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SERIE C NR 791 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 76 NR 4

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ALKALI METASOMATISM IN THE ORE-BEARING METAVOLCANICS OF CENTRAL SWEDEN

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ABSTRACT

Frietsch, Rudyard, 1982-02-23: Alkali metasomatism in the ore-bearing metavolcanics of Central Sweden. Sveriges geologiska undersökning, Ser. C, No. 791, pp. 1–54, Uppsala 1982.

The Early Proterozoic metavolcanics of Central Sweden (> 1 900 Ma) consist predominantly of felsic, quartz-alkali feldspar rocks of rhyolitic composition; dacites and andesites are subordinate. The felsic volcanics show a division into Na- and K-rich members, often in combination with a high silica content. These features are most pronounced in the volcanics which contain syngenetic, volcanogene deposits of iron ore, manganese ore and Cu-Fe and Zn-Pb-Fe sulphide ore. The ore-bearing volcanics differ from the barren varieties by:

1, the high content of SiO_2 which largely exceeds 75%,
2, the extreme division into Na- and K-rich members characterized by more than 5% Na_2O or K_2O; alkali-intermediate rocks are relatively rare,
3, the low content of Ca bound to silicates and
4, the paucity of mafic members.

A secondary internal reconstruction of the chemistry of the volcanics in connection with the ore-forming process is anticipated. The volcanics were subject to large-scale metasomatic alterations brought about by hydrothermal fluids. The original high temperature pre-alteration volcanics were extensive and more mafic, being possibly andesitic-dacitic in composition. It is worth noting that well-preserved mafic volcanics, which are Ca-bearing and alkali-intermediate, never contain ores. The mechanism resulting in rocks of extreme Na and K compositions is obscure although it may be attributed to different degrees of hydration or the sequence of mineral crystallization following devitrification of the volcanics. A close correlation exists between the enrichment of either sodium or potassium in the volcanics and the composition of the ore. For example, the Na-rich volcanics contain Ca-Mg silicate-bearing iron ores with Cu-Fe sulphides, whereas the K-rich volcanics contain Ca-Mg-Fe-Mn silicate-bearing iron ores with Zn-Pb-Fe-(As) sulphides, Fe-Mn oxide-silicate ores and Fe-Mn silicate rocks (eulysites). The Mn-Fe-Zn-Pb association in the potassic volcanics is formed at a low Eh and relatively high pH whereas the Fe-Cu association in the sodic volcanics indicates a more oxidizing and acid environment.

Comparisons with other metasomatically Na-K differentiated volcanic suites in New Zealand, south-eastern Ireland, New Brunswick, and Missouri, show that the ore-bearing volcanics of Central Sweden are exceptional in their combination of high $Na_2O + K_2O$ contents (mostly exceeding 6%) and a high content of SiO_2 (on average 72.7%). Ore-bearing volcanics with an alkali distribution similar to those in Central Sweden are scarcely found elsewhere. In south-western Finland, where there is a direct continuation of the volcanics of Central Sweden, the rocks are less metasomatically altered and consequently contain fewer ore deposits. Moreover the volcanics of the Tetagouche group in New Brunswick, with associated Zn-Pb-(Cu) sulphide ores and iron formations, resemble in some respects the ore-bearing volcanics of Central Sweden, but are predominantly potassic, the sodic varieties being less prominent.

It has been previously proposed that the volcanics of Central Sweden are the result of an island arc-type of volcanism in a subduction zone. This hypothesis has been partly based on the calc-alkaline character of the volcanism, but seems unlikely due to the dominance of the acidic rocks. If formed in a subduction zone, the overlying crust must have been of a considerable thickness to account for the acidic volcanism. However a regional metasomatic alteration of the original extensive andesites and dacites may present an alternative explanation for this feature. The volcanics, occurring mainly in a N–S extension, cover a large part of eastern and south-eastern Sweden, and therefore the hypothesis supporting an arc-formed structure seems unlikely.

INTRODUCTION

The iron, manganese and sulphide ores of Central Sweden occur in felsic metavolcanics with intercalated horizons of limestone and dolomite. The main part of the ores are present within the Bergslagen region which is situated about 150 km WNW of Stockholm (Fig. 1). The felsic metavolcanics, together with minor mafic metavolcanics, form an integral part of an Early Proterozoic supracrustal complex. This complex also includes metasediments consisting mainly of mica schists and mica gneisses reflecting original sediments of an argillaceous and greywacke character. Associated with the metasediments are subordinate mafic volcanics.

