

## The major element geochemistry of the 1.9–1.86 Ga Bergslagen Older Granite Suite, W. Bergslagen, Central Sweden



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### Abstract

The 1.9–1.86 Ga Bergslagen Older Granite Suite forms part of a co-magmatic series together with a > 10 Km thick sequence of felsic metavolcanics developed in the 3000 km<sup>2</sup> of western Bergslagen, Central Sweden. The granites, divided into three geographical groups, are fine to medium grained biotite granites, with field and petrological evidence of high level emplacement, the intrusions cutting their own extrusiva. Post-magmatic hydrothermal alteration has resulted in albitization and variable iron oxidation ratios. Unaltered granite samples are characterized by a high silica content and weak inter-element variations, showing restricted minimum melt compositions. In terms of multicationic classifications the granites belong to an aluminous association, compatible with an origin by anatexis of a felsic to intermediate precursor, with no significant contribution from mafic sources. An origin by anatexis supports current models for a rifted intra-continental or continental margin setting.

### Introduction

West Bergslagen, Central Sweden is characterised by an immense amount of Proterozoic felsic rocks, both intrusive and extrusive, and in that sense can be considered a granite province. The granites have been divided radiometrically into two groups. An older group, the Bergslagen Older Granite Suite (Oen, 1987), formerly known as Urgraniter or Primorogenic granites, falls in the age range 1.9–1.86 Ga (U-Pb zircon; Welin et al., 1980; Åberg et al., 1983a; Rb-Sr whole rock; Oen et al., 1984). These granites are considered co-magmatic

with the felsic extrusives (Oen, 1987; Baker, 1988), which have similar radiometric ages (Åberg et al., 1983b), and are contemporaneous with the lithostratigraphic Middle and Upper Leptite Groups of the Bergslagen Supracrustal Sequence (Oen et al., 1982; Oen, 1987). A younger Svecokarelian Granite group (including the Filipstad, Dala – Järna, and Rockesholm granites), dated at 1.78–1.6 Ga (Rb-Sr whole rock; Welin et al., 1977; Oen, 1982, 1983; Åberg & Frederiksson, 1985), is also present in the area, but will not be considered here. Previous descriptions of the older granites in this area are given by Törnebohm (1880), Blomberg (1897),

