

SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 802 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 77 NR 4

RUDYARD FRIETSCH

PETROCHEMISTRY
OF THE IRON ORE-BEARING
METAVOLCANICS
IN NORRBOTTEN COUNTY
NORTHERN SWEDEN



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ABSTRACT

Frietsch, Rudyard, 1982-12-23: Petrochemistry of the iron ore-bearing metavolcanics in Norrbotten county, northern Sweden. Sveriges geologiska undersökning, Ser. C, No. 802, pp. 1-62. Uppsala 1984.

The iron ore-bearing Early Proterozoic (c.1.9 Ga) metavolcanics in northernmost Sweden are described and compared petrochemically. The stratigraphically lower Greenstone group, with skarn iron ores and minor quartz-banded iron ores, comprises pillowed basalts and minor andesites with a medium K_2O content, a low ferric/ferrous iron ratio and a high magnesium/iron ratio. The Porphyry group, with iron ores of the Kiruna type, comprises rhyolites, trachytes, subordinate andesites and minor basalts. The suite has a high alkali content, a high ferric/ferrous iron ratio and an intermediate magnesium/iron ratio. Both volcanic suites are tholeiitic to calc-alkaline with, however, alkaline affinities for the Porphyry group. The rocks of the Greenstone group are oceanic, whereas those of the Porphyry group are continental. The differences in the chemical features of the two groups are similar to those found in modern island arc environments where the evolution changes from tholeiitic to calc-alkaline volcanism. It is presumed that the Greenstone group and the Porphyry group are formed close in time by a related magmatism.

The two magmatic suites have developed separate trends during differentiation due to different oxygen fugacity of the magma. In the Greenstone group, characterized by a low oxygen fugacity, there was an enrichment of iron and constant silica content, whereas in the Porphyry group, with a contrastingly high oxygen fugacity, there was a decrease of the iron and phosphorus contents and an increase of the silica content. In the latter suite iron and phosphorus separated at an early stage forming a melt which was retained in the magma chamber until it became injected into the volcanics subsequent to their extrusion. A depletion of iron and phosphorus is also found in intermediate to acid porphyritic dykes, which form a late phase in the volcanism resulting in the

Porphyry group. The iron-phosphorus depletion in the volcanics and dykes supports the magmatic concept of formation for the Kiruna type of ore. Iron and phosphorus were separated into an intrusive phase which gave rise to the ores during a late stage of the magmatism.

The iron ores of the Kiruna type are spatially connected with extensive fault lines that to a large extent have governed the development of depositional basins containing supracrustal rocks (volcanics and sediments) in northernmost Sweden. The fault systems, reactivated repeatedly from Archean times, have largely guided the emplacement of the ore material. That the formation of the Kiruna iron ores is connected with rifting is shown by the alkaline affinity of the host rock volcanics.

Petrochemical comparisons of the plutonites in Northern Sweden show that the 1.9 Ga old Granodiorite suite (gabbro to granite with dominating granodiorite) is similar to the Greenstone group. Spatially their close association indicates that the plutonites were possibly formed by anatexis of the volcanics. The 1.5 Ga old perthite monzonites and perthite granites are in composition and space related to the Porphyry group. The difference in age between the plutonites and volcanics precludes an origin of the plutonites as a retarded magma intrusion; instead, a mobilization of the volcanics must be presumed.

INTRODUCTION

The Precambrian metavolcanics present in Norrbotten county; Northern Sweden, are the host rocks to the iron ores of the Kiruna type, skarn iron ores and quartz-banded iron ores, which together form the main part of the iron ore reserves of Sweden. The purpose of the present paper is to deal with the petrological and chemical features of the ore-bearing volcanics. Special attention is paid to the role of iron enrichment in the volcanics, and its bearing on iron ore formation particularly concerning the Kiruna type of ore. In addition, the internal relationship between the different volcanics and their relation to the plutonites of the region is reviewed. A short appraisal of the relations between volcanism and associated iron ores has been previously presented by Frietsch (1980a, 1980b).

GEOLOGICAL SETTING

The bulk of the iron ores of Norrbotten county occur in a wide zone of Early Proterozoic supracrustal rocks extending roughly E-W on both sides of Kiruna (Fig. 1). Intrusive rocks of somewhat different age characterize a large part of the region.

The oldest supracrustals are mafic volcanics of the Greenstone group. Basalts dominate with subordinate andesites and ultramafites; intercalations of pyroclastics and chemical precipitates are locally important. The rocks of the Greenstone group were deposited in relatively restricted basins along rift zones, partly bordering on the Archean craton. The basins, formed by vertical block movements and down-faulting, have a (geophysically estimated) depth of 1-4 km (Henkel 1977).

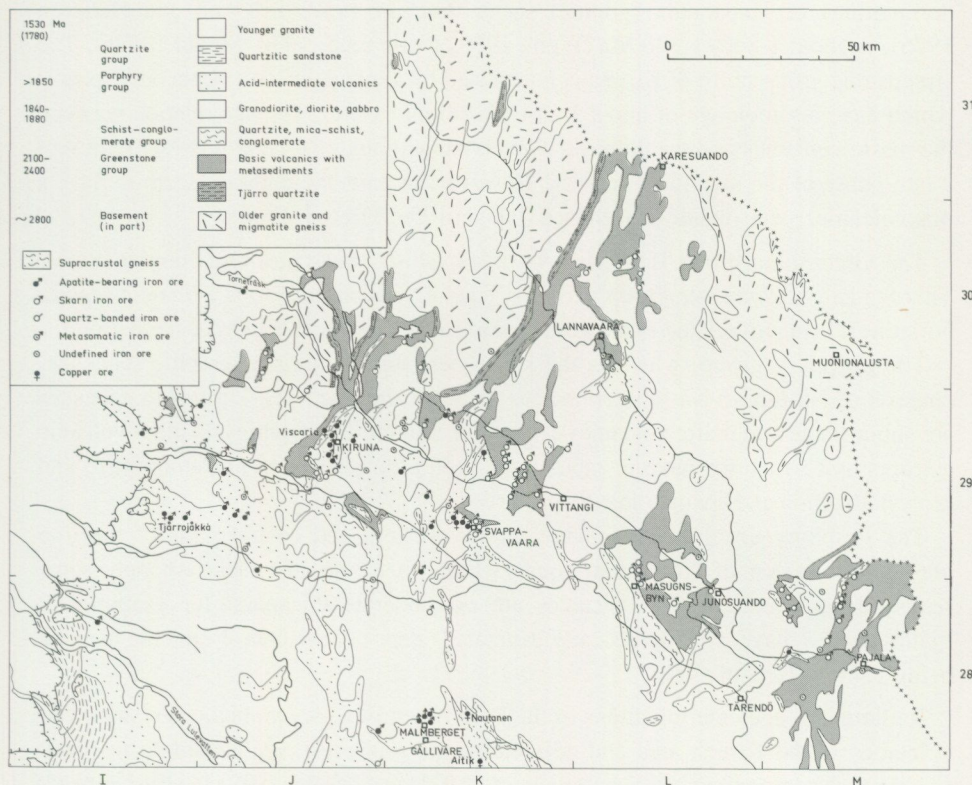


Fig. 1. The iron ore deposits in the northern part of Norrbotten county.

The Greenstone group in the area north of Kiruna is underlain by a gneissose granite belonging to the Archean basement. The U-Pb age of the granite is about 2 750–2 800 Ma (Welin *et al.* 1971). Further to the northeast granitoid gneisses have a U-Pb age of > 2 800 Ma showing traces of a metamorphic event at about 2 700 Ma (Skiöld 1979b).

A Sm-Nd mineral isochron for a basalt from the Greenstone group at Kiruna gives an age of 1 932 Ma (Skiöld and Cliff, in press). In Northern Finland the Upper and Middle Jatulian mafic metavolcanics and associated metasediments, which show lithological similarities to the rocks of the Greenstone group, have an age of 2 000–2 400 Ma (Sakko 1971, Simonen 1980, Meriläinen 1980a, 1980b, Perttunen 1980). Older mafic volcanics and sediments (of Lower Jatulian and Lapponian age, 2 400–2 800 Ma old) reported by Silvennoinen *et al.* (1980) are possibly equivalents to the Tjörro quartzite formation that underlies the Greenstone group (Eriksson and Hallgren 1975, Ambros 1980; cf. p. 49). The Greenstone group was intruded by synkinematic plutonites, varying in type from granite, granodiorite and diorite to gabbro. The Rb–Sr age of the Granodiorite suite (granodiorites are quantitatively

dominating) or Haparanda (granite) series (Ödman 1957, Eriksson and Hallgren 1975), is about 1 840–1 880 Ma (Welin 1970, Welin *et al.* 1970, Skiöld 1979a). The Greenstone group north of Kiruna is intersected by albite diabases ("Leucodiabases") which have a zircon age of about 1 874 Ma (Skiöld 1981). The age relation between the mafic volcanics and the diabases is uncertain although the latter possibly represent a late phase of the magmatic activity. However, in part, the diabases seem to have a postvolcanic, metasomatic provenance (Padget 1959, Frietsch 1966).

The Greenstone group is overlain by mica schists, quartzites and conglomerates. This Schist-conglomerate group is of restricted extension but forms a distinct marker horizon. It is in part related to the same depositional basins as the Greenstone group.

The Porphyry group, which is the subsequent unit in the stratigraphic sequence, consists of Na-rich to Na-K-intermediate rhyolites and trachytes. Dacites to andesites are subordinate and mafic volcanics even less common. Porphyritic and other volcanic textures and structures have in most cases been effaced by later metamorphism and recrystallization and are only locally preserved.

The Porphyry group occurs mainly in the western and central parts of the iron ore-bearing region of Norrbotten county (Fig. 1); to the east there are only some scattered occurrences. The volcanics are of moderate thickness; for example, at Fjällåsen they have a (geophysically estimated) dept of less than 2 km, the average being 1.4 km (Henkel 1975).

Radiometric age determinations of the Porphyry group give ambiguous results. The volcanics in the Kiruna area and adjacent to the southwest, are according to Rb-Sr (whole rock) determinations by Welin *et al.* (1971) and Welin (1979) 1 570–1 600 Ma old. More recent U-Pb (zircon) determinations seem to favour older ages, *i.e.* 1 873 Ma (E. Welin, oral comm. 25.5.1982). Determinations made on the sphene from the Kiruna area yield 1 850 Ma and must be considered as a minimum value (O. Kouvo and co-workers, oral comm.). Volcanics at four localities in the Kiruna-Gällivare region have given zircon ages of 1 909 Ma (Skiöld and Cliff, in press). A similar relatively high age is supported by determinations made on a migmatite granite which cuts the volcanics southwest of Svappavaara. The Rb-Sr system of the granite is disturbed and the time of emplacement is probably indicated by 1 800 Ma old zircons from this nearby similar granitoids (Skiöld 1981 and later oral comm.).

Radiometric determinations of a minor occurrence of acid volcanics at Latvajärvi, west of Kittilä, in Northern Finland, give an age of about 1 885 Ma (Rastas 1980). The volcanics, which include intermediate volcanics, a conglomerate and a minor iron ore occurrence, are lithologically similar to the Kiruna volcanics of the Porphyry group. The Latvajärvi volcanics are, however, characterized by a high potassium content.

In the Porphyry group, and less usually in the Greenstone group, there are dykes of metabasites and acid to intermediate porphyries. The latter are compositionally similar to the volcanics of the Porphyry group and possibly represent, together with the mafic dykes, a late phase in this magmatism.

The youngest supracrustal unit is the Quartzite group which consists of quartzitic sandstone with conglomerates and occasionally intercalations of phyllite. The group is of restricted extent. It has been formed by sedimentation in shallow basins, which were bordered by vertical faulting and spatially closely related to the Greenstone group depositories.

The supracrustal rocks and the plutonites of the Granodiorite suite are traversed by late-kinematic potassium granites with pegmatites and aplites. The Rb-Sr age of the Lina granite, which is the most widespread of the somewhat different granites, is about 1 530 Ma (Welin 1970, Welin *et al.* 1971, Welin 1979). For some granites, however, an age of about 1 780 Ma has been recorded. The relation between the younger and older granites is not known. Restricted areas are covered by perthite granites and perthite monzonites having a Rb-Sr age of 1 505–1 530 Ma (Gulson 1972, Welin 1979).

The geologic evolution of the ore-bearing region in Norrbotten county has involved one stage of denudation and at least two fold phases. The Archean basement was folded and eroded (as shown by bottom conglomerates) before the later Svecokarelian folding. Between the Greenstone, Schist-conglomerate, Porphyry and Quartzite groups, no major discordances can be discerned. The age of the Svecokarelian folding and metamorphism is uncertain although it is plausible that the supracrustals, at least those relevant to the Greenstone and Schist-conglomerate groups, were folded and metamorphosed prior to or coeval with the intrusion of the Granodiorite suite (Frietsch 1967a). Even though it is not possible to find out if there was a separate phase of folding and metamorphism connected with the late (Lina) granites, it is obvious that the intrusion of these granites extensively affected the older rocks by migmatization.

IRON ORES

Skarn iron ores and very minor quartz-banded iron ores occur in the Greenstone group within sedimentary intercalations present in the upper stratigraphic horizons. The associated sediments are tuffs, tuffites, phyllites, graphite-bearing schists, limestones-dolomites, marls, and cherts. Both types of ores have a volcano-sedimentary origin (Frietsch 1977).

The skarn ores are composed of magnetite (often Mg-bearing), Ca-Mg-silicates (tremolite-actinolite, diopside and less commonly hornblende) and Mg-silicates (phlogopite-biotite, serpentine and less commonly olivine, chlorite, talc and chondrodite). Small amounts of pyrite and pyrrhotite and accessory amounts of chalcopyrite are typical; the content of sulphur is mostly higher than 1 %. The content of phosphorus (in apatite) is mainly lower than 0.2 %, but is in some deposits up to several per cent.

The quartz-banded iron ores consist of quartzites with magnetite and Fe^{2+} -Mg-(Mn) silicates mostly occurring as distinct layers. The most common silicates are horn-

blende, grunerite, clinoenstatite, hedenbergite, and almandite; small amounts of pyrite and pyrrhotite are usually found in association.

The Kiruna type of ore, or the apatite iron ores, occur in the acid to intermediate volcanics of the Porphyry group. The mode of occurrence is as elongated tabular bodies or, in part as veinlets forming an irregular net-work ('ore breccia'). The content of phosphorus is mostly around 1 %, but some deposits, or sections of deposits, are low in phosphorus. Some deposits contain between 2 and 5 % P. The ore predominately consists of magnetite and/or hematite with small amounts of fluorine-apatite, actinolite-tremolite and diopside. The ores and the host volcanics are considered to have resulted from the same process of magmatic differentiation (Geijer 1931b, Frietsch 1978); the ore was injected as a late phase into the host rocks. An exhalative-sedimentary hypothesis for the formation of the Kiruna ores has been forwarded by Oelsner (1961) and Parák (1975a, 1975b).

PETROLOGICAL-CHEMICAL FEATURES OF THE METAVOLCANICS

A total of 184 analyses have been used for the interpretation of the chemical features that characterize the host rock volcanics of the iron ores in Northern Sweden. The analyses, which comprise 29 samples from the Greenstone group, 141 samples from the Porphyry group and 14 samples from the dyke rocks, have been taken from Offerberg (1967, pp. 114–117), Padget (1970, pp. 72–73), Witschard (1970, pp. 89–95), Witschard (1972, p. 30), Hallgren (1973, pp. 22 and 24), Frietsch (1974, pp. 16 and 25), Eriksson and Hallgren (1975, pp. 170–189), Witschard (1975, pp. 70–85), Padget (1977, p. 35), Frietsch (1979a, p. 66), Eriksson and Frietsch (1979, p. 10), and Lundberg and Smellie (1979, p. 1137). In addition, three unpublished analyses from the host rocks of the Lannavaara iron ore have been included.

The volcanics have been chemically divided into the following classes based on the SiO₂ content: less than 45 % ultramafite, 45–52 % basalt, 52–58 % andesite, 58–64 % dacite, 64–71 % rhyodacite and more than 71 % rhyolite. It should be emphasized that in all occasions where the content of different elements is related to the silica content, expressed as weight % SiO₂, the Niggli *si* value or the solidification index $SI = 100 \text{ MgO}/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O})$ by Kuno (1968), a high silica content or low solidification index does not necessarily imply a late formation of the rock. The diagrams presented below merely express the chemical variations with varying acidity, but not the temporal relations. However, following common convention, the assumption has been made that within the magma series a continuous increase of the acidity has taken place, *i.e.* a sequence of crystallization from basic rocks to acid rocks.

GREENSTONE GROUP

The volcanics of the Greenstone group comprise basalts, subordinate andesites and minor ultramafites (Fig. 2). The designation of rocks of andesitic composition either to the Greenstone group or the Porphyry group is uncertain. Andesites are more common in the Greenstone group than in the Porphyry group, but are locally important in the latter. For example, the basic syenite-porphyrries of the Porphyry group in the Kiruna and Vittangi regions are petrologically similar to the andesites of the Greenstone group in the same regions (cf. Offerberg 1967, Eriksson and Hallgren 1975). Thus the assignment of the andesitic rocks either to the Greenstone group or the Porphyry group is often based on the lithological environment. If the associated volcanics are mainly basalts, the andesites are referred to the Greenstone group, whereas andesites in a trachytic-rhyolitic environment are referred to the Porphyry group.

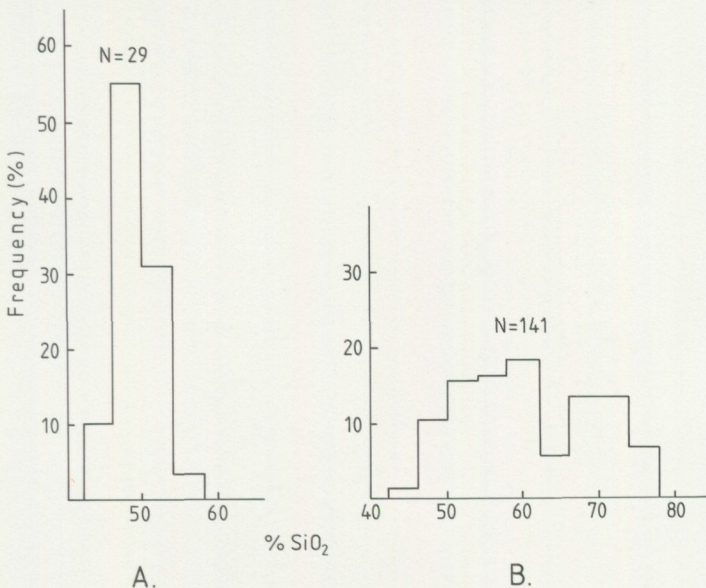


Fig. 2. Frequency distribution of the SiO₂ content (weight %) in the metavolcanics of northern Sweden. A. Greenstone group. B. Porphyry group.

It is important to determine the original composition of the altered rocks when dealing with the chemical features of the volcanics of the Greenstone group. This concerns especially the content of the alkalis. Basalts may be affected by spilitization and by submarine, chemical weathering, both processes being active coeval or subsequent to the deposition of volcanics. The main process involved in spilitization is the extraction of calcium and the addition of sodium. A high content of sodium coupled with a low content of calcium is therefore used as a criterion for distinguishing spilites from normal basalts (Graham 1976, Stillman and Williams 1978, Stephens 1980).

The primary nature of the Kiruna greenstones, belonging to the Greenstone group, has been discussed by Sundius (1915, 1930) and Geijer (1931a, 1958). According to Sundius (1915) the albite in the Kiruna greenstones is secondary and has replaced a more anorthitic plagioclase. Original basalts and diabases were by metasomatic processes altered to spilites. Later Sundius (1930) changed his view-point, favouring instead a primary origin of the albite. Geijer (1931a, 1958), also considered the albite in the Kiruna greenstone as primary. The sodic character of the feldspar was, however, secondary in the sense that the albitization had taken place through autolytic reactions between an already formed calcic plagioclase and a residual magma rich in sodium.

