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Geochemistry of the Fellingsbro type granites, South Central Sweden

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Abstract

The Fellingsbro granite *sensu stricto* is a massive coarse-grained rock characterized by red, angular microcline megacrysts up to 7 cm long. The Lisjö granite is of the same type as the Fellingsbro granite but is situated 20 km to the NE. Both intrusions belong to a belt of c. 1.78 Ga old granites coinciding with the major so-called *Central Swedish Gravity Low.* Gravity studies suggest that the Fellingsbro and Lisjö granites rose from a huge granite ridge through structurally controlled root zones, forming mushroom-shaped intrusions. These porphyritic granites have the geochemical characteristics (e.g. high Y, Nb, Zr and HREE) of granites generated in 'within-plate' or tensional rifting environments. Even-grained granites of approximately the same age occurring in heterogeneous mixtures of granites, pegmatites, xenoliths and partly assimilated country rocks e.g. in the Fellingsbro and Låsen areas, probably represent minimum melt type rocks that have not moved far from their source. The even-grained interior of the Lisjö granite and the contemporaneous Dingtuna and Pingstaberg granites, were generated by differentiation of granites with similar characteristics as the porphyritic Fellingsbro granite.

Recently published U-Pb zircon datings have demonstrated that the Småland-Värmland granite-porphyry Belt has approximately the same age as the granites in this study. We speculate that both groups were emplaced in a tensional environment on the continental side of a subduction related calc-alkaline belt, remnents of which may be preserved in the SW Swedish Gneiss Region. The Fellingsbro and Lisjö granites were generated more towards the interior of the pre-existing c. 1.89 Ga old continent than the Småland-Värmland granites.

Introduction

Traditionally the development of Svecofennian (Svecokarelian) granitoids in Sweden was thought to be dominated by two major stages (Lundqvist 1979). Recent U-Pb zircon datings confirm the field observation of two major age groups (Wilson et al. 1985; Patchett et al. 1987; Skiöld 1987; Welin 1987). During the early stage (1.89–1.86 Ga), granitoid suites were formed. These granitoids have wide compositional ranges and are commonly foliated. Most of the supracrustal rocks present were deposited during this early period or slightly before. The supracrustal rocks, as well as the early granitoids, have been affected by a major episode of deformation and metamorphism (Lundqvist

1979). The younger granitoids (1.80–1.75 Ga) consist of suites with more restricted compositional ranges. These are generally true granites. In the following text, the two groups of granitoids will be referred to as older and younger granitoids, respectively.

A belt of c. 1.78 Ga old (Patchett et al. 1987) granite intrusions (Fig. 1) occurs at the southern margin of the Vdala-Uppland older batholith (compositional range gabbro to granite). This granite belt coincides with a major negative gravity anomaly, the so called *Central Swedish Gravity Low,* striking from the Baltic Sea north of Norrtälje down to Lake Mälaren, where it changes direction and follows the Mälaren-Hjälmaren synclinorium (Stephansson 1975). Detailed gravity studies suggest that the large negative gravity anomaly is caused by a huge granite ridge, and that the exposed granite intrusions have risen from this ridge through rather narrow root zones (Öhlander & Zuber 1988).

This paper summarizes the results of geochemical studies of two of the exposed intrusions (Öhlander & Zuber in press) the Fellingsbro and Lisjö granites (Fe and Li and Fig. 1), and compares them with new chemical analyses of the contemporaneous Dingtuna, Låsen and Pingstaberg granites (D, Lå and P in Fig. 1). We discuss some aspects of the genesis of the younger granites in south central Sweden. The Fellingsbro, Lisjö and Dingtuna granites are situated just southeast of the old mining district Bergslagen, while the Låsen and Pingstaberg granites lie in the centre of it.

Rocks studied

The Fellingsbro granite complex

This complex has been U-Pb zircon dated to 1.78 ± 0.01 Ga (Patchett et al. 1987), and a similar granite (close to M in Fig. 1) has been Rb-Sr dated to 1.72 ± 0.01 Ga (Oen & Verschure 1985). The Fellingsbro granite *sensu stricto* is a massive, medium- to coarse-grained rock characterized by red angular perthitic microcline megacrysts up to 7 cm long (Lundegårdh 1983). The matrix is red to reddish grey. Microcline, plagioclase (andesine), quartz and biotite are the major minerals. Minor hornblende occurs in the quartz-poorest varieties. The mafic minerals, the feldspars and often quartz occur as clearly defined well-shaped crystals indicating crystallization from a melt. Common accessory minerals are opaques (particularly magnetite) sphene, zircon, apatite, epidote, allanite and fluorite. The plagioclase is always sericitized to some extent and the biotite is often chloritized. The Fellingsbro granite has sharp contacts and no chilled margins (Gorbatschev 1972; Lundegårdh 1983). However, large microcline megacrysts are developed in the adjacent surrounding rocks.

Although even-grained varieties are occasionally included in the normal variation of the Fellingsbro granite, clearly defined areas of fine- to medium-grained massive granites occur, both within and outside the porphyritic granite (Gorbatschev 1972). The even-grained granites are slightly younger than the porphyritic granite, and particularly outside the Fellingsbro granite massif, characterized by abundant pegmatites, xenoliths and ghost structures, in marked contrast to the Fellingsbro granite *sensu stricto.*

The Lisjö granite complex

This forms an elliptical exposure situated c. 20 km NE of the Fellingsbro area (Fig. 1). The marginal zone of the Lisjö granite is a highly magnetic, coarse porphyritic granite, similar to the Fellingsbro granite. The frequency of microcline megacrysts decreases irregularly towards the interior of the intrusion where even-grained varieties occur (Lundegårdh & Nisca 1978). An underlying magnetic granite just reaching the present surface forms the magnetic rim of the intrusion (Öhlander & Zuber 1988). The Lisjö granite, like the porphyritic Fellingsbro granite, is characterized by a lack of pegmatities and the rare occurrence of xenoliths. A molybdenite-mineralized aplite near the northeastern part of the granite was mined during World War II (Hübner 1971).

The Dingtuna granite

This occurs just to the SE of the Lisjö massif. It is a medium grained, even-grained and light pinkish grey granite which resembles leucocratic varieties