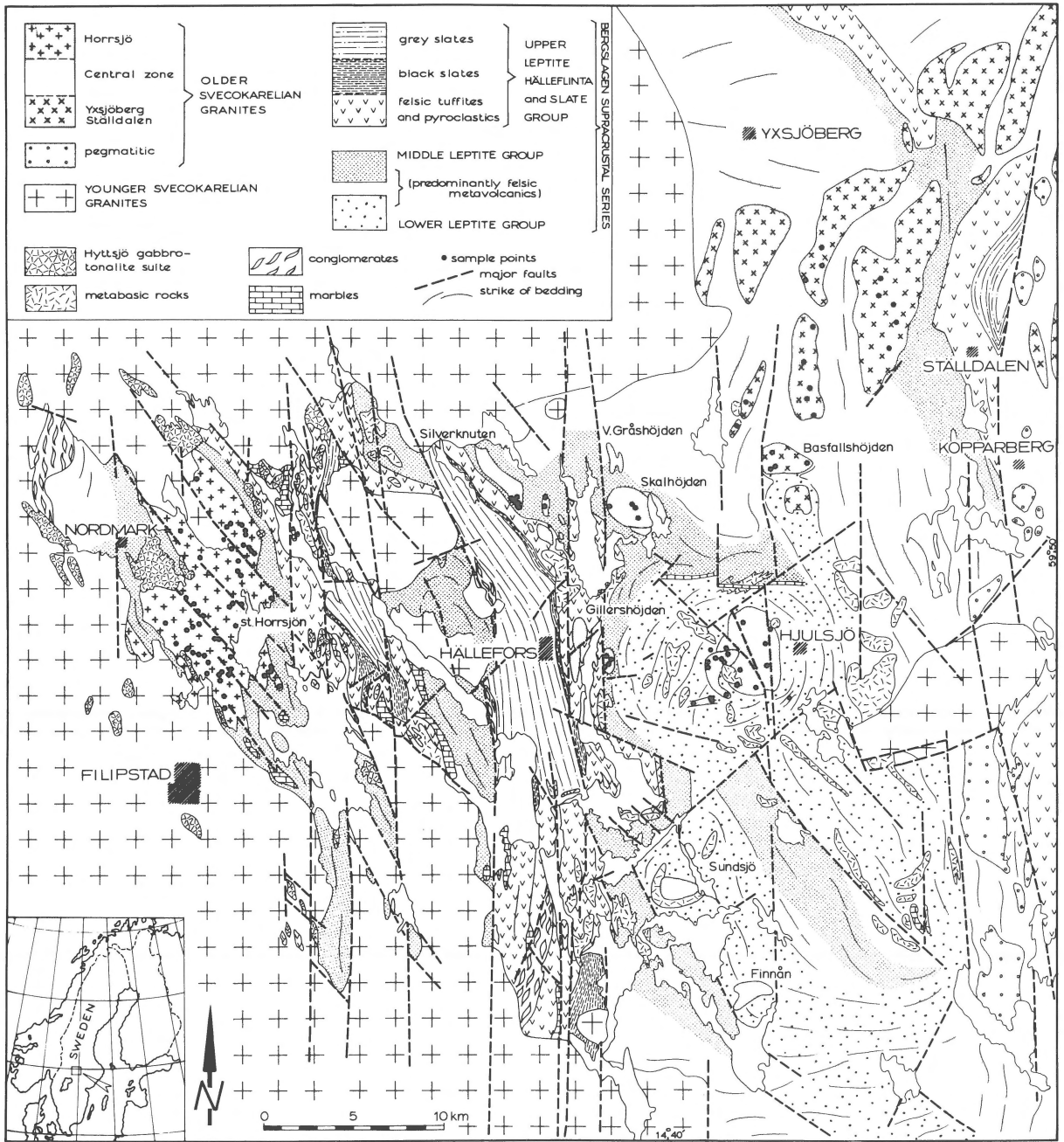


Fig. 1. Geological sketch map of the Filipstad – Hjulsjö-Kopparberg region of W. Bergslagen, showing sample location points for the three groups of granites analysed. Compiled from Oen et al. (1982), Oen (1987), and unpublished Msc theses, University of Amsterdam.

Sundius (1923), Magnusson (1925, 1929, 1930, 1940), Magnusson & Granlund (1928), and Magnusson & Lundqvist (1932).

The Bergslagen Older Granite Suite in the Nora – Filipstad-Kopparberg region can be divided spa-

tially into three groups (Fig. 1), with a central group forming a NNW–SSE zone of high level intrusives, flanked by the largest intrusion, the Horrsjö granite in the west, and the Yxsjöberg – Stålldalen granites in the east. This paper presents

major element evidence which supports an origin for these granites by anatexis of a preexisting probably felsic to intermediate precursor.

### General aspects and petrography

Detailed descriptions of the field relationships and petrography of the granites analysed in this study have been given by Baker & Drucker (1985), so only a summary is given here. While the granites are intrusive, with cross cutting relationships, their contacts with the host felsic metavolcanics often are subparallel. The granites show variable deformation, from undeformed to foliated or L-tectonites, and are generally fine to medium grained, high level intrusives. They are biotite granites, with quartz (sometimes as pseudomorphs after high temperature quartz), microcline microperthite and albite-oligoclase feldspar, with generally less than 3% biotite as a late stage, interstitial phase. Hornblende is occasionally present. Mirolitic cavities with minerals such as celadonite and celestine are common. Several granophyres, with hypersolvus mineralogies have been found. Accessory minerals include zircon, sphene, xenotime, tourmaline, apatite, fluorite, rutile and pyrite.

### Major element chemistry

#### *Hydrothermal alteration – alkali metasomatism*

120 samples, representative for the granite suite were analysed for major elements by standard XRF techniques. Ranges in chemistry and standard deviations for samples screened for the effects of hydrothermal alteration are given in Table 1. The macroscopic and microscopic evidence of hydrothermal alteration, including albitization and sericitization, together with the potential for element mobility during deformation means the data set had to be screened to select the least altered samples. Alkali exchange in the granites and comagmatic felsic metavolcanics is a well known phenomenon in Bergslagen (Frietsch, 1982; Baker, 1985a,b; Lagerblad & Gorbatshev, 1985; Hellingwerf, 1987). Alkali exchange, particularly albitization, in the Bergslagen Older Granite Suite is shown in the 'igneous spectrum' of Hughes (1972) Fig. 2. The granites of the central zone, intruded to a higher level in the crust, show a much greater degree of albitization than the Horrsjö and Yxsjöberg-Ställdalen granites which textural and field relationships show were emplaced at a greater depth. Only those samples with  $K_2O/(K_2O + Na_2O)$  ratios falling within the unaltered field of granites in the igneous spectrum are used in an interpretation of primary magmatic characteristics.

Table 1. Major element ranges, averages and standard deviations for the Horrsjö, Central Zone, and Yxsjöberg-Ställdalen granites. Data set of unaltered samples selected from an original set of 120 analyses.  $Fe_2O_3^*$  = total iron.

	Horrsjö			Central zone			Yxsjöberg-Ställdalen		
	range	ave n = 30	std dev	range	ave n = 17	std dev	range	ave n = 21	std dev
$SiO_2$	75.45–78.88	77.75	0.87	73.78–77.30	75.85	1.12	72.46–79.00	76.90	1.62
$TiO_2$	0.050–0.220	0.118	0.049	0.017–0.228	0.122	0.053	0.041–0.031	0.127	0.065
$Al_2O_3$	11.61–12.59	12.09	0.22	11.93–13.13	12.61	0.34	11.18–13.58	12.30	0.60
$Fe_2O_3^*$	0.90–2.98	1.73	0.57	0.33–2.19	1.26	0.51	0.56–2.85	1.49	0.50
$MgO$	0.09–0.80	0.21	0.17	0.0–0.35	0.13	0.13	0.03–0.69	0.19	0.17
$CaO$	0.11–0.89	0.49	0.15	0.26–0.82	0.55	0.18	0.20–1.73	0.66	0.37
$Na_2O$	2.77–4.37	3.49	0.31	3.17–4.59	3.80	0.40	3.16–4.22	3.56	0.33
$K_2O$	2.49–5.27	4.17	0.59	2.76–5.72	4.34	0.73	2.74–4.67	4.10	0.57
$P_2O_5$	0.010–0.050	0.027	0.010	0.013–0.054	0.027	0.012	0.011–0.070	0.032	0.015