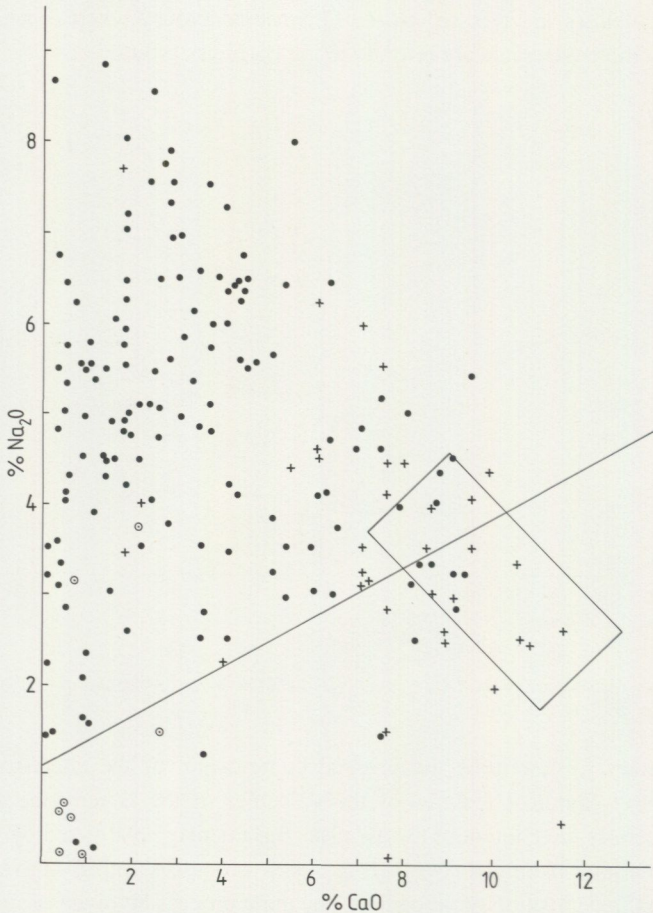


Fig. 3. The relationship between (weight %) Na₂O and CaO in the volcanics of the Greenstone group (crosses) and of the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden. Straight line separates high-Na₂O and low-Na₂O rocks according to Graham (1976). Box outlines normal, unaltered basalts according to Stephens (1980).

In order to find out if the volcanics of the Greenstone group were affected by spilitization, the contents of sodium and calcium have been plotted in Fig. 3. Only a small number of the rocks can be interpreted as spilitized, viz. those showing a combination of a high content of sodium with a low content of calcium. All analyses with high Na_2O contents are found relatively near Kiruna. However, most of the volcanics fall within, or near to, the field for normal unaltered basalts. The volcanics of the Greenstone group from different parts of Norrbotten county have almost similar sodium contents. The average sodium content allocated to the different map sheets are: Vittangi 3.6 % Na_2O , Pajala 3.5 % Na_2O , Kiruna and Tärendö both 3.3 % Na_2O and Lainio 2.6 % Na_2O . The average for all analyses is 3.3 % Na_2O . The volcanics of the Greenstone group have a moderate content of potassium, the average being 1.0 % K_2O . The following average contents allocated to the different map sheets are: Tärendö 2.5 % K_2O , Kiruna and Lainio both 1.0 % K_2O , Vittangi 0.7 % K_2O and Pajala 0.4 % K_2O .

If the proportions of Na and K in the volcanics of the Greenstone group are plotted according to Hughes (1973), with weight % $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus $100 \text{K}_2\text{O}/(\text{K}_2\text{O} + \text{Na}_2\text{O})$, about half of the analyses fall within the "igneous spectrum" comprising

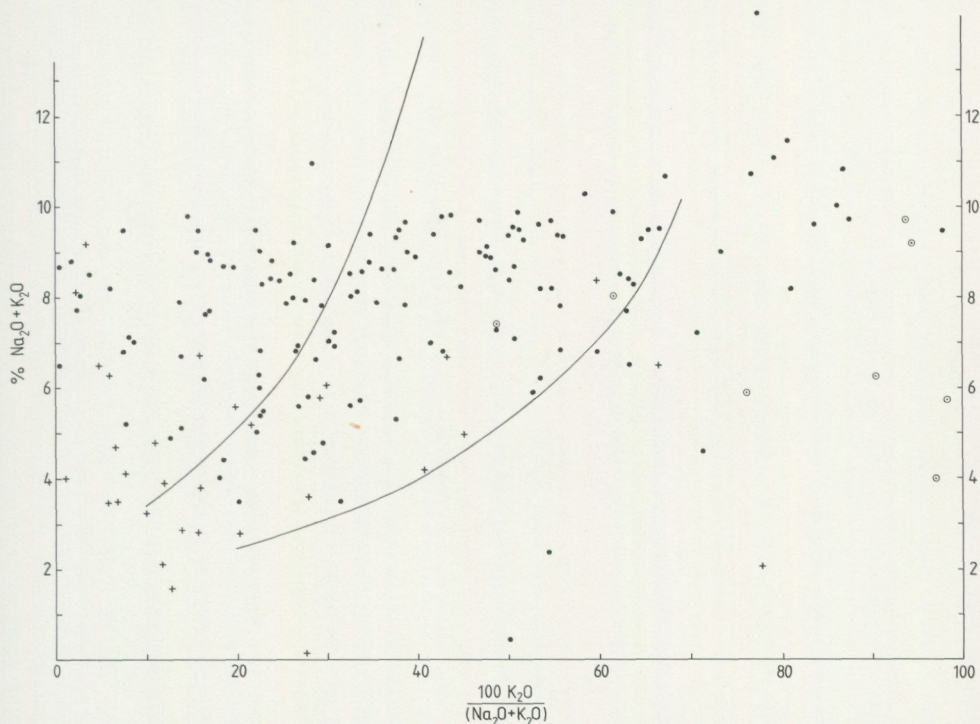


Fig. 4. The relationship between alkalis and potassium, expressed as (weight %) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus $100 \text{K}_2\text{O}/(\text{Na}_2\text{O} + \text{K}_2\text{O})$ according to Hughes (1973), in the volcanics of the Greenstone group (crosses) and Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden. The field limited by heavy lines indicates the "igneous spectrum" after Hughes (ibid.).

normal, unaltered magmatic rocks (Fig. 4). The main part of the analyses which lie outside this field are sodium-rich and possibly represent a primary trend within the magma. The Greenstone group as a whole does not appear to have been affected by large-scale metasomatic alterations and therefore consists to a large extent of normal basaltic rocks.

In an alkali/silica diagram (Fig. 5) the volcanics of the Greenstone group fall almost equally within the alkaline and sub-alkaline fields. A large percentage of the rocks lie within the alkali basalt and high-alumina basalts fields as discussed by Kuno (1968); only a few of the analyses are found within the tholeiitic field. In the AFM diagram (Fig. 6) the volcanics lie equally within the tholeiitic (pigeonitic) and calc-alkaline (hypersthentic) fields.

The Niggli values *alk* and *al*, if plotted against each other (Fig. 7), show that the volcanics of the Greenstone group are alkali-intermediate or relatively alkali-poor. The Niggli values *al*, *fm*, *c*, and *alk*, if plotted against the *si* value, show typical trends for a uniform differentiation process; i.e. with an increasing *si* value the *alk* and *al* values increase and the *fm* and *c* values decrease (Fig. 8).

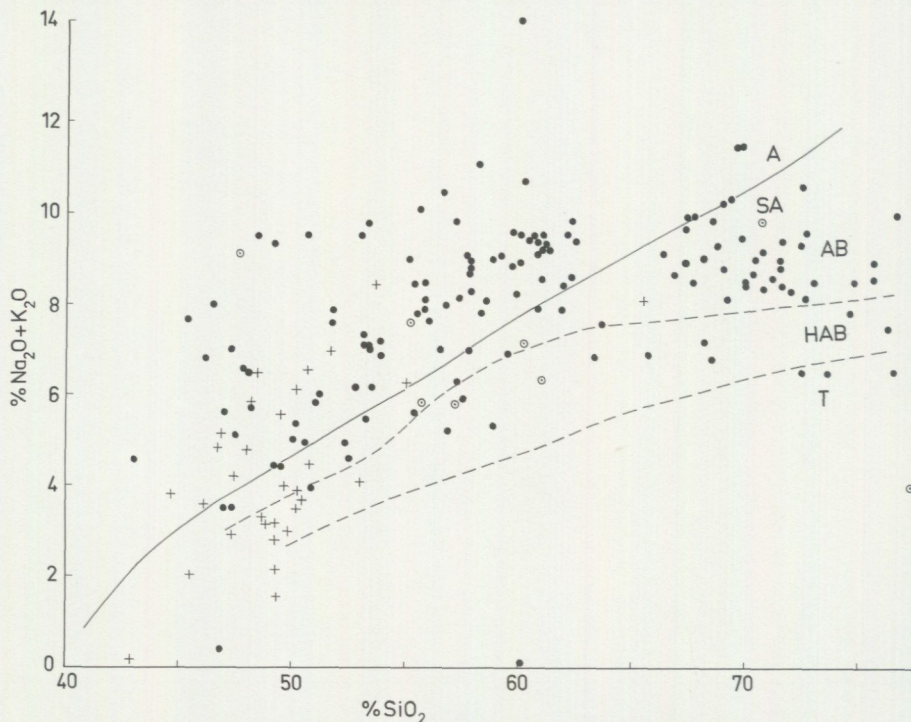


Fig. 5. Alkali-silica diagram (weight %) for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by encircled point) in northern Sweden. The upper continuous line after Irvine and Barager (1971) determines the alkaline (A) and the sub-alkaline (SA) fields, the broken lines after Kuno (1968) determines the alkali basalt (AB), the high-alumina basalt (HAB) and the tholeiite (T) fields.

When plotting the content of the different major elements against the "solidification index" of Kuno (1968), calculated as $100 \text{ MgO}/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O})$, there is in the Greenstone group a decrease of CaO and MgO as well as a slight increase of $\text{FeO} + \text{Fe}_2\text{O}_3$ and Na_2O , whereas SiO_2 , K_2O and P_2O_5 remain constant (Fig. 9). If plotted against the silica content the same tendency is found for the content of iron (Fig. 10) and phosphorus (Fig. 11).

The degree of oxidation, expressed as the $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Fe}^{2+})$ ratio, is below 0.5 in the Greenstone group and is unrelated to the silica content (Fig. 12).

The relationship between the $\text{Mg}/(\text{Mg} + \text{Fe})$ and $\text{K}/(\text{K} + \text{Na})$ ratios to the $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Fe}^{2+})$ ratio in the Greenstone group is unclear (Figs. 13 and 14). The $\text{K}/(\text{K} + \text{Na})$ ratio is mostly low and independent of the silica content (Fig. 15). The $\text{Mg}/(\text{Mg} + \text{Fe})$ ratio is relatively high (0.3–0.7) and decreases with increasing silica content (Fig. 16). The latter feature is typical for most magmatic suites, in particular calc-alkaline ones, which are formed by fractional crystallization.

On the basis of the normative composition the volcanics of the Greenstone group

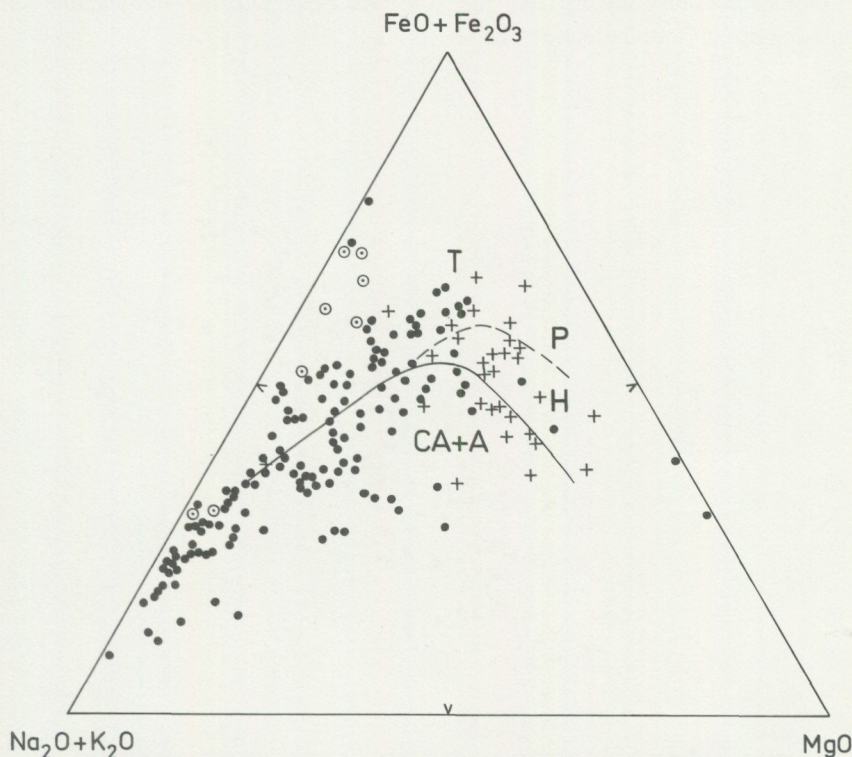


Fig. 6. AFM diagram (weight %) for volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden. The continuous line after Irvine and Barager (1971) determines the tholeiitic (T) and the calc-alkaline + alkaline fields (CA + A); the broken line after Kuno (1968) determines the fields of the pigeonitic (P) and the hypersthentic (H) rocks series.

belong to the olivine basalt series. The analyses by Offerberg (1967) as well as Eriksson and Hallgren (1975) show the following normative composition: Q and Ne are mostly not present, or only in small amounts (<5 %); Wo is absent; Di is present up to 20 %; Hy up to 30 %, and Ol up to 30 %. According to the division by Wilkinson (1974) this indicates (undersaturated) olivine tholeiites or olivine basalts.

A comparison of the major element chemistry in recent orogenic lavas and in the Greenstone group makes it possible to indicate the geotectonic setting in which the Greenstone group was formed. For example, Chayes (1964) and Chayes and Velde (1965) showed that the TiO_2 content can be used to discriminate between Cenozoic intra-oceanic and circum-oceanic basalts. The basaltic lavas of oceanic-island arc environment are much richer in TiO_2 (more than 2 %) than the lavas found in the circum-oceanic basalts (less than 2 %). The Greenstone group is relatively poor in TiO_2 , the content being mostly smaller than 2 % (Fig. 17). On the basis of the titanium content the volcanics of the Greenstone group should therefore belong to the circum-oceanic and tholeiitic associations. According to Whitehead and Goodfellow (1978), the titanium contents suggest that the volcanics belong to the sub-alkaline suite, comprising ocean floor tholeiitic basalts.

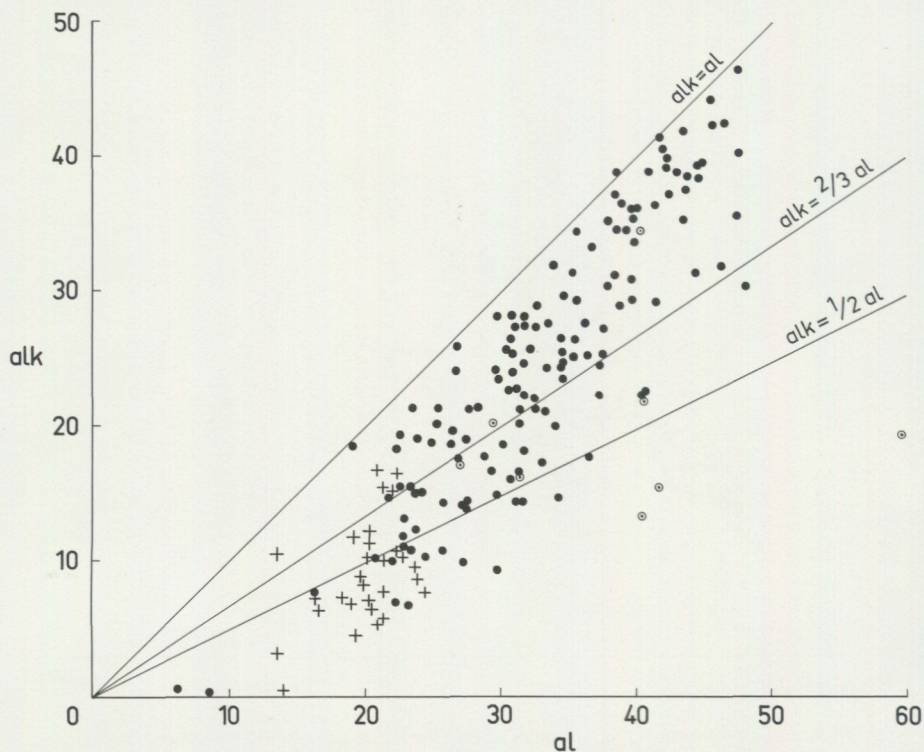


Fig. 7. The relationship between the Niggli values alk and al for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

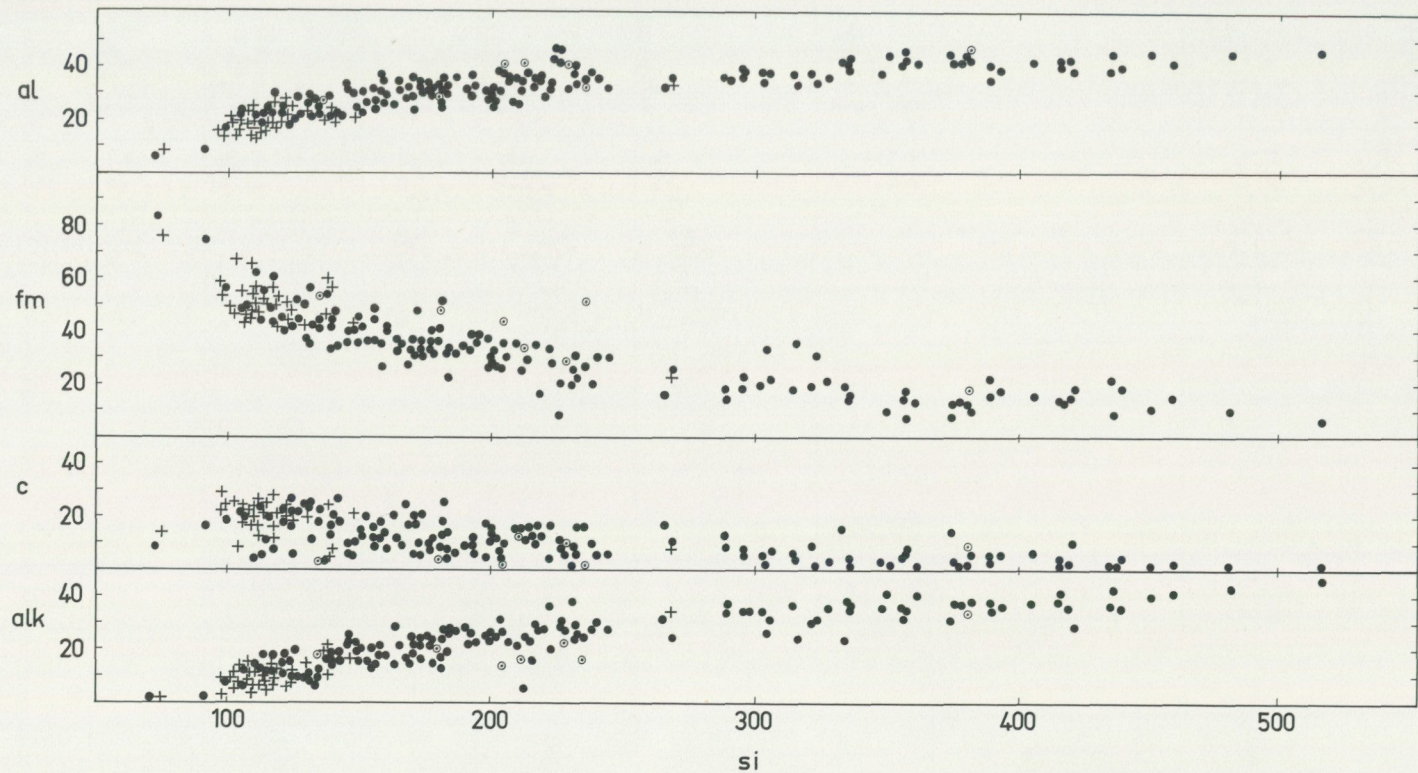


Fig. 8. The relationship between the Niggli values *al*, *fm*, *c*, *alk*, and *si* for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

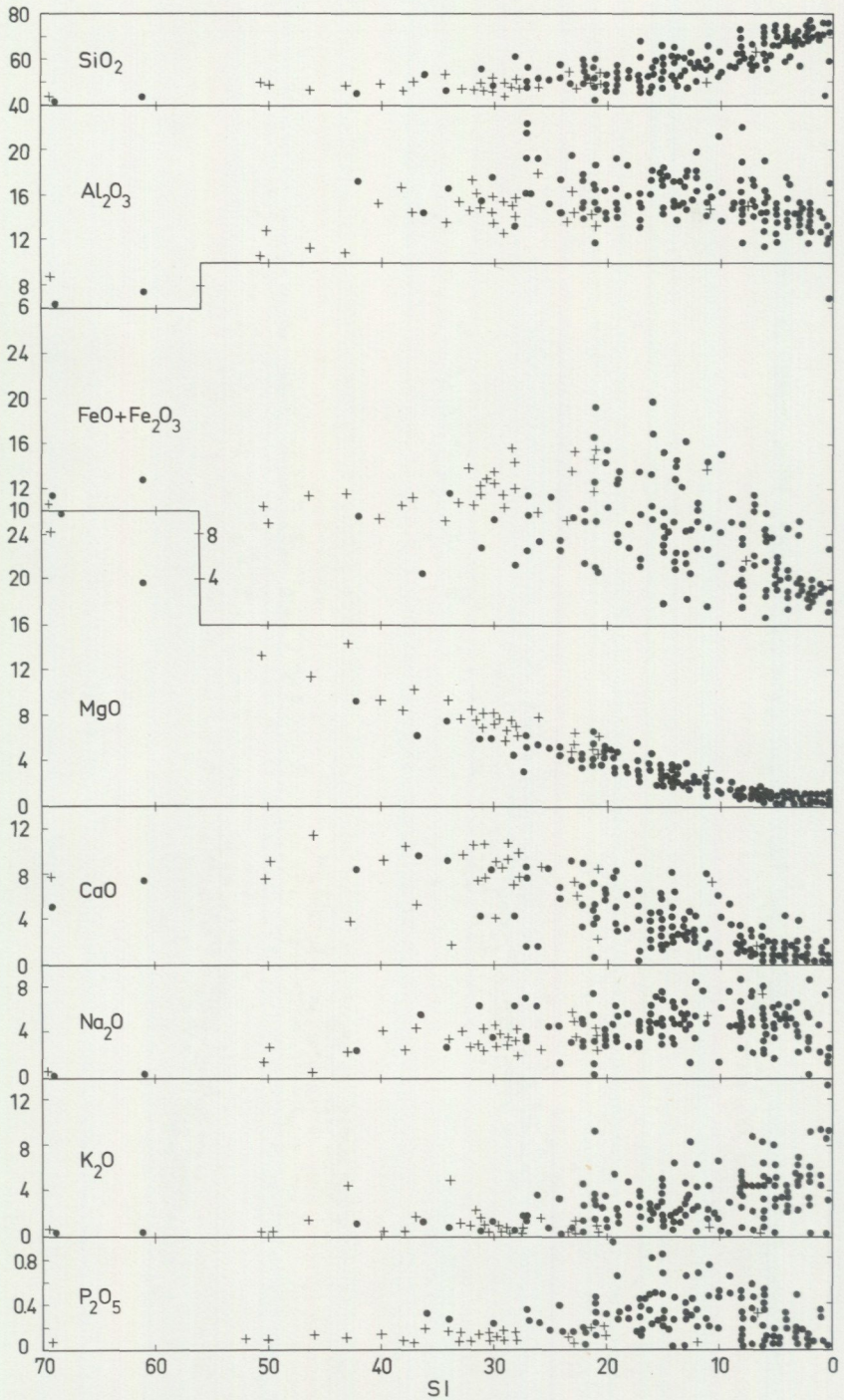


Fig. 9. The relationship between the contents of different elements (weight %) and "solidification index" ($SI = 100 \text{ MgO}/(\text{MgO} + \text{FeO} + \text{Fe}_2\text{O}_3 + \text{Na}_2\text{O} + \text{K}_2\text{O})$) according to Kuno (1968) in the volcanics of the Greenstone group (crosses) and the Porphyry group (dots) in northern Sweden.