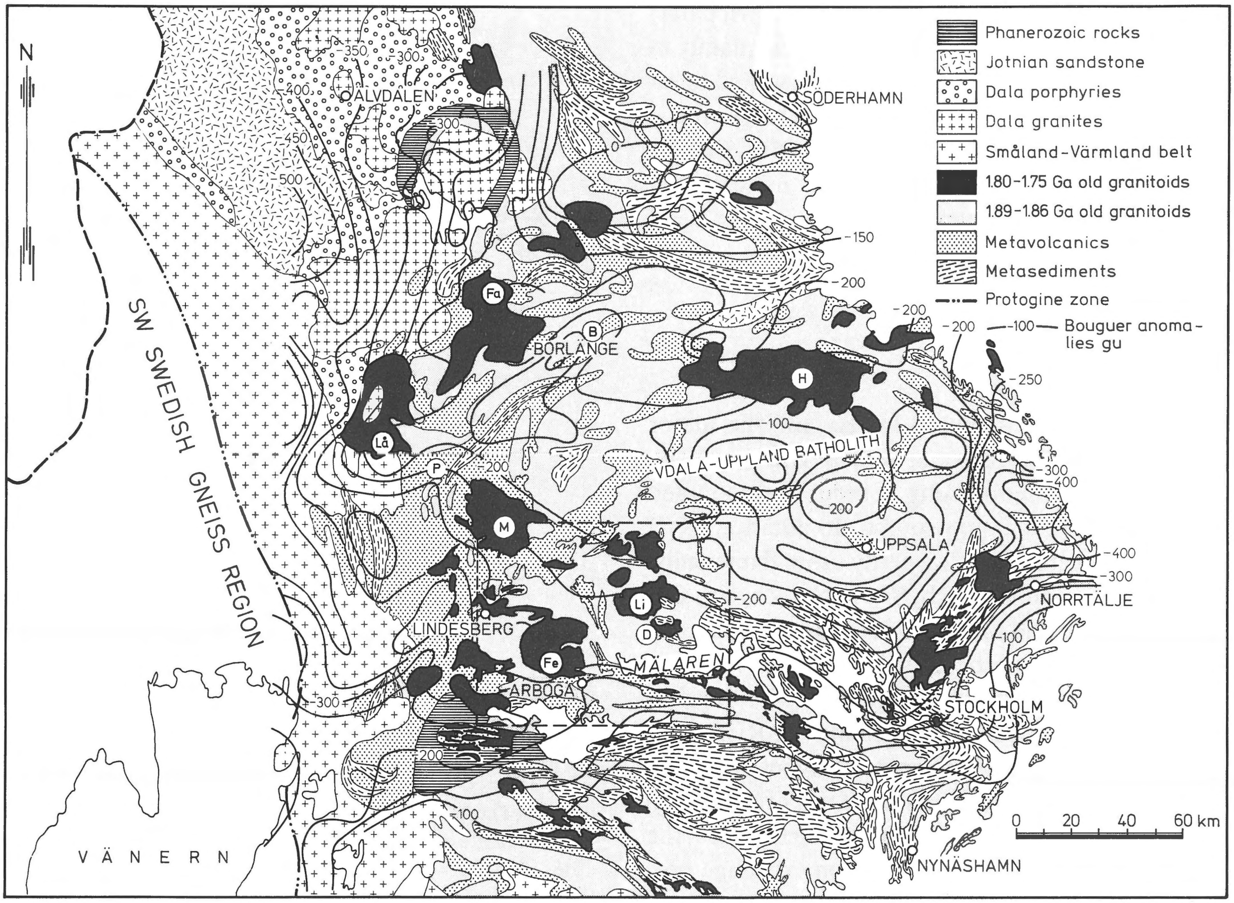

Fig. 1. Generalized geology of South Central Sweden. Modified after Magnusson et al. (1960). The area with detailed gravity measurements presented by Zuber (1985) and Öhlander & Zuber (in press) is marked by a rectangle. The Bouger anomalies are according to Wideland (1946). Fe = The Fellingsbro granite complex, Li = The Lisjö granite complex, D = The Dingtuna granite, P = Pingstaberg granite (note that the size of granite is much smaller than the P on the map), Lå = The Låsen granite. Fa, M, H and B represent granites that are discussed in the text.

occurring in the interior of the Lisjö granite. Almost aplitic varieties have been observed. In one sample (not the most leucocratic) small quantities of molybdenite were observed.

The Pingstaberg granite

This forms a small semi-circular exposure (Fig. 1) (diameter 1.0–1.5 km) U-Pb zircon dated to 1.78 ± 0.05 Ga (Billström et al. 1988 this issue). The southeastern part of the intrusion is mineralized with molybdenite. The Pingstaberg granite is a fine- to medium-grained granite, generally massive, but along the northern contact weakly foliated varieties occur. It is a red granite, but becomes greyish in the mineralized part. The contact with the surrounding rocks is not well defined and apophyses of pegmatites and aplites are common; even at some distance from the central intrusion.

The major minerals are quartz, microcline and oligoclase. Accessory minerals are biotite, zircon, magnetite, fluorite, apatite and xenotime. Sericite, chlorite and epidote occur as secondary minerals. In the mineralized zones, molybdenite, pyrite and occasionally chalcopyrite occur.

The Låsen granite

This occurs about 20 km NW of the Pingstaberg granite (Fig. 1) (Hjelmqvist 1966). Both coarse porphyritic varieties (mainly in the northern parts) and even-grained finer grained varieties (mainly in the southern parts) occur. Pegmatities and remnants of country-rocks are common. The granite is a quartz-microcline-oligoclase rock with varying amounts of biotite. Typical accessory minerals are zircon, apatite and magnetite.

Geochemistry

Analytical methods

All samples were analysed for Ba and the major elements (except K_2O) at Luleå University by emission spectroscopy using an inductively coupled plasma as the excitation source. In addition, K_2O was analysed at Luleå University using flame emission. Trace amounts of Rb, Sr, Y, Nb, Zr, Ga, Cu, Zn, Pb, U, Th and Mo were determined by energy dispersive XRF at the Open University, Milton Keynes, England. In six samples of the Fellingsbro granite and four of the Lisjö granite the REE were analysed at the Open University using instrumental neutron activation analysis. In four of the Pingstaberg samples, and two of the Låsen samples, the REE were concentrated by a cation exchange procedure (Thompson & Walsh 1983) and then analysed at Luleå University by ICP-spectroscopy.

Major element chemistry

Chemical analyses of typical samples are presented in Table 1. In the discussion of the chemistry, the Fellingsbro granite complex has been subdivided into porphyritic granites (Fellingsbro granite type *sensu stricto*) and finer, even-grained varieties. The Lisjö granite complex has been subdivided into granite of the 'magnetic-rim' and 'normal' Lisjö granite. In all samples analysed K_2O (wt.%) dominates over Na_2O.

All samples have been classified using the Q-P diagram (Fig. 2) of Debon & LeFort (1982). Almost all samples from the Fellingsbro granite complex fall in the granite field of the diagram, with a clear separation between the porphyritic and even-grained rocks; the latter lying slightly above and to the right of the former, mainly due to higher SiO_2 and lower CaO contents. A similar separation can be found in the Lisjö granite complex where the samples from the magnetic rim resemble the least silicic porphyritic Fellingsbro samples. The Pingstaberg samples, and most of the Låsen samples, fall in the field of the even-grained Fellingsbro granite and in the uppermost part of the field of the porphyritic Fellingsbro granite. Only one of the Dingtuna samples lies outside the latter field.

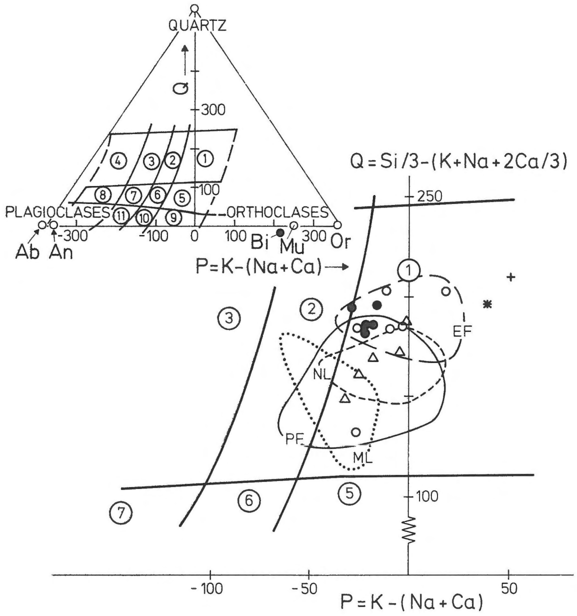

Fig. 2. Q–P diagram after Debon & LeFort (1982). Molar proportions. The individual sample points are not shown for the Fellingsbro and Lisjö granites, but are instead shown as lines encircling the samples. PF = the porphyritic Fellingsbro granite, EF = Even-grained granites from the Fellingsbro area, ML = The magnetic rim of the Lisjö granite, NL = Normal Lisjö granite, star = outlier of the porphyritic Fellingsbro granite, plus sign = outlier of the even-grained granite from the Fellingsbro area, triangles = The Dingtuna granite, filled circles = The Pingstaberg granite, open circles = The Låsen granite. The classification fields are as follows: 1 = granite, 2 = adamellite, 3 = granodiorite, 4 = tonalite, 5 = quartz syenite, 6 = quartz monzonite, 8 = quartz diorite, 9 = syenite, 10 = monzonite, 11 = monzogabbro, 12 = gabbro.