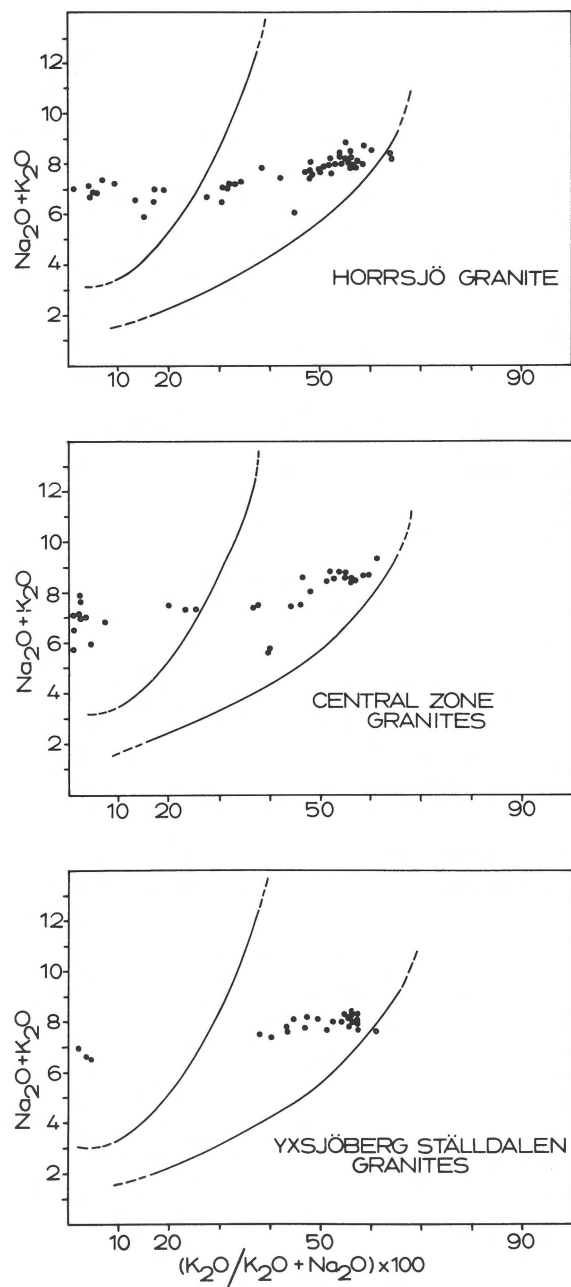


Fig. 2. Na-K relationships for the three groups of granites shown in the igneous spectrum of Hughes (1972). Samples falling inside the funnel shaped area have magmatic Na/K ratios; those falling to the left are albitized.

#### Oxidation state of the granites

The widespread hydrothermal alteration in the Bergslagen Older Granite Suite suggests that the iron oxidation ratio,  $\text{Fe}_2\text{O}_3 / (\text{Fe}_2\text{O}_3 + \text{FeO})$ , mea-

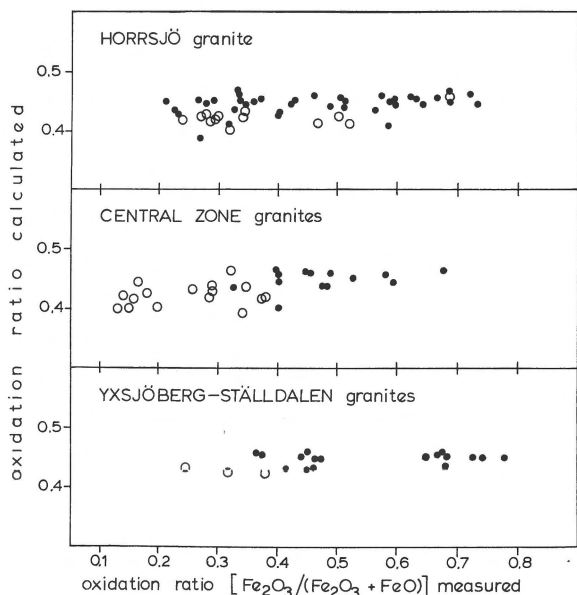


Fig. 3. Iron oxidation ratio  $\text{Fe}_2\text{O}_3 / (\text{Fe}_2\text{O}_3 + \text{FeO})$  calculated using the method of Le Maitre (1976) versus measured values. Albitized samples – open symbol; magmatic Na/K ratio – closed symbol.

sured in the granite samples, may not be magmatic. Albitization of the Bastfallshöjden granite (Baker, 1985b) caused a drop in the oxidation ratio from 0.45 to 0.25. Adjacent to albitized zones the ratio increased to 0.75, though total Fe content and other major element contents did not vary. Le Maitre (1976) devised the equation:  $\text{FeO} / (\text{FeO} + \text{Fe}_2\text{O}_3) = 0.88 - 0.0016 \text{ SiO}_2 - 0.027 (\text{Na}_2\text{O} + \text{K}_2\text{O})$  to calculate the oxidation ratio from a major element analysis. Since the Le Maitre equation uses total  $\text{Na}_2\text{O} + \text{K}_2\text{O}$ , it is insensitive to alkali alteration (see Fig. 2). Applying this to the W. Bergslagen suite, (Fig. 3) the calculated values fall in the range 0.41 to 0.47, similar to the measured value in the unaltered Bastfallshöjden granite (Baker, 1985b). This contrasts with the wide spread of values from about 0.2 to 0.8, measured in the granite suite. Albitized samples typically have low oxidation ratios, confirming the effects of alteration on the oxidation state of iron in these granites.

