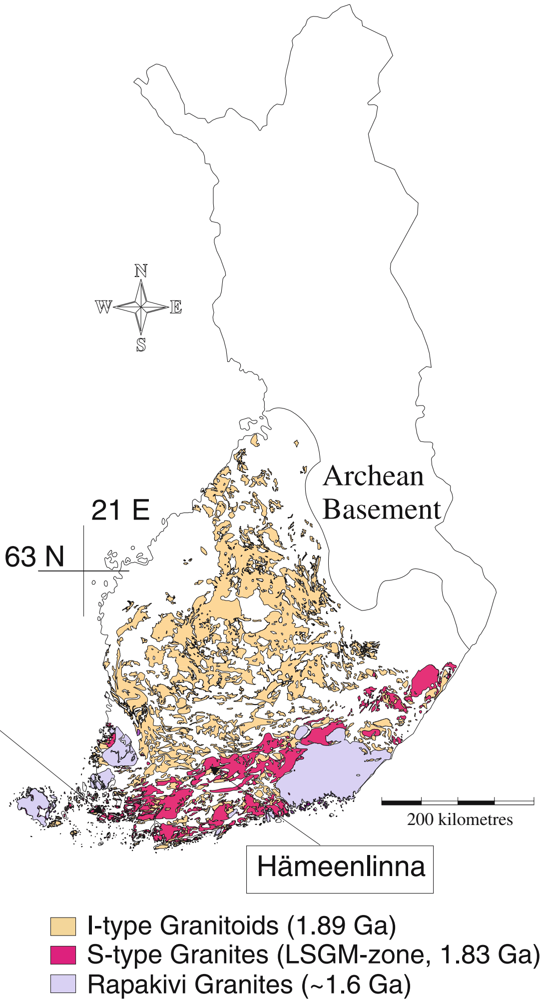

Fig. 1 Geological overview of southern Finland showing Precambrian granites and the two locations discussed in this paper. The Late Svecofennian granite–migmatite zone (*red-coloured* on the map) is bordered both in the north and the south by major transpressive shear zones. Digital data from Geological Survey of Finland

transpressive shear zones border it. General discussions on migmatites and granites can be found in e.g. Brown and Solar (1998a, b). The migmatite granites in southern Finland have previously been described by e.g. Eskola (1914), Sederholm (1932, 1934), Nurmi and Haapala (1986) and Selonen et al. (1996). Stålfors and Ehlers (2000a, b, 2001, 2003) have discussed their emplacement mechanisms suggesting that partial melts moved through the crust to form either granitic massifs in the middle and upper crust, or froze as migmatites at greater depths. The LSGM zone is a tectonic and metamorphic zone that transects both the earlier Svecofennian granitoids and the E–W-trending threshold between thinner and thicker crust that underlies southern Finland (Luosto 1997). In this paper, we show evidence indicating that late-orogenic plutons in southern Finland were built up by successive accumulations of small individual batches of crustally derived melt. Some plutons are visibly composed of different layers of granites, and they show individual variations in their REE compositions.

Tectonic setting

Three regional deformation episodes are identified in the Svecofennian rocks in southern Finland: D_1 D_2 and D_3. The late Svecofennian granites have recorded only the D_3 structures, defining the "late-tectonic" timing of the emplacement. Due to the high metamorphic grade, the oldest deformational structures are very sparse, even if some isoclinal F_1 folds can be observed. Most recorded F_1 folds are intrafolial small folds, while the F_2 folds occur at all scales and dominate among the early structures. The tight F_2 folds are overturned towards W or NW with north–westerly vergences, while the F_3 folds are upright and transpose earlier structural features parallel to the steep E–W-striking F_3 axial planes (Fig. 2). The F_3 folds are mostly open in areas that are dominated by early Svecofennian competent granitoids, whilst areas dominated by less competent supracrustal layers usually shows tighter F_3 folds. The late-orogenic granites were emplaced and locally deformed during D_3 (Fig. 3). Tiling (imbrication) of microcline phenocrysts in horizontal granite sheets indicates syn-magmatic shear during D_3 (Selonen et al. 1996) and the tiling of the microcline phenocrysts indicates a top to the west or NW movement. Continuing deformation after the emplacement resulted in the strongly sheared fabric, squeezing out the last melt fractions. The granites intruded along sub-vertical ductile D_3 shear zones, defining a major transpressive shear system, and were

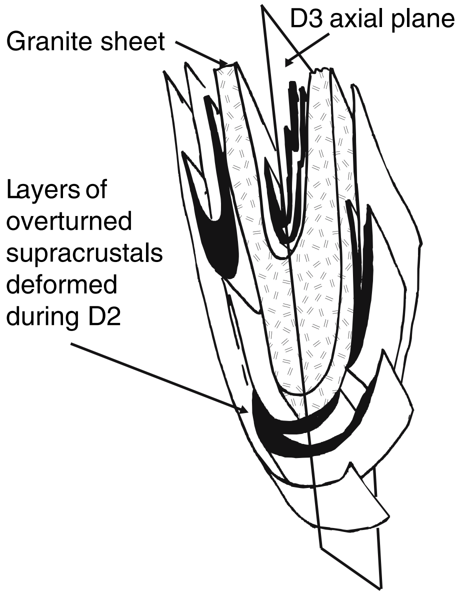

Fig. 2 Structural model of the bedrock in SW Finland. Late-orogenic granites are emplaced parallel to earlier D_2 structures which were re-folded during D_3. The D_3 structures range from open to tight folds throughout southern Finland

Fig. 3 Tiled microcline phenocrysts in granite showing W–NW vergence (*left* in figure) during D_3 deformation. Sub-horizontal granite sheet, east of Turku

emplaced along sub-horizontal surfaces parallel to the overturned D_2 axial planes. The driving force has been suggested to be strike-slip dilatancy pumping with alternating compressional and extensional areas (Selonen et al. 1996).