Pearce *et al.* (1975) used the "incompatible elements" titanium, potassium and phosphorus to discriminate between oceanic and non-oceanic basalts, the diagram being effective for non-alkaline "primitive" basalts with less than 20 % total alkalis of a total sum of $(\text{FeO} + \text{Fe}_2\text{O}_3) + \text{MgO} + (\text{Na}_2\text{O} + \text{K}_2\text{O})$. Only a relatively small number of the volcanic rocks from Norrbotten county fulfill these requirements; besides all analyses do not comprise phosphorus. Fig. 18 represents 19 analyses of the Greenstone group which indicate that the basalts of the Greenstone group have an oceanic character. There are, however, some rocks from the Kiruna map sheet (analysis No. 31, Offerberg 1967 and analysis No. 2, Eriksson and Frietsch 1979) and the Tärendö map sheet (analysis No. 2, Padget 1970 and an analysis in Witschard 1973, p. 30) which fall outside the area covered by oceanic basalts; these rocks instead being continental. Whether this feature is a primary one or due to secondary alterations is unknown. The two analyses from the Kiruna map which plot on the continental side represent intrusive greenstones and thus differ from the main effusive varieties.

The ternary plot $\text{MgO}-\text{FeO}^x-\text{Al}_2\text{O}_3$ has been used by Pearce *et al.* (1977) to distinguish between five tectonic environments for sub-alkaline, basaltic to andesitic (51–56 % SiO_2) rocks. Of the Greenstone group there are three analyses in the 51–56

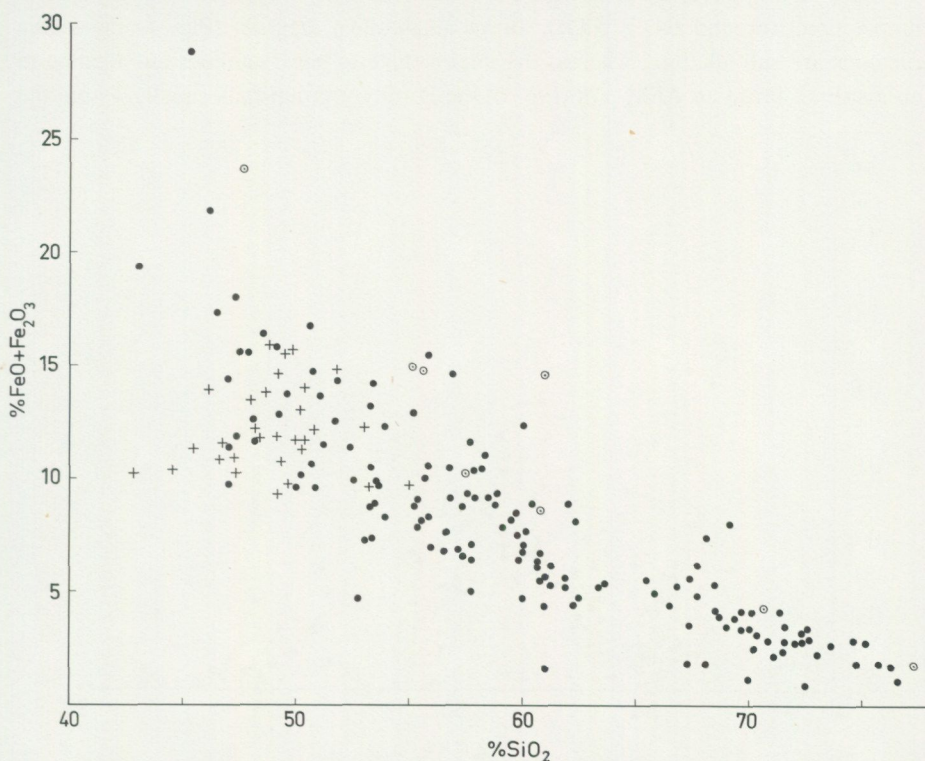


Fig. 10. Iron-silica diagram (weight %) for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

% SiO₂ range, and the only one which is sub-alkaline (<6 % Na₂O+K₂O) falls within the ocean island environment (Fig. 19).

In summary, the volcanics of the Greenstone group, comprising basalts with andesites and occasional ultramafites, are tholeiitic to calc-alkaline in composition. The Di-Hy-Ol normative composition indicates olivine tholeiites or olivine basalts. The relationship between Ti-Si, K-Ti-P and Mg-Fe-Al suggests oceanic affinity in a modern geotectonic setting. The volcanics are only to a small extent spilitized, viz. they have a high sodium content in combination with a low calcium content. In addition, the Na-K distribution shows that the original composition of the volcanics is largely preserved. The behaviour of most major elements and the Mg/(Mg+Fe) ratio with increasing silica content indicates that the volcanics have been formed by a uniform magmatic differentiation.

PORPHYRY GROUP

The Porphyry group represents a volcanic suite comprising basalts to rhyolites (Fig. 2). There is, however, a decrease in the number of analyses of dacite to rhyodacite compositions (around 64 % SiO₂). In an alkali-silica diagram (Fig. 5) the acidic volcanics are sub-alkaline, whereas the intermediate to basic varieties are alkaline to sub-alkaline. From an AFM plot (Fig. 6) the Porphyry group falls equally within the

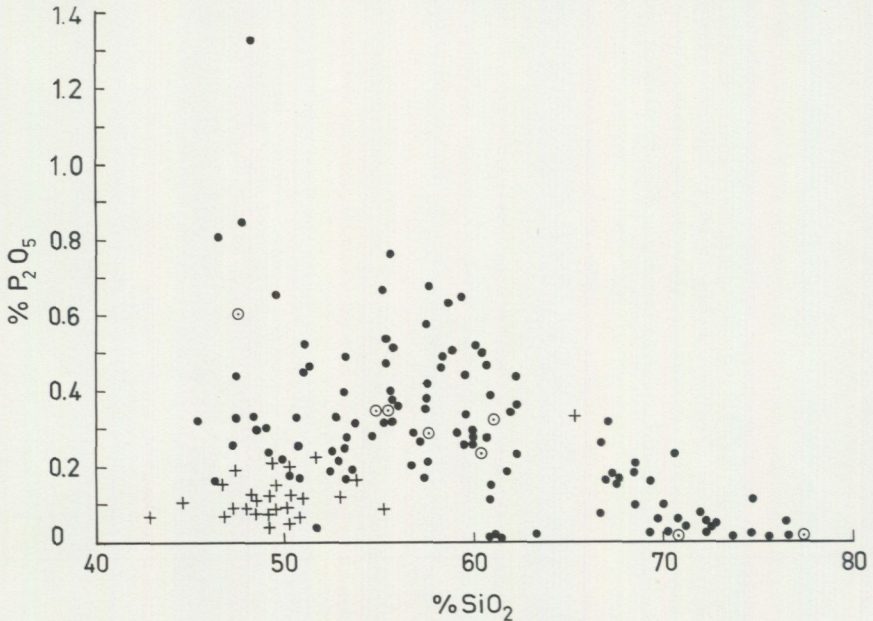


Fig. 11. Phosphorus-silica diagram (weight %) for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

tholeiitic (pigeonitic) and calc-alkaline (hypersthentic) fields. An interesting feature is represented by the number of analyses close to the $\text{Na}_2\text{O}+\text{K}_2\text{O}$ apex, which plot as a group isolated from the main part of the volcanics. These analyses have a higher $\text{MgO}/(\text{MgO}+\text{FeO}+\text{Fe}_2\text{O}_3)$ ratio, about 0.5, compared to the main part of the volcanics which have a ratio of 0.1–0.4. The Mg-enriched and Fe-depleted volcanic rocks probably represent two separate differentiation trends. In this respect they show similarities with some of the Porphyry group dyke rocks which are late magmatic differentiates (cf. p. 26).

The Niggli values *alk* and *al*, if plotted against each other (Fig. 7), show that most of the volcanics of the Porphyry group are relatively alkali-rich ($al > alk > 2/3$). The rest are alkali-intermediate ($2/3 al > alk > 1/2 al$) or relatively alkali-poor ($alk < 1/2 al$). The Niggli values *al*, *fm*, *c*, and *alk*, if plotted against the *si* value, show typical trends for a uniform differentiation process; with an increasing *si* value the *alk* and *al* values increase and the *fm* and *c* values decrease (Fig. 8). The earlier-mentioned decrease in the number of analyses representing rhyodacitic and dacitic compositions in the Porphyry group is in this diagram rather pronounced; between *si* values 250–290 there is only one analysis.

In the Porphyry group there is a rather abrupt decrease in the iron content with increasing silica content (Fig. 10). For example, the acidic rocks have a $\text{FeO}+\text{Fe}_2\text{O}_3$ content of less than 5%. The same feature is found when plotting the iron content versus the "solidification index" by Kuno (1968), calculated as $100 \text{MgO}/(\text{MgO}+\text{FeO}+\text{Fe}_2\text{O}_3+\text{Na}_2\text{O}+\text{K}_2\text{O})$. From this plot most elements in the Porphyry groups vary

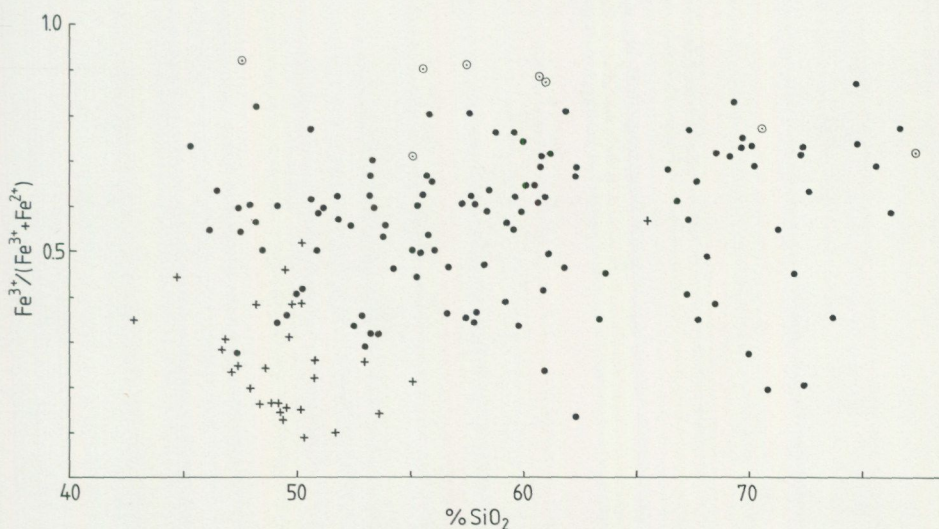


Fig. 12. Atomic ratio $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ against weight % SiO_2 in the volcanics of the Greenstone group (crosses) and Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

according to a normal differentiation trend: CaO and MgO decrease, SiO₂ increases and for Na₂O and K₂O there is a slight increase (Fig. 9). The phosphorus content is relatively high, less than 0.8 % P₂O₅, and decreases with proceeding crystallization (Fig. 9) and increasing silica content (Fig. 11).

In the Porphyry group the Mg/(Mg+Fe) ratio decreases with increasing silica content (Fig. 16), a feature which is in accordance with the behaviour of, in particular, calc-alkaline magmatic suites. The K/(K+Na) ratio is mainly less than 0.5 and is independent of the acidity, even if a weak increase of the ratio can be discerned for high SiO₂ contents (Fig. 15). This feature is also characteristic for a magmatic suite formed by differentiation; normally there is an increase in alkali content with increasing acidity, this being somewhat greater for potassium than for sodium.

The degree of oxidation expressed as the Fe³⁺/(Fe³⁺+Fe²⁺) ratio is mostly greater than 0.3 in the Porphyry group and unrelated to the silica content (Fig. 12). The ratio is negatively correlated to the Mg/(Mg+Fe) ratio (Fig. 13). A high K/(K+Na) ratio is found in rocks with a high Fe³⁺/(Fe³⁺+Fe²⁺) ratio (Fig. 14). Both these features are pronounced in the volcanics which have been hydrothermally altered (sericitized and silicified). In these rocks there is a high Fe³⁺/(Fe³⁺+Fe²⁺) ratio combined with a high K/(K+Na) ratio and a low Mg/(Mg+Fe) ratio. Other chemical changes found in

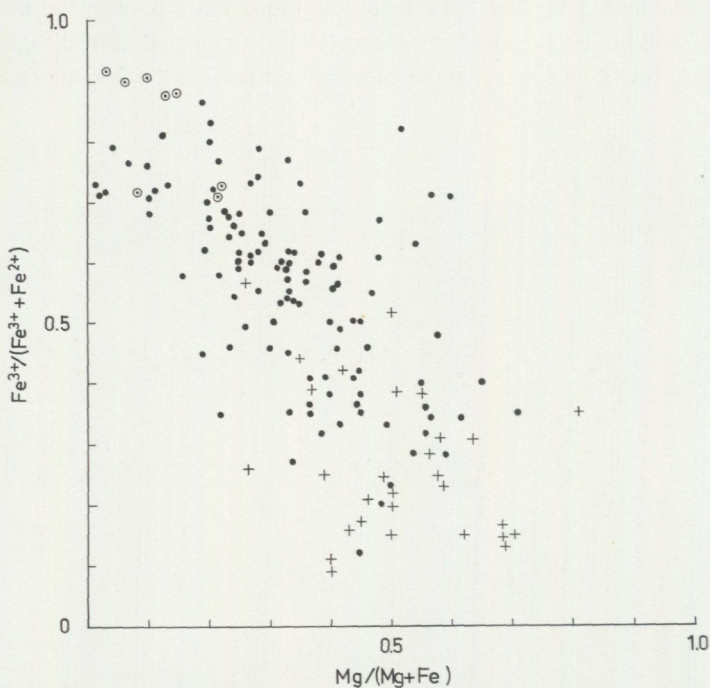


Fig. 13. The relationship between the atomic ratios Fe³⁺/(Fe³⁺+Fe²⁺) and Mg/(Mg+Fe) in the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

connection with the alteration are a diminution of Na and Ca (Fig. 3), a slight increase of the total amount of iron (Fig. 10) whereas the total amounts of $\text{Na}_2\text{O} + \text{K}_2\text{O}$ (Fig. 5), P_2O_5 (Fig. 11) and TiO_2 (Fig. 17) have remained constant. This metasomatic process is at least partly connected with the formation of the iron ores of the Kiruna type, the alteration representing the latest phase of the volcanism (Frietsch 1967b).

The volcanics of the Porphyry group are rich in alkalis, containing 4–10 % $\text{Na}_2\text{O} + \text{K}_2\text{O}$. Although high sodium contents (6–7 % Na_2O) are found in the trachytic members, high potassium contents are rare and of very restricted extension. The amount of sodium and potassium is approximately the same in the different areas covered by the Porphyry group. The average contents of sodium and potassium on the different map sheets are: Vittangi 5.0 % Na_2O and 3.0 % K_2O , Kiruna 4.5 % Na_2O and 3.2 % K_2O , Fjällåsen 4.4 % Na_2O and 3.8 % K_2O , Lainio 4.2 % Na_2O and 3.9 % K_2O , and Pajala 3.5 % Na_2O and 3.2 % K_2O , the average of 116 analyses being 4.6 % Na_2O and 3.4 % K_2O . Potassium-rich volcanics, with more than 8 % K_2O and less than 2 % Na_2O , occur in the Kiruna area (Frietsch 1979a), in the Ekströmsberg area (Frietsch 1974b, 1979a), at Ruotjatjåkka NNW of Ekströmsberg (Offerberg 1967), and at Svappavaara (Frietsch 1966). The potassic rocks are mostly of rhyolitic composition and have, at least locally, as at the Rektor iron ore near Kiruna, been developed as ignimbrites (Frietsch 1979a). Some of the potassium-rich rocks are

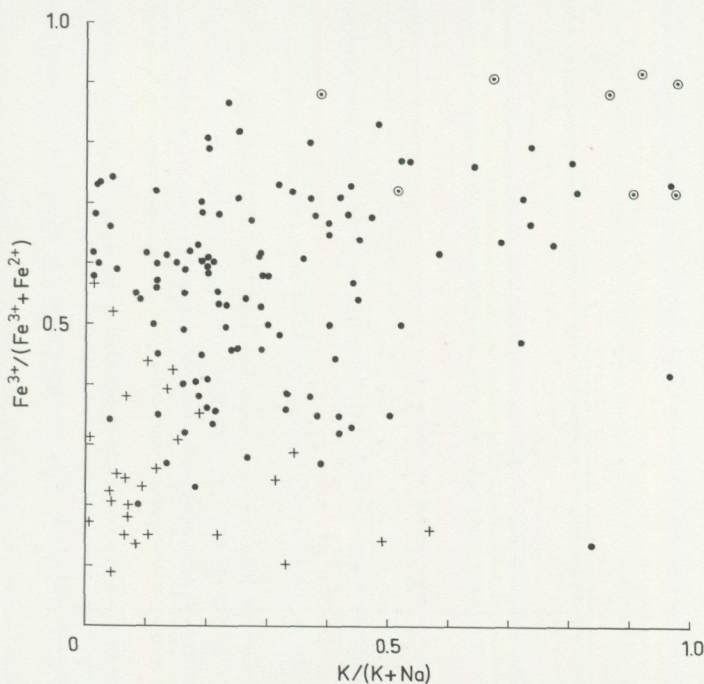


Fig. 14. The relationship between atomic ratios $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Fe}^{2+})$ and $\text{K}/(\text{K} + \text{Na})$ for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

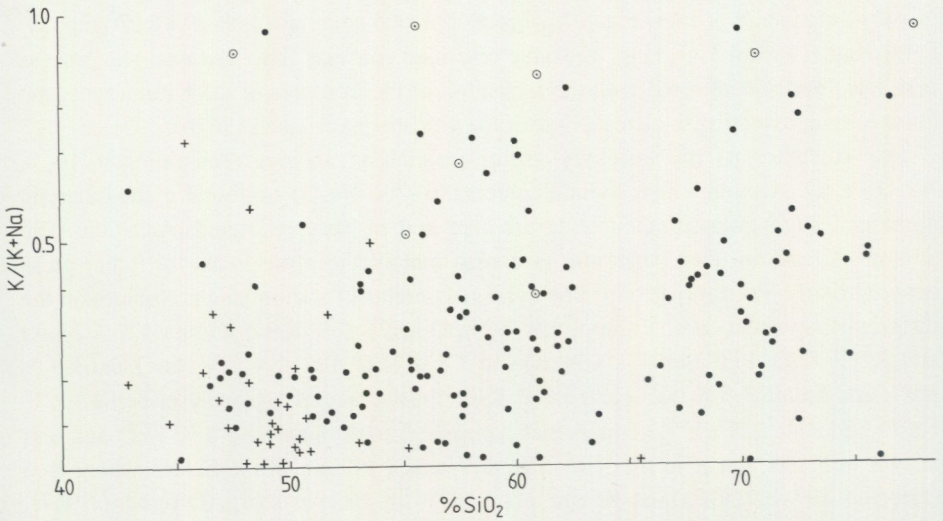


Fig. 15. Atomic ratio $K/(K+Na)$ against weight % SiO_2 in the volcanics of the Greenstone group (crosses) and of the Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