#### Interelement variations

The unaltered granite samples from the three gran-

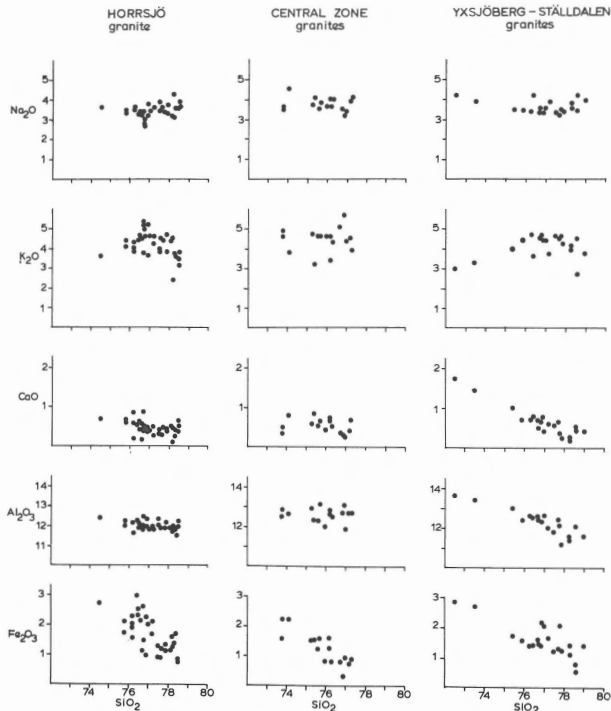


Fig. 4. Major element variations with respect to  $\text{SiO}_2$  in the Horrsjö, Central Zone and Yxsjöberg-Ställaldalen granites.

ite groups are characterised by a high silica content and a corresponding limited range in other major elements (Table 1). The granites are mildly peraluminous, with low CaO and MgO content. Interelement variations are generally poor (Fig. 4).  $\text{Na}_2\text{O}$ ,  $\text{K}_2\text{O}$ , CaO and  $\text{Al}_2\text{O}_3$  do not correlate with  $\text{SiO}_2$  in the Horrsjö and central zone granites.  $\text{Al}_2\text{O}_3$  and CaO show negative correlations with  $\text{SiO}_2$  in the Yxsjöberg-Ställaldalen granites, though calcium contents are low in all cases. There is a negative correlation between total iron and  $\text{SiO}_2$  in all the granites. The strong negative correlation between  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  (Fig. 5) is characteristic for these granites. The minor oxides  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$  show positive correlations with total iron. CaO and  $\text{TiO}_2$  show positive correlations with  $\text{Al}_2\text{O}_3$  in the Yxsjöberg-Ställaldalen granites, while in the Horrsjö granite the samples apparently divide into two groups with different  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios. In terms of normative Q-Ab-Or content (not shown), the central zone granites cluster about the 0.5 Kbar eutectic minimum, while the other granites fall in the Q-field just above the minimum.

#### Multicationic classifications and the W Bergslagen granites

A drawback of commonly used major element granite classifications is that they are not based on a consideration of the complete analysis. Additionally, classifications designed for interpreting mafic suites are not necessarily applicable to granitic suites. Thus the AFM diagram is totally unsuited to distinguish granitic suites, (e.g. MacGeeham, 1978; Batchelor & Bowden, 1985). De la Roche (1964, 1980), De la Roche et al. (1980) devised a multicationic approach to granite classifications and interpretations, refined by Debon & Le Fort (1983) and Batchelor & Bowden (1985), which takes the complete major element analysis into account in defining a granite association. Oxide percentages are recast to millication values per 100 g (see De la Roche, 1980; Debon & Le Fort, 1983). The Q3-F3-B3 projection of the quartzfeldspars-muscovite-biotite framework (De la Roche, 1980) shows the three groups of the Bergslagen Older Granite Suite forming a cluster in a field defined by migmatite compositions, and do not define any trend (Fig. 6). This position could be interpreted as either the end point of an igneous fractionation trend, or the product of anatexis of older crustal material. The vectors  $R_1$  to  $R_5$  indicate decreasing muscovite participation in crustal anatexis. The plot does not separate calc-alkaline and sub-alkaline trends, unlike the SS-AC-MM projection (Fig. 7) of the quartz-annite-muscovite-phlogopite tetrahedron (De la Roche, 1980). The restricted compositions of the W. Bergslagen granites once again means they form a cluster rather than define a trend, suggesting an origin by anatexis may be more likely than considering the granites form part of a fractionated series. Debon and Le Fort (1983) define three major magmatic associations, namely *cafemic*; suites derived from mantle sources, *aluminous* suites derived predominantly by anatexis of continental crust, and *alumino-cafemic*; suites intermediate between the other two. The A-P diagram (Fig. 8) separates these three associations. The W. Bergslagen granites satisfy the criteria of the aluminous association, all samples falling in the peraluminous field, and not defining a negative trend towards mafic compo-