The felsic metavolcanics have long since attracted special interest by their distinctive mineralogical and chemical composition. A salient feature is their extreme subdivision into sodium and potassium varieties; alkali-intermediate types are relatively rare. A very high silica content is commonly another marked feature in addition to the fact that silica-intermediate and particularly basic rocks which dominate in most volcanic suites, are of little importance among the metavolcanics of Central Sweden.

The main aim of the present investigation concerns the petrological and chemical features of the felsic metavolcanics. The present author considers that the unusual composition of these rocks is not of a primary magmatic origin, being due instead to large-scale metasomatic alterations brought about late in the volcanism. The chemical changes are most pronounced in the ore-bearing volcanics which indicate a close genetical association between the post-volcanic alterations of the metavolcanics and the ore-forming processes.

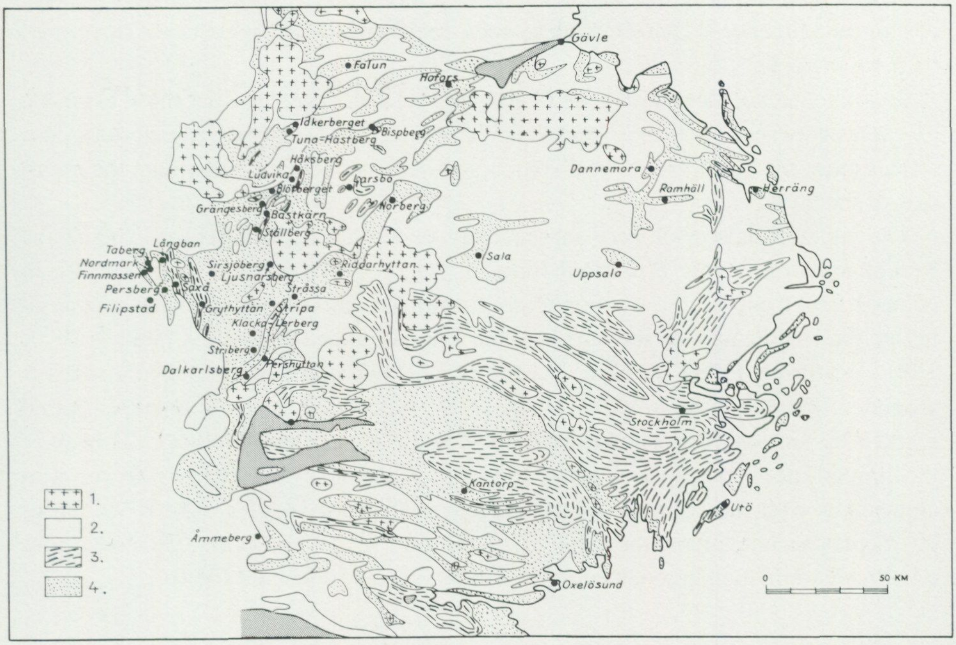


Fig. 1. Geological sketch map of the Precambrian of Central Sweden. The location of some iron ore and sulphide ore deposits is shown. From Magnusson (1966).
1. Late Svecokarelian granites. 2. Early Svecokarelian gabbros-granodiorites-granites. 3. Metasediments (argillites, greywackes and minor quartzites). 4. Metavolcanics (mainly felsic). Grey = Jotnian and Cambro-Silurian metasediments.

GEOLOGICAL SETTING

The volcano-sedimentary complex of Central Sweden includes a large number of basinal structures largely distorted by later folding. The supracrustal rocks occur in long narrow belts with lengths up to 100 km and the greatest thickness of the sequence is found in the southern part of the Bergslagen region. In an area extending from Grythyttan in the west to Stråssa and eventually to Riddarhyttan in the east (cf. Fig. 1), the volcano-sedimentary complex has a geophysically estimated depth of 6–10 km (Werner *et al*. 1977). The depths of the other belts are in the order 1–3 km.

The internal stratigraphy of the volcano-sedimentary complex is not yet fully established, but a threefold division seems most probable (Frietsch, in prep.). In the western part of the ore-bearing area the felsic metavolcanics are overlain by meta-argillites, metagreywackes and minor mafic volcanics. The metasediments occur in synforms mostly of restricted size, the largest being the Grythyttan and Saxå synforms (cf. Fig. 10). In the east, along the coast of the Baltic sea, the felsic metavolcanics are underlain by mica schists and mica gneisses of argillite to greywacke composition. In part similar metasediments are here also lying above the metavolcanics. There seems to be a general tendency that within the felsic metavolcanics the stratigraphically lower part of the sequence is characterized by sodic rocks and the stratigraphically upper part by potassic rocks.