In Figure 3 the alumina saturation is plotted against the sum of mafic major elements (after Debon & LeFort 1982). Leucogranites of most granitoid series converge to a slightly peraluminous character, but granitoid series derived by remobilization of sedimentary rocks tend to be completely peraluminous (Debon & LeFort 1982). It is obvi-

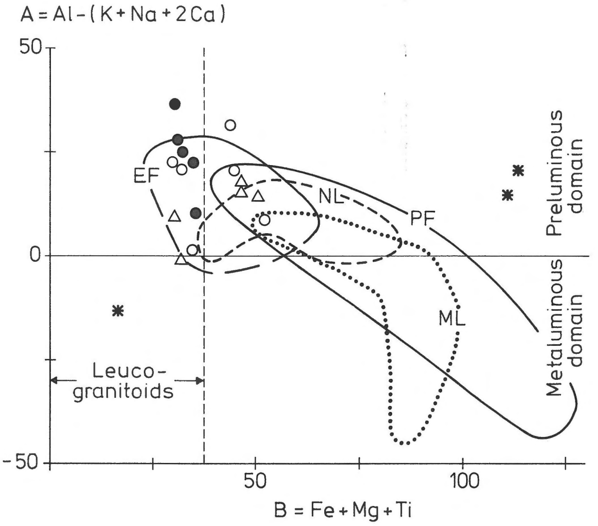

Fig. 3. A–B diagram after Debon & LeFort (1982). Molar proportions. Symbols as in Fig. 2.

ous in Figure 3 that the least differentiated samples from both the Fellingsbro and the Lisjö areas are distinctly metaluminous.

The porphyritic Fellingsbro granite has, on average, higher contents of TiO_2, Fe_2O_3-tot, MnO, MgO and CaO but lower contents of SiO_2 than the even-grained granite. The contents of Al_2O_3, Na_2O and K_2O are roughly equal. The same observation can be found for the Lisjö granite complex where the samples of the magnetic rim have higher contents of the mafic elements, and lower of SiO_2, in comparison with the normal Lisjö granite. In this context the Dingtuna, Pingstaberg and Låsen granites resemble the even-grained Fellingsbro and the normal Lisjö granites, Pingstaberg being most leucocratic. Although the SiO_2 ranges are rather narrow, 65.2–76.8 wt.% for the Fellingsbro granite complex, the trends on variation diagrams are distinct (Fig. 4). There is no discontinuity between the porphyritic Fellingsbro granite and the even-grained granites.

Trace elements

The trace element characteristics confirm the similarity between the Fellingsbro and the Lisjö granite complexes (Table 1). The magnetic rim of the Lisjö granite has almost the same trace element contents as the porphyritic Fellingsbro granite. The normal Lisjö granite is somewhat intermediate in trace element characteristics between the porphyritic Fellingsbro granite and the even-grained granite from the Fellingsbro area. As could be expected from the major element chemistry, the porphyritic Fellingsbro granite has higher contents of Sr, Ba, Zn and Zr than the even-grained granite. In addition, the same is true for Y and Nb while the reverse is true for U, Th and Rb. For Pb, Ga, Mo and Cu no significant differences have been observed. The magnetic rim of the Lisjö granite complex has higher contents of Ba, Zn, Sr, Y and Zr than the normal Lisjö granite, and lower contents of U, Th and Rb. No obvious differences were observed for Mo, Nb, Cu, Pb and Ga.

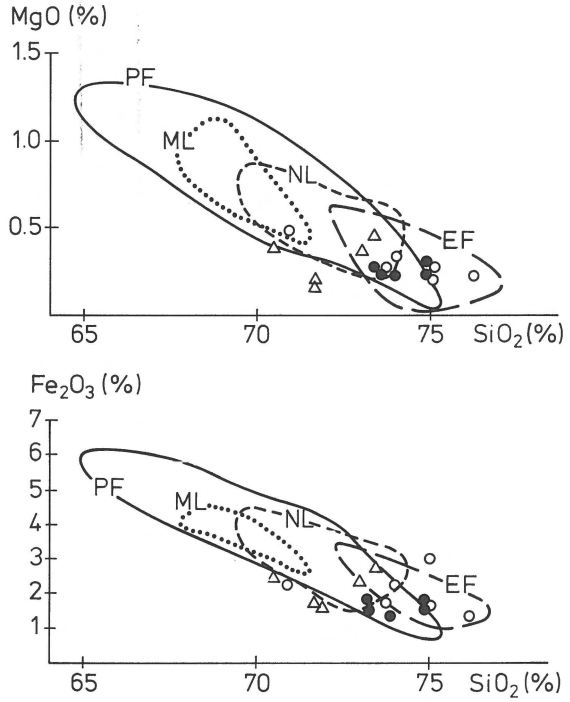

Fig. 4. Variation diagrams. All values are in wt.%. Symbols as in Fig. 2.

The Dingtuna, Pingstaberg and Låsen granites have trace element contents resembling those of the even-grained Fellingsbro and the normal Lisjö granites. All three have, however, lower Pb-content, and the very leucocratic Pingstaberg granite has lower contents of Sr and Zn and much higher of Y and U. One significant difference between the

Låsen granite and all the other granites is its lower Rb content. It tends to have slightly lower contents of Y and Nb, even when compared with the even-grained granite from the Fellingsbro area which otherwise has the lowest contents of these elements.

The high contents of Y and Nb ensure that most samples fall distinctly in the within-plate granite field in the Rb vs. Nb + Y diagram (Fig. 5) as defined by Pearce et al. (1984). Some samples of the even-grained granite from the Fellingsbro area, normal Lisjö granite and Låsen granite fall outside this field.

As with the major elements, most samples lie on

Table 1. Chemical analyses of typical samples of the various granite types. SiO_2-LOI in wt.%, Ba-Lu in ppm.