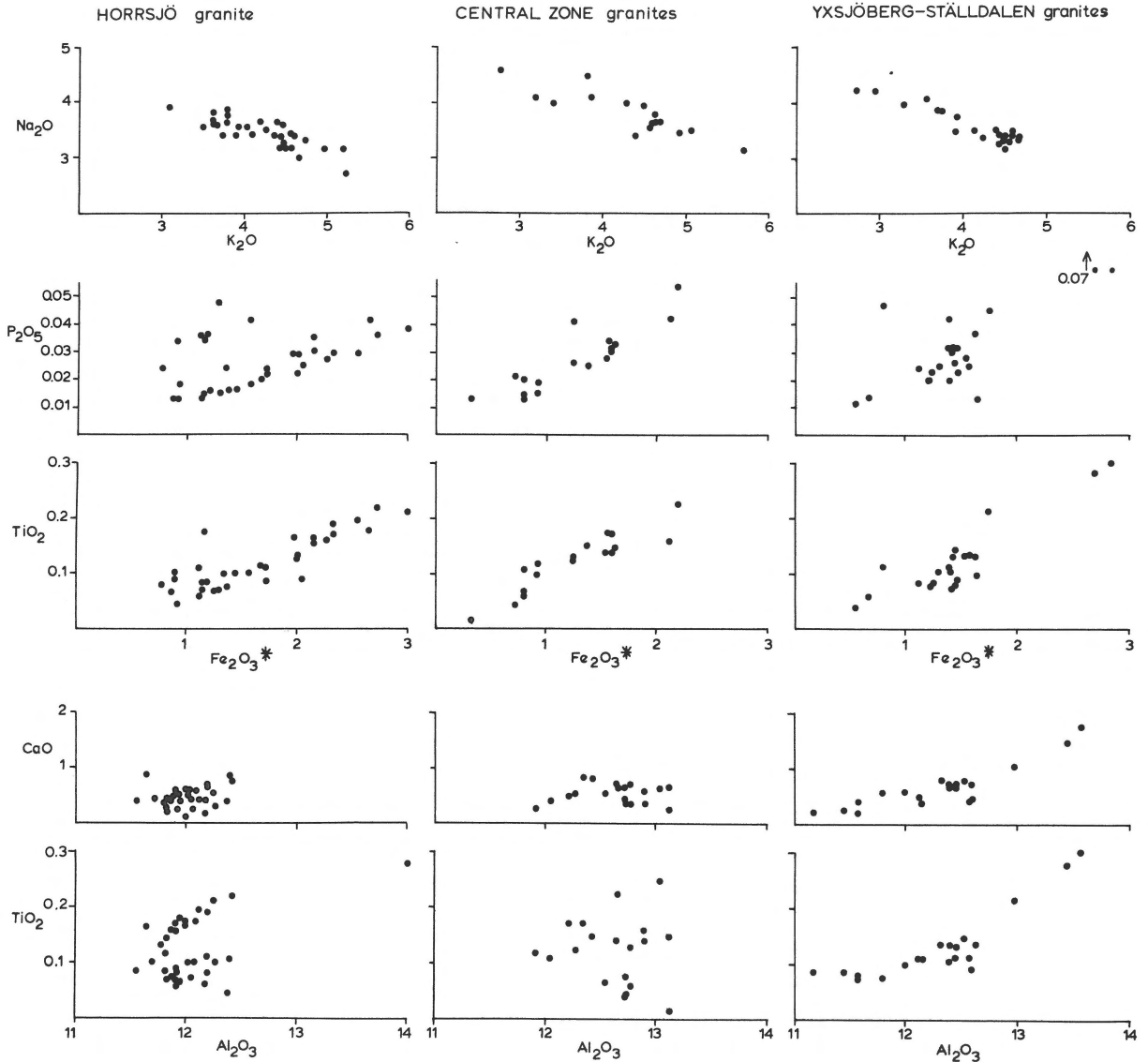


Fig. 5. Major element variations in the three granite groups:  $\text{Na}_2\text{O}$  versus  $\text{K}_2\text{O}$ ;  $\text{P}_2\text{O}_5$  and  $\text{TiO}_2$  versus  $\text{Fe}_2\text{O}_3^*$ ;  $\text{CaO}$  and  $\text{TiO}_2$  versus  $\text{Al}_2\text{O}_3$ .

sitions in the metaluminous sectors 4 or 5. Most of the samples fall in the leucogranite field. Batchelor & Bowden (1985) applied the  $R_1$ - $R_2$  vectors of De la Roche et al. (1980) to granite suites from known tectonic settings, to distinguish different petrogenetic models. Granites from different tectonic settings define separate fields in the  $R_1$ - $R_2$  diagram (Fig. 9). The W. Bergslagen granites define a small field in the region occupied by anatectic or anorogenic granites, with no trend to more mafic compositions.

### Granitic magmatism and the tectonic setting of Bergslagen

Recent models for the tectonic evolution of W. Bergslagen have emphasized a continental setting (Oen et al., 1982; Vivallo & Rickard, 1985; Baker, 1985a; Oen, 1987; De Groot et al., 1988). Oen et al. (1982) and Oen (1987) noted the importance of rift-related processes in the development of the BSS. Evidence for rifting, and rifting of an interme-