The southern margin of the zone of migmatite sheets is well exposed in the SW archipelago as a regional ductile shear zone (Figs. 4, 5). The shear zone can be traced ca. 200 km along the southern coast of Finland, and it truncated by ca. 1.6 Ga rapakivi granites in the NW. The area to the NE of the shear zone is dominated by migmatitic supracrustal rocks forming gently dipping dome and basin structures. The area in the SW consists of early Svecofennian granodioritic–tonalitic gneisses.

Sampling methods and analytical procedures

A total of 42 granitic samples were collected from two sets of outcrops to perform geochemical whole rock analyses for petrological interpretations. Grab samples weighing between 3 and 9 kg were crushed with a jaw crusher. About 200 g of each sample were pulverised and analysed at Activation Laboratories Ltd in Canada. The major elements were analysed with ICP-AES and all the other elements with ICP-MS. The complete set of analytical data can be obtained from the authors upon request.

Geochemistry

Two sub-areas (see Fig. 1) will be discussed within the LSGM zone representing two examples of pooling and formation of sub-horizontal granitic sheets in a mid-crustal setting.

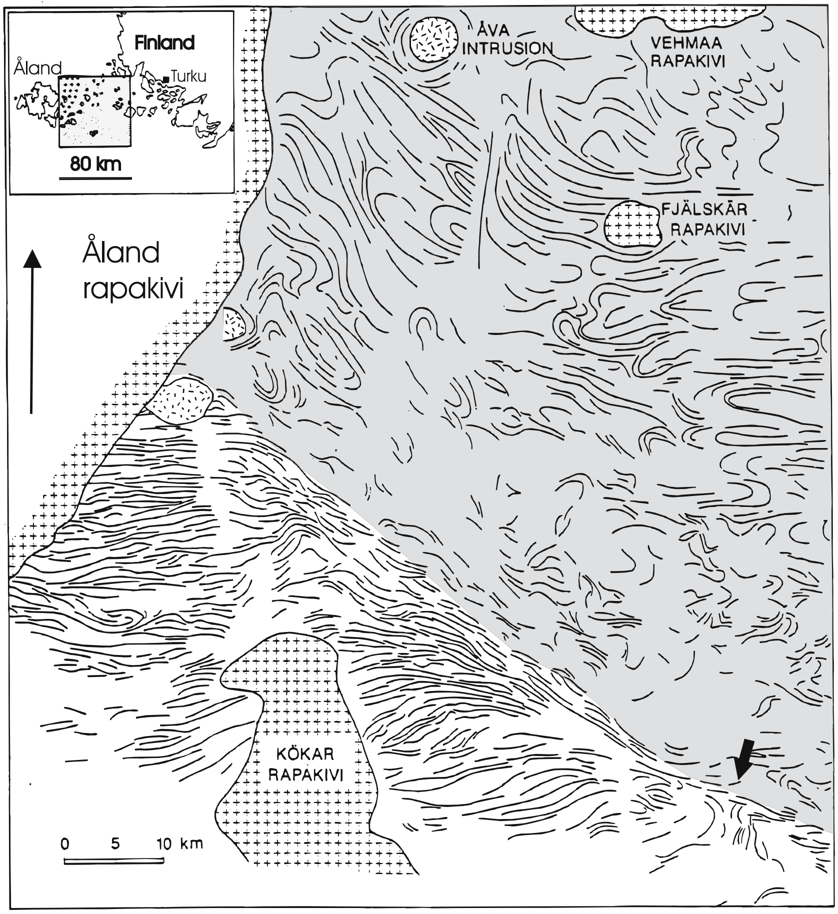

Fig. 4 The southern margin of the zone of migmatite sheets is well exposed in the SW archipelago as a regional NW–SE-trending ductile shear zone. The map area is roughly 7,000 km^2 and shows the strike of foliations of the rocks. The area NE of the shear zone is dominated by gently dipping dome and basin structures in migmatitic supracrustals. The area in the SW consists of granodioritic-tonalitic gneisses. In the NW the shear zone is truncated by ca. 1.6 Ga rapakivi granites. The *arrow* shows the location of the outcrop in Fig. 5. (modified after Ehlers and Lindroos 1990)

Fig. 5 Photo showing a detail of the shear zone in Fig. 4. Strongly brecciated competent gabbro mixed with granitoids and shear parallel fine-grained granite veins

The Hämeenlinna area represents a crustal section with chemically fractionated granitic magmas forming composite sheets consisting of separate thin layers (intrusion pulses?) intruded into less migmatitic meta-supracrustals.

The Nagu area in the SW represents a section of the crust exposing a concentration of granitic magmas trapped under a roof of originally sub-horizontal amphibolitic layers. The source rocks lie as migmatitic layers closely underneath the granitic sheets.

We suggest that the sub-areas in Hämeenlinna and Nagu represent different levels of emplacement relative to the source regions.

The layered granite at Hämeenlinna

The Hämeenlinna layered granite pluton is located close to the northern border of the LSGM zone, about 10 km south of the town Hämeenlinna (Fig. 1). The composite granite sheets in the area (Fig. 6) are intruded into gently D_3-refolded supracrustal rocks which, according to our field observations, are metamorphosed in amphibolite facies. The layers of this pluton dip 30° to the north.

Eleven samples, spacing about 2–5 m, were collected from this pluton. The pluton consists of separate layers of granites, from less than a metre to a few metres in thickness (Fig. 6). Despite their similarity in outcrop, the individual granite sheets can be easily separated into two chemically different magma-types. Some of the samples show a cumulate-like geochemistry with a positive Eu-anomaly, while the other samples have a negative Eu-anomaly, being peraluminous granites (Fig. 7). The only difference in the field and in thin sections is that only the peraluminous granites contain biotite. The chemical heterogeneity indicates a history of repeated influxes of small melt batches.