Radiometric age determinations of the metavolcanics are few, but those available give ages between 1 900 and 1 830 Ma (Welin *et al.* 1980a, 1980b). In part these ages reflect more the stage of recrystallization and intrusive activity rather than the extrusion of the lavas.

The supracrustal rocks were subsequently folded and metamorphosed during the Svecokarelian orogenic evolution. Early in the orogeny, plutonic rocks ranging in composition from gabbro to granite were intruded, the granitoids being emplaced before the folding and the main peak of the Svecokarelian deformation (Stålhös 1979, 1981, Wikström 1979a, 1979b). The Rb/Sr radiometric age of the plutonic suites is around 1 900 Ma (Åberg 1978, Welin *et al.* 1980a). After a non-orogenic period marked by tensional forces and intrusion of mafic dykes (amphibolites), the peak of the orogeny took place resulting in the migmatization of the supracrustal rocks in connection with the intrusion of the Late Svecokarelian granites. The K-Ar age of pegmatites accompanying the latter is 1 826–1 712 Ma (Welin *et al.* 1980a), whereas a U-Pb determination has yielded 1 795 Ma (Welin and Blomqvist 1964).

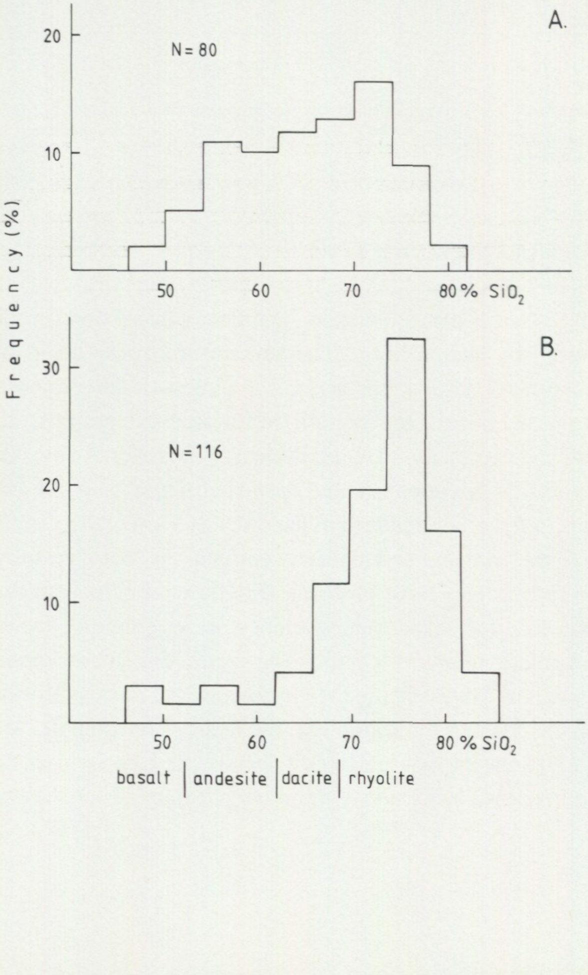


Fig. 2. Frequency distribution of the SiO_2 content (weight %) in the metavolcanics of Central Sweden. A. Ore-free rocks. B. Ore-bearing rocks.

DESCRIPTION OF THE METAVOLCANICS

The metavolcanics of the volcano-sedimentary complex are dominantly rhyolites (Fig. 2) with subordinate amounts of dacites and andesites accompanied by minor basalt occurrences. Within the acidic members, intercalations of limestones and dolomites are locally important.

Rhyolites — The rhyolites are composed of tuffs and tuffites, minor lavas and quite subordinate agglomerates. Volcanoclastic sediments containing a restricted amount of epiclastics comprise most of succession. The rocks are mostly layered, the width of the single layers varying from some millimetres to some decimetres. Cross-bedding and small-scale graded bedding occur occasionally and the whole sequence probably reflects deposition in a shallow subaqueous (submarine) environment.

