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Evidence of plutonic magma-mixing, southern Sweden

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Introduction

The Transscandinavian Igneous Belt (TIB) (Fig. 1), runs NNW through SE Sweden and continues beneath the Caledonides (GORBATSCHEV, 1985). It is of Middle Proterozoic age (1.8-1.7 Ga) (PATCHETT et al., 1987). An association of coarse porphyritic, K-feldspar megacrystic granites with mafic rocks is rather common in the belt. Earlier the mafic rocks were interpreted as being older (e.g.: MAGNUSSON, 1962; GORBATSCHEV, 1971, 1976; PERSSON, 1981; VINNEFORS, 1985; WILSON et al., 1986). However, new evidence now emerging from recent mapping, as well as mineralogical/chemical investigations, points towards a modified view (WIKSTRÖM et al., 1985; this work).

The investigated area constitutes part of a complex of coarse porphyritic granite and mafic rocks trending approximately E-W in central southern Sweden (Fig. 1). The relationship between these rocktypes suggests that they are either contemporaneous magmas or that the mafics are slightly younger. The observed structures show that magma-mixing and mingling have taken place with the creation of a range of hybrid rocks, with compositions between gabbroic and granitic endmembers.

Field relations & petrography

A more detailed study was undertaken in the area outlined by the frame in Fig. 1. This rock association consists of hybrids, with the most mafic rocks occurring in a zone along the southern margin and in the north, surrounded by coarse porphyritic granite. In the central part of the structure a red leucogranite complicates the pattern. This kind of leucogranite is commonly interpreted to be the youngest rock of the TIB, derived from the last phases of fractionation in the granitoid magma (e.g.: GORBATSCHEV, 1971; PERSSON, 1981). Its presence here may be a pure coincidence, because such granites are common in various kinds of environment in the TIB. Furthermore, it takes no part in the hybridization. The hybrids result from the interaction between coarse porphyritic granite magma and mafic magma. The most mafic rocks exposed are quartz diorites/tonalites, which also exibit some hybridic features. Assimilation as an explanation for the hybrids is unlikely because of the gradual contacts, absence of xenoliths, and their homogeneity. They are generally megascopically homogeneous but show a range in composition depending on mixing proportions (e.g. 56-63% SiO_2). The contacts towards the quartz diorites/tonalites are gradual, with some diffuse pillows appearing locally. Towards the surrounding granite the contacts are well defined although not always sharp in outcrop scale. The quartz diorite/tonalite shows rather distinct contacts towards the granite in the south, with the anatectic generation of some aplitic material derived from the granite. Pillowlike structures have also been recorded here. The leucogranite has sharp contacts with its surroundigs.

Megascopically, the hybrids display an intermediate appearance, having more dispersed megacrysts than the granite, thus being richer in the darker matrix. The megacrysts mainly consist of K-feldspars (2-4 cm), which in the more basic parts become corroded and decrease in size due to destabilization in a changed physicochemical environment. The matrix of the hybrids often contains clinopyroxene, with different degrees of amphibole alteration, and large zoned plagioclase, rich in inclusions of Fe-Ti oxides, biotites and amphiboles (cpx pseudomorphs), derived from the basic mixing parent.

Magnetic data

Connected to this rock association is a large aeromagnetic anomaly (Fig. 2), indicating large amounts of mafic rocks at depth. A low in the anomaly is connected with the central leucogranite. Smaller anomalies occur in the granite south of the association. Outcrop susceptibility measurements correspond closely with the aeromagnetic map (Fig. 3). This suggests that the aeromagnetic anomalies are not entirely caused by mafic rocks at depth, but also in part reflect the hybridization. There is also a co-variation between magnetic and chemical data (Fig. 4), which in connection with the smaller anomalies in the south, indicates a hybridization component also within the granite, causing a chemical overlap between the hybrids of the main association and the surrounding granite.