The granites with a cumulate-like geochemistry must have lost a melt fraction either during crystallisation or at some earlier stage. The large variations in the concentrations of the heavy rare earth's (Fig. 7a) are due to garnet fractionation. The fractionation trend seen in the ternary diagram in Fig. 7b implies that both of these melt types are fractionated to some degree and that none of them represent protoliths. Another reason for dividing the samples into two groups is the LREE contents. The cumulates show lower contents of LREE than the granitic samples, and were apparently left behind after the extraction of a melt portion, enriched in the LREE's. These layers have, therefore, retained low REE values with the exception of Eu, due to the low partition coefficients of the REÉs (Rollinson 1993). This is an expected feature in quartz-feldspar dominated partial melts since these minerals incorporate only minor amounts of the LREE's (with the exemption of Eu). The granitic samples, or fractionates, represent melts that have undergone further fractionation and are thus enriched in the LREE's.

This same bimodality is also visible when comparing the zirconium contents of the samples. In Fig. 8 there

Fig. 6 Composite granitic sheets intruded into supracrustal rocks metamorphosed in amphibolite facies. From here, 11 samples were collected, spacing about 2–5 m. The six southernmost sampling sites are marked with *arrows*. The photo shows only the southern part of the sampled area. The view is towards the east, south of the town of Hämeenlinna

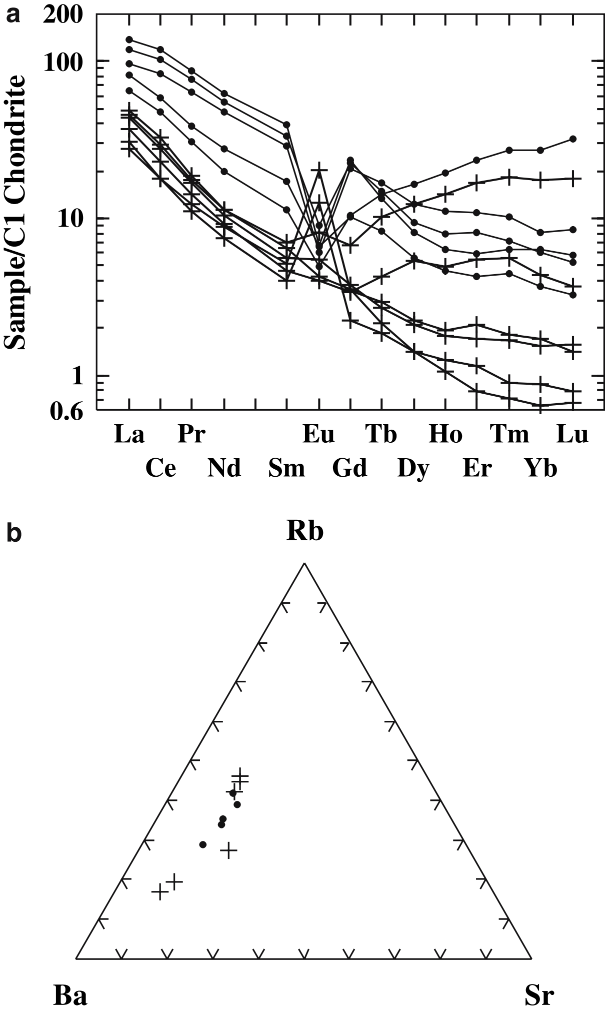

Fig. 7 a REE diagram showing two types of melts in the Hämeenlinna pluton. The peraluminous granites are marked with *dots* and the cumulates with *crosses*. The only difference between these two types of rocks in the field is that the cumulates do not contain biotite. **b** Rb–Ba–Sr diagram showing the fractionation trend of the samples. *Symbols* are the same as in (a)

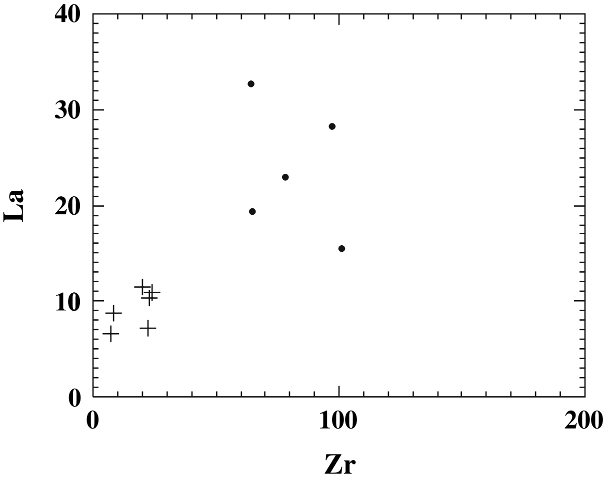

Fig. 8 Zirconium concentrations in the rocks show the same separation into two distinct populations as the REE in Fig. 7; the symbols are the same as in Fig. 7

are two distinct zirconium populations. Watson and Harrison (1983) proposed that Zr-concentration could be used as a measure of temperature, based on the solubility of Zircon in the melt. This does, however, require zirconium to be saturated in the melt, a prerequisite that is not reached in the granites of the LSGM zone due to the continuos squeezing out of the melt batches that are created. During transpressive deformation, every melt percentage above the critical melt fraction (Arzi 1978) is squeezed out of the system, leaving no time for zirconium to reach the maximum saturation. In addition, there are usually residual zircons in crustally derived granites, which is reflected as a deviation from the actual solubility of the melt. The observed division into two populations is thus rather a measure of fractionation than of temperature. Because of the small size of the zirconium-minerals (along with monazite) they are carried away in the melt-phase, leaving behind the coarser-grained restitic phases (Clemens 2003). During fractional crystallisation, they act as nuclei for early crystallising mafic silicates (usually biotite), which then enclose and protect zirconium, ensuring that the refractory zirconium survives further attack of melt.