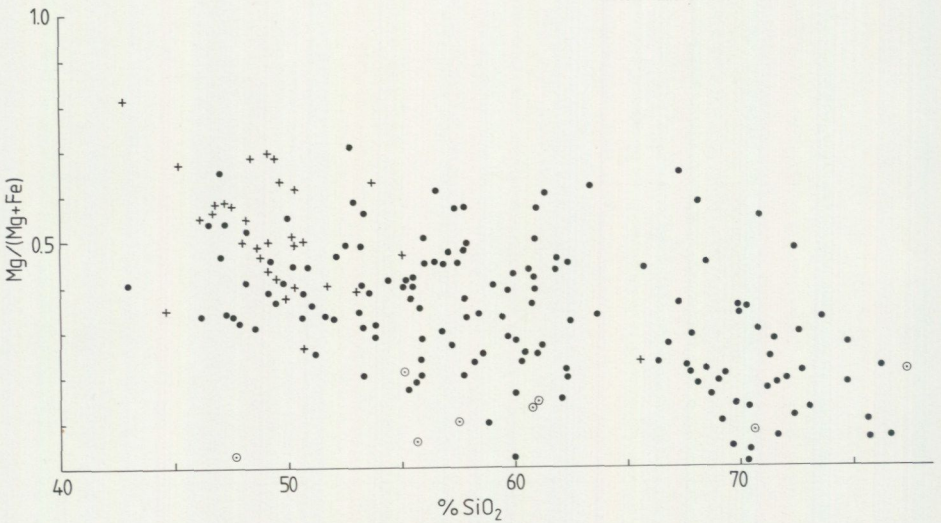


Fig. 16. Atomic ratio $Mg/(Mg+Fe)$ against weight % SiO_2 in the volcanics of the Greenstone group (crosses) and Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden.

ryhodacites (Tjåorekah and Ruotjatjåkka) and andesites (Gruvberget). In addition, there are trachytes at Mertainen containing 2–4 % Na₂O and 6–7 % K₂O (Lundberg and Smellie 1979). At all localities the areal extent of the potassic rocks is restricted, and they are usually surrounded by sodic or alkali-intermediate lavas. The local occurrence of the potassium-rich volcanics within terrains dominated by sodic volcanics is enigmatic. The high content of potassium can either be a primary magmatic feature, or a secondary one due to hydrothermal alteration which is coeval or directly subsequent to the volcanism. The occurrences at Ekströmsberg and at Ruotjatjåkka are spatially connected with a large NNW fault zone which obliquely cuts the Kiruna map sheet (Fig. 30). At Ruotjatjåkka there is an intense metasomatic alteration of the volcanics (Offerberg 1967). The potassium-rich rocks at Kiruna and Svappavaara are possibly connected with metasomatic alterations which are considered late phenomena in the process that gave rise to the iron ores of the Kiruna type. The alterations comprise sericitization, in part also silicification and kaolinization.

In general, however, the Porphyry group have their primary composition largely preserved. The restricted alteration of the volcanics is shown by the mainly undisturbed distribution of the alkalis (Figs. 3 and 4). The degree of spilitization is limited as shown by the Na-Ca relationship (Fig. 3). The analyses plotted cover the field for

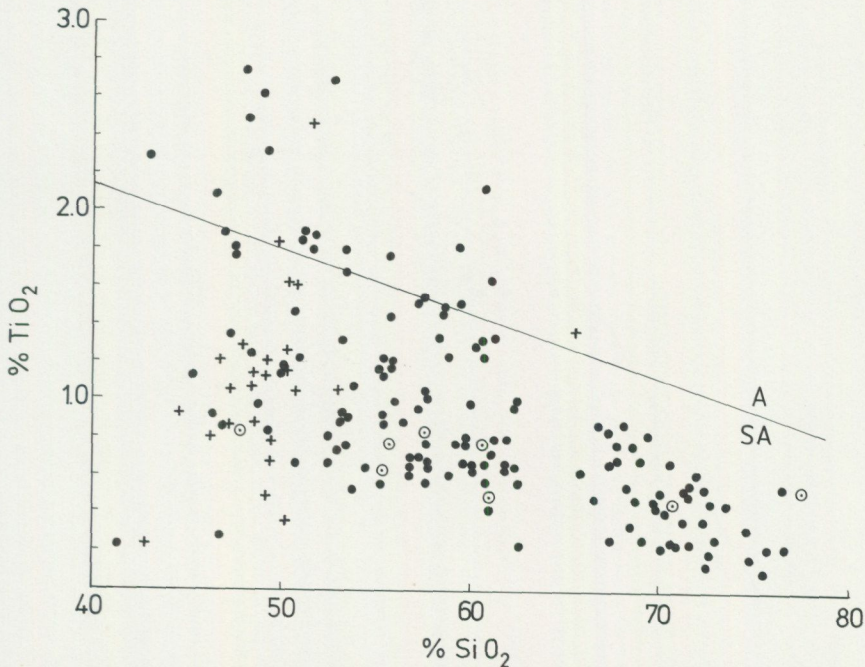


Fig. 17. TiO₂ against SiO₂ for the volcanics of the Greenstone group (crosses) and Porphyry group (dots; if sericite-altered they are represented by an encircled point) in northern Sweden. Weight %. The oblique line is after Whitehead and Goodfellow (1978) and determines the sub-alkaline (SA) and alkaline (A) fields.

normal unaltered rhyolites, trachytes, dacites, and andesites. The Na-K diagram in Fig. 4 also shows a moderate change of composition for these rocks. Although the bulk of the analyses lie within the field of unaltered magmatic rocks, there are rather many which plot in the sodic part of the diagram. However, they possibly reflect only the primary richness in sodium of the magma. It should be pointed out that the enrichment of sodium and the depletion of potassium is much less pronounced than in the ore-bearing volcanics of central Sweden, which is considered as being caused by a large-scale metasomatic alteration (Frietsch 1982). All the above-mentioned high-K volcanics fall outside the "igneous spectrum" in Fig. 4, thus favouring a metasomatic provenance of these rocks.

The normative composition of the volcanics of the Porphyry group, based on the analyses by Offerberg (1967) as well as Eriksson and Hallgren (1975), shows that the nature of the mafic members is unclear as both Q and Ne are present. The norm of the acidic members with both Q and Hy indicates, according to Wilkinsson (1974), oversaturated tholeiites.

The volcanics are relatively poor in TiO_2 (mostly $< 2\%$; Fig. 17), and thus they show similarities with the volcanics of the Greenstone group. The division on the basis of the titanium content should thus place the Porphyry group, in similarity with the Greenstone group (p. 14), in circum-oceanic and tholeiitic associations according to

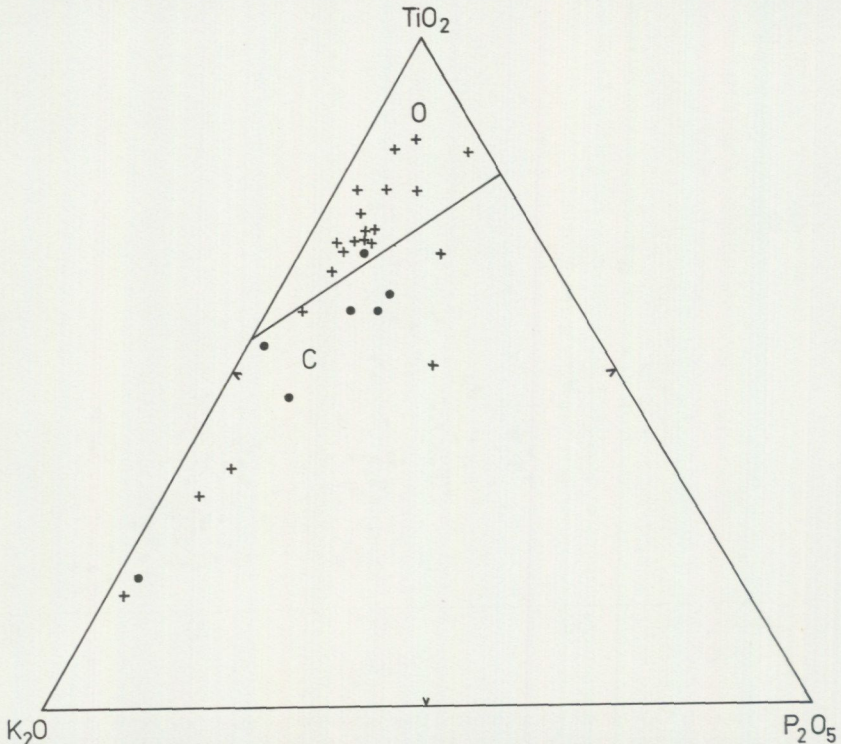


Fig. 18. The relationship between TiO_2 , K_2O and P_2O_5 (weight %) for the basalts of the Greenstone group (crosses) and the Porphyry group (dots) in northern Sweden. The oblique line at the TiO_2 apex is after Pearce *et al.* (1975) and determines the upper oceanic field (O) and the lower continental field (C).

Chayes (1964) as well as Chayes and Velde (1965), and in the calc-alkaline basalt association according to Whitehead and Goodfellow (1978). The basic members of the Porphyry group should, however, according to the latter division, belong to ocean island alkali basalts. In the TiO_2 - K_2O - P_2O_5 diagram of Pearce *et al.* (1975) the few analyses which are considered non-alkaline "primitive" basalts (cf. p. 17) fall within the continental field (Fig. 18).

In the ternary plot MgO - FeO^x (total iron)- Al_2O_3 used by Pearce *et al.* (1977) to distinguish between different tectonic environments for sub-alkaline, basaltic to andesitic (51–56 % SiO_2) rocks, the volcanics of the Porphyry group fall within the spreading centre island, continental and orogenic environments (Fig. 19). However, the analyses which fulfil the requirement to be sub-alkaline (less than 6 % Na_2O+K_2O) fall within the latter two fields.

In summary, the rocks of the Porphyry group, comprising rhyolites, trachytes and subordinate andesites and occasional basalts, are tholeiitic to calc-alkaline, with an alkaline affinity for the basic to intermediate members. The Di-Hy ($\pm OI$ - Q - Ne)-normative composition indicates oversaturated tholeiites. The relationship between Ti - Si , K - Ti - P and Mg - Fe - Al indicate formation in a continental environment.

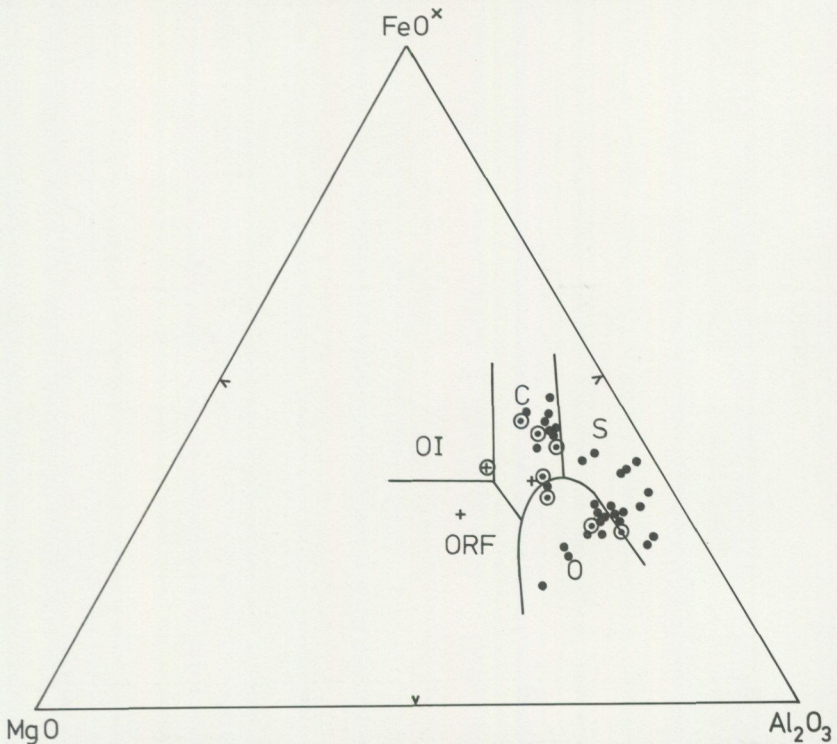


Fig. 19. The relationship between MgO - FeO^x (total iron) - Al_2O_3 for the volcanics of the Greenstone group (crosses) and the Porphyry group (dots) in northern Sweden. Only rocks with 51–56 weight % SiO_2 are plotted. Circles indicate rocks with less than 6 weight % Na_2O+K_2O . The boundaries after Pearce *et al.* (1977) determine the following environments: OI = ocean island, C = continental, S = spreading center island, ORF = ocean ridge and floor and O = orogenic.

DYKE ROCKS

Dykes of metabasites and intermediate to acid porphyries occur locally in the rocks of the Porphyry group, whereas they are rare in the rocks of the Greenstone group. At many localities the dykes are observed intersecting the apatite-bearing iron ores of the Porphyry group. The intermediate to acid porphyritic dykes are related in composition to the volcanics of the Porphyry group. The age of the dykes is uncertain; it is not known whether one or several intrusive phases are involved. Most possibly, however, all dykes, including those in the rocks of the Greenstone group, are contemporaneous, forming a late phase in the volcanism that gave rise to the Porphyry group. In the following discussion, only those dykes which have been analysed chemically will be considered.

In the foot-wall unit (syenite-porphyry) at Kiirunavaara there are dykes of syenite-porphyry (rhyodacite). Some of the dykes are older than the ore body and some are younger (Geijer 1910, 1960). The rock hosting the skarn iron ore at Vieto, west of Kiruna, is an basaltic greenstone of the Greenstone group. It is cut by dykes of trachytic composition (Eriksson and Frietsch 1979). On the Tärendö map sheet there is an andesite-porphyry (dacite) at Haukkalaki which presumably is younger than the

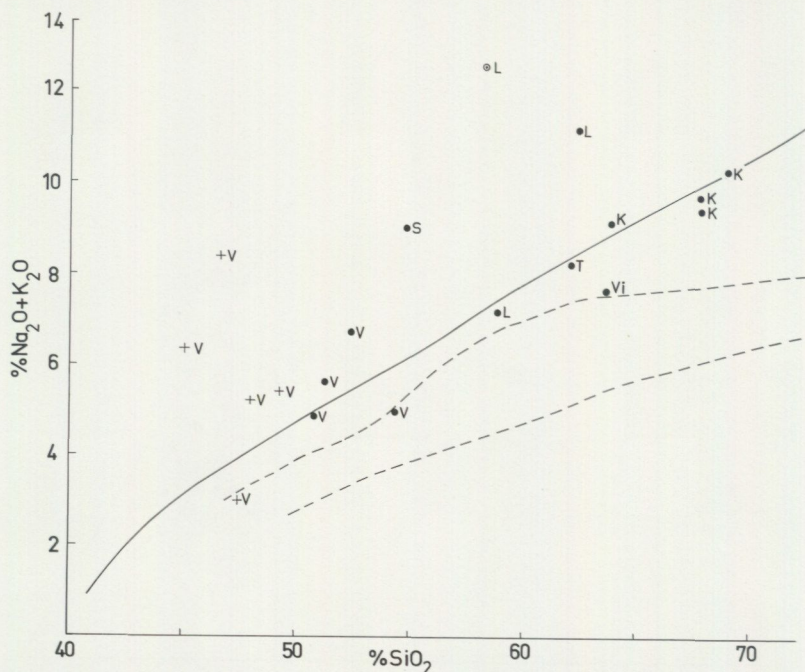


Fig. 20. Alkali-silica variation diagram (weight %) for dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. Abbreviations: K = Kiirunavaara, L = Leveäniemi, S = Sautusvaara, T = Tärendö map sheet, V = Vittangi map sheet and Vi = Vieto. For the meaning of continuous and broken lines see Fig. 5.

Greenstone group (Padgett 1970). The other analysed dykes are from the Vittangi map sheet (Eriksson and Hallgren 1975). The porphyry dykes have an intermediate composition (from andesite to dacite) and the metabasites have a basaltic composition. Most of the dykes are located in rocks of the Porphyry group, *e.g.* within the Leveäniemi apatite-bearing iron ore. Only a few occur in the Greenstone group, *e.g.* the skarn iron ore at Sautusvaara.

The porphyry dykes are in many respects chemically similar to the volcanics of the Porphyry group, but differences do exist. In the alkali-silica diagram (Fig. 20) the dykes show an alkaline affinity which is more pronounced than for the volcanics of the Porphyry group. If plotted in an *alk-al* Niggli variation diagram (Fig. 7), the dykes at Kiirunavaara and some of the dykes at Leveäniemi are close to the peralkaline field ($alk > al$). The rest of the porphyry dykes are alkali-intermediate and thus similar to the rocks of the Porphyry group.

If the Niggli values *al*, *fm*, *c*, and *alk* are plotted against *si* the dyke rocks are similar to the rocks of the Porphyry group (Fig. 8). The more acidic dykes have a slight tendency to show lower *fm* values than the Porphyry group. Variation of the different Niggli values with varying *si* value is the normal observed trend for differentiation.

An apparent chemical difference between the porphyry dykes and the rocks of the Porphyry group is that some dykes are lower in iron than the volcanics. The dykes at Kiirunavaara, Leveäniemi and Sautusvaara contain less than 4 % FeO+Fe₂O₃ (Fig. 21). Most of the dykes have, however, a similar or only somewhat lower iron content compared to the volcanics of the Porphyry group (Fig. 10). The iron deficiency of these dykes is also apparent in the AFM diagram (Fig. 22); the dykes are rich in alkalis and thus plot against the MgO side. However, the content of magnesium in

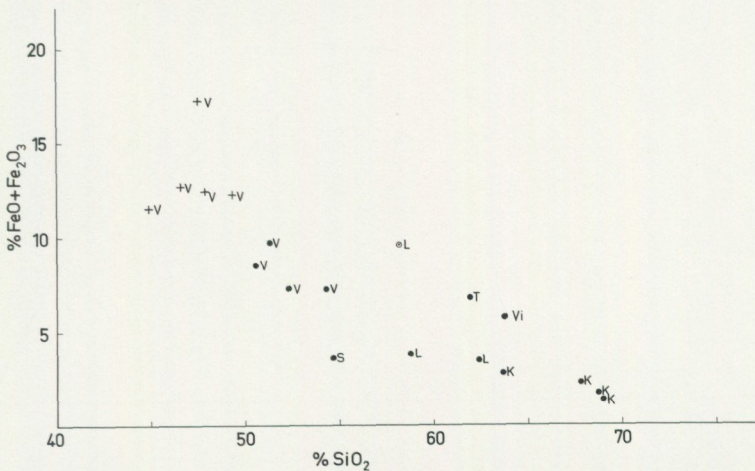


Fig. 21. Iron-silica diagram (weight %) for dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. For abbreviations see Fig. 20.

these "anomalous" dykes is the same as in the volcanics of the Porphyry group, and the dykes have consequently a higher $Mg/(Mg+Fe)$ ratio (Fig. 23) than the latter (Fig. 13). As seen from the same diagram the degree of oxidation, or the $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ ratio, is in all dykes similar to that of the rocks of the Porphyry group.

Other chemical differences exist between the dykes and the rocks of the Porphyry group. Concerning the alkalis, the dyke rocks are somewhat more enriched in sodium relative to potassium than the Porphyry group. The $K/(K+Na)$ ratio in the dykes is mostly less than 0.3 (Fig. 24), compared to less than 0.8 in the Porphyry group. In addition, the content of phosphorus is lower in the dykes (below 0.4 % P_2O_5) than in the Porphyry group (below 0.8 % P_2O_5 ; Fig. 25); this is very pronounced for the Kiirunavaara dykes. The content of TiO_2 in the dykes is the same, or somewhat lower, than in the Porphyry group (Fig. 26).