Geochemistry

The geochemical data correspond with linear trends on element-element diagrams, for all major and trace elements, though the degree of scatter varies (Fig. 5-6). A linear correlation is required by simple mixing, and least square fitted lines have been added. Values for the leucogranite and microgranitoid enclaves have been included for comparison. The overlap between hybrids and surrounding granite as discussed above is evident in these diagrams. An overlap between quartz diorites/tonalites and hybrids is also observed, indicating a degree of hybridization also affecting the most mafic rocks exposed. Major elements are plotted on Harker diagrams, whereas trace elements are plotted against MgO, the latter to expand and elucidate the diagrams. Above approx. 65% SiO_2, a departure from linearity is observed in the major elements, most obvious for sodium. Correspondingly, in the trace element diagrams, this departure is recorded below approx. 1.5% MgO. The mixing lines have therefore been calculated only at compositions more mafic than these. For the trace elements a drop in Ba, Zr, Hf, Ta and REE is observed,

Fig. 1. — Geological map of an E-W trending zone of granite-basite association, central southern Sweden. Simplified after Wikström (in prep.). 1) Coarse porphyritic granites; 2) Basic plutonics; 3) Hybrids (discussed in this study); 4) Older Svecofennian volcanics, main acid; 5) Older Svecofennian plutonics, mainly granodiorites; 6) Leucogranites; 7) Fault lines. The frame outlines area of this study. Inset map shows the position of the enlarged map. A) Transscandinavian Igneous Belt (1.8-1.7 Ga); B) Caledonian rocks (600-400 Ma); C) Svecofennian province (2.0-1.8 Ga).

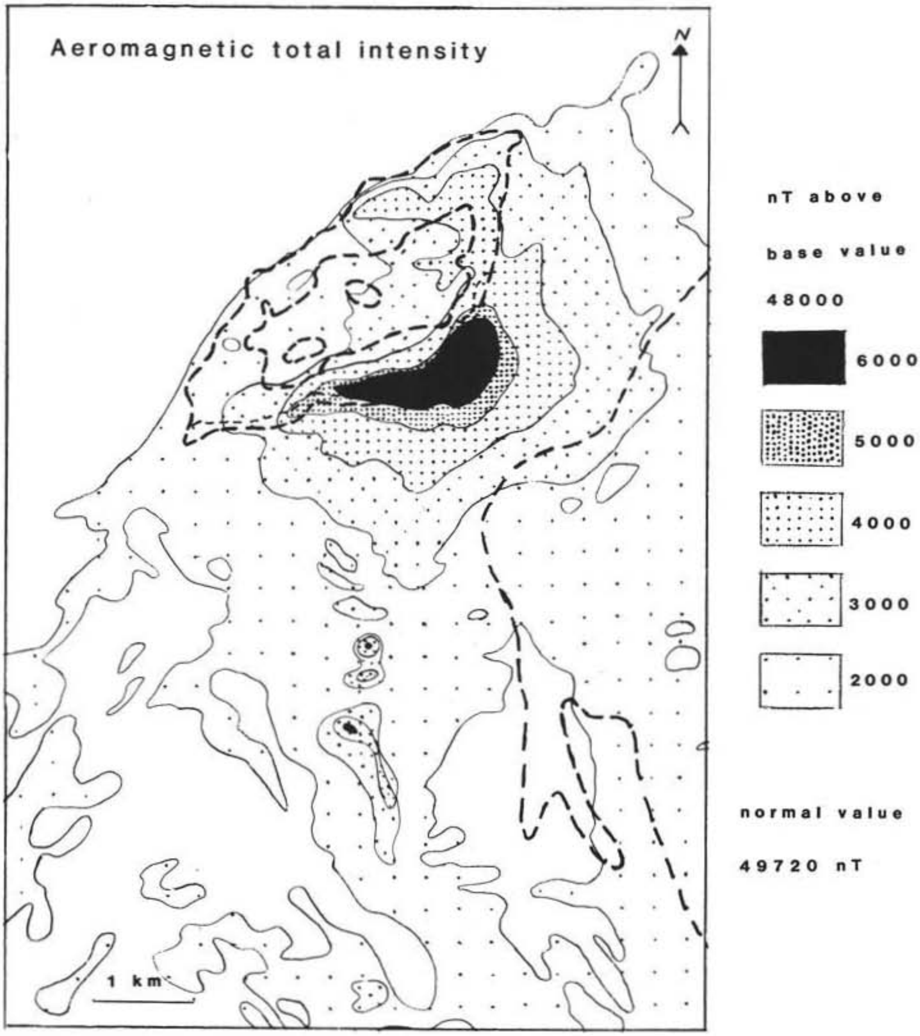


Fig. 2. — Aeromagnetic total intensity map (simplified after Geol. surv. of Sweden, 1981). The geology is outlined in broken lines. Smaller anomalies are evident in the granite south of the main association.

while Rb and Th increase. This indicates that another petrogenetic process, apart from mixing, affected the felsic parts of the coarse porphyritic granite, probably crystal fractionation. Effects, as seen in the diagrams, should have involved the removal of apatite, zircon, and hornblende. The possible derivation of the central leucogranite by further fractionation in the granitoid suite would involve plagioclase and K-feldspar, to obtain the effects as observed in the diagrams.