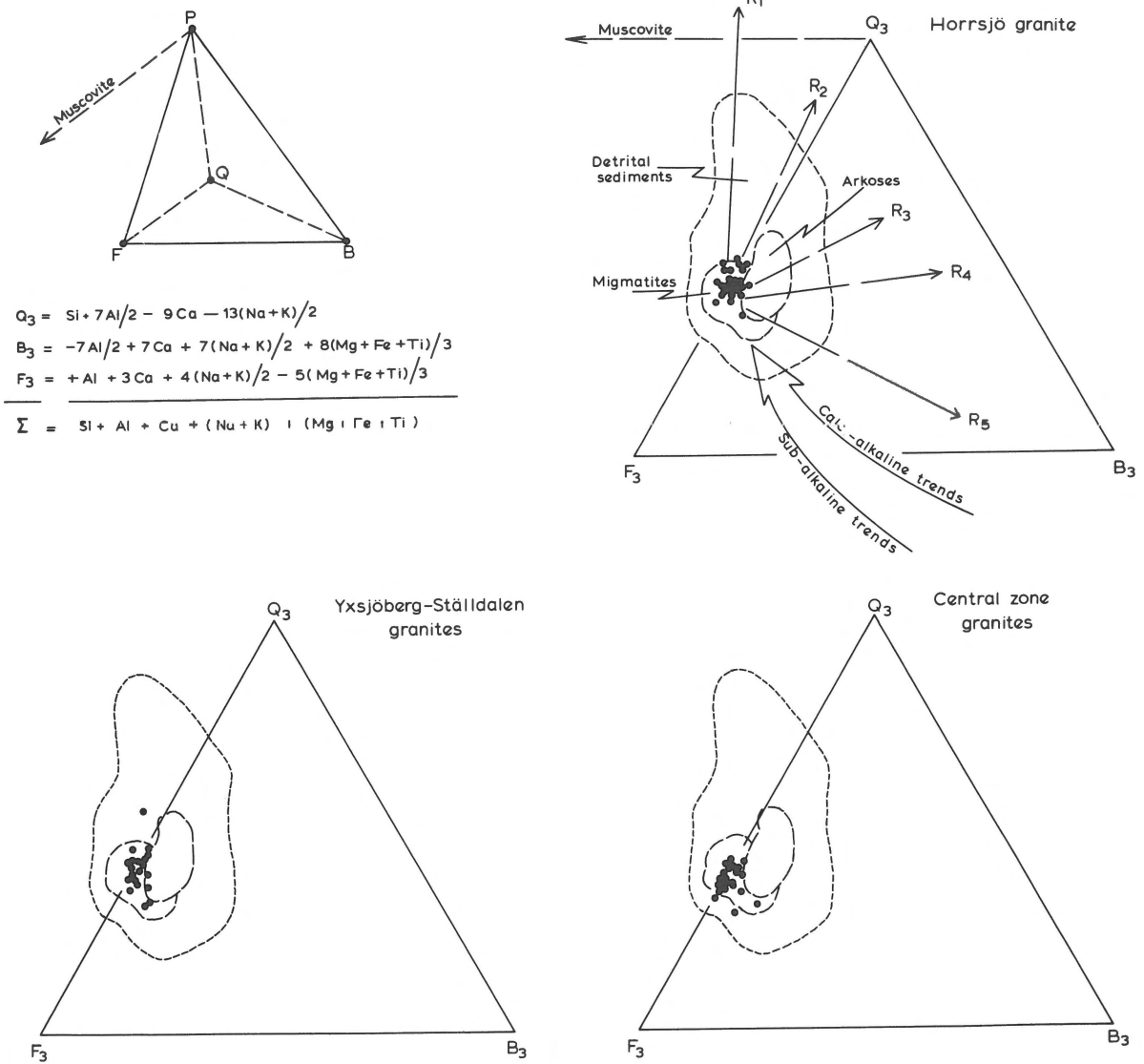


Fig. 6. Q<sub>3</sub>-F<sub>3</sub>-B<sub>3</sub> plot of De la Roche (1980) showing multicationic projection used (inset), and the three groups of W. Bergslagen granites, which fall in the field of anatectic melts.

diate to felsic precursor to the BSS of western Bergslagen is compelling.

The bimodal nature of the magmatism in Bergslagen (Van der Velden et al., 1982; Vivallo & Rickard, 1985; Lagerblad & Gorbatshev, 1985) is a striking feature, and is in itself evidence of an extensional regime (Martin & Piwinski, 1972; Emshie, 1978; Petro et al., 1979).

Sm-Nd isotopic data (Beunk et al., 1985; Miller et al., 1986; Patchett et al., 1987; Valbracht, un-

publ. data) from Bergslagen are consistent with an origin for the BSS by recycling of a slightly older ( $\pm 2.1$  Ga) Proterozoic crust, with only minimal (< 10%) Archean component or mantle contribution.

Homogeneous Pb-Pb isotope compositions of galena from Bergslagen suggest the pre-ore-bearing successions were felsic to intermediate in composition (Johansson & Rickard, 1985).