In summary, most of the porphyry dykes are chemically similar to the rocks of the Porphyry group, but in some respects, and especially for some localities (Kiirunavaara, Leveäniemi and Sautusvaara), there exist obvious differences. The dykes are mainly alkaline whereas the volcanics of the Porphyry group are alkaline to sub-

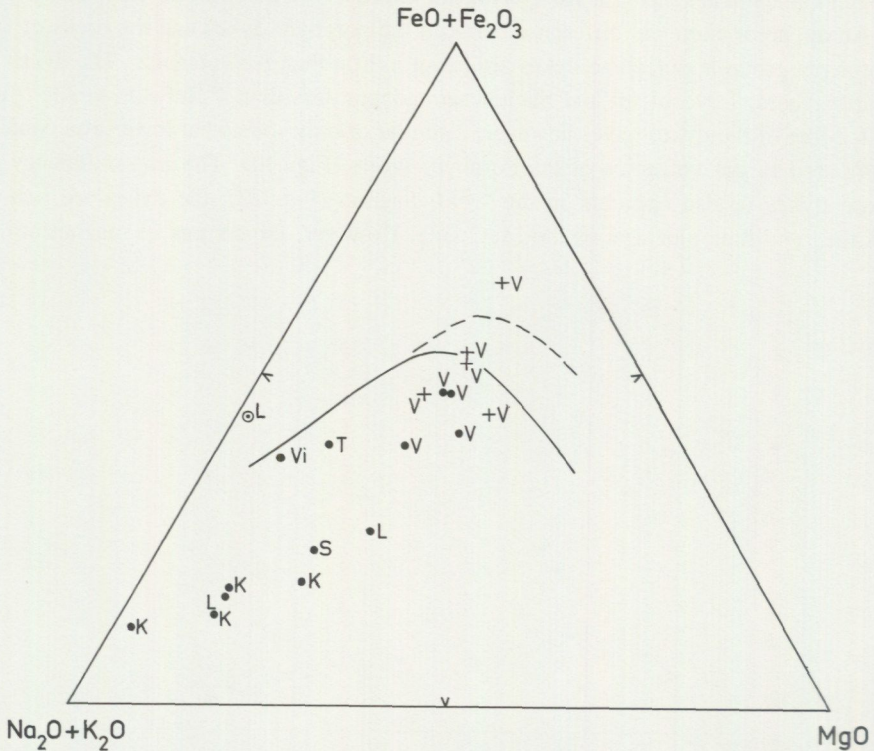


Fig. 22. AFM diagram (weight %) for dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. For abbreviations see Fig. 20. For the meaning of continuous and broken lines see Fig. 6.

alkaline. The dykes have a lower $K/(K+Na)$ ratio than the Porphyry group. These differences are most probably due to the late formation of the dyke rocks resulting from the same magmatism that gave rise to the rocks of the Porphyry group. The late formation of the dykes meant that the magma was depleted in iron and phosphorus, both elements having been separated during the fractionation process which resulted in the iron ores of the Kiruna type. The late phase was also enriched in sodium compared to potassium.

It should be pointed out that there are certain analyses among the volcanics of the Porphyry group that are chemically similar to the iron-phosphorus-deficient and sodium-magnesium-enriched dykes. These volcanics (Fig. 6) form a cluster clearly separated from the main part of the volcanics of the Porphyry group. It starts from the Na_2O+K_2O apex and is shifted against the MgO apex comprising the 14 following analyses; quartz-bearing porphyry from Skåukemjokk (No. 66, Offerberg 1967), metaporphyry and acid volcanite from the Fjällåsen map sheet (Nos 41 and 31, Witschard 1975), trachyte from Leveäniemi (No. 55, Eriksson and Hallgren 1975), syenite-porphyry from Kiirunavaara (No. 49, Offerberg 1967), Na-trachyte from Gruvberget (No. 45, Eriksson and Hallgren 1975), andesite from Altavaara, albite-porphyrityte from Pahtavaara and Na-rich rhyolitic trachyte from Tansari (Nos 36, 37

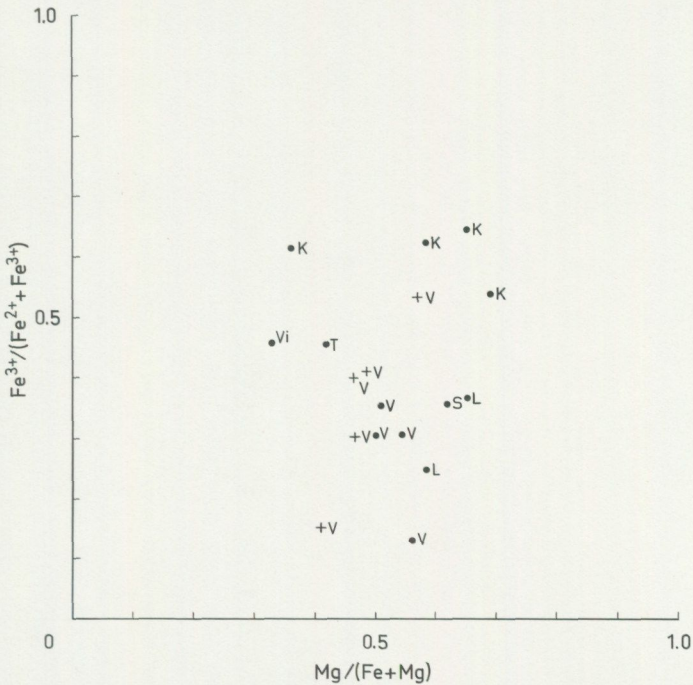


Fig. 23. The relationship between atomic ratios $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ and $Mg/(Mg+Fe)$ in dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots) in northern Sweden. For abbreviations see Fig. 20.

and 58, Eriksson and Hallgren 1975), andesite from Puoltsa (No. 1258, Hallgren 1973) and andesite from Fjällåsen map sheet (No. 55, Witschard 1975). In an iron-silica diagram these analyses plot at the lower, iron-poor area which represents rocks of the Porphyry group (Fig. 10). These volcanics thus display a shift to a higher $Mg/(Mg+Fe)$ -ratio; 10 analyses have a value of 0.5 and higher, whereas most of the rocks of the Porphyry group have ratios lower than this value. The iron-deficient volcanics also differ in their potassium-sodium relationship from the majority of the volcanics representing the Porphyry group; 10 analyses have a $K/(Na+K)$ ratio smaller than 0.2, 3 analyses indicate ratios between 0.2 and 0.4 and one analysis (from Skåukemjokk) 0.8. Most of the volcanics have a ratio above 0.2 (Fig. 15).

The relationship between the iron-phosphorus-depleted and sodium-enriched volcanics and the dykes is uncertain. It is plausible, however, that these volcanics, together with the dykes, form a late differentiation phase in the same volcanism that resulted in the main part of the Porphyry group. It should also be emphasized in this connection that many of the mentioned volcanics are found close to iron ores. They are mostly of the apatite-bearing (Kiruna) type, namely Kiirunavaara, Leveäniemi, Gruvberget, Tansari, or related late hydrothermal hematite impregnations, such as Skåukemjokk. The Sautusvaara ore is of the skarn iron ore type. The genetic classification

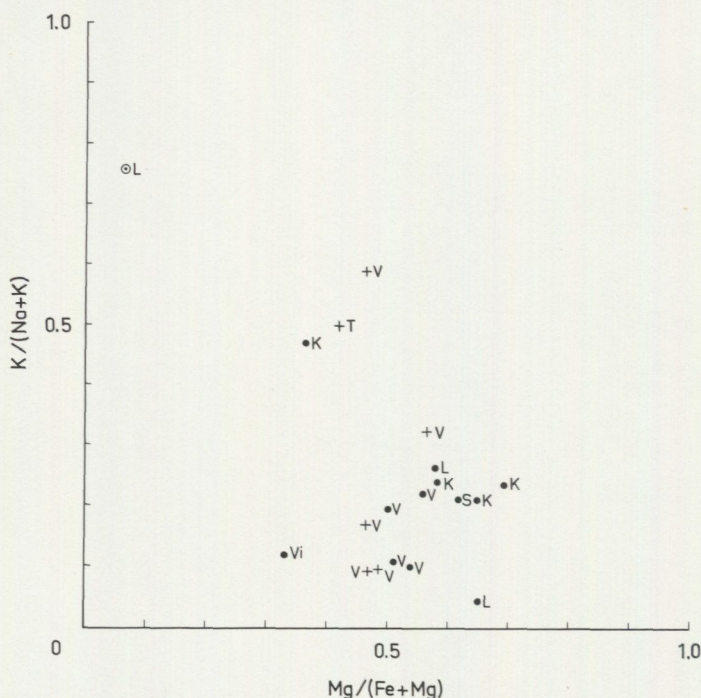


Fig. 24. The relationship between the atomic ratios $K/(K+Na)$ and $Mg/(Mg+Fe)$ in dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. For abbreviations see Fig. 20.

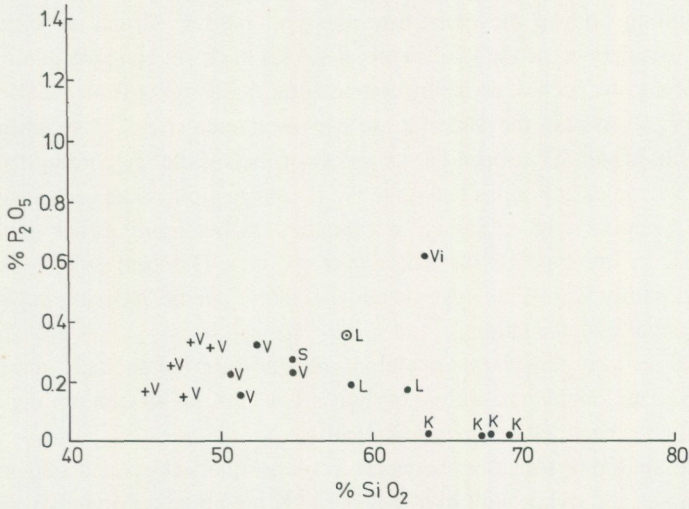


Fig. 25. Phosphorus-silica diagram (weight %) for dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. For abbreviations see Fig. 20.

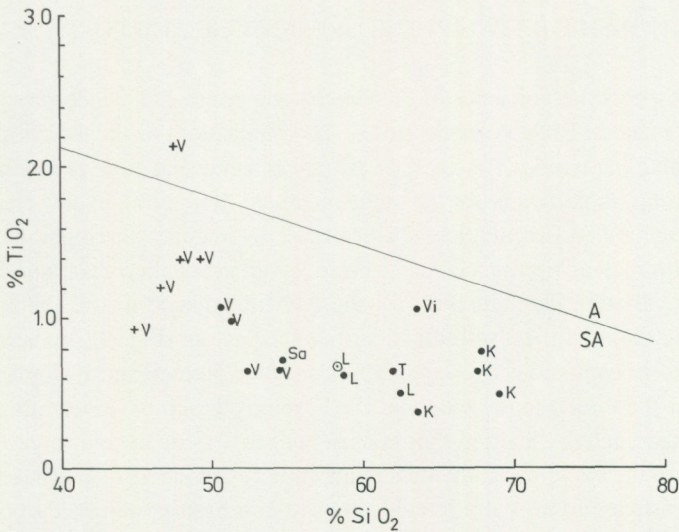


Fig. 26. The relationship between weight % TiO_2 and SiO_2 in dyke rocks (metabasites = crosses and acidic-intermediate porphyries = dots; if sericite-altered they are represented by an encircled point) in northern Sweden. For abbreviations see Fig. 20. The oblique line is after Whitehead and Goodfellow (1978) and determines the sub-alkaline (SA) and alkaline (A) fields.

of the Altavaara iron ore is unclear as the ore is rich in skarn, but shows ambiguous features pointing both to the skarn iron ore type and the Kiruna ore type (Frietsch 1970). The same concerns the Puoltsa ore, also rich in skarn. Here the dominating host rock is a porphyritic rock of andesitic composition, but varying from basalt to trachyte (Hallgren 1973). Within the andesite are narrow intercalations of subordinate rhyodacite, both of which have been cut by dykes of metabasite. According to Offerberg (1967), the volcanics at Puoltsa belong to the Porphyry group. The genesis of the ore is unclear as it cannot with certainty be classified as belonging either to the Kiruna (apatite-bearing) ore type or the skarn iron ore type (Frietsch 1970). The Puoltsa rhyodacite possibly represents dykes somewhat later than the andesite, but can also be extrusive, coeval with the latter.

The Fjällåsen iron-phosphorus-depleted volcanics are not spatially related to iron ore deposits. The Pahtavaara albite-porphyrite lies close to an iron ore deposit which most possibly has been formed metasomatically.

The close spatial association between iron-phosphorus-depleted and sodium-enriched volcanics and dykes with iron ores of the Kiruna type is certainly significant. It supports the magmatic concept of formation for this ore type. During magmatic fractionation, there occurred in both the volcanics and the dykes a depletion in iron and phosphorus. These elements were concentrated into an intrusive phase at a late stage of the magmatism, subsequently giving rise to the ores.

THE RELATIONSHIP BETWEEN THE GREENSTONE AND PORPHYRY GROUPS

In certain respects the volcanics of the Greenstone group and the Porphyry group are chemically related. Both volcanic suites show transitions from tholeiitic and calc-alkaline to alkaline trends. The alkaline affinity is somewhat more pronounced for the Porphyry group, in particular for the mafic members. Both groups show clear trends of uniform magmatic differentiation characterized by regular variations of the major elements with increasing silica content. From the differentiation diagrams, such as the alkali-silica variation diagram (Fig. 5), the AFM diagram (Fig. 6), the Niggli value diagram (Fig. 8), and the "solidification index" diagram (Fig. 9), the analyses from both suites form continuous overlapping fields. These petrochemical similarities might indicate that the Greenstone group and the Porphyry group have been formed by the same magmatic activity and are thus consanguineous. In order to evaluate a common provenance of the two groups, the field relations between them are discussed below.

The Greenstone group is stratigraphically overlain by the younger Porphyry group. Both groups, together with rocks of the Schist-conglomerate group, have been affected by the same tectonic episode, probably connected with the Svecokarelian orogeny which occurred between 1 900 and 1 750 Ma (Lundqvist 1979). Accepting the 1 600 Ma age of the Porphyry group (p. 6), the folding phase must therefore be younger

although no such orogenic activity is known in the Precambrian of Sweden, except for the Dalslandian tectogenesis in southwestern Sweden between 1 100 and 950 Ma. In addition both groups are intersected by the 1 530 (–1 780) Ma old Lina granites and related igneous rocks. The Porphyry group is also cut by the 1 505–1 530 Ma old perthite granites and monzonites. The Granodiorite suite, about 1 840–1 880 Ma old, has intruded the Greenstone group. The field relations of this older igneous suite to the Porphyry group is unknown as they are nowhere in contact with each other. As described earlier, the radiometric age determinations show that both the Greenstone group and the Porphyry group were formed close to 1.9 Ga. The age of 1 600 Ma for the latter is almost certainly too low and is thought to be the result of an "updating" of an older age by metamorphic events, probably in connection with the intrusion of the Lina granites and the perthite granites-monzonites. According to Skiöld (1979a) the 1 600 Ma age of the Porphyry group volcanics may reflect the closure of the Rb-Sr system during a subsequent metamorphic event.

There is no major unconformity between the volcanics of the Greenstone group and Porphyry group. The metasediments of the Schist-conglomerate group are considered to occur stratigraphically between the two groups and are conformable. Clearly interlayered between the Greenstone and Porphyry groups is the Kurravaara conglomerate at Kiruna; its formation is closely related in time to the underlying Kiruna greenstones (Frietsch 1979a). According to Geijer (1931a) the rock sequence in the Kiruna area is an example of associated spilites (Kiruna greenstones) and keratophyres (trachytes of the Porphyry group); the sodic character of both rock suites being a primary feature of the same magma. This point of view was further evaluated by Geijer (1958) who considered that the sequence Kiruna greenstones–volcanics of the pebbles of the Kurravaara conglomerate–keratophyres of the iron ores of Kiruna, reflected a continuous magmatic evolution.

A close temporal (and spatial) relationship between the volcanics of the Greenstone and Porphyry groups in the Svappavaara area, east of Kiruna, has previously been outlined by the present author (Frietsch 1966). Both groups are thought to have the same age, but to represent different facies, the Porphyry group being terrestrial and the Greenstone (Svappavaara) group water-deposited. This view was mainly based on intercalations of marls and limestones present in the trachytes near the Leväniemi iron ore deposit. Identically similar rocks form an essential part of the nearby Greenstone group.

There are thus indications that the time interval between the deposition of the volcanics of the Greenstone and Porphyry groups is relatively moderate, in any cases smaller than recently believed. Consequently sedimentation in connection with the formation of the Schist-conglomerate group represents a short event, caused by a rather rapid infilling mainly in the same basins as occupied by the Greenstone group.

It is therefore postulated, on the basis of petrochemical features and field relations, that the Greenstone and Porphyry groups have a common magmatic provenance. The formation of the volcanic suites represents two largely distinct stages of the same

volcanism. The changes in chemical features between the two groups are similar to those found in recent volcanic environments. For example, in the volcanic rocks of orogenic areas, *viz.* mainly island arcs, from tholeiitic rocks to calc-alkaline rocks and finally to shoshonites or alkaline rocks, there is according to Jakeš and Gill (1970) and Jakeš and White (1972) 1, an increase of K₂O at a given value of SiO₂, 2, an increase of the K₂O/Na₂O and ferric/ferrous ratios and 3, a decrease of the iron enrichment. The change in composition from the Greenstone group to the Porphyry group is mainly in accordance with such a development. There is an increase in the K₂O content from medium (0.2–1.5 %) to high (0.5–9 %), an increase of the K/(K+Na) ratio from low (<0.5 %) to high (<0.8) and an increase of the Fe³⁺/(Fe³⁺+Fe²⁺) ratio from low (0.1–0.5) to high (0.2–0.8). In addition, the total amount of iron as well as the Mg/(Mg+Fe) ratio decreases from high (0.4–0.7) to low (0.1–0.6). The trends in the Greenstone group and the Porphyry group for the above-mentioned elements are thus in accordance with what is found between tholeiitic and calc-alkaline suites in recent orogenic areas.

THE RELATIONSHIP BETWEEN PLUTONITES AND METAVOLCANICS

The plutonites in the northern part of the Norrbotten county are, as previously described (p. 5), of three types and ages. The oldest belong to the Granodiorite suite, or Haparanda (granite) suite, with an age of 1 840–1 880 Ma. The most important plutonite in terms of areal extent is the potassium-rich Lina granite with ages ranging from 1 530 to 1 780 Ma. The youngest members, aged 1 505–1 530 Ma, are the perthite granites and the perthite monzonites.

The Granodiorite suite, composed dominantly of granodiorite but also comprising granites and more intermediate rocks-types, is almost exclusively associated with the rocks of the Greenstone group, a fact already stated by Ödman (1957). The occurrence of the Granodiorite suite is thus mainly restricted to the eastern part of the Norrbotten county and tends not to be found west of a line from Piteå to Kiruna and further north. It is possible that this line represents a large tectonic zone and that different metamorphic conditions prevailed on both sides of it. To the east, the rocks have been affected by intense thermal metamorphism due to deeper burial than the rocks have to the west. East of this line the rocks of the Greenstone group were mobilized giving rise to the Granodiorite suite. Large areas with supracrustal gneisses, mainly derived from the Greenstone group, are connected with the rocks of the Granodiorite suite, and this supports the possibility of an intense regional metamorphism being the source of the Granodiorite suite.

The internal genetic relationship between the two younger plutonic suites is unsettled. According to Ödman (1957) both have been formed by palingenesis but in different tectonic environments. However, a sharp division between the two suites is not possible. The Lina granite is bound to zones of high metamorphism and is clearly

palingenetic, occurring in connection with migmatitic terrains and accompanied by pegmatites and aplites. The source material is thought to have been mainly pelitic sediments.

As pointed out by Geijer (1931a), Ödman (1957) and Witschard (1975), the perthitic plutonites have a close genetic and spatial relationship to the volcanics of the Porphyry group. The perthitic rocks lack foliation, are often porphyritic, especially in the marginal parts, and contain partly resorbed fragments of the volcanics. The contacts against the volcanics are sharp and the plutonites truncate the volcanic structures. Occasionally these contacts show a transition between the volcanics and the plutonites, the main differentiating features being grain size and texture. The mineralogical and chemical compositions are the same on both sides of the border (Frietsch 1974). The Perthite suite is considered by Ödman (1957) to have been formed at the fold belt margins by deep burial and remelting of the volcanics.

In comparing the petrochemical features of the Granodiorite suite with the Greenstone group, the perthite granites and perthite monzonites with the Porphyry group, and, in addition, the Lina granite with the Porphyry group, chemical analyses taken from publications referred to on p. 8 have been used. These include 29 analyses from the Granodiorite suite, 25 analyses from the Lina granite and 33 analyses from the Perthite suite.