	Porphyritic Fellingsbro granite					Even-grained granite from the Fellingsbro area		Magnetic rim of the Lisjö granite		Normal Lisjö granite		Pingstaberg granite		Dingtuna granite		Låsen granite	
	85002	85008	85012	85014	85022	85001	85027	85102	85104	85101	85112	84602	84618	86043	86045	84613	84615
SiO_2	69.4	69.6	71.3	65.2	68.4	73.7	75.7	68.0	69.9	70.3	72.2	73.4	74.9	72.4	72.1	73.7	70.8
TiO_2	0.46	0.55	0.46	1.00	0.69	0.18	0.21	0.63	0.59	0.30	0.48	0.13	0.14	0.24	0.13	0.04	0.11
Al_2O_3	14.1	13.6	13.5	13.8	12.6	13.8	12.7	14.1	13.9	13.9	14.0	13.1	14.0	14.0	13.6	13.5	16.2
Fe_2O_3-tot	3.79	4.12	3.10	6.03	4.19	2.08	2.14	4.03	3.86	3.35	3.38	1.46	1.42	2.68	1.72	1.60	2.09
MnO	0.07	0.07	0.06	0.11	0.09	0.04	0.04	0.06	0.06	0.04	0.06	0.02	0.02	0.04	0.03	0.04	0.08
MgO	0.67	0.58	0.56	1.26	0.90	0.33	0.31	0.85	0.83	0.62	0.63	0.23	0.22	0.43	0.17	0.23	0.29
CaO	1.81	1.51	1.29	3.18	1.59	0.72	0.76	2.62	1.99	1.20	1.33	0.69	0.79	1.05	0.96	0.81	1.58
Na_2O	3.05	2.71	2.84	3.00	2.87	3.16	2.02	3.29	3.17	3.25	3.43	3.19	3.49	3.20	3.86	3.24	3.18
K_2O	5.75	5.85	6.10	4.35	4.65	5.50	6.45	5.70	4.93	5.75	5.15	4.72	5.11	5.60	5.10	5.18	5.11
LOI	0.93	0.91	0.95	0.84	0.83	0.95	0.92	0.55	0.81	1.01	0.92	–	–	0.68	0.44	–	–
Ba	967	1140	1600	1550	876	281	546	1700	1050	520	742	376	423	469	198	377	1095
Rb	258	214	224	156	252	339	370	240	247	302	354	330	327	366	362	193	179
Sr	163	167	214	304	192	50	36	339	269	71	112	51	61	68	48	59	176
Cu	8	<5	<5	<6	<5	<5	12	6	9	<5	<5	<5	8	5	6	<5	<5
Zn	72	85	66	107	78	48	39	61	50	34	28	15	14	70	25	38	50
Pb	49	52	45	36	46	46	46	42	40	35	41	30	34	27	39	47	25
Zr	331	391	262	473	332	168	195	303	311	319	335	134	139	187	132	125	205
Nb	30	31	25	35	40	30	23	27	33	36	46	30	31	27	47	14	23
Ga	19	18	18	20	20	21	17	20	21	21	20	18	19	21	24	17	17
Mo	<1	<1	<1	2	2	<1	<1	2	2	5	3	<1	13	398	<1	<1	<1
Th	59	29	8	15	38	46	40	25	29	37	47	34	34	47	52	39	38
U	11	<4	<4	4	7	5	8	8	<4	7	7	28	30	12	17	16	12
Y	70	76	54	77	88	57	48	58	67	67	134	145	69	66	111	83	42
La	110	161	65.4	–	107	53.1	80.1	92.0	67.1	94.7	113	42.9	35.4	–	–	48.5	57.2
Ce	232	319	130	–	216	121	157	197	143	195	243	87.1	73.6	–	–	96.5	118
Nd	94.3	124	59.3	–	91.3	53.2	70.6	74.0	64.8	84.0	103	41.9	35.4	–	–	43.2	50.7
Sm	16.2	21.2	11.7	–	17.5	11.6	12.6	12.6	12.4	16.1	20.8	8.80	6.55	–	–	11.3	10.6
Eu	1.81	2.29	2.25	–	1.80	0.68	0.70	2.21	1.74	0.83	1.02	0.64	0.51	–	–	0.65	0.93
Gd	13.0	17.3	9.9	–	17.0	10.0	9.6	11.2	11.9	14.0	19.1	11.2	7.55	–	–	7.73	5.81
Tb	2.32	2.61	1.60	–	2.66	1.78	1.45	1.66	1.88	2.22	3.46	–	–	–	–	–	–
Dy	–	–	–	–	–	–	–	–	–	–	–	19.1	10.8	–	–	7.93	6.04
Er	–	–	–	–	–	–	–	–	–	–	–	14.2	7.72	–	–	5.23	3.89
Tm	1.10	0.99	0.79	–	1.26	0.93	0.63	0.90	1.08	0.86	2.05	–	–	–	–	–	–
Yb	7.13	6.18	4.88	–	7.65	6.20	4.24	5.95	7.07	5.54	12.7	14.2	9.27	–	–	4.53	3.47
Lu	1.22	0.98	0.80	–	1.14	1.04	0.71	0.96	1.20	0.96	1.94	2.74	1.28	–	–	0.60	0.70

– Not analysed.

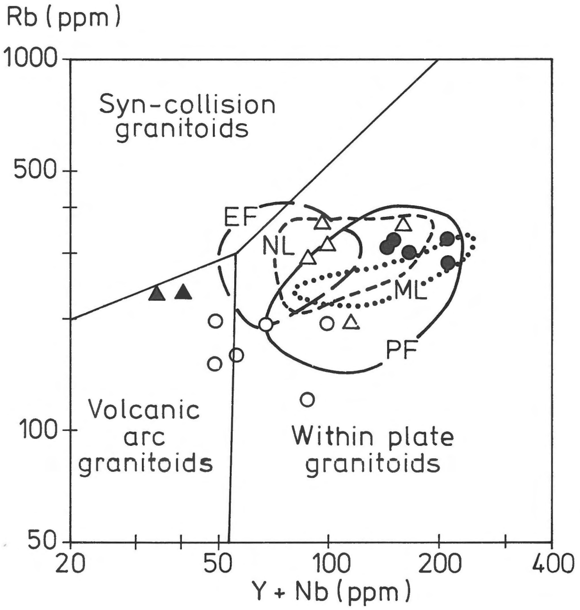

Fig. 5. Rb vs. Y + Nb diagram after Pearce et al. (1984). All values are in ppm. Symbols are as in Fig. 2, except the filled triangles which represent outliers of the normal Lisjö granite.

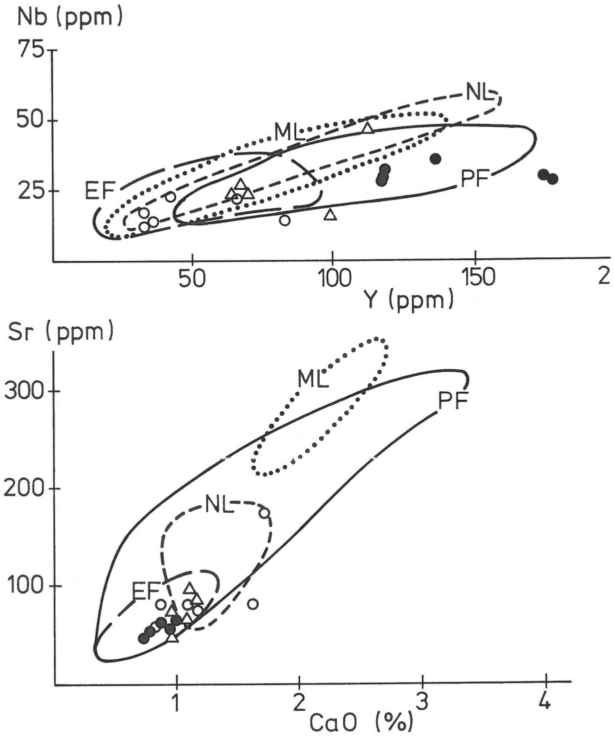

Fig. 6. Variation diagrams. Nb, Y and Sr are in ppm. CaO is in wt.%. Symbols as in Fig. 2.

well-defined trends in trace element variation diagrams (Fig. 6). The correlations for the Fellingsbro and Lisjö granite complexes are remarkably good considering the restricted SiO_2-range.