Contrary to the cumulates, the granites or fractionates contain biotite, which is the mineral accompanying zirconium in the system. The late fractionates are thus enriched in these two minerals. The correlation between the concentrations of the lanthanides and that of the zirconium suggests that the pluton is constructed of several individual batches of melt, which were not all molten at the same time.

The order of intrusion of the individual layers in Fig. 6 is unknown, but the nature of a differentiated and complex origin is still obvious. Our interpretation is that the pluton is built up of small layers of distinctly different granitic magmas that successively intruded in a random manner, thus constructing a visibly layered pluton with occasional remnants of earlier mica gneisses separating some layers.

The Nagu area

The Nagu area (Fig. 9) is characterised by a series of synforms, dominated by amphibolite and meta gabbro, enclosing mostly un-migmatised garnet—mica schists. The synforms are tectonically sandwiched amphibolite layers or nappe structures forming sub-horizontal layers as a result of the regional F_2 folding (Ehlers et al. 1993). The synforms "float" on top of a sheet of banded and deformed (sheared) granites that downward grade into partially melted less sheared pelitic migmatites. The maximum thickness of these composite granitic sheets is about 2 km.

Three main types of granites occur in the banded granite layers in Nagu: thick layers of porphyritic

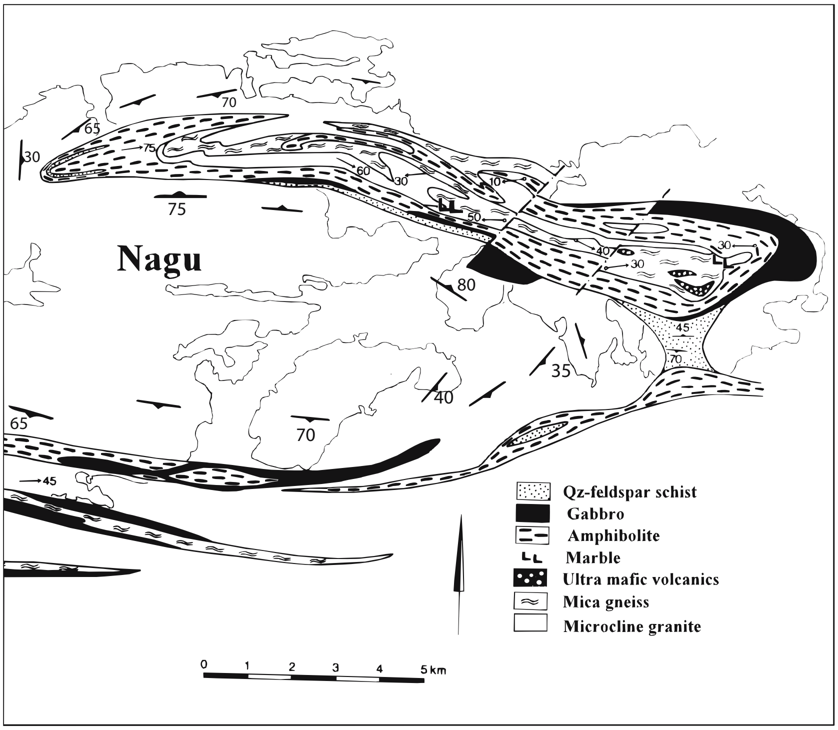

Fig. 9 Simplified geological map of the Nagu area, SW Finland. The discussed area is in the NW part of the Nagu synform

granite (Fig. 10) with tightly packed and tiled K-feldspars indicating syn- and post-emplacement shearing. Leucocratic veins (Fig. 11) with a cumulate composition (mostly positive Eu anomalies, see Fig. 14) and sometimes abundant garnets. Sparse thin (sheared) dark sills (Fig. 10) of granitic composition transect the porphyritic granite. Underneath the granitic sheets are partially melted migmatitic mica gneisses, cut by granitic veins (Fig. 12). Occasional pegmatites are also present throughout the area.

The porphyritic granites

The kilometre-thick sequence of coarse-grained granites is dominated by banded, porphyritic microcline granites with large feldspar phenocrysts that are tiled and subsequently strongly sheared (Fig. 10). The tiling indicates syn-tectonic emplacement of the layers permitting the phenocrysts to rotate after which the continuing deformation resulted in the strongly sheared fabric, squeezing out the last melt fractions. We, therefore, suggest a tectonic origin for this late-magmatic fractionation. The granite banding forms a concentric pattern around the Nagu schist and amphibolite synform, indicating that the banding was formed and the granite intruded before or syntectonically with the D_3 deformation (Fig. 9). The banded granite sheets are, in places, cut by younger granites and pegmatites, increasingly abundant closer to the granite–migmatite contact at the bottom of the sequence. Higher up in the sequence, even though gradually more and more obliterated, there are occasional granitic (and pegmatite) veins cutting the strong E–W-striking layering of the porphyritic granites. This feature strongly indicates that the granite sequence is made up of several successive generations of melt.

The dark, sheared sills (like the one shown in Fig. 10) are made up by biotite-rich granite. Such sills are even-grained and relatively fine-grained and they contain abundant biotite compared to the porphyritic granites. These late granites are, as earlier mentioned, slightly discordant, transecting the banding in the porphyritic granites.

Leucocratic veins

The leucocratic veins (Fig. 11) contain mostly quartz, microcline, some residual plagioclase and in places garnet. The veins vary in appearance in different parts of the area. They range in orientation from layer-parallel to crosscutting in relation to the porphyritic granites. In places, there are two or more generations of leucocratic veins using the same zone of weakness (zones of extension) resulting in a zoned vein, where the older pulse can be garnet-bearing whilst the later one is garnet absent, perhaps indicating a continued filter-pressing that leaves a garnet-rich residue behind.