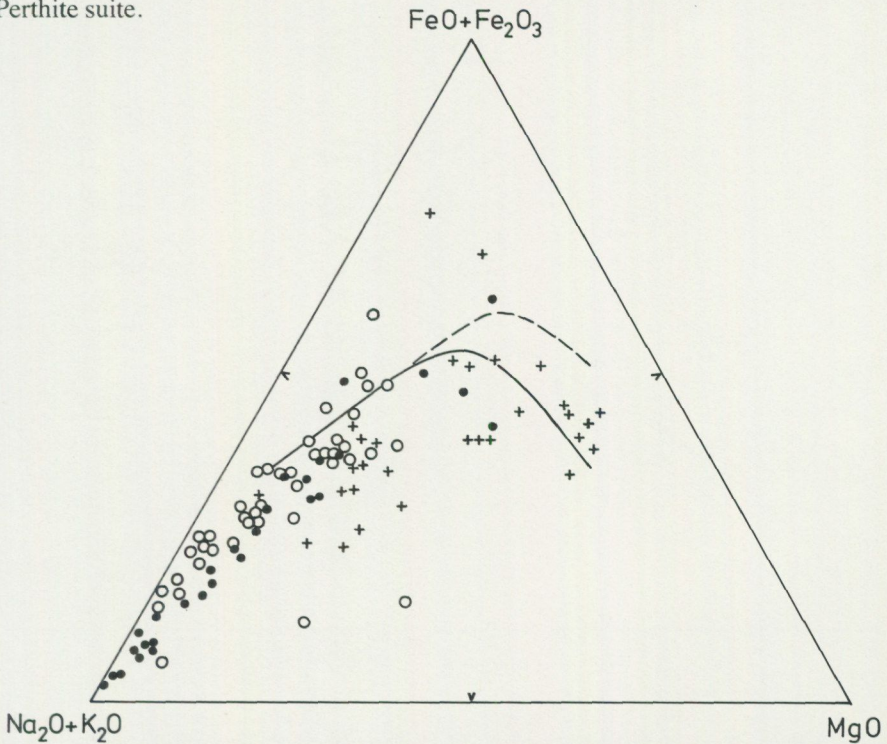


Fig. 27. AFM diagram (weight %) for plutonites in northern Sweden. Points = Lina granite suite, circles = perthite granite-monzonite and crosses = Granodiorite suite. For the meaning of the continuous and broken lines see Fig. 6.

AFM diagrams show that the perthite granites and perthite syenites (Fig. 27) are chemically similar to the rocks of the Porphyry group (Fig. 6). The rocks of the Perthite suite have a calc-alkaline to alkaline character. Three analyses deviate by having a higher $MgO/(FeO+Fe_2O_3)$ ratio, namely a perthite granite from Puoltsa (Hallgren 1973) and two rocks, a quartz-monzonite and a dioritic monzonite, from the Fjällåsen map sheet (Nos 13 and 17, Witschard 1975). This bimodal behaviour is similar to that found in the volcanics of the Porphyry group and the dyke rocks. The "diverging" perthite rocks are also chemically similar to the "diverging" volcanics and dykes in the following features: 1, they are low in iron (the sum $FeO+Fe_2O_3$ is 0.7–2.7 weight %), 2, have a high $Mg/(Mg+Fe)$ ratio (0.63–0.81) and 3, partly a low $K/(K+Na)$ ratio (0.03 in the Puoltsa granite and 0.13–0.44 in the Fjällåsen monzonites). These perthitic rocks thus show a depletion in iron and an enrichment in sodium similar to that in the "divergent" volcanics and dykes.

The Lina granite (Fig. 27) is similar to the perthitic granites and perthitic syenites, but is somewhat richer in alkalis and somewhat poorer in iron compared to the perthitic rocks.

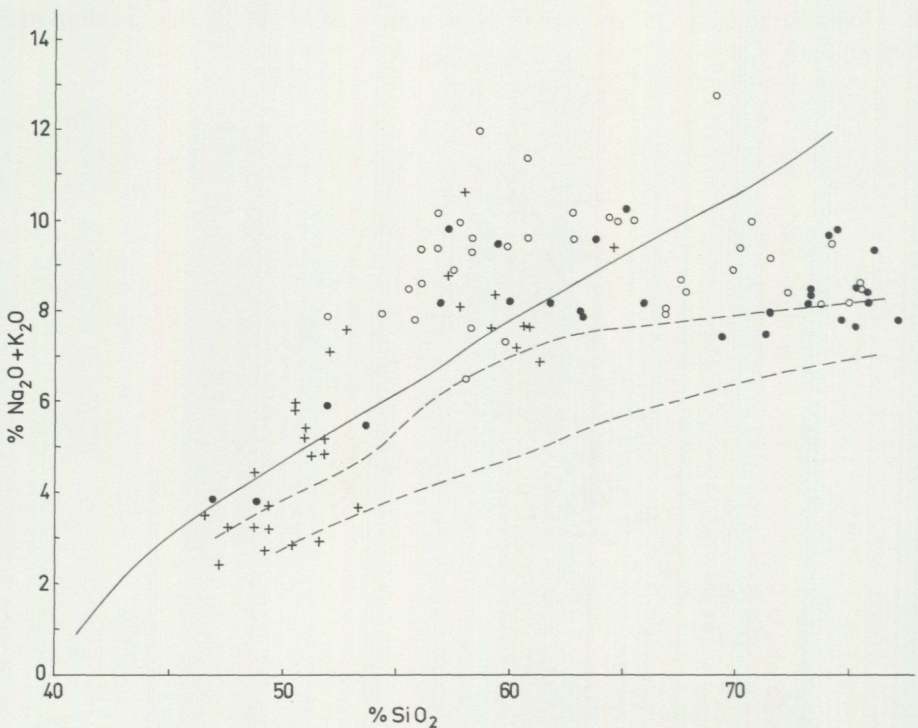


Fig. 28. Alkali-silica variation diagram (weight %) for plutonites in northern Sweden. Points = Lina granite suite, circles = perthite granite-monzonite and crosses = Granodiorite suite. For the meaning of the continuous and broken lines see Fig. 5.

The intermediate plutonites of the Granodiorite suite are calc-alkaline whereas the mafic (gabbroic) members are partly tholeiitic (Fig. 27). The Granodiorite suite thus resembles the Greenstone group (Fig. 6).

In an alkali-silica diagram (Fig. 28) the mafic rocks of the Granodiorite suite plot within the sub-alkaline field and approximately extend over the same area as the rocks of the Greenstone group (cf. Fig. 5). The Lina granite and the Perthite suite are sub-alkaline to alkaline, with a tendency for the perthitic rocks to be somewhat more enriched in alkalis. Both suites cover the same fields as the Porphyry group and, in common with the Porphyry group, acidic members of both suites plot within the sub-alkaline field. In addition, the plutonites show a "silica gap" around 65 % SiO_2 , which is similar to the Porphyry group.

Fig. 29 shows that the Niggli values *al*, *fm*, *c* and *alk* when plotted against the *si* value are approximately the same for the Granodiorite suite, the perthitic rocks and the Lina granites; they all indicate a normal differentiation trend. By comparison with Fig. 8 it is evident that the rocks of the Granodiorite suite are similar to the rocks of the Greenstone group, and that the perthitic rocks and Lina granite plot in the same area as the Porphyry group. The *alk* values in the Perthite suite are somewhat higher than in the Lina granite suite. The *fm* values from the acidic part of the Lina granites are somewhat lower than the rocks of the Porphyry group and the Lina granites contain somewhat less iron than both the Perthite suite and the Porphyry group.

These petrochemical similarities, further supported by the spatial association which exists between the rocks of the Greenstone group and the Granodiorite suite, and between the rocks of the Porphyry group and the Perthite suite, suggest a genetic relationship between the volcanics and the plutonites. Remobilization seems a plausible origin for the rocks of the Granodiorite suite. Mobilized material from the Greenstone group, probably comprising both basic volcanics and associated sediments, has contributed to the compositional deviation and greater spread of plotted analyses exhibited by the Granodiorite suite.

The chemical affinities and spatial association between the volcanics of the Porphyry group and the Perthite suite indicates a close genetic kinship. It thus seems plausible that the plutonites have formed by melting of the volcanics coeval with regional processes. According to Witschard (1975) the perthitic rocks on the Fjällåsen map sheet have originated from a slow, isochemical crystallization of the Porphyry group volcanics. It is unlikely that the plutonites represent a subvolcanic type of intrusion, contemporaneous with the volcanics. The volcanics have undergone folding and deformation, whereas the perthitic rocks are undeformed. This indicates an important time gap between the volcanics and the plutonites. Radiometric age determinations confirm this interpretation; the Perthite suite has an age of 1 505–1 530 Ma compared to the volcanics of the Porphyry group which is c.1.9 Ga old (cf. p. 6).

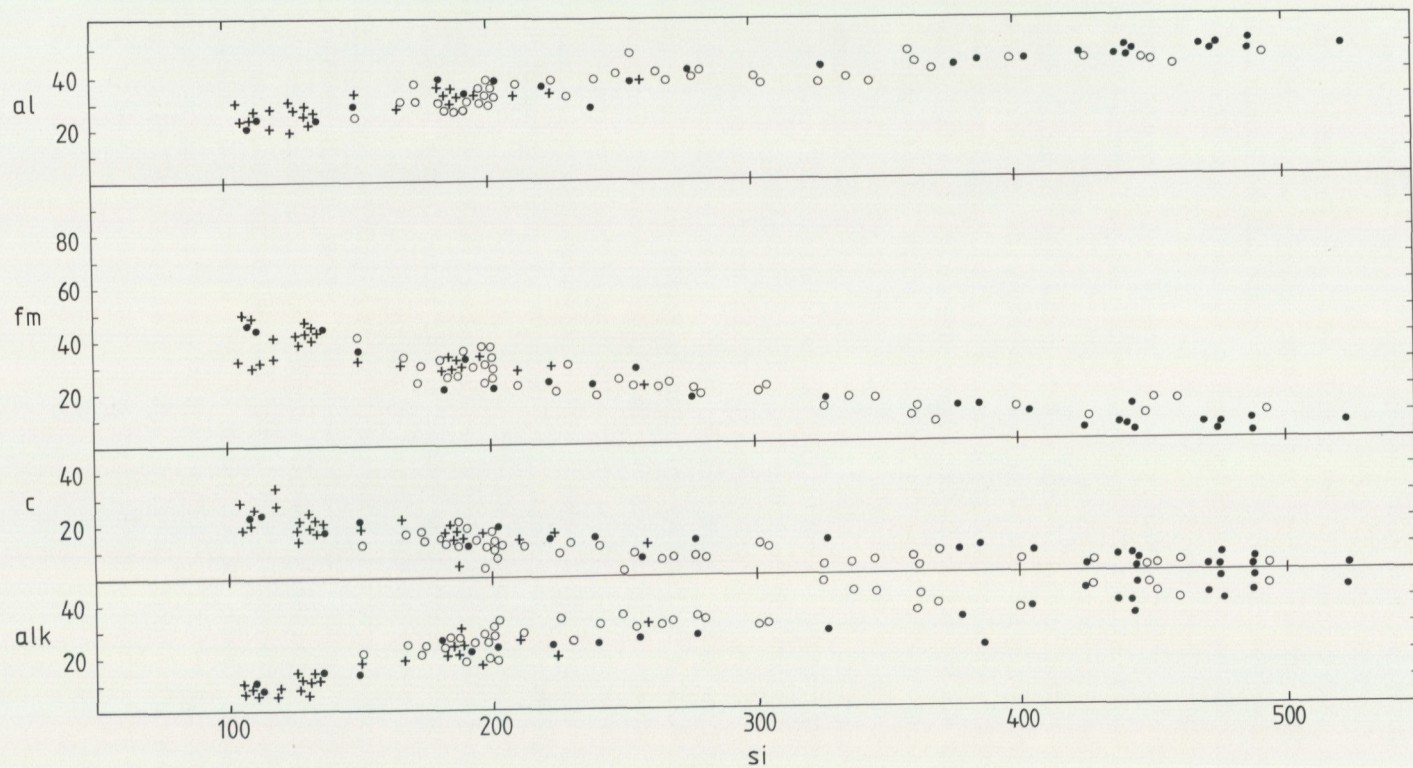


Fig. 29. The relationship between the Niggli values *al*, *fm*, *c*, *alk*, and *si* for plutonites in northern Sweden. Points = Lina granite suite, circles = Perthite granite-monzonite suite and crosses = Granodiorite suite.

IRON-PHOSPHORUS VARIATION IN THE METAVOLCANICS

In the volcanics of the Greenstone and Porphyry groups compositional changes occur with increasing acidity which indicate a normal differentiation trend. Overlapping fields in the variation diagrams point to a common provenance for both groups. However, important petrochemical differences exist between them, in particular the variation of iron and phosphorus with varying silica content. As discussed below the oxygen fugacity has been of crucial importance for the evolution of the two magma types.

With increasing silica content, the content of iron decreases in the Porphyry group, whereas it remains constant in the Greenstone group (Figs. 9 and 10). In the Porphyry group the degree of oxidation is comparatively high (0.2–0.8), whereas it is relatively low in the Greenstone group (0.1–0.5; Fig. 12). The Greenstone group has a constant, relatively low content of phosphorus (less than 0.2 % P_2O_5) whereas in the Porphyry group it tends to be higher (less than 0.8 % P_2O_5) and decreases with increasing solidification (Fig. 9) and silica content (Fig. 11). It should be emphasized that the phosphorus content can be used to distinguish between the intermediate to basic members in both groups.

During differentiation the Greenstone group showed a slight increase in iron but phosphorus remained constant. This in contrast to the Porphyry group where both elements increased. These features probably reflect primary magmatic differences and variations in oxygen fugacity.

The oxidation state, or the ferric-ferrous equilibria, in magma suites is mainly controlled by temperature and oxygen fugacity which is in turn mainly determined by the water pressure in the melt (Osborn 1959, Wones and Eugster 1965, Hamilton and Anderson 1967, Dodge 1972, Maury *et al.* 1978). The oxygen fugacity in lava rocks is in almost all cases below the (synthetic) hematite-magnetite buffer (10^{-5} atm. at 1 000°C) and above the (synthetic) fayalite-magnetite-quartz buffer (10^{-12} atm. at 1 000°C) as shown by Fudali (1965), Carmichael (1967), Carmichael and Nicholls (1976), Nicholls and Carmichael (1969), Nash and Hausel (1973), and Haggerty (1976). According to Fudali (1965) the oxygen fugacity increases with increasing acidity of the rock. Haggerty (1976) showed that at high but particularly intermediate temperatures acid extrusive suites are more highly oxidized than intermediate or basic suites. The ferric-ferrous ratio of magmatic rocks is taken as an indicator of the depth of the intrusions (Stzukin 1963, Kutzev 1964). According to Kutzev (1964) the ratio increases with increasing acidity and is higher in effusive rocks than in intrusive rocks, being highest in pyroclastics. The increase in the oxidation state in magmatic suites with increasing acidity is due to a successive increase of volatiles during the fractional crystallization. In most cases water vapour is responsible for the change. The high degree of oxidation in effusive rocks is due to the presence of atmospheric oxygen.

The ferric-ferrous equilibria in a magma can also be determined by the content of alkalis in the crystallizing liquid. There seems to be a general tendency for the ratio to

rise with increase in total alkali, and residual alkali-rich liquids become progressively more oxidized as fractionation proceeds (Carmichael *et al.* 1974). Alkali olivine basalts have a higher ratio than sub-alkaline basalts (Carmichael and Nicholls 1967, Andersson 1968). According to Carmichael and Nicholls (1967), the ferric-ferrous ratio (in alkali-silicate glasses) is influenced by the alkalis so that potassium is more oxidizing than sodium. Moreover, according to Fyfe and Kerrich (1976), Kerrich *et al.* (1977), and Fyfe *et al.* (1978), the oxidation state, or the ferric-ferrous ratio, of rocks undergoes little change during regional metamorphism. The oxidation-reduction regime is largely controlled by the original state of the rock.

It is here assumed that the volcanics of the Greenstone and Porphyry groups have not undergone any radical changes in the oxidation state during regional metamorphism. The relatively low oxidation state in the Greenstone group and the relatively high one in the Porphyry group most probably reflect the original conditions of formation. It should, however, be emphasized that the volcanics of the Porphyry group have been partly sericitized by hydrothermal solutions representing a late phase during the formation of the apatite-bearing iron ores of the Kiruna type. These metasomatically altered, K-rich and Mg-poor rocks have a high ferric-ferrous ratio mostly above 0.9 (Figs. 13 and 14). In both the Greenstone and Porphyry groups there is no change in the ferric-ferrous ratio with variation in the silica content (Fig. 12), which shows that during differentiation the oxidation state of the magmas has remained constant. As indicated above, a dominance of potassium over sodium would preferentially lead to a higher degree of oxidation. To a certain degree this is valid for the volcanics of the Porphyry group; a high potassium-sodium ratio is associated with a high degree of oxidation in contrast to a low potassium-sodium ratio with the oxidation degree varying between low and high (Fig. 14).

The difference in oxygen fugacity within the magma which produced the Greenstone and Porphyry groups has resulted in two distinct differentiation trends. In the Porphyry group, subjected to a higher degree of oxidation, there occurred a continuous depletion of iron (as magnetite) whereas in the Greenstone group there was a slight enrichment of iron. In a fractional crystallization, the evolutionary trend of the magma is dependent on the composition of the liquid, the temperature and the oxygen fugacity. The oxygen fugacity is most important for the crystallization of phases in the system $MgO-FeO-Fe_2O_3-SiO_2$. At a high oxygen fugacity magnetite is separated, and at low oxygen fugacities it tends to be iron-rich olivine or pyroxene. Depending on the oxygen fugacity two contrasting magmatic trends can be discerned, largely determined at the stage when magnetite starts to settle (Kennedy 1948, 1959, Osborn 1962, Hamilton and Anderson 1967, Coats 1968, Kuno 1968, Carmichael *et al.* 1974, Thomson 1975, Haggerty 1976). If the magma is "dry" and consequently at a low oxygen pressure, iron-olivine crystallizes rather than magnetite, and the liquid thus becomes enriched in iron and depleted in silica. This constant ("dry") composition fractional crystallization (the "Fenner trend" or the pigeonitic series according to Kuno 1968) thus leads to an iron enrichment. This is typical for layered intrusions. At

a high, constant oxygen pressure during the fractionation, magnetite coprecipitates with the silicates, and the liquid becomes enriched in silica and alkalis without any iron enrichment. During this constant oxygen pressure fractionation – the "Bowen trend" or the hypersthenic series according to Kuno (1968), the development is very similar to calc-alkaline igneous rocks of orogenic belts. According to Kuno (1968) the $\text{Fe}_2\text{O}_3/\text{FeO}$ value tends to be low within high-iron fractionation concentrates, thus suggesting a crude correlation between the $\text{Fe}_2\text{O}_3/\text{FeO}$ value and the rate of iron setting with fractionation. This diversity of the iron content during differentiation, which depends on the oxygen fugacity, can well be applied to the iron-bearing volcanics in northern Sweden.

The volcanics of the Greenstone and Porphyry groups thus show different differentiation trends. The magma of the Greenstone group (low degree of oxidation) becomes slightly enriched in iron and remains constant in silica during the solidification process. The magma of the Porphyry group (high degree of oxidation) tends to be depleted in iron and enriched in silica. These observations indicate that the Greenstone group magma followed the "Fenner trend" of differentiation, whereas the Porphyry group magma followed the "Bowen trend".

Within the Porphyry group, the iron ores formed at a late stage after the extrusion of the volcanics and their subsequent solidification (Geijer 1931b, Frietsch 1978). The latest phase of the magmatic activity resulted in the dyke rocks which are depleted in iron. During the fractionation of the Porphyry group there was a simultaneous depletion of the phosphorus content. On the other hand the later-formed volcanics are enriched in sodium and magnesium. The fact that iron and phosphorus were separated from the magma during differentiation supports the magmatic hypothesis of formation of the iron ores of the Kiruna type. Iron and phosphorus were thus retained in the magma chamber and were injected into volcanics at a late stage during the magmatism.

FRACTIONATION OF THE IRON ORES OF THE KIRUNA TYPE AND THE ROLE OF PHOSPHORUS

Earlier in this paper it has been postulated that the iron ores of the Kiruna type are magmatic. The iron oxide-apatite assemblage was separated from the parental magma by fractionation and, subsequent to the extrusion and consolidation of the volcanics, it was intruded into these same volcanics. The salient features in the process forming the Kiruna type of ore are as follows: 1, the ores represent a late formation, and 2, there are no gradational phases between the ores and the host rock volcanics. The primary homogeneous silicate melt was split up prior to the final crystallization into two melts, *i.e.* the iron oxide-apatite assemblage and the intermediate to acid, relatively alkaline magma. The late formed volcanics were depleted in iron and phosphorus and enriched in sodium and magnesium. The high content of apatite played an important role in the process by lowering the melting point of the iron oxide assemblage.

The process causing the primary magma to split into two melts is obscure, but most possibly fractional crystallization was crucial. However, the separation of the iron-rich magma is similar to that resulting from the liquation of silicate melts. Such a fractionation process has been outlined by Asklund (1949a, 1949b); the ores of the Kiruna type are differentiation products of low order from special parental magmas (low in silica and high in sodium) brought about by liquid immiscibility. Lundberg and Smellie (1979) considered the iron-rich melt as formed by assimilation of iron-rich material; the separation of the iron-rich melt was a result of immiscibility aided by a high content of volatiles.