Rare earth elements

The results of the REE analyses are included in Table 1. Chondrite normalized patterns are displayed in Fig. 7. All samples have rather high contents of the REE, in accordance with the high Y-abundances. Furthermore, all samples, except those of the Pingstaberg granite, show the typical granite pattern (Cullers & Graf 1984) with a higher enrichment of light REE than heavy REE, and with distinct negative Eu-anomalies. The La abundances range from 519 to 159 (when Pingstaberg is excluded) times chondrite (Boynton 1984), and Lu contents 60.3 to 18.6 times chondrite. It is, however, particularly the heavy REE contents that are high in comparison with most granites (Cullers & Graf 1984).

In accordance with the very high Y-abundances in the Pingstaberg granite, is has high contents of HREE. The Lu abundances range from 85 to 40 times the chondritic value. The Pingstaberg granite is characterized by almost flat REE patterns with very large negative Eu-anomalies, a feature considered to be characteristic of granitoids associated with Mo- and W-occurrences in Bergslagen (Baker & Hellingwerf 1988). The La content range between 114 and 146 the chondritic value. Similar results were obtained by Baker & Hellingwerf (1988) on two samples of the Pingstaberg granite.

The normal Lisjö granite has larger negative Eu-anomalies than the magnetic rim, and the porphyritic Fellingsbro granite has smaller negative Eu-anomalies than the even-grained granites. Larger negative Eu-anomalies in more leucocratic rocks is a sommon feature in genetically related granitic rocks due to feldspar fractionation or fractionation of REE-rich accessory minerals (Cullers & Graf 1984). The results of the Låsen granite resemble those of the even-grained granite from the Fellingsbro area.

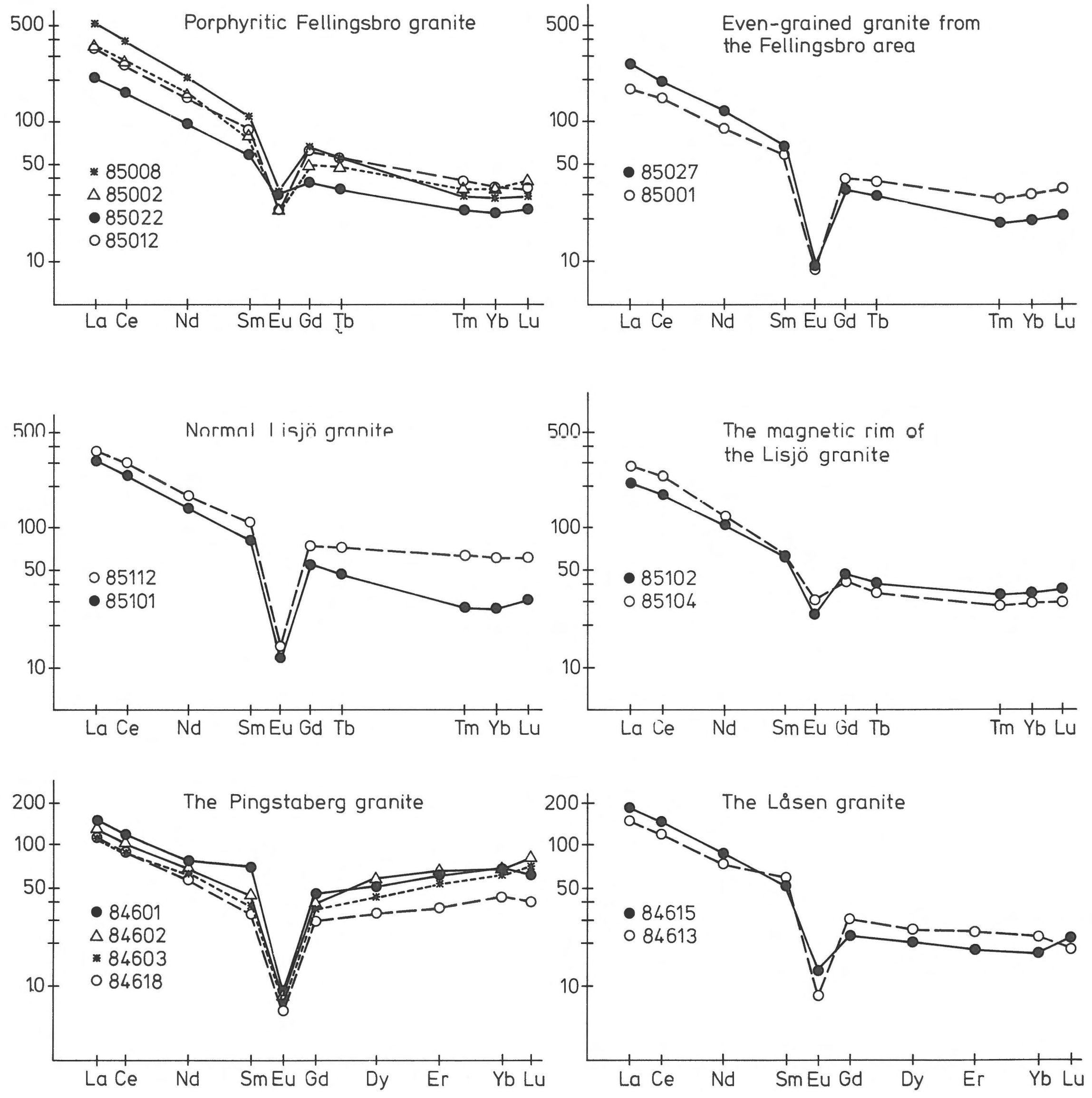

Fig. 7. Chondrite-normalized REE patterns. Normalizing values from Boynton (1984). The numbers 85008 etc refer to the sample numbers in Table 1.

Discussion

The chemical properties of the Fellingsbro and Lisjö granite complexes, particularly of the porphyritic granites, are such that it is probable that they were generated in an ensialic tensional environment. They are potassic granites having the high abundances of Y and Nb which, according to Pearce et al. (1984), are typical for 'within-plate' granites. Further, they have rather high contents of e.g. REE, Zr, Th and U.

One important result of the gravity measurements presented by Öhlander & Zuber (1988) is that they suggest that crustal weakness zones in two main directions (Fig. 8) controlled the emplacement of the Fellingsbro, Lisjö and Dingtuna granites. The gravity results indicate that the porphyritic granites were generated at the base of the crust,