The REE patterns of the coarse porphyritic granites, hybrids and quartz diorites/tonalites also display the overlaps described above (Fig. 7). The hybrids totally overlap the most mafic rocks for most elements, indicating that the latter do not represent the mafic endmember. A general feature of the diagram is, however, that the mafic rocks are higher in REEs than the granite. If this was due to crystal fractionation it could involve minerals like clinopyroxene, hornblende, zircon, apatite and monazite (HANSON, 1978; CLARK, 1984). However, clinopyroxene, hornblende and

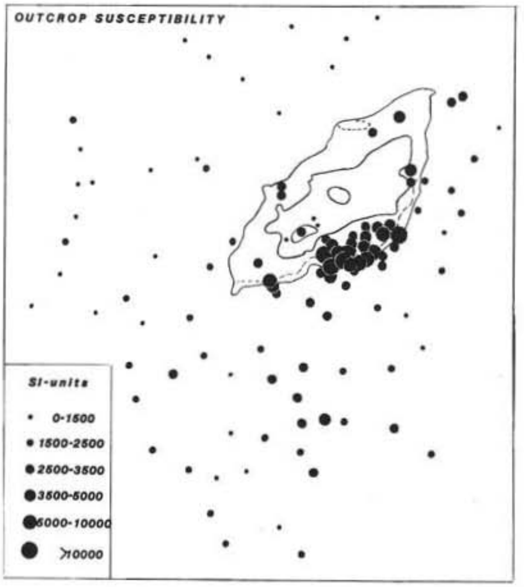


Fig. 3. — Outcrop susceptibility. It corresponds closely with the aeromagnetic map (Fig. 2). The smaller anomalies in the south can also be recognized here. See text for discussion.

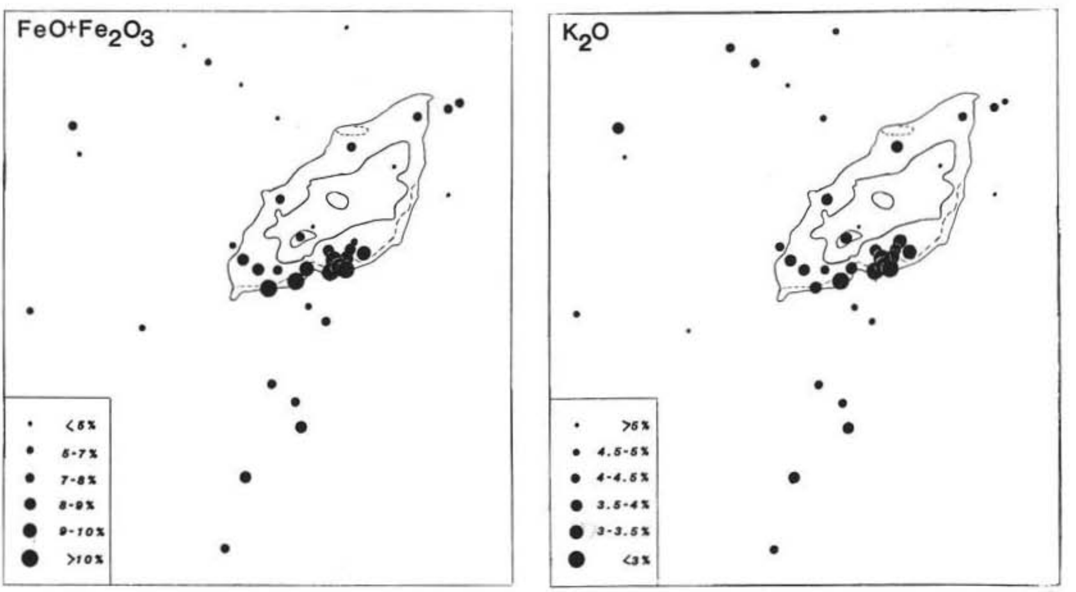


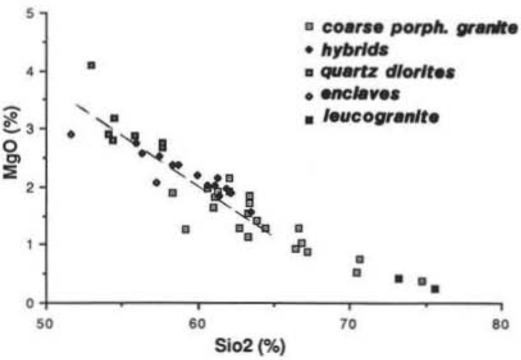
Fig. 4. — Selected chemical parameters. Correspondance with the geomagnetic data is clear (Figs. 2-3). See text for discussion.