Migmatites

Structurally underneath the banded granite sequence, there are migmatitic mica gneisses (Fig. 12a). Several (later) granitic veins (Fig. 12b) cut the layering of the migmatitic gneiss at different angles. The contact be-

Fig. 10 Porphyritic granite with strongly deformed and sheared K-feldspars. The phenocrysts in the area show C/S-structures. It is cut by dark-coloured Bt-rich granite. These thin and sheared Bt-rich sills are often discordant against the porphyritic granites. Northern shore of Nagu island

Fig. 11 Leucocratic vein within porphyritic granite; Northern shore of Nagu island

Fig. 12 **a** Northwards into the adjacent antiform, a deeper section is exposed. The granitic sheets are underlain with partly melted migmatitic mica gneisses. The photo shows a migmatite layer (to the *right*) exposed under a sub-horizontal sheet of accumulated porphyritic granite. **b** Granitic vein (feeder dyke) cutting through exposed migmatites. Note that the granitic melt followed a reactivated channel created by an earlier pegmatite

tween the migmatites and the granite is very sharp, and the discordant granitic veins cut into the overlaying granite. There are, however, remnants of mica gneisses higher up within the sheeted granites (Fig. 13). They exist as unmelted, even though sometimes migmatised, fragments or layers, usually layer-parallel to the sheets of porphyritic granites. The existence of these layers in the kilometre thick sequence strongly suggests a structure built up by repeated influxes of small melt batches conformably intruding the mica gneisses beneath the impenetrable "roof" of amphibolites.

Supracrustal rocks

The early Proterozoic supracrustal sequence consists of ca. 500–700 m thick layers of metagabbros and basaltic meta-volcanics, often with pillow lava structures. They are overlain by marbles and mica gneisses (Fig. 9). The amphibolites (discordantly?) overlie a sequence of strongly migmatitic garnet-mica gneisses. This sequence is regionally folded into a series of large upright D_3

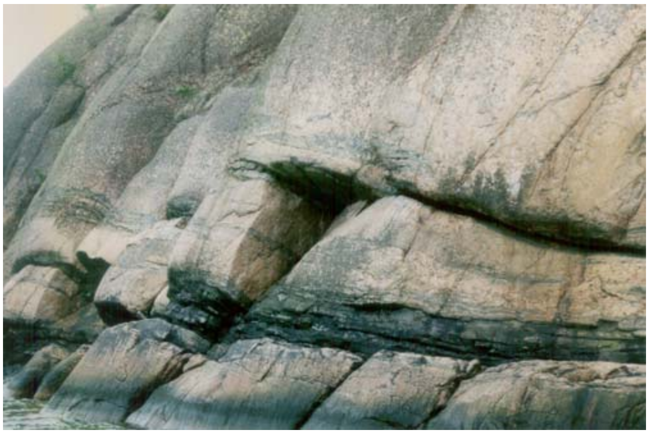

Fig. 13 Layer of unmelted mica schist within porphyritic granite suggesting batch-like melting and emplacement of the granites. Building up the sheeted granites as small batches, enabled these supracrustal layers to withstand melting

synforms, forming an "en echelon" pattern (Fig. 16). Presently the supracrustal synforms are "floating" on top of approximately, a 2-km thick sequence of inhomogeneous granite sheets replacing the underlying migmatites, and the amphibolites have acted as an impenetrable roof to the accumulating granitic sheets.

The steep layering becomes gradually more gently dipping as we move northwards into the adjacent antiform (moving structurally downwards). Here, partly melted migmatitic mica gneisses, that underlie the granitic sheets, are exposed (Fig. 12).

Geochemical characteristics

We have analysed 31 samples from the Nagu area. Sixteen of the samples are from the porphyritic granites in the middle part of the massive sequence and three granitic samples are taken just above the granite–migmatite contact. Three samples are from the biotite-rich granites and six samples from the leucocratic veins. In addition, we collected three samples from the granitic veins cutting the migmatites in the structurally lowest part of the sequence.

There are no significant geochemical variations between the different types of granites. All the granites in the area are peraluminous with negative Eu-anomalies in their REE pattern (Fig. 14). They have, however, undergone different degrees of fractionation, which is reflected in variations both in the LREE's and the Rb–Sr–Ba ternary diagram. The REE patterns suggest strong involvement of the accessory phases Zircon and Monazite, which is reflected as a positive correlation in the P_2O_5–Ce diagram (Fig. 14d) with the exemption of the leucocratic veins that show no enrichment in Ce. The thin biotite-rich granites in Fig. 10 represent the most depleted residual melts (based on high REE and Zirconium contents, not specified in Fig. 14) squeezed out from the deforming porphyritic granites.

The leucocratic veins have cumulate-like REE pattern (Fig. 14). They have a positive or only slightly negative Eu anomaly and the LREE values are low compared to the granitic samples. But, in general, they show the same type of characteristics as the granitic samples in the area.

Closer to the adjacent antiform in the north, partly melted migmatitic mica gneisses, that underlies the granitic sheets, are exposed (Fig. 12). Even though the trace element geochemistry is similar for all the different granites, the samples at the granite–migmatite contact deviate from then rest of the granites with respect to the major elements.

The K_2O–Ba diagram (Fig. 15) divides the samples into two distinct trends. The late veins, along with the adjacent granites in Fig. 12a, b, have apparently a slightly differing history from the granites higher up in the rock sequence. Our interpretation is that they represent one of the latest intrusive events in the building up of the sheeted massifs. The plots of the leucocratic veins are more scattered than the porphyritic granites, indicating more varied histories of fractionation during partial crystallisation.

In addition, the "feeder dykes" cutting the migmatites have a steeper slope in their LREÉs and they show a strong negative Eu-anomaly compared to the adjacent granites (Figs. 12, 14b), possibly indicating more advanced partial melting and fractionation for the dykes than for the lowermost granite sheets that they intrude.