The long, narrow, synformal sediment-filled ba-

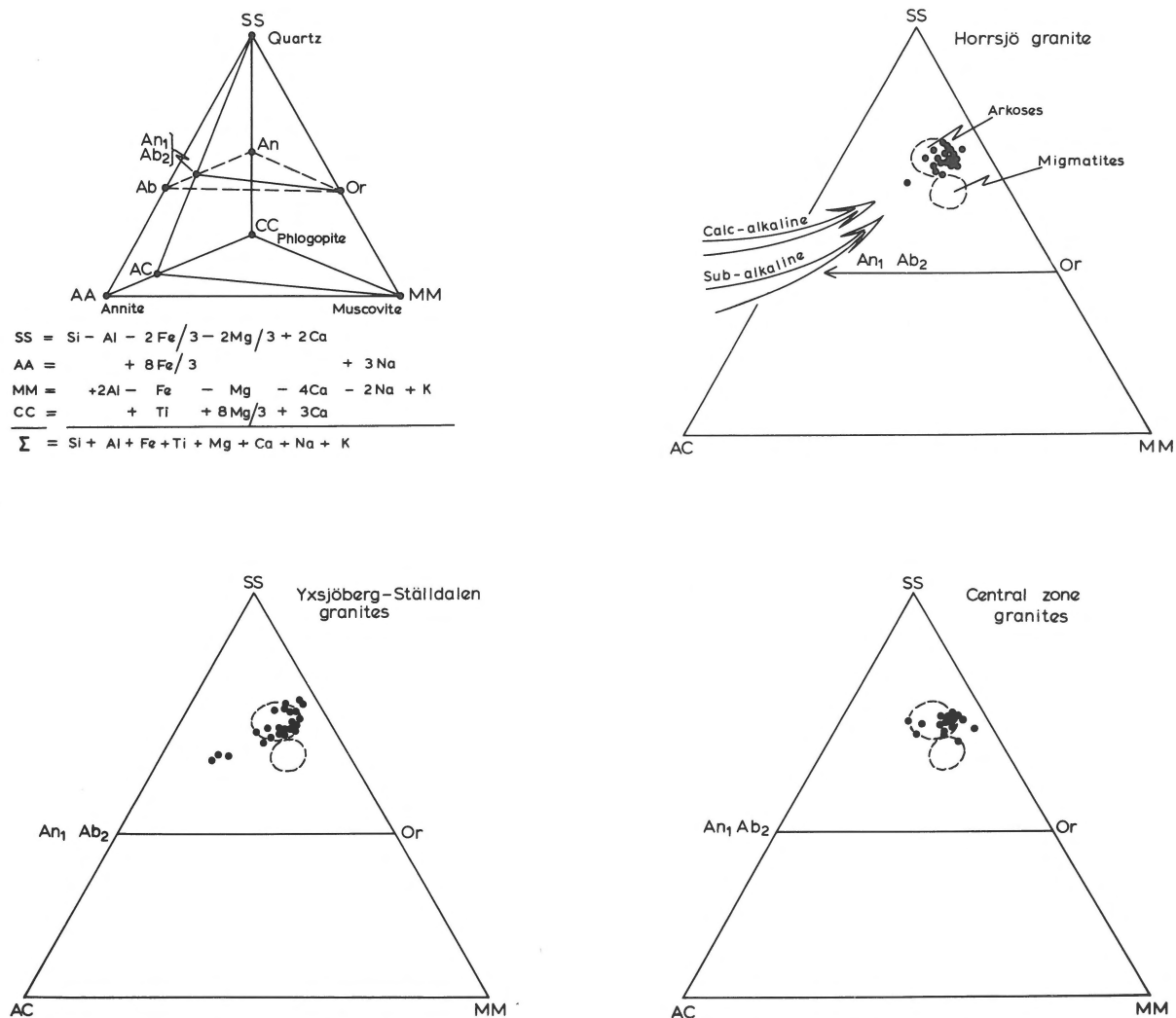


Fig. 7. SS-AC-MM plot of De la Roche (1980), showing multicatic projection used (inset), as well as the three granite groups whose restricted compositions fall in the field of anatectic melts.

sinal structures of W. Bergslagen are separated by wider areas of felsic metavolcanics which do not form anticlinal structures (see De Groot et al., 1988). The supracrustal sequence comprises >10 km of felsic metavolcanics (Oen et al. 1982; Baker 1985a), which cannot reasonably be considered the fractionated part of a mafic magma.

The geochemistry of the older granites in W. Bergslagen, can provide additional information on the tectonic setting of the area. The Bergslagen Older Granite Suite is characterised by restricted minimum melt compositions. Applying the multi-

catic approach to the data set shows that the suite has an anorogenic character, with the samples falling in fields defined by anatectic compositions (Figs. 6–9). An origin for the Bergslagen Older Granite Suite by melting of a felsic to intermediate precursor is thus likely, and is also valid for the comagmatic felsic metavolcanics (Baker, 1988). A similar aluminous granitic suite from Afghanistan has been attributed to anatexis of continental crust following large scale linear crustal thinning in an initial magmatic phase prior to the breakup of Gondwanaland (Debon et al., 1987).

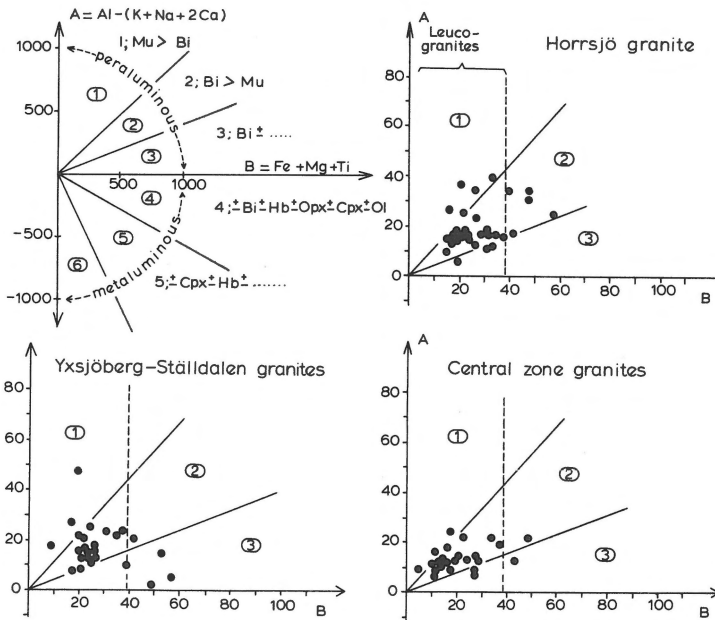


Fig. 8.  $A = \text{Al}-(\text{K}+\text{Na}+2\text{Ca}) - B = \text{Fe}+\text{Mg}+\text{Ti}$  multicationic plot of Debon & Le Fort (1983), showing the three granite groups falling in the peraluminous domain, with no trend towards calcalkaline (metaluminous) compositions.