zircon would preferentially deplete middle and heavy rare earths to the light, whereas monazite would give the opposite effect, in contradiction to the subparallel nature of the diagram. Furthermore, hornblende is common in the granite but only present as local alterations of clinopyroxene in the quartz diorites/tonalites. If apatite was removed this would reduce the negative Eu-anomaly, which is not seen. On the other hand the major element trends require the removal of some Ca-Fe-Mg phase, contradicting the above. Furthermore no curvature can be detected for the hybrid data, which would be expected for some major and compatible trace elements. Crystal fractionation can thus be rejected for the hybrid association.

The rocks could principally be derived by different degrees of partial melting of the same parent material, leaving plagioclase in the residue (negative Eu-anomaly) (CULLERS & GRAF, 1984; TAYLOR & MCLENNAN, 1985), e.g. Na-granitic and amphibolitic rocks present in the older Svecofennian province (2.0-1.8 Ga) nearby in the east (Fig. 1). This is not in conflict with a mixing origin of the hybridization, because the magmas might be generated at different locations or dephts. However, the large aeromagnetic anomaly indicates the existence of substantial volumes of more mafic mantle derived magma responsible for the interaction with the granitic magma.

Enclaves

Furthermore, microgranitoid enclaves (VERNON, 1983) occur both in the hybrid zone and in the surrounding granite (most frequent in the high magnetic areas in the south). These mostly ellipsoidal, 0.1-1 m bodies often carry xenocrysts (mainly K-feldspars) incorporated from the surroundings and exhibit a more or less hybridic texture with evidence of rapid cooling (apatite needles) (WYLLIE et al., 1962). The least hybridized (without xenocrysts) and thus most mafic enclaves are quartz diorites. Two analysed enclaves, one quartz diorite and one more hybridized, differs geochemically from the quartz diorites/tonalites of the association by having lower MgO but higher MnO, K_2O, Sc, Zr, Hf and HREE (Figs 5-6). Although the data are scarce a tentative interpretation is that they are slightly more evolved. These kinds of microgranitoid enclaves have commonly been interpreted as magma globules intermingled in a granitic crystal-mush during interaction of a mafic and felsic magma (e.g.: BLAKE et al., 1965; DIDIER, 1973, 1987; YODER, 1973; OTTO, 1974;