An evolutionary model for the Nagu area

Based on field observations and geochemical analyses, we propose the following evolutionary history for the Nagu area (see Fig. 16). About 1.88 Ga ago (age estimate after Nironen 1997), the amphibolites and mica schists were recumbently folded or sandwiched during the F_2 fold phase. About 50 million years later, at 1.83 Ga, the F_2 folds were refolded by F_3 synchronously with partial melting of the supracrustals. During this transpressive event, the interconnected melt channels became mobile and granitic magmas moved upwards and were trapped against the massive amphibolitic roof. Constant influxes of small pulses of granitic melt spread out beneath the "roof", and upon solidification, forced later pulses to collect further down from the amphibolite at the top, forming a concentric pattern of banded granites around the amphibolites. Since the melt production was continuous during the transpression, the melt was transported as small batches, which made it possible for parts of the earlier structures (e.g. supracrustal layers and migmatites) to survive at all scales (Fig. 13). Simultaneously with the production of melt within the pelites, fractional crystallisation combined with deformation resulted in the geochemical variations observed within the sequence of granites. The latest stages of this process are the feeder dykes cutting the migmatites and the associated lowermost granite sheets in the Nagu synform.

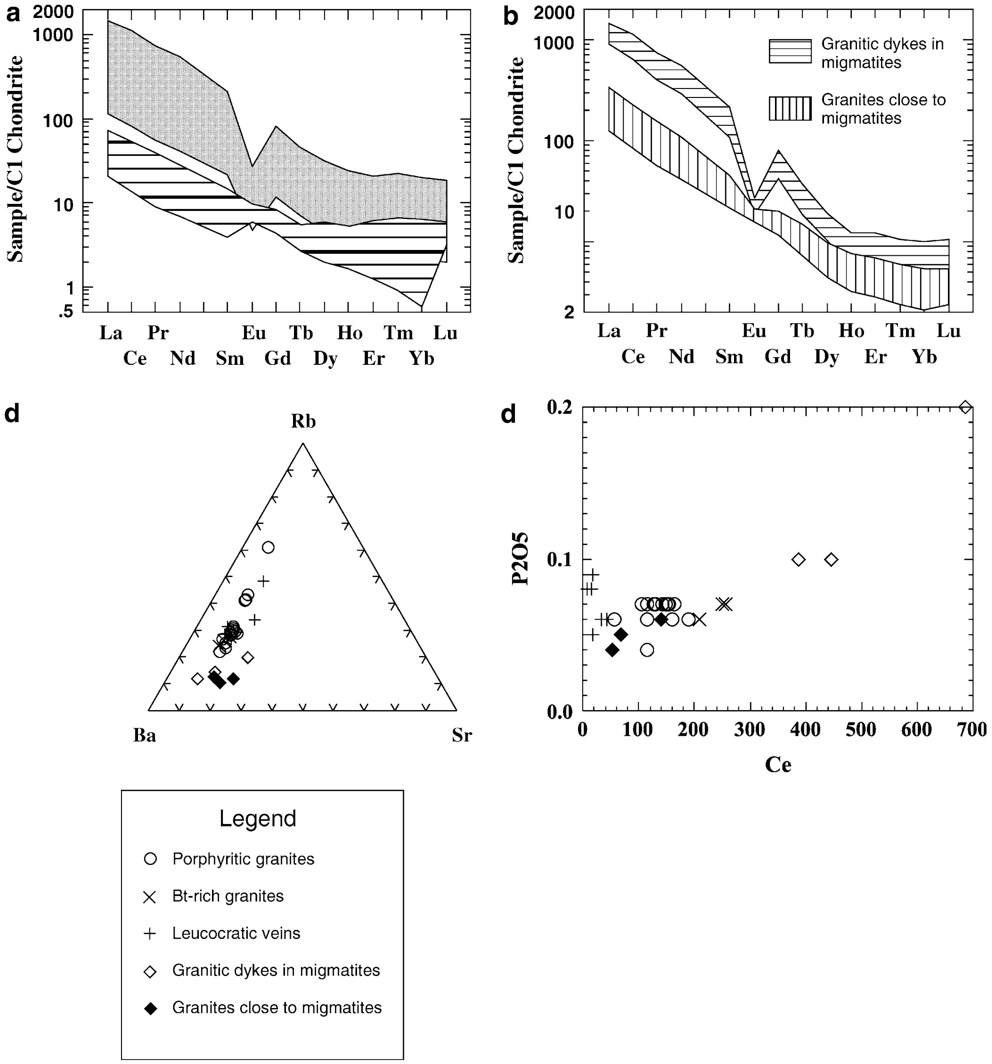

Fig. 14 Geochemical diagrams of the different types of melts in the Nagu area. **a** The *shadowed area* include the various granites, whilst the *lined area* include the leucocratic veins. **b** Granitic feeder dykes show a steeper slope in the LREE than does the adjacent granite. See text for discussion. **c** Rb–Ba–Sr diagram showing the different granites and leucocratic veins. **d** A P_2O_5–Ce diagram indicates fractionation of accessory minerals in the different granites. The leucocratic veins do not, however, show any enrichment in Ce

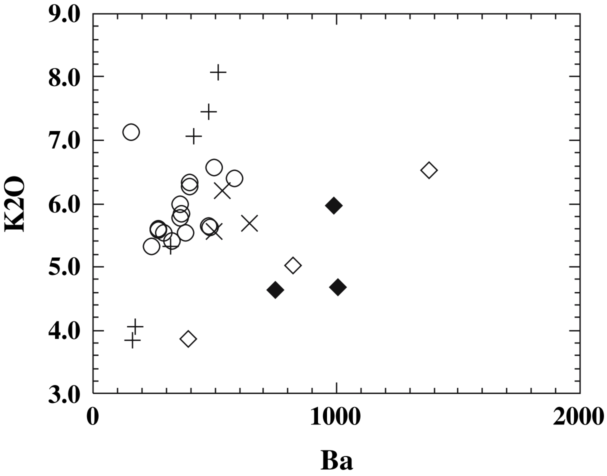

Fig. 15 K_2O–Ba diagram of the different melts in Nagu. The granite dykes in the migmatites, along with the granitic sheets adjacent to the migmatites, show a differing trend than the rest of the samples, indicating a separate (later) intrusion event for these dykes. The *symbols* are the same as in Fig. 14

The Nagu granites are probably closer to their source compared with the layered granites at Hämeenlinna, where the individual intrusion pulses are chemically more distinct.