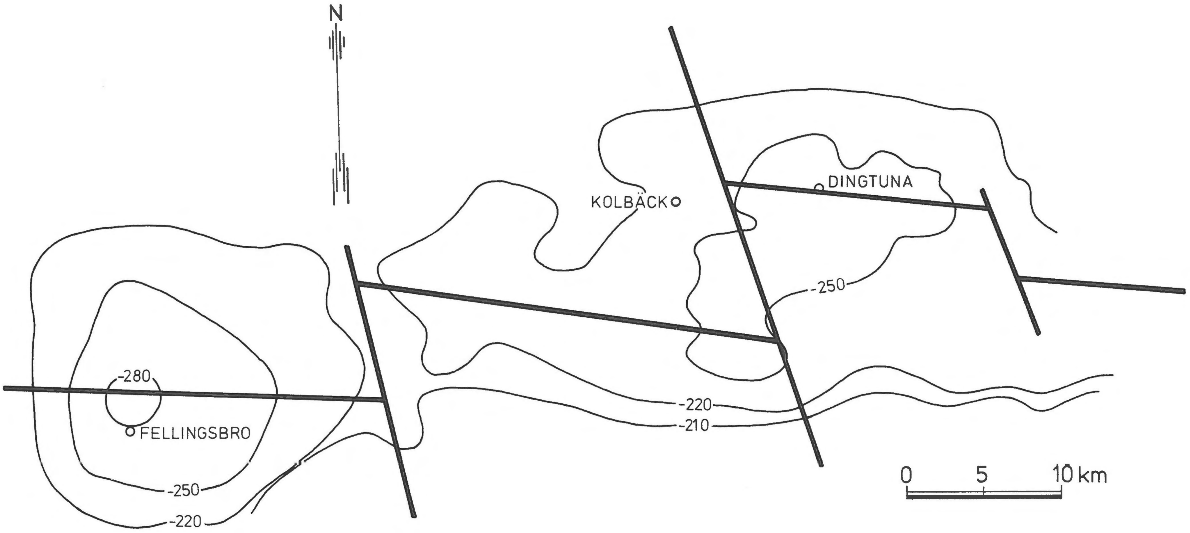

Fig. 8. Simplified interpretation of the striking directions of the most pronounced negative gravity anomalies (interpreted as the striking directions of the granite root zones) indicated by thick lines. Also shown are the −210, −220 and −250 gu Bouguer anomaly contour lines (after Öhlander & Zuber, in press).

i.e. at a depth of 35–40 km. The model with narrow root zones is supported by the fact that where the zones of the most distinct gravity lows do not coincide with the major exposed granites, abundant pegmatites and small diffuse masses of fine-grained granites occur indicating larger bodies of underlying granites (Öhlander & Zuber 1988). An obvious example in this context is the area south of the Lisjö massif. The Vdala-Uppland older batholith north of Lake Mälaren (Fig. 1) acted as a homogeneous unit while major weakness zones and subsequent younger granites were developed around it (Stephansson 1975).

Although the granites studied may have been generated in a tensional setting, it is unlikely that a true continental rift was developed. Neither mafic nor acid volcanics of the same age as the younger granites are known in the investigated area. In continental tensional environments, degassing of the mantle occurs (Bailey 1977, 1983). Continued heating by the gas flux may lead to melting of the upper mantle and lower crust. When the lower crust melted, the trace element characteristics were obtained by the mixing of the mantle gases, (rich in CO_2, alkalies and the trace elements characteristic of 'within-plate' granites) with the crustal fusion products. The melting of the lower crust produced the huge granite ridge striking along the *Central Swedish gravity low*.

In both the Lisjö and the Fellingsbro complexes clear chemical differentiation trends were found. These, together with the igneous texture described above, indicate crystallization from a melt. The differentiation trends within the porphyritic group partly overlap the trends for the even-grained granites. It is thus not likely that the even-grained granite from the Fellingsbro area respresents simply a late product of differentiation of the porphyritic granite. Elements such as Y and HREE are often enriched in residual granitic melts (Cullers & Graf 1984), but the porphyritic granite has the highest contents at these elements among the granites in the Fellingsbro area. The normal Lisjö granite and the Dingtuna granite may have been generated by differentiation of large masses of porphyritic granite, but heterogeneous mixtures of even-grained granites, pegmatites and remnants of country rocks such as in the Låsen area, the Malingsbo area (M in Fig. 1, Magnusson 1940) and the area SW of the Fellingsbro granite (Gorbatschev 1972) probably to a large extent represent minimum-melt type remobilisation of country-rocks. The latter two of these heterogeneous massifs have small cores of exposed porphyritic granite. The minimum-melt granites have not moved far from their source region. Pegmatites crystallise from H_2O-saturated melts (Jahns & Burnham 1969). As high H_2O contents of granitic magmas occur in the initial stage of fusion, or in the closing stage of crystallization (Wyllie 1983), it is likely that the Pingstaberg granite with its Mo-mineralization, enrichment of e.g. Y and HREE, and associated pegmatites, represent a late residual portion of large granite masses. The Bispberg granite (B in Fig. 1), which contains an intra-granitic Mo-mineralization, is of the same type and has similar geochemical characteristics as the Pingstaberg Granite (Martinsson 1987). The K_2O-rich younger granite in the Falun area (Fa in Fig. 1) has rather high contents of Y and Nb (Kresten 1985), and the large Hedesunda granite massif (H in Fig. 1) is of the same type as the Fellingsbro granite complex (Lundegårdh 1967). This together with the occurrence of several major negative gravity anomalies in Bergslagen, not directly corresponding to exposed granites (Sture Werner pers. comm. 1987), suggests that the genetic model discussed for the Fellingsbro-Lisjö area may be worth discussing in the whole Svecofennian region of south-central Sweden. The suggestion that many of the even-grained granites have remobilized country-rocks as important source material is supported by the aluminous character (Fig. 9) of such granites occurring in the metasedimentary areas close to Stockholm (Fig. 1).

The Småland-Värmland granite-porphyry Belt (Fig. 1) was previously thought to be distinctly younger than the Svecofennian younger granites (Wilson 1980). This conclusion was, however, based mainly on Rb-Sr datings. New U-Pb zircon datings show that these two groups of rocks have approximately the same age (Patchett et al. 1987, Jarl & Johansson 1988). Nyström (1982) concluded that the Småland-Värmland Belt was generated in an andinotype orogeny where the emplacement of the granites and the volcanites was structurally controlled. Major element studies of Småland-Värmland granites show that they are alkali-calcic, i.e. they are K-rich and have rather high content of alkalies even at low SiO_2-contents (Lindh & Gorbatschev 1984). The few trace element analyses published indicate that the Småland-Värmland granites have similar characteristics as the Fellingsbro and Lisjö granites (Wilson et al. 1986), e.g. high abundances of Y and Nb although not as high as the porphyritic Fellingsbro and Lisjö granites. The Småland-Värmland granites, furthermore, are often coarse and porphyritic and have a low frequency of pegmatites (Lundqvist 1979).

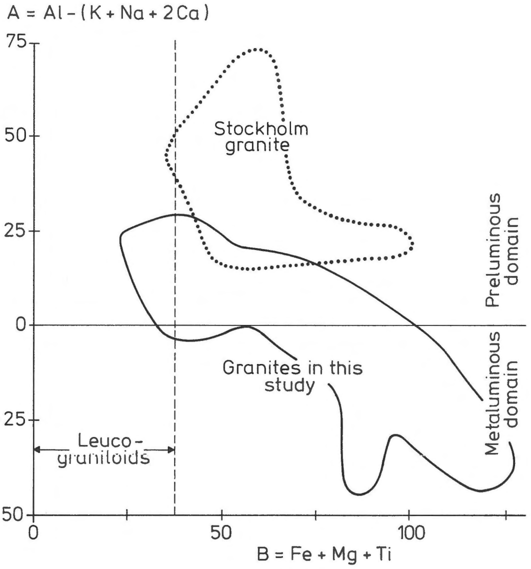

Fig. 9. A–B Diagram after Debon & LeFort (1982). Molar proportions. All samples in this study are encircled and compared with the younger granites from the Stockholm area (data from Stålhös, 1962; 1969).