The volcanics, according to their metamorphic state, are divided into dense ''hälleflintas'' (< 0.03–0.05 mm grain size) and fine-grained ''leptites'' (0.03–0.05 to 0.5 mm grain size). Texturally well-preserved ''hälleflintas'' are encountered farthest west in the low metamorphic (greenschist facies) terrains of Grythyttan and Filipstad. Beyond devitrification the metamorphic changes are small; the groundmass shows micropoikilitic, vitroclastic (shard), spherulitic, and granophyric textures (Sundius 1923, Magnusson 1925). In the tuffaceous sediments phenocryst fragments and fragments of rhyolites, trachytes and keratophyres occur. In part fluidal textures are preserved. It is probable that they represent ash-flow tuffs. In the porphyritic (lava) parts are present phenocrysts of quartz (most common), albite and microcline (rare).

In the ''leptites'' the primary textures have been destroyed by recrystallization which has resulted in a granoblastic texture. Exceeding the maximum grain size for the leptites (0.5 mm), the rocks are designated as ''leptite gneisses''. Due to the total recrystallization of the leptites none of the above described textures of the ''hälleflintas'' can be seen; the only primary texture that has been preserved is the porphyritic one. Within the ''leptites'', tuffs and lavas are still more difficult to distinguish. As a rule porphyritic rocks are never stratified, whereas the even-grained ''leptites'', expecially those rich in potassium, are stratified and thus clearly suggest tuffs. In the Dannemora and Ramhäll areas (cf. Fig. 1) there are ''leptitic'' rocks which are abnormally rich in ''phenocrysts'' of quartz and less commonly of microcline, albite and perthite. These volcanics, which gradually pass into breccias with cm-large rock fragments are, by Lindroth (1916) and Geijer and Magnusson (1944), considered to be of pyroclastic origin representing tuffaceous sediments and tuff breccias. On the whole there seems to be among the ''leptites'', similarly to the ''hälleflintas'', a dominance of pyroclastic sediments with real lavas playing only a subordinate role. Coarser fragmental rocks, such as agglomerates, are of quite local extension found both in ''hälleflintas'' (Sundius 1923) and ''leptites'' (Lindroth 1916, Magnusson 1940b, Lundegårdh *et al.* 1972).

The mineralogical composition of the rhyolitic metavolcanics can be simply described as quartz-feldspar rocks with only small amounts of dark minerals. The content of quartz is mostly high, 20–40 volume %, occasionally rising to 50 volume % or even more; the feldspar content is about 30–50 volume %. As already mentioned there is a subdivision of the metavolcanics into Na- and K-rich members, the former dominated by plagioclase (mostly albite or albite to oligoclase) and the latter by microcline. In the sodic metavolcanics the plagioclase content is about 30–40 volume % and the microcline content is low, not exceeding 10 volume %. In the potassic metavolcanics microcline comprises at most 50–60 volume %. There is therefore a great variation in the plagioclase and microcline contents.

It was considered previously (cf. for example Magnusson 1940b and Geijer 1963) that volcanics with an intermediate proportion of alkali feldspar are relatively rare. This statement needs, however, some modification. As will be shown below, alkali-intermediate volcanics are present, even if in minor amounts, particularly in areas not affected by ore-forming processes. There are alkali-intermediate volcanics in which quartz, plagioclase and microcline comprise 30 volume % each. These occur in the Örebro area (Lundegårdh *et al.* 1972), the Uppsala area (Stålhös 1972) and the Eskilstuna area (Lundegårdh 1974). Even in the ore-bearing metavolcanics, where the alkali division is most pronounced, a larger extension of alkali-intermediate rocks is found at Silvberg-Säter (Geijer and Magnusson 1944). In the Nordmark area, within the stratigraphically lower volcanic unit, there is an intense interlayering between sodic and alkali-intermediate volcanics (Magnusson 1925). The latter are also locally found in the Ljusnarsberg area at the Lomberg and Svartvik ore deposits (Magnusson 1940b).

In part the quartz-feldspar minerals occur as coarser phenocrysts. In the sodic volcanics the phenocrysts are quartz and plagioclase, and, in the potassic volcanics, quartz and microcline.

The content of mafic minerals within the rhyolites is mostly low, 5–20 volume %, consisting mainly of biotite; muscovite–sericite is present partly as an alteration of plagioclase. In the potassic, microcline-dominated volcanics, muscovite–sericite makes up 5–20 volume % and chlorite is mostly present in small amounts often replacing biotite. Minerals occurring in small or accessory amounts are epidote, iron oxides (magnetite or hematite), apatite, zircon, sphene, and calcite. Calcite, which in most cases is a primary constituent, can also locally enter the volcanics in larger amounts.