Emplacement of granites

The great volumes of chemically variable late-orogenic granites and migmatites indicate that the melts were transported and emplaced as small batches, possibly extracted from different protoliths. The migmatites and granites, generated and emplaced at a depth of about 12–15 km (based on temperature and pressure estimates) were not all molten simultaneously. If all the granitic material had been molten at the same time, the self-supporting palaeosome structures (mesosome) would have collapsed. The palaeosome structures are expected to collapse when the amount of melt exceeds the critical melt fraction (30–50%) (Arzi 1978; van der Molen and Paterson 1979). Preserved pre-migmatitic and migmatitic

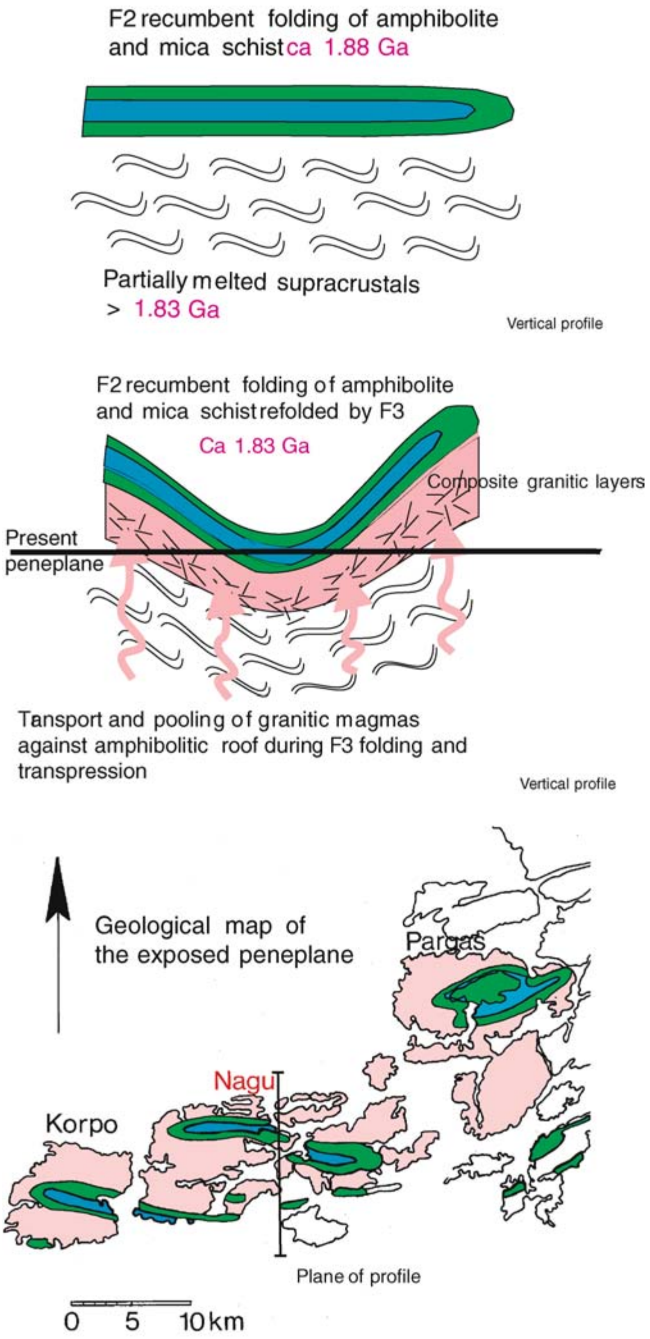

Fig. 16 An evolutionary model for the Nagu area. The granites are in *red*, the amphibolites in *green* and the mica schists in *blue*. See text for explanation

structures, even in places with total melt percentages exceeding 50%, indicates that this is the result of several successions of melt production. If stress is applied to the system, even smaller amounts of melt will result in a breakdown of the crustal skeleton. Experiments (e.g. Miller et al. 1988) indicate that during deformation, an initial dramatic weakening will occur at melt fractions as low as 10–15%. Since the late-Svecofennian granites and migmatites were generated and emplaced during transpressive deformation, the melt fraction had to remain below this critical value, even though the cumulative melt-percentages at the end of the extraction process was much higher. Johannes et al. (2003) estimated the portion of melt produced by dehydration melting in the surrounding migmatites to be around 20 weight percent.

During plastic deformation, every melt volume above the permeability threshold (1–5%, Maaløe 1982) will be squeezed out of the matrix provided that the melt can migrate to areas with lower pressures (Sawyer 1991). Low-pressure sites are generated throughout a transpressional regime; e.g. due to ductility differences between the adjacent layers, so the melt volumes never need to exceed a couple of percentages.

An emplacement model for granite batches on a regional scale

The 1.84–1.83 Ga old LSGM zone is a distinct feature characterised by abundant crustally derived migmatites and granites that overprint earlier structures. The granites were emplaced in a transpressional tectonic regime during the D_3 deformational episode.

This transpressional tectonic regime with a component of E–W extension allowed ascent of the microcline granites and trapped them into sub-horizontal layers within the previously overturned volcanics and earlier granitoids, i.e. the emplacement structure was controlled by regional tectonic features (connected vertical and horizontal shear zones).

We propose the following model of emplacement for granites of the LSGM zone. The microcline granites (S-granites) occurred as sub-horizontal sheets surrounded by more intensely deformed and sheared zones. The sheets were gently folded and stretched during the D_3 episode, while the steep dykes of the granite occurring along the margins of the sheets were strongly deformed and drawn out into boudins during the final D_3 deformation. Figure 17 shows the granites as they appear on the Kemiö Island in SW Finland. It is based on the observations made by the authors in the field and on Seitsaaris map (1955).