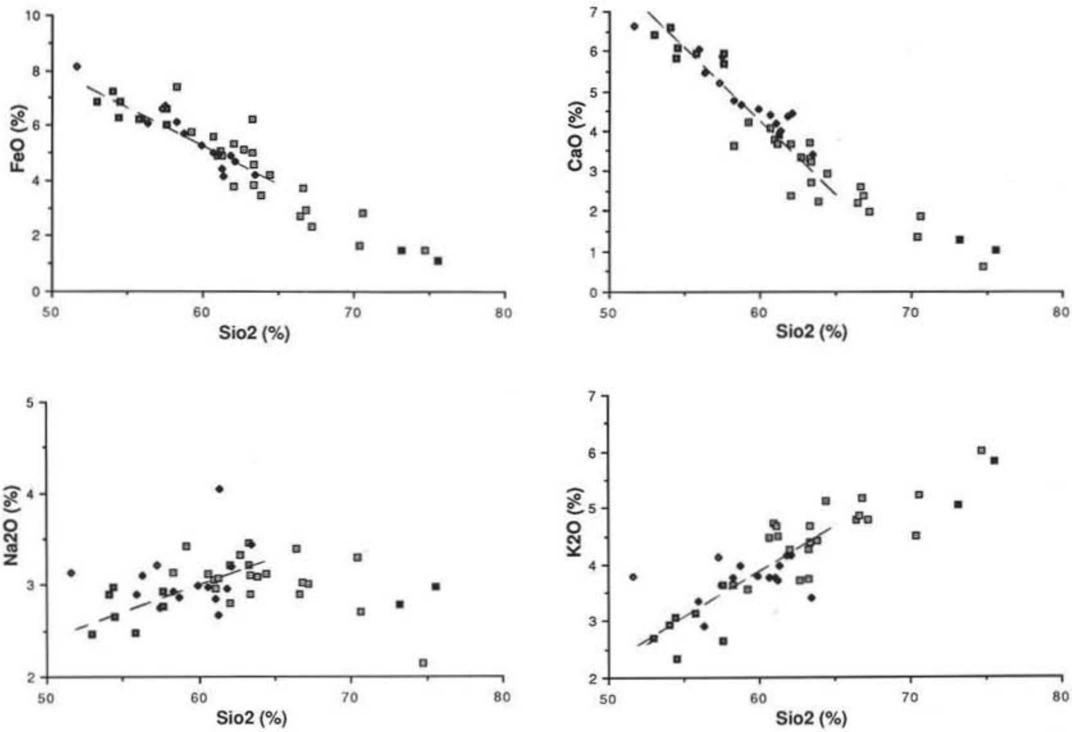


Fig. 5. — Harker diagrams for selected major elements. The data agree with a linear relationship, which is expected by simple mixing. Above approx. 65% SiO_2, however, a departure from linearity is observed in the granite.

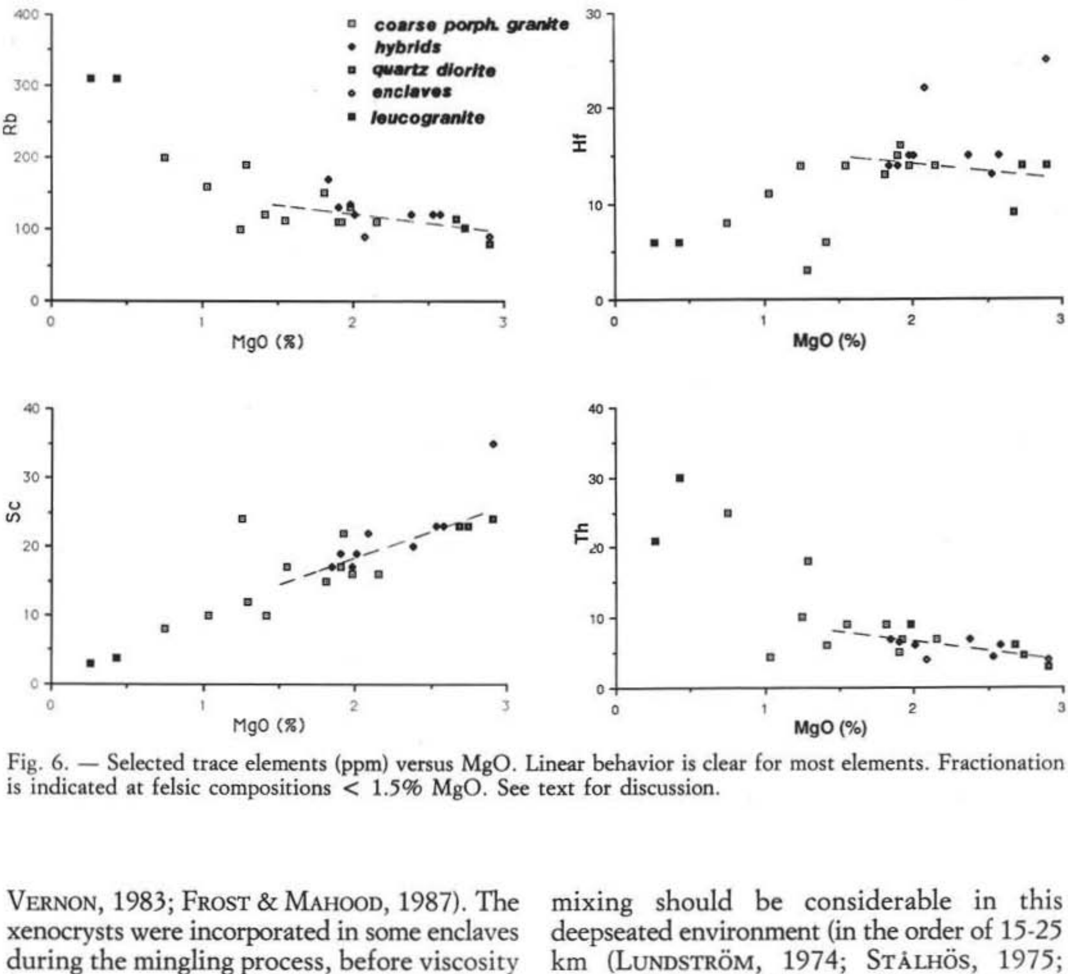


Fig. 6. — Selected trace elements (ppm) versus MgO. Linear behavior is clear for most elements. Fractionation is indicated at felsic compositions < 1.5% MgO. See text for discussion.