Whether the iron ores of the Kiruna type are formed by liquid immiscibility is an open question. There are no textural indications of such a process in the rocks or the ores. In some deposits, such as Kiirunavaara and Mertainen, the host rock volcanics locally contain small, rounded or elongated cavities filled with magnetite, hornblende, biotite, sphene, and apatite in varying amounts. The fillings are mostly surrounded by a narrow halo of light-coloured, feldspar-rich material, which locally can take up an important part of the rock groundmass. The mode of formation of these structures is controversial as they might represent either amygdules (*i.e.* vesicles filled with secondary minerals) or globules (*i.e.* magmatic segregations). Lundberg and Smellie (1979, p. 1149) considered the origin of these magnetite-dominated infillings at Mertainen as uncertain: "Whether these structures are genetically true globules, *i.e.* due to immiscible droplets forming within a melt prior to consolidation, or infillings of preexisting gas bubbles or cavities is a debatable point". The present author is in agreement with Smellie (1980) inclined to consider the magnetite cavities at Mertainen as infilling phenomena. This point of view is mainly based on the successive gradations that exist between these magnetite concentrations and intrusive veins of magnetite. In addition, the cavities have a varying mineralogy; besides the dominant type characterized by a high magnetite content with associated actinolite, sphene, apatite, biotite, quartz, and feldspar, there are others which contain actinolite (-sphene) or calcite (-actinolite-biotite). This contradicts an origin by immiscibility; globules formed by such a process should be essentially uniform in composition (Roedder 1979). The same features are found in the hornblende-sphene-magnetite-apatite-biotite-filled cavities at Kiirunavaara where all gradations from hornblende-dominated to magnetite-dominated fillings are found. The hornblende-filled structures sometimes coalesce to vein-like aggregates. Geijer (1960) characterized the fillings as typical vesicles or as "embryonal nodules", the latter being less common.

Even if liquid immiscibility seems rather obscure in connection with the formation of the Kiruna iron ores, this process is of importance for some related magmatic rocks and ores and will therefore be discussed at some length.

Liquid immiscibility in silicate melts has commonly been considered as a restricted phenomenon, found in "freak" geological associations representing unlikely temperatures and compositions. Furthermore, synthetic immiscibility was considered to take place only at extremely high temperatures. Recent investigations, both in nature and in

the laboratory, show, however, that natural silicate immiscibility may be a much more common feature than was formerly believed (Roedder 1978). Liquid immiscibility as a rock-forming process has thus gained support from evidence of sulphide-silicate immiscibility and from observations in lunar and terrestrial basalts (Roedder and Weiblen 1970, 1971, 1972, De 1974). Experimental work has showed that some of the compositions in the Skaergaard intrusion could have formed by immiscibility at geologically reasonable temperatures (McBirney and Nakamura 1974, McBirney 1975). Carstens (1979) indicated liquid immiscibility in basic alkaline magmas especially in the presence of water. Most of the natural immiscibilities yield a felsic, alkali-aluminosilicate (granitic) melt and a mafic (ferro-basaltic) melt of varying composition but rich in iron, magnesium, calcium, and titanium (Roedder 1978).

Liquid immiscibility means the breaking up of the chainlike polymerized structure of a melt consisting of tetrahedral Si (Roedder 1979). Ryerson and Hess (1978) showed the importance of the silicate liquid structure upon mineral-liquid partitioning concerning immiscible granitic and ferro-basaltic magmas. The structure of a silicate liquid is a function of composition, temperature and pressure. There are several other factors that effect the liquid immiscibility in a melt. For example, Naslund (1976) showed that the immiscibility (in the system $\text{KAlSi}_3\text{O}_8\text{-NaAlSi}_3\text{O}_8\text{-FeO-Fe}_2\text{O}_3\text{-SiO}_2$) increased as the oxygen fugacity increased (from 10^{-12} to $10^{-0.7}$ atm.). According to Irvine (1975) the immiscibility gap between a silica melt and common mafic melt silicates and oxide minerals is promoted by the presence of water and alkalis, which contribute to the lowering of liquidus temperature. High concentrations of TiO_2 and P_2O_5 may also contribute significantly to the silica immiscibility effect, especially in the alkali basalt series.

The importance of phosphorus (apatite) in the formation of silicate melts has been recognized by many authors. Liquid immiscibility in the silicate—iron oxide—calcium phosphate system has been demonstrated by Olsen and Wiener (1942), Olsen and Metz (1945–46), Fischer (1950) and Muan and Osborn (1965). In the three first mentioned investigations the presence of sodium was considered important. Philpotts (1967) postulated a high content of sodium in alkaline magmas as a necessary prerequisite in forming an immiscible liquid of magnetite-apatite in dioritic and alkaline rocks. According to Bergstøl (1972) the jacupirangite at Kodal, southern Norway, shows an eutectic mixture of iron-titanium oxides and apatite which is assumed to form an immiscible liquid with silicate melts of monzonitic composition. According to McBirney and Nakamura (1974) the presence of potassium and phosphorus is of critical importance for the immiscibility in the late-stage magmas of the Skaergaard intrusion. Frutos and Oyarzún (1975) stated that apatite may lower the crystallization temperature of magnetite from 1 500 to about 1 000–800°C, making it possible for such a magma to exist in volcanic environment. This lowering of the melting point would be sufficient to permit eruptions of magnetite. Roedder and Weiblen (1970, 1971) found that in lunar samples the content of phosphorus is much higher in the iron-rich melt than in the silica-rich melt, contrary to that expected from

normal crystal fractionation, where phosphorus is enriched in late-stage residual liquids. A similar partition of phosphorus was reported by De (1974) from the Skaergaard intrusion. Watson (1976) investigated the partition of phosphorus in immiscible basic and acidic liquids in the system $K_2O-Al_2O_3-FeO-SiO_2$ and found that phosphorus at 1 180°C is strongly enriched in the basic melt. According to Watson (1980) apatite solubility in magmas decreases markedly with increasing SiO_2 content and falling temperature. The high solubility of apatite in basic magmas precludes the occurrence of residual apatite in mantle source regions. Apatite saturation will be common in intermediate magmas and inevitable in silicic ones.

Nash (1972) showed that the P_2O_5 activity in magmatic liquids depends on the oxygen fugacity. Thus the fugacity of phosphorus in tholeiitic, low oxygen fugacity basalts is about four orders of magnitude lower than for magnetite-olivine, high oxygen fugacity basalts.

Ryerson and Hess (1980) found that the role of phosphorus in a silicate melt is complex. P_2O_5 depolymerizes pure SiO_2 melts by entering the network as a fourfold coordinated cation but polymerizes melts in which additional metal cations other than silicon are present. The effect of polymerization is apparent in the widening of the granite-ferro-basalt two-liquid solvus. The behaviour of phosphorus in the two major igneous fractionation sequences depends on the state of the polymerization in the magma. In the "Fenner trend" which involves enrichment of alkalis and iron, with silica and aluminium remaining constant, the state of polymerization in the liquid residual is constant. Consequently apatite crystallizes at a late stage. In magmas which are differentiated according to the "Bowen trend", involving an enrichment of silica, there is thus an increase in the state of polymerization and the phosphate minerals crystallize at an earlier stage of fractionation.

It can thus be indicated that liquation of silicate melts is not as uncommon as formerly believed and that the presence of apatite in some cases is of great importance in this connection. The latter feature is highly relevant for the iron ores of the Kiruna type. Irrespective if they are formed by fractional crystallization or by liquid immiscibility, the presence of apatite has been crucial for lowering the melting temperature of magma and allowing the iron-apatite assemblage to separate as liquids rather than as solids. The iron-phosphorus separation out of the magma occurred at a relatively early stage, and the late host rock volcanics are depleted in both elements. The separation of iron-phosphorus is in accordance with some of the chemical features indicated above for liquid immiscibility. The content of sodium is in some investigations considered as important, and in the volcanics of the Porphyry group the content of sodium has increased in the later phases. The high oxygen fugacity in the Porphyry group should mean, in accordance with the findings of Nash (1972), a high phosphorus activity. The differentiation of the Porphyry group followed the "Bowen trend" with an enrichment of silica and a high oxygen fugacity, and apatite should in accordance with the investigations by Ryerson and Hess (1980) crystallize early.

IRON-RICH TRACHYTES IN THE PORPHYRY GROUP

According to Lundberg and Smellie (1979) the iron ores at Mertainen and Painirova (SE of Kiruna, cf. Fig. 30), both of Kiruna type of ore, are associated with iron-rich trachytes which do not form part of a magmatic differentiation series. It is suggested that these trachytes are formed from assimilation of iron-rich material during their formation. The iron ores are the result of immiscibility aided by a high volatile content. The Mertainen and Painirova ores moved to the surface with the trachyte rocks, or at least in very close association. There exists an intimate relationship between trachyte, magnetite trachyte and iron ore. This assimilation mechanism is applicable to all the other deposits of the Kiruna type in Northern Sweden. Smellie (1980) gave a somewhat modified model for the ore formation, comprising the following stages: 1, assimilation of iron-rich material ('greenstones') at depth resulting in an iron-rich primary magma, 2, differentiation of this magma into an iron-rich and phosphorus-rich part and 3, immiscible separation of the magnetite-apatite liquid.

In the opinion of the present author objections against these points of view are motivated. The statement about the trachyte-magnetite association is true for the Mertainen and Painirova deposits, but is not generally applicable on the other deposits of the Kiruna iron ore type. According to Lundberg and Smellie (op. cit.) most of the deposits are associated with trachytic rocks, especially those rich in magnetite. However, of the 27 Kiruna ore type deposits in Northern Sweden (Fig. 30), the host rocks are composed of rhyolite (and minor trachyte) in 10 deposits, of trachyte in 9 deposits, of both rhyolite and trachyte in 7 deposits, and of both trachyte and andesite in one deposit. Trachytes as host rocks to the ores of the Kiruna type are thus of minor importance in many of the deposits. In addition it should be emphasized that magnetite-rich trachytes are only present in some deposits (such as Mertainen and Painirova) whereas the main part of the trachytes are not especially high in iron. Most of the trachytes are felsic albite-rich rocks with sparse amounts of dark minerals. They contain around 60 % SiO_2 and 6–7 % $\text{FeO} + \text{Fe}_2\text{O}_3$, contents which are in accordance with the average values for trachytes (Le Maître 1976). The trachytes from the Mertainen-Painirova area listed by Lundberg and Smellie (op. cit.) contain 47.3–62.0 % SiO_2 (average 55.5 %) and 7.9–16.8 % $\text{FeO} + \text{Fe}_2\text{O}_3$ (average 12.3 %). The iron-rich trachytes, or magnetite-syenite-porphyrines, in the Kiruna area contain 45 % SiO_2 and 29 % $\text{FeO} + \text{Fe}_2\text{O}_3$ (Geijer 1910). They have restricted extension, occurring in a small area north of Luossavaara. The iron content is extremely high for a lava rock. According to Lundberg and Smellie (1979) the iron ores in the Svappavaara area (Gruvberget and Leveäniemi) are also associated with iron-rich trachytes. However, the trachytes at Gruvberget have a 'normal' iron content of 5–7 % $\text{FeO} + \text{Fe}_2\text{O}_3$ (Frietsch 1966), whereas the iron content of the Leveäniemi trachytes is somewhat higher, namely 9–11 % $\text{FeO} + \text{Fe}_2\text{O}_3$ (Parák 1965). This indicates that there is no

general affinity between magnetite-rich trachytes and iron ores of the Kiruna type. The magnetite-trachytes occur only in a few deposits, and are in some of them of very minor importance. Most of the ores occur in trachytes and in rhyolites which are low in iron.

According to Lundberg and Smellie (1979) there is in the Kiruna area and the Mertainen and Páinirova deposits a distinct genetical difference between rhyolites and trachytes to magnetite-trachytes. The rhyolites are sub-alkaline whereas the trachytes are alkaline. The two rock types do not therefore belong to the same differentiation suite, instead being formed out of separate melts. In the opinion of the present author this is a debatable statement. The separate origin of the trachyte and the rhyolites proposed by Lundberg and Smellie (op. cit.) is mainly based on their distribution in an alkali-silica diagram such as in Fig. 5. It is correct that within the Porphyry group the rhyolites are dominantly sub-alkaline and that the trachytes and related andesites and minor basalts, covering the 45–65 % SiO_2 interval, are mainly alkaline. However, there are rather many trachytes and related andesites and basalts which are sub-alkaline. Fig. 5 shows in addition that there is scarcely any discontinuity between rhyolites and trachytes on the basis of the alkali-silica relationship, as proposed by Lundberg and Smellie (op. cit.). There is however, as previously pointed out, an obvious drop in the number of analyses around 65 % SiO_2 . This "analytical gap" is probably of petrogenetical importance and not caused by underrepresentation in the sampling. Chayes (1963) and Upton (1974) reported minimas of the silica content in volcanic suites, and according to the first author the silica gap indicated that the fractional crystallization must be questioned. On the other hand, as pointed out by McDonald (1974, p. 444) "silica-gaps are characteristic of differentiated intrusions which provide some of the best evidence for fractional crystallization". In this connection the previously mentioned silica gap around 65 % SiO_2 in the igneous rocks of the Perthite suite and the Lina granite in Norrbotten county (Fig. 28) should be emphasized. The silica gap in the Porphyry group does not therefore necessarily mean that two different magma stems are present. If other correlation diagrams (Figs. 8, 9, 10, 11 and 17) are considered it is evident that there is no genetical difference between rhyolites and trachytes/andesites. The analytical points merely indicate that all rocks of the Porphyry group belong to the same magmatic suite formed by a normal differentiation.

According to Lundberg and Smellie (1979) the iron in the ores of the Kiruna type and associated trachytes originates from assimilation of iron-rich materia at depth. The ore formation is considered analogous to the El Laco magnetite-apatite ores in Chile where the magnetite has been derived by fusion of underlying itabirite iron-formations. No information is given about the nature and origin of the iron-rich source material in Northern Sweden, but it is logical that this material must be older than the Porphyry group. The only iron-bearing formations that can come into question are the skarn iron ores of the Greenstone group. The quartz-banded iron ores in the latter have such a restricted extension in the whole of Northern Sweden that they need not to be

considered. Smellie (1980) suggested the basic volcanics ('greenstones') of the Greenstone group as a possible source material.

For several reasons it is unlikely that the provenance of the ores of the Kiruna type and the iron-rich trachytes has to be sought in the skarn iron ores and the rocks of the Greenstone group. There is no spatial relationship between the skarn ores and associated rocks of the Greenstone group and the Kiruna type of ore and associated magnetite-trachytes. Most of the ores of the Kiruna type lie in regions where the Greenstone group is not present (cf. Fig. 1). This is, however, not a weighty argument as the assimilation of the skarn ores may have occurred at great depths, far from the present site of ores of the Kiruna type. An important objection is, however, implied in the compositional differences between the two ore types indicating that the skarn iron ores scarcely can have been the source material for the Kiruna iron ores and the associated magnetite-rich trachytes. The skarn iron ores contain small amounts of iron sulphides with a sulphur content mostly around 1–2 %. The Kiruna ores are sulphur-free. An original content of sulphur might, however, have been expelled by anatexis. Apatite is a typical component in the Kiruna type of ore and most deposits contain on an average around 1 % P. In a few deposits the content is higher (up to 5 %). The skarn iron ores are mostly apatite-free, containing less than 0.1 % P although a few deposits encountered contain up to some per cent phosphorus. The magnetite in the Kiruna ore type and in the trachytes has a different composition compared to the magnetite in the skarn iron ores (Frietsch 1970). The latter contains a relatively high content of magnesium (up to several per cent) and chromium (up to several hundred p.p.m.). Even if the magnetite had been mobilized during anatexis, these elements should with all certainty have entered the crystal structure and should consequently occur in the Kiruna ores. Their content of these elements is, however, low, in most cases lower than 0.2 % Mg and 20 p.p.m. Cr.

TECTONIC CONTROL OF THE EMPLACEMENT OF THE IRON ORES OF THE KIRUNA TYPE

FAULT SYSTEMS AND GRABEN FORMATION

In the northern part of Norrbotten county occur long linear belts of Svecofennian supracrustals comprising both metavolcanics and metasediments (Fig. 1). These are here considered to be due to repeated fracturing, mainly originating from the Archean sialic basement. Basins were formed by vertical block movements within the unstable crust. This structural pattern largely controlled the deposition of the Early Proterozoic volcanogenic and sedimentary rocks at different epochs.

Prior to, or coeval with, the deposition of the Greenstone group, the already folded and metamorphosed Archean basement was fractured and subsequently divided into rectilinear blocks bounded by faults mainly striking NE–NNE and NW. The NE–NNE

fault system is the most prominent. The NNE dislocation from Porjus in the south through Malmberget and Svappavaara to Karesuando in the north has a continuous length of more than 350 km (Henkel 1978). A section of this fault system is shown on

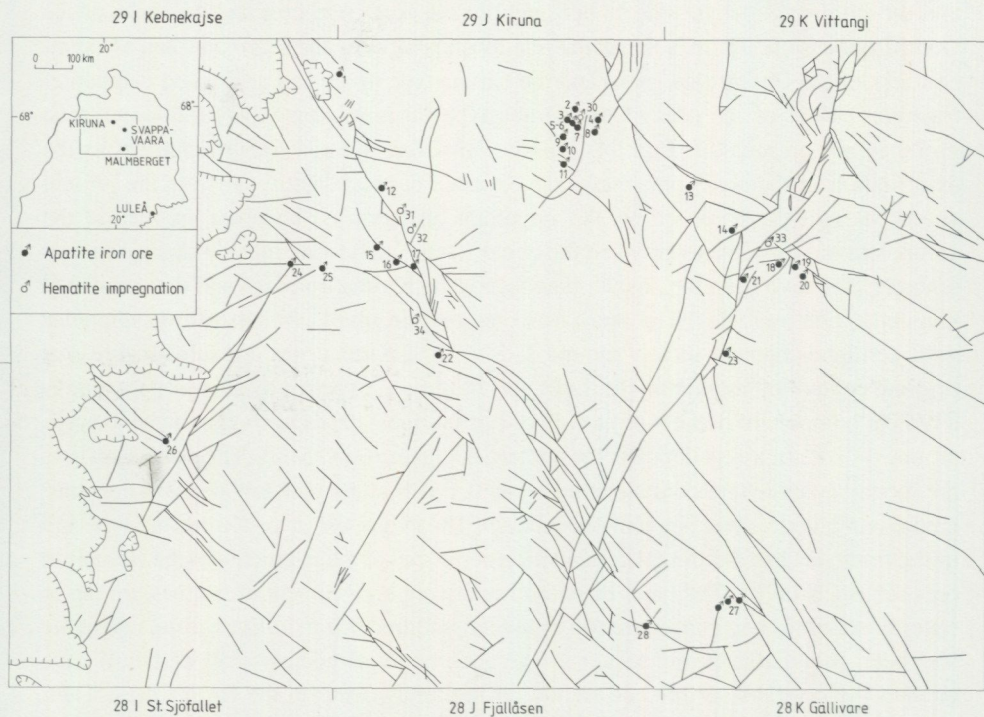


Fig. 30. Map showing the site of the main part of the deposits of the Kiruna ore type in northern Sweden. The fault lines are taken from the geological map sheets 29J Kiruna (Offerberg 1967), 29K Vittangi (Eriksson and Hallgren 1975), and 28J Fjällåsen (Witschard 1975). Additional data are taken from Henkel (1978), unpublished geological map sheets 28I St. Sjöfallet, 28K Gällivare and 29I Kebnekajse by F. Witschard and an unpublished lineament map of the whole area by J.E. Ehrenborg.

Apatite-bearing iron ores

1. Eustilljåkk
2. Nukutus
3. Luossavaara
4. Tuollujärvi
5. Rektorn
6. Lappmalmen
7. Haukivaara
8. Tuolluvaara
9. Luossajärvi
10. Kiirunavaara
11. Konsuln, Sigrid, Viktor
12. Ekströmsberg
13. Kuosanen
14. Mertainen
15. Tjåorika
16. Renhagen
17. Harrejaure

18. Tansari
19. Gruvberget
20. Leveäniemi
21. Painirova
22. Pattok
23. Ylipääsnjaska
24. Tjårrojåkka
25. Luppovare
26. Satisjaure
27. Malmberget
28. Sikträsk

Hematite impregnations

30. Hauki
31. Pidjastjåkko
32. Skuokimjåkk
33. Ainasjärvi
34. Kuosatjvare

Fig. 30 intersecting the Vittangi and Fjällåsen map sheets. In the area north of Kiruna a N–S striking fault system is prominent.

The NE–NNE and the N–S systems to a large extent demarcate the border between the Archean and the Proterozoic. The fracturing of the Archean basement has facilitated the intrusion of ultrabasic dykes which are intraorogenic with respect to the Archean and Svecokarelian foldings. The dykes mostly follow the NE striking contact between the Archean and the Proterozoic in the area between Svappavaara and Karesuando. The NW striking fault system is well developed on the Kiruna, Fjällåsen and Gällivare map sheets (Fig. 30).

Within these down-faulted troughs, superimposed upon the Archean basement, depositional infilling started with a basal unit of sericite quartzite and orthoquartzite with intercalations of siltstone and dolomite. This Tjärro Quartzite formation (Eriksson and Hallgren 1975, Ambros 1980) represents epicontinental deposition and indicates uplift and erosion of the basement before the deposition of the Greenstone group. The Tjärro Quartzite formation is found in NE–NNE, and less commonly, NW aligned basins which border the Archean basement (Fig. 1). The quartzite horizon between Svappavaara and Karesuando has a length of about 70 km.