The melt batches were transported through repeatedly activated vertical shear zones created during D_3 and were emplaced at a structural level in the crust, perhaps corresponding to the brittle-to-ductile transition zone or some other horizontal discontinuity. In the Nagu area, the melt was trapped and spread out under a roof of overturned amphibolites that collected the melt batches by cutting off the escape route. Our study of two independent areas within the LSGM-zone thus shows that a granitic pluton is an accumulation of several individual sub-horizontal layers with individual layer-thicknesses at metre-scale or less. Field observations and geochemical data further suggest that all the material in neither a granitic pluton nor a migmatite were molten at the same time. The failure of the palaeosome structures was prevented during the late stages of the Svecofennian orogeny by keeping the amount of melts present at any time

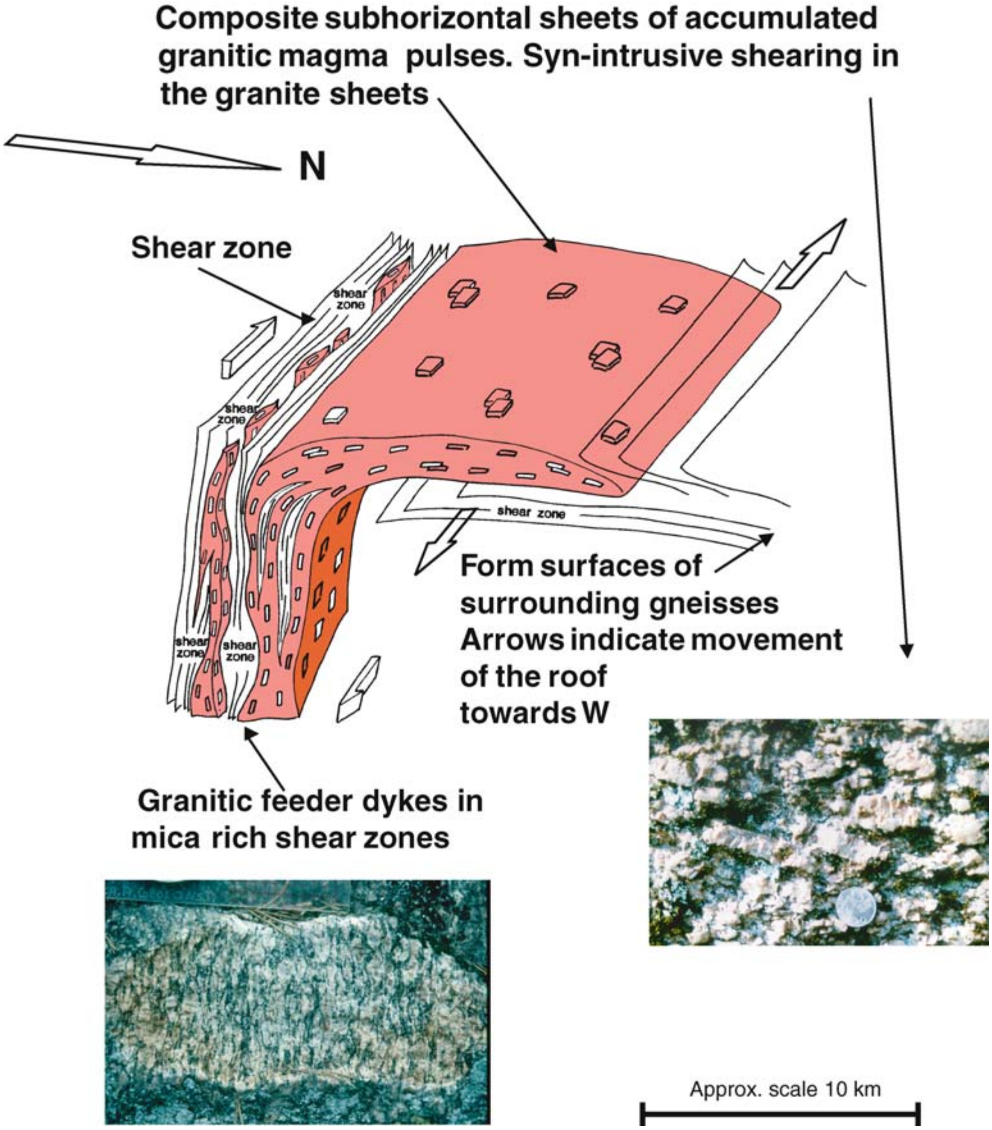

Fig. 17 A model for intrusions on a local scale. The granite melt was transported upwards along sub-vertical shear zones and was emplaced as sub-horizontal sheets with thicknesses at metre-scale. Older granodiorite sheets stabilised the sub-horizontal structures, forming areas that resisted or minimised the deformation caused by the transpressive movements. These structures acted as repositories for granite melt batches that were squeezed from the surrounding, more intensely folded and sheared supracrustal gneisses. Modified after Selonen et al. (1996) and Seitsaari (1955)

well below the melt fraction needed for the internal structure to fail.

Local concentrations of older, competent granodiorite sheets (1.89 Ga) stabilised the sub-horizontal D_2 structures forming areas that resisted or minimised the subsequent F_3 folding. These structures acted as melt traps and repositories for granite melt batches that were squeezed from the surrounding, more intensely folded and sheared supracrustal gneisses. The stretched and deformed granite dykes in the gneiss area suggest a strike-slip dilatancy pumping as a possible mechanism for the transport of granite melts from the shear zones to the sub-horizontally layered sheeted massifs. Sheets of intruded granodiorites are frequently exposed sub-horizontally interlayered with the later S-granites (Figs. 2, 17).

The fractionation we observe today in the sub-horizontal granitic sheets is a result of the heterogeneous history of partial melting, transport and fractional crystallisation within the transpressive shear zones.

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