Dacites–andesites–(basalts) — The intermediate to basic metavolcanics of Central Sweden vary in composition from dacites to andesites, basalts being rare (cf. Fig. 2). They differ from the acidic volcanics by a lower content of quartz and higher contents of a more calcic plagioclase and of dark minerals. The intermediate to basic rocks are often porphyritic with phenocrysts of plagioclase, less commonly of quartz.

The mineralogical composition of the metadacites consists of quartz (10–30 volume

%), andesine plagioclase (30–50 volume %), biotite (10–20 volume %), and hornblende (up to *c*. 10 volume %); microcline occurs in varying but mostly small amounts. The metaandesites are composed of quartz (less than 20 volume %), plagioclase (andesine to labradorite; 25–50 volume %), biotite (10–25 volume %), and hornblende (10–40 volume %, occasionally up to 55 volume %). Microcline is not present. Iron oxides, chlorite, epidote, sphene, and apatite occur in small amounts (up to several volume %) or as accessories.

The intermediate to basic metavolcanics have restricted extension occurring in only a few areas scattered over Central Sweden. Dacites are found in subordinate amounts at Riddarhyttan (Geijer 1923), at Norberg (Geijer 1936) and in the Larsbo area (Hjelmqvist 1938); in the latter area there are also some minor basalts. Dacites and andesites are encountered at Garpenberg (Lindroth 1924, Geijer and Magnusson 1944). Dacitic and andesitic lavas appear in increasing amounts in the eastern and south-eastern part of Central Sweden (see below).

It has previously been stated (cf. for example Geijer and Magnusson 1944) that the mafic volcanics are interlayered with the acidic potassic metavolcanics existing high up in the stratigraphy and that they are restricted to the eastern and central part of Central Sweden. However, this statement needs some modification. It is true that the mafic volcanics are mostly found in the eastern and central parts of the region, but occurrences are also found in the west, for example, west and south-west of Lindesberg dacites and quartz-dacites cover a large area (Koark and Lundström 1979). The stratigraphic position of these mafic metavolcanics must be regarded as unknown or at least uncertain. In the Lindesberg area these rocks definitely occur in the stratigraphy underlying the felsic metavolcanics (Koark and Lundström, *ibid.*). The same seems to be valid for the Örebro area where metabasites of andesitic composition occur relatively abundantly in the lower sodic felsic metavolcanics, and to a lesser extent in the upper potassic felsic metavolcanics (Lundegårdh *et al.* 1972). In the sodic volcanics the metabasites occur at the bottom of the sequence. Other occurrences of the intermediate to basic volcanics, mostly metaandesites and metaquartz-andesites, have a less well-definded stratigraphic position. There is however a general tendency that the mafic metavolcanics occur near to the potassic acidic metavolcanics or metasedimentary schists and gneisses mostly of argillitic composition, overlying the felsic volcanics. Examples are found in the Nyköping area (Lundström 1974, 1976), the Norrköping area, where the mafic metavolcanics comprise the main part of the volcanic rocks (Kornfält 1975, Wikström 1975), and from the Uppsala area (Stålhös 1972). At Grängesberg the mafic volcanics are more related to the potassic volcanics than to the sodic ones (Magnusson 1938). In the Garpenberg area the association between the mafic volcanics and the potassic felsic volcanics is less obvious; here the mafic volcanics mostly pass into alkali-intermediate acidic volcanics with minor intercalations of potassic rocks (Lindroth 1924).

CHEMICAL FEATURES OF THE METAVOLCANICS

The most outstanding petrochemical feature of the acidic metavolcanics of Central Sweden is their division into alkali-extreme (sodium or potassium) members and their partly very high content of silica (75% SiO_2 or more).

A great number of analyses have been used in determining the chemical character of the volcanics. The analyses have been divided by the present author into two groups according to whether they occur in areas which are ore-bearing or not. As will be shown the composition of the volcanics is dependent on whether they are associated with ores or not. This division is naturally rather arbitrary and consequently not without contradictions. Volcanics which are not directly associated with ore but which occur in an area that on the whole is ore-bearing, are assigned as ore-bearing volcanics. For example, all analyses of volcanics on the Filipstad NV map sheet are considered as ore-bearing, even if the distance of the volcanics to the nearest ore deposit is of the order of one to several kilometres. On other words it is supposed that the volcanics have been affected on a regional scale by the ore-forming processes. Most of the ore-bearing analyses are thus found in the north-western part of Central Sweden within the Bergslagen region; additional ore-bearing volcanics occur in the east along the coast in the Utö, Nyköping, Ramhäll, and Herräng areas. Ore-free volcanics are mainly found in southern and south-eastern Central Sweden around Uppsala, Norrköping, Eskilstuna, and Örebro.