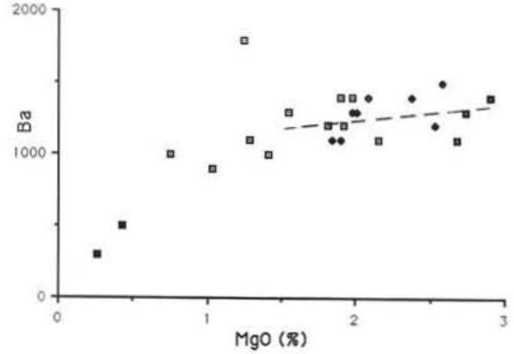
VERNON, 1983; FROST & MAHOOD, 1987). The xenocrysts were incorporated in some enclaves during the mingling process, before viscosity contrasts prevented further mixing.

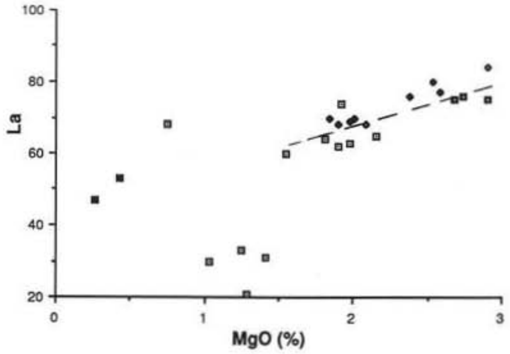
Discussion

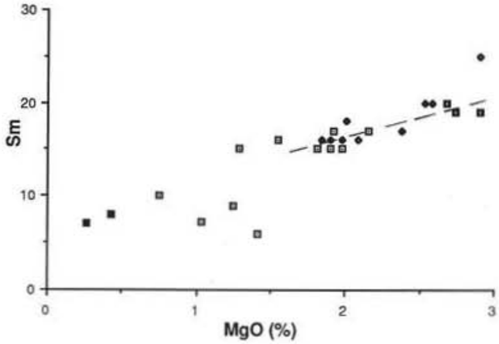
According to FROST & MAHOOD (1987), the nature of mafic-felsic magma interaction depends on several parameters, which control the viscosity contrast at thermal equilibrium between the endmembers. Low contrasts in viscosity, and hence hybridization, is promoted mainly by large mass fraction of mafic magma, but also by low contrasts in composition and initial temperature, low water contents and a long available time for mixing to occur.

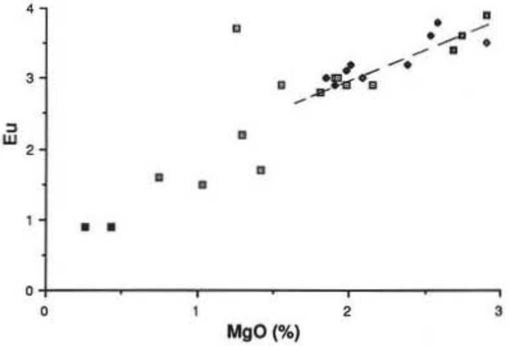
A tentative application of this model to the area investigated here indicates: a) Large local mass fraction of mafic magma as seen in the magnetic anomalies; b) The time available for mixing should be considerable in this deepseated environment (in the order of 15-25 km (LUNDSTRÖM, 1974; STÅLHÖS, 1975; VINNEFORS, 1985)); c) The observed compositional contrasts are moderate (10-15% SiO_2). The mafic endmember is, however, not exposed; d) in view of the rather high crystallinity (> 50%, WINKLER & SCHUTLES, 1982) of the granite at the time of interaction, deduced from the presence of granite derived K-feldspar xenocrysts in the hybrid rocks, its temperature should be below 700°C (~ 655°C, WINKLER & SCHULTES, 1982). The initial temperature difference is then expected to be in the range 150-400°, depending on the composition of the mafic magma (quartz diorite-basalt); e) No control of the water content is yet established.