The main infilling material of the tectonic basins comprises volcano-sedimentary deposits of the Greenstone group. Some basins are at a great distance from the Archean craton. The more extensive areas with rocks of the Greenstone group are delineated by NE to NNE and NW fractures, or as in the area north of Kiruna, by N–S ones. The most continuous deposits of the Greenstone group (approx. length of 150 km) occur in a basin bordering the Archean, which is orientated in a NNE direction from Svappavaara to Karesuando (Fig. 30), and from there into Finland. The NE striking basins at Kiruna and Pajala are about 50 km long. The NW striking basins with rocks of the Greenstone group are considerably smaller; at Masugnsbyn and Lannavaara they have a length of about 20 km.

These down-faulted grabens have subsequently influenced the deposition of the ensuing geological formations. As mentioned previously, the Schist-conglomerate group, comprising the Pahakurkio group (Padget 1970) and Kiilavaara quartzite group (Frietsch 1966, Eriksson and Hallgren 1975) shows a spatial association to the rocks of the Greenstone group. These sedimentary deposits strike NW, as at Masugnsbyn, at Pajala and southeast of Kiruna, or strike NE, as at Kiruna. The sediments, which have a thickness of about 1 000 m, or exceptionally as at Tärendö almost 4 000 m, consist of cross-bedded feldspar-rich quartzites and quartz-mica-schists (pelites). Northeast of Kiruna this sedimentary group comprises the Kurravaara conglomerate which is a clastic deposit formed at a late stage of the volcanism that gave rise to the Greenstone group (Frietsch 1979a). The Schist-conglomerate group has been deposited in shallow basins on, or adjacent to, the rocks of the Greenstone group. However, the sedimentary material constituting the quartzites is not derived from the Greenstone group, instead possibly from the Archean granite gneiss basement.

The deposition of the volcanics of the Porphyry group is only to a minor extent related to the above described fault systems. West of Svappavaara and Malmberget the volcanics are in part delineated by the NNE striking Svappavaara-Karesuando lineament; in the region southwest of Kiruna the NNW fault system seems to be of some importance. In contrast to the other supracrustal rocks in northern Norrbotten, which are submarine and restricted to depositional basins, the rocks of the Porphyry group had a subaerial mode of formation and were spread out over large areas. The volcanics of the Porphyry group are, at least concerning the acidic members, presumably ash flows formed by explosive fissure eruptions. The high volatile content of the ash flows has resulted in a large areal extent of deposition, in contrast to that normally associated with acidic, highly viscous lavas. The apparent connection between the NNE and NW fault lines and the extension of the volcanics is possibly due to large scale fissure eruptions oriented along these directions. The NNE fault system from Svappavaara extending southwards to Malmberget and Porjus and from there to Jokkmokk seems to have been of crucial importance in that it delineates the Porphyry group to the east. East of this fault system there are only scattered occurrences of the Porphyry group between Tärendö and Lannavaara (Fig. 1). Furthermore, it should be emphasized that the Granodiorite suite, which is spatially connected with the rocks of the Greenstone group, occurs exclusively east of this fault line, even if there are relatively large occurrences of the Greenstone group to the west of it. The southern continuation of the Karesuando-Svappavaara fault zone has thus exerted a considerable influence on the extent of volcanism which gave rise to the Porphyry group. The zone represents a deep fracture in the Earth's crust along which the volcanics erupted. The interpretation this major structure is, however, unclear. The variable distribution of the Porphyry group and the Granodiorite suite on both sides of this line could also be explained as two blocks exposing different levels of erosion and metamorphism.

During the formation of the ensuing Quartzite group together with quartzitic sandstones, minor phyllites and intraformational conglomerates, the NE striking and, to a lesser extent, the NW striking fractures were reactivated again. The bulk of the sediments were deposited in graben-like basins, mostly bounded by dislocations aligned in a NNE direction (Frietsch 1979). North of Svappavaara the quartzites are partly delineated by NW faults. The depth of the grabens is moderate and the thickness of the sediments is about 1 000 m. The material deposited was derived by rapid erosion of nearby source areas of substantial relief, most probably comprising rocks of the Porphyry group.

In summary, the Early Proterozoic volcanics and sediments in the northern part of the Norrbotten county were largely formed in connection with linear belts, some of which have great extension. The nature of these belts is due to rigid tectonics representing dislocations or transform faults. The fracturing of the crust had commenced already in the Archean with reactivation during different epochs. The supracrustals were in part deposited at the margins of the stable craton with the Archean basement.

The outlined geotectonic pattern for the formation of the supracrustals in Norrbotten county is in some respects similar to what has been envisaged by Witschard (1980); the stratigraphy and geotectonic evolution of northern Norrbotten county is characterized by four tectogenic episodes which have given rise to sedimentation, plutonism and volcanism. In the main an intra-cratonic tectonism has been active.

There are examples of Precambrian mobile belts which were formed by intraplate tectonics on a pre-existing sialic crust (Sutton and Watson 1974, Kröner 1976, 1977, McElhinny and McWilliams 1977, Plumb 1979, Katz 1980). The formation of these ensialic zones of mobility did not imply any considerable plate movement, and the tectonics is thus different from the present-day plate tectonics. Typical for the mobile belts is a repeated activity along ancient lineaments and mobile zones (Kröner 1976, 1977). The belts are often shear zones of transform nature (Katz 1980). The linear belts of Norrbotten county could well be of similar nature, with the position of the linear zones of Proterozoic age governed by the Archean block pattern.

THE SPATIAL RELATIONSHIP BETWEEN THE IRON ORES OF THE KIRUNA TYPE AND THE BLOCK FAULTING

The rifting outlined above has possibly played an important part in the formation of the iron ores of the Kiruna type. The deposits in Northern Sweden are related to regional fault systems which in part are the same that governed the development of the depositional basins of the supracrustal rocks. The fault systems consist of deeply penetrating fractures which have enabled the ore-bearing fluids to reach the surface. The iron ores occur in a region where the major fault systems trend NW–WNW and NNE. In addition, there are less persistent faults which trend ENE, E–W and N–S (Fig. 30). The iron ores in general are spatially related to the NW–WNW and NNE fault systems whereas the deposits near Kiruna area follow the latter one. The ores located in the western part of the Kiruna map sheet lie close to the NW fault system; the deposits at Malmberget and Sikträsk occur at the southern continuation of it. The deposits at Tjärrojåkka (map sheet 29I Kebnekajse) and Satisjaure (map sheet 28I Stora Sjöfallet) are close to a prominent NNE trending fault system. At Tjärrojåkka this system is intersected by an E–W striking system, apparent as a large fault immediately south of the ore. East of Tjärrojåkka and near to the E–W fracture the Luppovare ore occurs. The ores in the Svappavaara area (map sheet 29K Vittangi) are found at the intersection of the NE striking Karesuando-Svappavaara fault system with a WNW oriented fault system.

In summary, the apatite iron in northern Sweden lie close to large-scale tectonic zones. These faults and fractures guided the emplacement of the ore material. The ores have penetrated along zones of weakness which have been reactivated at different periods, both pre- and post-dating the ore formation.

A tectonic control is also prevalent for the emplacement of the iron ores of the Kiruna type in the Precambrian of southeastern Missouri. The ores occur in a region

which is intersected by numerous faults (Kisvarsanyi and Proctor 1967, Kisvarsanyi and Kisvarsanyi 1976). The tectonic disturbances are mainly epeirogenic and include broad doming, warping, fracturing and considerable vertical faulting. Faults, fractures and brecciation of the country rock are prominent near the contacts with the ores (Kisvarsanyi 1966). The emplacement of the iron ore bodies at Shepherd Mountain and Pea Ridge appears to be controlled by faulting (Kisvarsanyi and Proctor 1967, Snyder 1969). The complicated structure of the Iron Mountain ore (Murphy and Ohle 1968) is largely related to fault zones. In addition, faulting is important in the Bourbon deposit, the grade of the ore being controlled by a N-S trending fracture, now occupied by a basic dyke (Snyder 1969). The faulting appears in some cases to be contemporaneous with the ore formation, as at the Shepherd Mountain deposit and possibly also at the Pea Ridge deposit (Kisvarsanyi 1966, Kisvarsanyi and Proctor 1967).

It is commonly recognized that the chemical composition of magmatic rocks and their tectonic setting are related. In general, alkali rock suites are associated with stable cratons whereas calc-alkali rocks are associated with orogenic belts. There is often a close relationship between alkaline magmatism and rifting. Even if the alkaline character of the volcanics of the Kiruna iron ores is weak, being most pronounced for the trachytic to andesitic members, this feature, reinforced by the continental character of the volcanism, favours the hypothesis of formation of the volcanics and associated iron ores in a stable craton environment.

SUMMARY

The iron ore-bearing Early Proterozoic (c.1.9 Ga) metavolcanics in northernmost Sweden comprise the older (stratigraphically lower) Greenstone group and the younger (stratigraphically higher) Porphyry group. These volcanic suites share certain petrochemical similarities.

The Greenstone group is composed of pillowed basalts associated with subordinate andesites and minor ultramafites. Intercalated are pyroclastic, epiclastic and chemical metasediments. Skarn iron ores consisting of magnetite, Ca-Mg silicates and small amounts of iron sulphides, as well as minor quartz-magnetite- Fe^{2+} -silicate-banded ores, occur within the sedimentary horizons, or rarely in the basalts. The volcanic suite is chemically characterized by medium K_2O contents (0.2–1.5 %), low $\text{K}/(\text{K}+\text{Na})$ ratios (smaller than 0.4), low $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ratios (smaller than 0.5) and high $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios (0.3–0.7). The rocks show an iron enrichment with increasing silica content. Plots of $\text{Na}_2\text{O}-\text{CaO}$ and $\text{Na}_2\text{O}-\text{K}_2\text{O}$ indicate that the rocks have only to a minor degree been influenced by later metasomatic processes such as spilitization. In alkali-silica and AFM plots the suite shows a tholeiitic to calc-alkaline trend, and the Di-Hy-Ol normative composition indicates olivine basalts. Compared with modern geotectonic settings $\text{TiO}_2-\text{SiO}_2$, $\text{K}_2\text{O}-\text{TiO}_2-\text{P}_2\text{O}_5$ and $\text{MgO}-\text{FeO}^x-\text{Al}_2\text{O}_3$ diagrams show that the rocks reflect an oceanic environment.

The Porphyry group comprises rhyolites, trachytes, subordinate andesites and occasional basalts. Rhyolites and trachytes are the host rocks of the Kiruna type of iron ore represented by a magnetite-hematite-apatite association. The series is characterized by chemical features such as high alkali contents (4–10 % $\text{Na}_2\text{O}+\text{K}_2\text{O}$), high K_2O contents (1–6 %), intermediate $\text{K}/(\text{K}+\text{Na})$ ratios (0.1–0.6), high $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ratios (0.2–0.8) and intermediate $\text{Mg}/(\text{Mg}+\text{Fe})$ ratios (0.1–0.7). During differentiation (increasing silica content) there has occurred a depletion of iron. In alkali-silica and AFM plots the suite falls equally within the tholeiitic and calc-alkaline fields; the basic to intermediate members represent, however, an alkaline trend. The Di-Hy normative composition, with additional Ol, Q and Ne, indicates oversaturated tholeiites. Judging from $\text{TiO}_2\text{--SiO}_2$, $\text{K}_2\text{O--TiO}_2\text{--P}_2\text{O}_5$ and $\text{MgO--FeO}^x\text{--Al}_2\text{O}_3$ diagrams, the rocks show continental affiliations.

The volcanics of the Porphyry group have locally, mostly in close connection to the iron ores of the Kiruna type, been metasomatically altered which implied sericitization and silicification. Compared to the unaltered volcanics the alteration rocks have high $\text{K}/(\text{K}+\text{Na})$ and $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ratios and a low $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio. Furthermore Na and Ca have diminished, Fe has increased whereas the total Na+K, P and Ti have remained unchanged.

Even if there are obvious chemical differences between the volcanics of the Greenstone group and the Porphyry group concerning mainly the iron enrichment and the $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ratios, these groups are characterized by many similarities. Differentiation diagrams show that they are mostly overlapping and both suites display clear trends of a uniform magmatic differentiation. The changes are similar to those found during the evolution of volcanic rocks in orogenic areas (island arcs). Between the Greenstone group and the Porphyry group there is an increase in the potassium content from medium to high, an increase of the $\text{K}/(\text{K}+\text{Na})$ and $\text{Fe}^{3+}/(\text{Fe}^{3+}+\text{Fe}^{2+})$ ratios, a decrease of the $\text{Mg}/(\text{Mg}+\text{Fe})$ ratio and an iron depletion. The same features are found in an island arc evolution which changes from a tholeiitic to a calc-alkaline character. Petrochemically, there is thus support for a comagmatic provenance of the Greenstone and Porphyry groups.

The field relations do not contradict a common origin for the Greenstone and Porphyry groups as there is no obvious discordance between the two volcanic suites. The metasediments of the Schist-conglomerate group, comprising mainly mica schists and quartzites of moderate thickness, are considered to occur stratigraphically between the two volcanic groups. Clearly interlayered between these is the Kurravaara conglomerate at Kiruna which contains pebbles of volcanites which show affinities both to the Greenstone group and the Porphyry group, thus indicating that there are transitions between them. Little is known about the absolute age of the Greenstone group. Its age-range is between 2 700 Ma (age of underlying Archean granite gneiss basement) and 1 900 Ma (intersecting plutonites of the Granodiorite suite). A Nd-Sm mineral isochron for a basalt from Kiruna gives an age of c.1.9 Ga. The Porphyry group is also c.1.9 Ga old, as shown by radiometric determinations on the volcanics

and on intersecting migmatite granites. On the basis of the radiometric age determinations, the petrochemical features and the field relations, it is therefore possible that the Greenstone and Porphyry groups are relatively closely related in time and that they belong to the same magmatic evolution.

Dykes of metabasites and intermediate to acid porphyries occur locally within the Greenstone group and the Porphyry group. The latter have in the main a composition similar to the volcanics of the Porphyry group, and the dykes probably represent a late phase in the same magmatism that gave rise to the Porphyry group. However, some of the porphyry dykes differ by exhibiting a more alkaline affinity, higher contents of sodium, lower contents of iron and phosphorus, higher $Mg/(Mg+Fe)$ ratios and lower $K/(K+Na)$ ratios. These differences are most probably due to the late formation of the dyke rocks from the same magmatism that gave rise to the Porphyry group, resulting in a depletion of iron and phosphorus and in an enrichment of sodium. The same features are found in some of the volcanics of the Porphyry group, especially rocks in the vicinity of the iron ores of the Kiruna type. The existence of iron-phosphorus-depleted and sodium-enriched volcanics and dykes supports the magmatic concept of formation for this ore type. Both iron and phosphorus were depleted and separated into an intrusive phase at a late stage of the magmatism, thus giving rise to the ores.

There are three plutonic suites intersecting the supracrustal rocks. The oldest is the Granodiorite suite, consisting of a differentiated series from gabbro to granite with granodiorite as the dominating rock. The age is about 1 840–1 880 Ma. The Lina and related granites, of large areal extent, as a rule have an age of 1 530 Ma although for some granites an age of 1 780 Ma has been recorded. Of local restriction are perthite granites and perthite monzonites dated to 1 505–1 530 Ma. The Granodiorite suite is almost exclusively spatially associated with the rocks of the Greenstone group. In the same way the perthitic plutonites show a close spatial relation to the volcanics of the Porphyry group. From different variation diagrams it is evident that the Granodiorite suite falls within the same fields as the Greenstone group and the Perthitic suite falls within the same fields as the Porphyry group. Some of the perthitic plutonites show a depletion in iron and an enrichment in sodium similar to the trend in the Porphyry group. The Lina granite is in many respects similar to the Perthite suite, but differs in being more enriched in alkalis and somewhat more impoverished in iron. The petrochemical similarities, reinforced by the spatial association, which exist between the Greenstone group and the Granodiorite suite as well as between the Porphyry group and the Perthite suite, indicates a genetic relationship. For the Granodiorite suite, an origin involving mobilization by ultrametamorphism of the Greenstone group is most likely. A similar connection is also feasible for the Perthite suite and the Porphyry group. A common origin of the plutonites as a late phase in the magmatism that gave rise to the volcanics is contradicted by the great difference in radiometric ages.

During the differentiation of the Greenstone group there occurred a slight increase in iron but phosphorus remained constant; this is in contrast to the Porphyry group where

both elements decreased. As regards the intermediate to basic members, the phosphorus content is low in the Greenstone group compared to the Porphyry group. The dissimilarities between the two volcanic suites is attributed to differences in the primary magma, mainly the oxygen fugacity. The magmatic differentiation thus proceeded differently. In the Porphyry group, characterized by a higher degree of oxidation, there was a continuous depletion of iron (as magnetite), whereas the iron content in the Greenstone group remained constant. The magma of the Greenstone group, characterized by a low degree of oxidation, was enriched in iron and depleted in silica during solidification, and has followed the "Fenner trend" of differentiation. The Porphyry group, depleted in iron and phosphorus and enriched in silica during fractionation, has thus taken the "Bowen trend" of differentiation. At a late stage of the magmatism, after the extrusion and the solidification of the volcanics, the iron and phosphorus removed and retained in the magma chamber was injected as iron ores of the Kiruna type. The porphyry dykes which appeared at a late stage of the volcanism became also partly depleted in iron.

The iron oxide-apatite-rich intrusions in the Kiruna ores were formed by fractional crystallization at a late stage of the volcanism that gave rise to the Porphyry group. The late volcanics were depleted in iron and phosphorus and became enriched in sodium and magnesium. The primary homogeneous silicate melt was split into two distinct chemical portions prior to final crystallization; the iron oxide-apatite assemblage and the intermediate to acid, relatively alkaline magma. The high content of apatite lowered the melting point of the iron oxide assemblage. As apatite is known to be important in the liquation of silicate melts, this could explain the separation of the iron-rich magma. P_2O_5 depolymerizes pure SiO_2 melts by entering the network as four-fold coordinated cation, but polymerizes melts in which additional metal cations other than silica are present. The behaviour of phosphorus in igneous fractionation sequences depends on the state of polymerization of the magma. In the "Fenner trend" the state of polymerization in the liquid residual is constant, and consequently apatite crystallizes at a late stage. In magmas which are characterized by an enrichment of silica, *i.e.* an increase in the state of polymerization, apatite crystallizes at an earlier stage of crystallization. In a differentiation following the "Bowen trend", with enrichment of silica and a high oxygen fugacity, as in the volcanics of the Porphyry group, apatite consequently crystallizes early, and is consequently removed with the iron.

The salient features in the process giving the Kiruna iron ores are as follows: 1, the ores represent a late formation and 2, there are no gradational phases between the ore and the host rock volcanics. Whether the separation of the iron-phosphorus melt occurred by fractional crystallization or by liquid immiscibility is an open question. There are no indications of the latter process in the ores and the host rocks. In some deposits the volcanics contain rounded or elongated fillings with magnetite, hornblende, sphene, and apatite in varying amounts. These structures are most possibly of secondary origin and do not represent globules of true magmatic origin.

The metavolcanics and metasediments in the ore-bearing area of Norrbotten county occur largely in long linear belts mainly striking NE–NNE and NW. They represent basins formed by vertical block movements. During different epochs the delineating faults controlled the deposition of the supracrustals. The fractures were formed by intraplate tectonics and have not necessitated plate movements. The first initiation of these down-faulted troughs occurred in the Archean granite gneiss basement which was divided into rectilinear blocks by fracturing. The faulting activity was reactivated at different events during the Svecokarelian.

The deposition of the Greenstone and the Quartzite groups was mainly governed by the linear structures. The Schist-conglomerate group is also largely bound to the same basins as the Greenstone group. The deposition of the Porphyry group is only to a minor extent governed by the fault lines. The volcanics are, at least concerning the rhyolitic members, ash flows which have erupted from large-scale fissures, some of which possibly followed the directions of the above-indicated fault systems. Of crucial importance is a large NNE fault crossing the whole ore-bearing region. The zone which delineates the extension of the volcanics to the east, possibly represent a deep suture in the Earth's crust.

The rifting of the Precambrian has been of importance for the formation of the iron ores of the Kiruna type. The deposits in Northern Sweden are spatially related to the same fault systems which governed the development of the depositionary basins for the supracrustal rocks. The main part of the ores occur adjacent to fault systems which trend NW and NNE, to a minor extent with E–W systems. These large-scale tectonic lines guided the emplacement of the ore material. The same dependence on rigid tectonic features is found for the iron ore of the Kiruna type in the Precambrian of Missouri. That the Kiruna type of iron ore is connected with rifting, is emphasized by the alkaline affinity of the host rock volcanics. Typical for rifting in stable cratons is the occurrence of alkaline rocks, and even if the alkalinity is weak for the volcanics of the Kiruna ores, they fit into such a pattern. The continental character of the volcanism strengthens the hypothesis of formation in stable cratons.

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 SGU = Sveriges geologiska undersökning

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