It has long been recognised that the older granites of Bergslagen could be intrusive equivalents of the felsic meta-volcanics (e.g. Sundius, 1923; Magnusson, 1925; Larsson, 1933), and this is supported by geochemical evidence (Oen, 1987; Baker, 1988). The least altered felsic meta-volcanics and older granites of the Falun area, some 120 km to the NE of the Filipstad-Nora-Kopparberg region have an identical aluminous, non-calcalkaline character, though they are more iron rich (Bromley-Challenger, 1988, this issue). The rocks of the Falun area clearly belong to the same suite as those described here, with no calc-alkaline affinity comparable to that found in one small area to the east at Garpenberg (Vivallo & Rickard, 1985). The model of an anatexitic origin for the felsic rocks discussed in this paper is also applicable to Falun.

Gaál & Gorbatshev (1987) suggest the rocks of the  $\pm 1.9$  Ga Svecofennian Domain, including the predominantly volcanic Southern Svecofennian Province from Bergslagen east to Tampere and Orijarvi in Finland, developed during the orogenic formation of continental crust. The nature of the orogenesis in the southern volcanic belt is, however, unclear. Patchett et al. (1987) considered that

continental growth occurred through accretion of a succession of subduction zones. However, there is no geological evidence for subduction in the Falun-Nora area, with no ophiolites or their equivalents, and metamorphism occurring subsequent to the 1.9–1.86 Ga period of magmatism.

The structural development of western Bergslagen has been summarized by De Groot et al. (1988), who distinguish the following four phases: 1) a primary crust forming event at  $\pm 2.1$  Ga, inferred from Sm-Nd data; 2) attenuation of this crust accompanied by melting to give large scale felsic volcanism, contained predominantly in developing rift grabens, and the initiation of granite diapirism; 3) a tectonic inversion, with uplift of graben floors, higher emplacement of granite diapirs, and development of second generation rift grabens, and 4) a post-metamorphic ( $< 1.84$  Ga) generation of granites. Such a development is likely in an intracontinental, or continental margin setting. The geotectonic evolution of W. Bergslagen, in the period 1.9 to 1.86 Ga, during which the supracrustal sequence was formed, is apparently one of non-orogenic development, a model supported by the chemistry of the granites which intruded in this period.

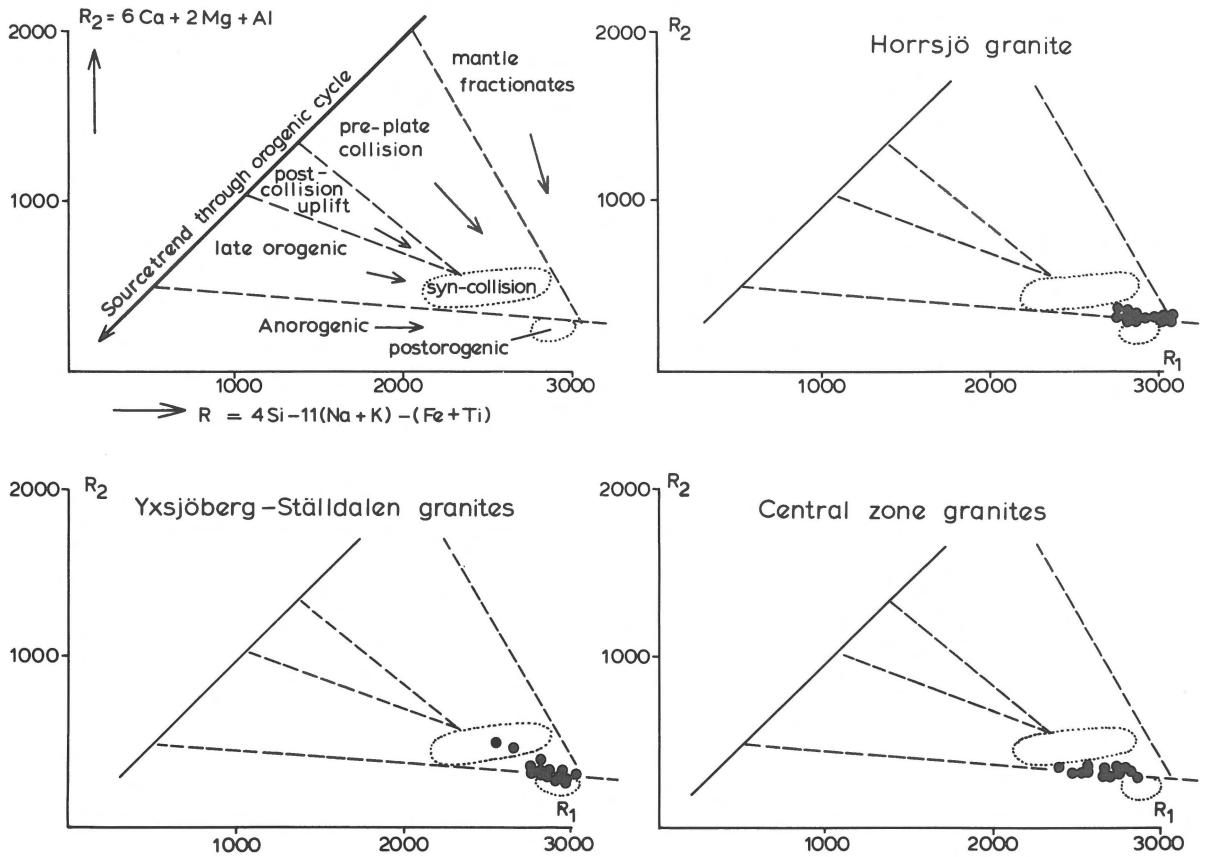


Fig. 9. R1-R2 discrimination plot of De la Roche et al. (1980) modified by Batchelor & Bowden (1985).

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