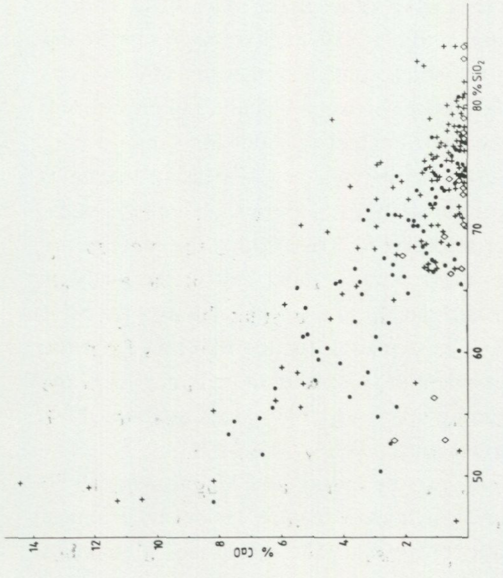
Analyses (66 samples) relating to ore-bearing volcanics are taken from Lindroth (1916, pp. 20, 25, 30, and 43), Geijer (1917, p. 36), Geijer (1923, pp. 14 and 17), Sundius (1923, pp. 91, 110, 115, 121, 128, and 151), Lindroth (1924, p. 594), Magnusson (1925, p. 47), Geijer (1927, p. 11), Geijer (1936, pp. 13 and 15), Magnusson (1938, p. 8), Magnusson (1940a, p. 19), Magnusson (1940b, pp. 24–27), Geijer and Magnusson (1944, p. 23), Hübner (1966), and Lundström (1974, p. 17). In addition 50 unpublished analyses have been taken from the Utö area (18 analyses from Stålhös 1982) and from the Filipstad NV map sheet (32 analyses collected by the late U. Wiklander). In all, some 116 analyses of ore-bearing volcanics have been treated. Locally, in the vicinity of the ores, the volcanics have been subject to a strong metasomatic alteration mainly resulting in an enrichment of magnesium. Seventeen analyses of Mg-rich alteration rocks have been taken from Geijer (1923, pp. 23–24), Magnusson (1925, pp. 128 and 136), Hübner (1966), and from geological map sheet Lindesberg SV (2 analyses from Lundström, in prep.). Eighty analyses of ore-free volcanics were taken from Lundegårdh (1956, p. 10: Uppsala area), Lundegårdh *et al.* (1972, pp. 94–95, 101, 104, and 106–107: Örebro area), Stålhös (1972, pp. 54 and 66: Uppsala area), Lundegårdh (1974, pp. 63–65: Eskilstuna area), Kornfält (1975, p. 15: Norrköping area), Wikström (1975, p. 24: Norrköping area), Lundström (1976, pp. 20 and 23: Nyköping area), and Stålhös (1979, p. 26: Nynäshamn area). The total number of analyses treated is 213.