Thus, according to this model, the enclaves represent the earliest stages of interaction, when the proportion of mafic magma was small resulting in relatively low equilibration









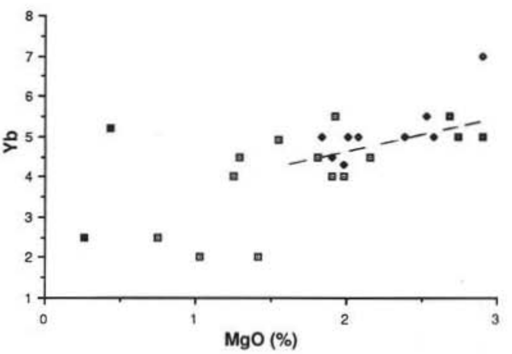


Fig. 6. *(Continued)* — Selected trace elements (ppm) versus MgO. Linear behavior is clear for most elements. Fractionation is indicated at felsic compositions < 1.5% MgO. See text for discussion.

temperatures and thus large viscosity contrasts. As more mafic magma was supplied the contrasts could be overcome, favoring conditions for hybridization.

Conclusions

1) The occurrence of younger and contemporaneous mafic magmas associated with coarse porphyritic granites of the Transscandinavian Igneous Belt (1.8-1.7 Ga) has been established.

2) Hybridization through magma-mixing is evidenced by: a) Megascopically intermediate appearance of hybrids; b) Intermingling and dispersal of crystals derived from the endmembers; c) Absence of xenoliths; d) Distribution of geomagnetic anomalies correlated with geochemistry and mineralogy; e) Linear patterns of major and trace elements on element-element diagrams and f) REE-spectra.

3) Features that can be accounted for by mingling processes include: a) Occurrences of more or less contaminated microgranitoid enclaves; and b) Pillowlike contact structures.

4) The geochemical behavior of the most felsic parts of the coarse porphyritic granite and the leucogranite does not correspond to mixing, but rather suggests late-stage fractionation processes.

5) Hybridization by magma-mixing is a very plausible process, according to modelling by Frost & Mahood (1987), for the plutonic conditions that prevailed in this area.

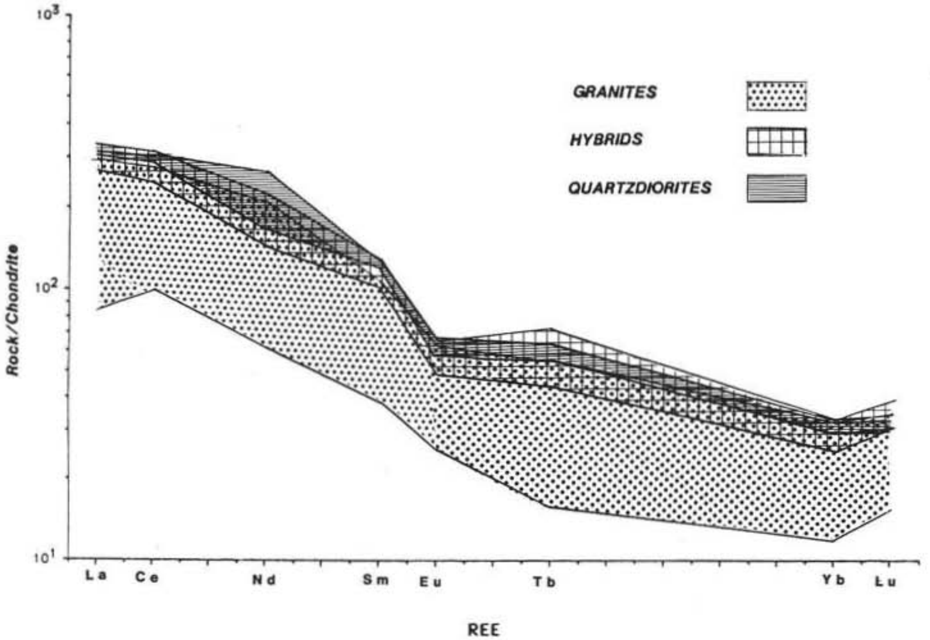


Fig. 7. — Chondrite normalized REE-patterns for quartz diorites/tonalites, hybrids and coarse porphyritic granites. Only granites for which fractionation is not inferred, are included. Extensive overlaps between the three main rock groups are observed (like in Figs. 5-6). The specta are subparallel, but quartz diorites/tonalites generally have higher REE content than the granites. Discussion in text.

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