The NNW-trending direction of the two major crustal weakness zone systems (Fig. 8) that governed the emplacement of the Fellingsbro and the Lisjö granites is parallel to the Småland-Värmland Belt, and to the border between this and the Southwest Swedish Gneiss Region. The border is a major crustal discontinuity termed the Protogine Zone (Gorbatschev 1980). In this context, it is interesting to note that the two main directions in Figure 8 are roughly parallel to the frequent large dolerite dykes that occur mainly south of Lake Mälaren, but also in the area studied here (Lopéz-Montano 1986). If these were emplaced contemporaneously with the younger granites, it would support the idea of a tensional setting. Very varying ages have been determined for dolerites in southern and central

Sweden (Gaál & Gorbatschev 1987), but the oldest so far is the 1.53 Ga age from the large Hällefors dyke (Patchett 1978). This is a Rb-Sr age determination, but it has been repeatedly demonstrated that Rb-Sr ages in the Precambrian of Sweden are too low, often 0.1–0.3 Ga lower than corresponding U-Pb zircon ages (e.g. Welin et al. 1983; Wilson et al. 1985; Patchett et al. 1987; Skiöld 1987). The possibility that at least some of the dolerites have almost the same age as the younger granites cannot be rejected. Another possible interpretation, not contradictory to the previous one, is that even younger dolerites intruded in fault zones created c. 1.78 Ga ago. In the Pingstaberg area, mafic dikes cutting the older but not the younger Svecofennian granitoids are very frequent (Ohlsson 1979). These dikes strike approximately E-W. Metamorphosed mafic dikes with such age relations buth with variable strike direction, occur in many places in Bergslagen, and around Lake Mälaren (Stålhös & Björk 1983). Stålhös & Björk (1983) suggested that these dykes are only slightly older than the younger granites.

According to Lindh (1987), the SW Swedish Gneiss Region (Fig. 1) was a zone of westward growth of the Baltic Shield. The ages of the younger granites and the Småland-Värmland granites are almost the same (or slightly higher) as those of the earliest I-type magmatism in SW Sweden (the 1.75–1.50 Ga Gothian orogeny, Welin et al. 1982; Gaal & Gorbatschev 1987). However, except for rocks thought to represent deformed rocks of originally the same type as the Småland-Värmland granites (Lindh 1987), ages as high as 1.78 Ga have not been found with U-Pb zircon dating W of the Protogine zone (Weling & Kähr 1980; Welin et al. 1982). Surprisingly, Rb-Sr ages are often higher than corresponding zircon ages in SW Sweden which indicates that the U-Pb zircon system may also have been disturbed in later metamorphic events (Welin et al. 1982). Even if the earliest Gothian tonalites-granodiorites, the Småland-Värmland granites and the Svecofennian younger granites are not exact age equivalents, it is probable that the origin of the latter two granite groups is related to the reworking of the ca 1.89 Ga old Svecofennian crust caused by the formation of Gothian crust in the southwestern Baltic Shield (Gorbatschev 1986, 1987, Gaál & Gorbatschev 1987). 'Post-orogenic' granite ring complexes were developed as early as 1.80 Ga ago in S Finland (Welin et al. 1983, Patchett & Kouvo 1986).

Linear belts of subalkaline to alkaline magmatism with typical 'within-plate' chemical characteristics, parallel to the main subduction associated cal-alkaline belts but situated more towards the interior of the South American continent, have been recognized in the Andes (Brown et al. 1984). These subalkaline to alkaline magmas were probably generated in association with tensional rifting (Levi & Aquirre 1981, Åberg et al. 1984). A speculative analogy in the Precambrian of Sweden would be that the Småland-Värmland Belt is such a belt situated more towards the continental interior in comparison with the earliest calc-alkaline magmatism in the SW Swedish Gneiss Region, or even farther west. Tensional stresses made it possible for granites to be generated even further towards the interior of the continental crust, which was created in the 1.89–1.86 Ga old tectonic event. The Fellingsbro and Lisjö granites are typical examples of this.

Conclusions

The 1.78 Ga old Fellingsbro and Lisjö granites were generated in a tensional environment. They presumably rose from a huge granite ridge through structurally controlled root zones forming mushroom- shaped intrusions. The results of this study indicate that the younger Svecofennian porphyritic granites not only are of the same age as the Småland-Värmland granites, but also have similar geochemical characteristics. We speculate that both groups were generated in a tensional environment on the continental side of a major subduction-related calc-alkaline belt; remnants of which may be presented in the Southwest Swedish Gneiss Region. The Lisjö and Fellingsbro granites were generated more towards the interior of the pre-existing c. 1.89 Ga old continent than the Småland-Värmland granites.

Even-grained granites of approximately the same age occurring in heterogeneous mixtures of granites, pegmatites and partly assimilated country rocks e.g. in the Fellingsbro and Låsen areas, represents mainly minimum melt type rocks that have not moved far from their source. The interior of the Lisjö granite complex, the Dingtuna granite and the Pingstaberg granite, on the other hand, were probably derived by differentiation of granites with similar characteristics as the porphyritic Fellingsbro type granite. The results presented in this study, and a review of published data, suggest that the genetic model obtained in the Fellingsbro-Lisjö area may be worth discussing in the whole Svecofennian region of south central Sweden.

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References

Åberg, G., Aguirre L., Levi B. & Nyström J.O. 1984 Spreading – subsidence and generation of ensialic marginal basins: an example from the early Cretaceous of central Chile – In, B.P. Kokelaar & Mr S. Howells (eds): Marginal basin geology: volcanic and associated sedimentary and tectonic processes in modern and ancient marginal basins – Geol. Soc. Spec. Publ. 16: 185–193

Bailey, D.K. 1977 Continental rifting and mantle degassing – In, E.R. Neumann & I.B. Ramberg (eds): Petrology and geochemistry of continental rifts NATO Advanced Study Inst. Ser. Reidel Publ. Co (Dordrecht): 1–13

Bailey, D.K. 1983 The chemical and thermal evolution of rifts – Tectonophysics 94: 584–597

Baker, J.H. & Hellingwerf R.H. 1988 The geochemistry of tungsten-molybdenum bearing granites and skarns from W. Bergslagen, Central Sweden – IAGOD proc. 5:2 Schweizerbart'sche Verlagsbuchhandlung, Stuttgart (in press)

Billström, K., Åberg G. & Öhlander B. 1988 Isotopic and geochemical data of the Pingstaberg Mo-bearing granite in Bergslagen, south central Sweden, and implications for its origin In: Baker, J.H. & Hellingwerf (eds): The Bergslagen Province, Central Sweden – Structure, stratigraphy and ore-forming processes. I.G.C.P. project 247 - 255–263 (this issue).

Boynton, W.V. 1984 Cosmochemistry of the rare earth elements: meteorite studies – In: P. Hendersson (ed.): Rare earth element geochemistry – Elsevier (Amsterdam): 63–114

Brown, G.C., Thorpe R.S. & Webb P.C. 1984 The geochemical characteristics of granitoids in contrasting arcs and comments on magma sources – J. Geol. Soc. Lond. 141: 431–426.

Cullers, R.L. & Graf J.L. 1984 Rare earth elements in igneous rocks of the continental crust: intermediate and silicic rocks – ore petrogenesis – In: P. Henderson (ed.): Rare earth element geochemistry – Elsevier (Amsterdam): 275–316

Debon, F. & LeFort P. 1982 A chemical mineralogical classification of common plutonic rocks and associations – Trans. Roy. Soc. Edinburgh: Earth. Sci. 73: 135–149

Gaál, G. & Gorbatschev R. 1987 An outline of the Precambrian evolution of the Baltic Shield – Precambr. Res. 35: 15–52

Gorbatschev, R. 1972 Beskrivning till berggrundskartbladet Örebro NÖ – Sver. Geol. Unders. Af 103: 1–70

Gorbatschev, R. 1980 The Precambrian development of southern Sweden – Geol. För. Förh. 102: 129–136

Gorbatschev, R. 1986 Den proteroizoiska jordskorpans bildning i Baltiska skölden – Abstr. 17th Nordic Geol. Wintermtg in Helsinki: 47

Gorbatschev, R. 1987 Chemistry and geotectonic position of Proterozoic granites in the Baltic Shield – Abstr. IGCP 217 mtg in Lund: 37–39

Hjelmqvist, S. 1966 Beskrivning till berggrundskarta över Kopparbergs län – Sver. Geol. Unders. Ca 40: 1–217

Hübner, H. 1971 Molybdenum and tungsten occurrences in Sweden – Sver. Geol. Unders. Ca 46: 1–29

Jahns, R.H. & Burnham W.C. 1969 Experimental studies of pegmatite genesis: I. A model for the derivation and crystallization of granitic pegmatites – Econ. Geol. 64: 843–864

Jarl, L.G. & Johansson Å. 1988 U-Pb zircon age of granitoids from the Småland-Värmland granite porphyry belt – Geol. För. Förh. 110: 21–28

Kresten, P. 1985 Geochemistry and tectonic setting of metavolcanics and granitoids from the Falun area, south central Sweden – Geol. För. Förh. 107: 275–285

Levi, B. & Aguirre L. 1981 Ensialic spreading subsidence in the Mesozoic and Palaeogene Andes of Central Chile – J. Geol. Soc. Lond. 138: 75–81

Lindh, A. 1987 Westward growth of the Baltic Shield – Precambr. Res. 35: 53–70

Lindh, A. & Gorbatschev R. 1984 Chemical variation in a Proterozoic suite of granitoids extending cross a mobile belt-craton boundary – Geol. Rundsch. 73: 881–893

Lopez-Montano, R. 1986 Origin and composition of the Hällefors composite dyke, central Sweden – Medd. Stockh. Univ. Geol. Inst. 267: 1–113

Lundegårdh, P.H. 1967 Berggrunden i Gävleborgs län – Sver. Geol. Unders. Ba 22: 1–303

Lundegårdh, P.H. 1983 Beskrivning till berggrundskartan Lindesberg SO – Sver. Geol. Unders. Af 139: 1–58

Lundegårdh, P.H. & Nisca D.H. 1978 Beskrivning till berggrundskartan och geofysiska kartorna Västerås SV – Sver. Geol. Unders. Af 122: 1–60

Lundqvist, T. 1979 The Precambrian of Sweden – Sver. Geol. Unders. C 768: 1–87

Magnusson, N.H. 1940 Ljusnarsbergs malmtrakt. Berggrund och malmfyndigheter – Sver. Geol. Unders. Ca 30: 1–188

Magnusson, N.H., Thorslund P., Brotzen F., Asklund B. & Kulling O. 1960 Description to accompany the map of the pre-Quaternary rocks of Sweden. With one map to the scale of 1:1,000,000 – Sver. Geol. Unders. Ba 16: 1–177

Martinsson, O. 1987 Bispbergs järnmalmsfält, en geologisk och geokemisk studie – Licentiatuppsats 1987-03L, Luleå University: 1–118

Nyström, J.O. 1982 Post-Svecokarelian Andinotype evolution in central Sweden – Geol. Rundsch. 71: 141–157

Oen, I.S. & Verschure R.H. 1985 Isotopic age determinations in Bergslagen, Sweden: VII. Fellingsbro-type granite east of Kopparberg – Geol. Mijnbouw 64: 385–388

Öhlander, B. & Zuber, J.A. 1988 Genesis of the Fellingsbro type granites: evidence from gravity measurements and geochemistry – Geol. För. Förh. 110: 39–54

Ohlsson, L.G. 1979 Tungsten occurrences in central Sweden – Econ. Geol. 74: 1012–1034

Patchett, P.J. 1978 Rb/Sr ages of Precambrian dolerites and syenites in southern and central Sweden – Sver. Geol. Unders. C 747: 1–63

Patchett, P.J. & Kouvo, O. 1986 Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes and U–Pb zircon ages in the Svecokarelian terrain in south Finland – Contrib. Mineral. Petrol. 92: 1–12

Patchett, P.J., Gorbatschev R. & Todt W. 1987 Origin of continental crust of 1.9–1.7 Ga age: Nd isotopes in the Svecofennian orogenic terrains of Sweden – Precambr. Res. 35: 145–160

Pearce, J.A., Harris N.B. & Tindle A.G. 1984 Trace element discrimination diagrams for the tectonic interpretation of granitic rocks – J. Petrol. 25: 956–983

Skiöld, T. 1987 Aspects of the Proterozoic geochronology of northern Sweden – Precambr. Res. 35: 161–168

Stålhös, G. 1962 Nya synpunkter på Sörmlandsgrejsernas geologi med särskild hänsyn till Stockholmstrakten – Sver. Geol. Unders. C 587: 1–137

Stålhös, G. 1969 Beskrivning till Stockholmstraktens berggrund – Sver. Geol. Unders. Ba 24: 1–290

Stålhös, G. & Björk L. 1983 Interpretation of late Svecokarelian metadiabases associated with eruptive breccias in south central Sweden – Geol. För. Förh. 105: 321–333

Stephansson, O. 1975 Polydiapirism of granitic rocks in the Svecofennian of central Sweden – Precambr. Res. 2: 189–214

Thompson, M. & Walsh J.N. 1983 A handbook of inductively coupled plasma spectromotry – Blackie and Son Ltd (London): 273 pp

Welin, E. 1987 The depositional evolution of the Svecofennian supracrustal sequence in Finland and Sweden – Precambr. Res. 35: 95–114

Welin, E. & Kähr, A.M. 1980 The Rb-Sr and U-Pb ages of Proterozoic gneissic granitoids in central Värmland, western Sweden – Sver. Geol. Unders. C 777: 24–28

Welin, E., Gorbatschev, R. & Kähr, A.M. 1982 Zircon dating of polymetamorphic rocks in southwestern Sweden – Sver. Geol. Unders. C 797: 1–34

Welin, E. Vaasjoki, M. & Suominen, V. 1983 Age differences between Rb-Sr whole rock and U-Pb zircon ages of syn- and postorogenic Svecokarelian granitoids in Sottunga, SW Finland – Lithos 16: 297–305

Wideland, B. 1946 Relative Shwerenmessungen in Süd- und Mittelschweden in den Jahren 1943–1944 – Rikets allmänna kartverk meddelande 6: 1–121

Wilson, M.R. 1980 Granite types in Sweden – Geol. För. Förh. 102: 167–176

Wilson, M.R., Hamilton, P.J., Fallick, A.E., Aftalion, M. & Michard, A. 1985 Granites and Early Proterozoic crustal evolution in Sweden: Evidence from Sm-Nd, U-Pb and O isotope systematics – Earth Planet. Sci. Lett. 72: 376–388

Wilson, M.R., Fallick, A.E., Hamilton, P.J. & Persson, L. 1986 Magma sources for some mid-Proterozoic granitoids in SE Sweden: geochemical and isotopic constraints – Geol. För. Förh. 108: 79–91

Wyllie, P.J. 1983 Experimental studies on biotite- and muscovite-granites and some crustal magmatic sources – In: M.P. Atherton & C.D. Gribble (eds): Migmatites, melting and metamorphism – Shiva (Nantwich, Cheshire): 12–26

Zuber, J.A. 1985 Geological interpretation of gravity and aeromagnetic surveys over the Fellingsbro–Blixterboda granite – Geol. För. Förh. 107: 203–913