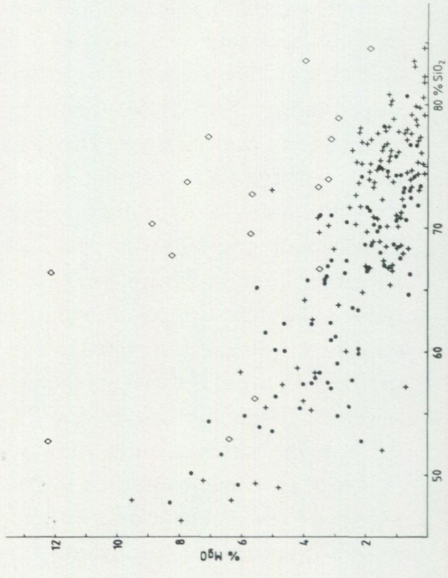
The silica content — The metavolcanics have been chemically divided into the following classes based in the SiO_2 content: less than 53% as basalt, 53–62% as andesite, 62–68% as dacite, and more than 68% as rhyolite. In the main the division is in accordance with that given by Stillman and Williams (1978), Cox *et al.* (1979) and Gill (1981). The frequency distribution of the silica content in the volcanic rocks is shown in Fig. 2 which illustrates obvious differences between volcanics in ore-bearing areas and in barren areas. The range of the SiO_2 content is about the same in both cases, but the SiO_2 distribution is quite different. Within the ore-bearing volcanics rhyolites dominate constituting about 85% of the analyses, and thus in comparison the intermediate and basic volcanics are under-represented. On average the ore-bearing volcanics contain 72.2% SiO_2. In the ore-free volcanics about half of the analyses show a rhyolitic composition and the other half dacitic to andesitic; the average SiO_2 content for all ore-free volcanics is 65.1%. Characteristic for the rhyolites from the ore-bearing areas is therefore the very high content of silica with more than 50% of the analyses containing above 75% SiO_2 including some extreme values attaining 85% SiO_2. In the barren rhyolites the silica content is mostly below 75% SiO_2.

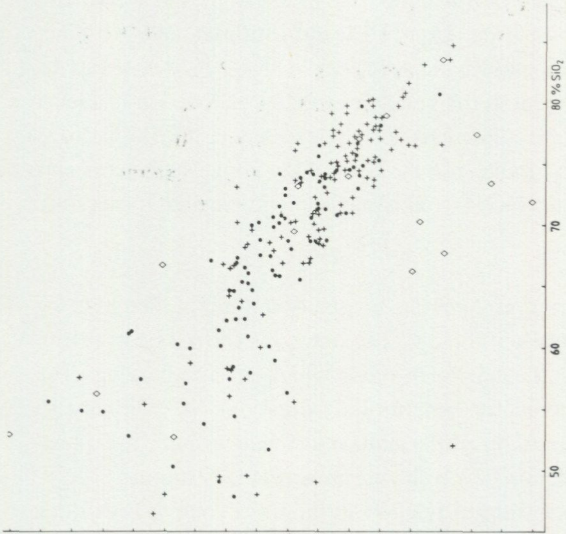
The high content of silica in the volcanics was by Geijer and Magnusson (1944) ascribed to the volcanic activity being a primary magmatic feature. However, it is most possibly caused by secondary metasomatic processes. The extremely high silica contents (exceeding 75% SiO_2) mainly found in the ore-bearing volcanics do not occur in normal magmatic volcanic rocks (Fig. 5C). In addition the frequency distributions of the SiO_2 percentages are different from most volcanic rocks of tholeiitic and calc-alkaline character; they have a basaltic to andesitic composition (Miyashiro 1974). Only in suites which have undergone metasomatic alterations are similarly high silica contents encountered. A frequency distribution in which high silica contents predominate occurs in the volcanics of south-eastern Ireland (Stillman and Williams 1978) which have been subjected to metasomatic processes (cf. p. 31). According to Lundström (1974) the high silica content in the volcanics of Central Sweden is due to sedimentary reworking. Although a sedimentary origin explaining the high SiO_2 contents cannot be excluded, it seems unlikely in the light of the above statements and the chemical features below presented which favour a metasomatic mode of formation.

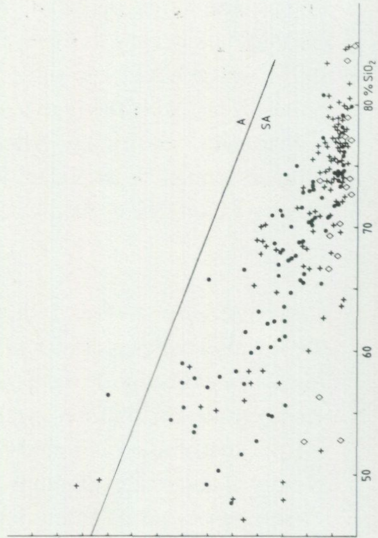
Other elements — Fig. 3 shows variation diagrams of major and minor elements for the metavolcanics plotted against the silica content. The diagrams show a large scatter for some elements in the volcanics, especially in those which are ore-bearing. The most erratic distribution is encountered for sodium and potassium. A relatively irregular distribution is found for aluminium, iron, manganese, magnesium, and phosphorus in contrast to titanium and calcium which show a more regular pattern.

The behaviour of sodium and potassium in relation to the SiO_2 content within the ore-free metavolcanics is in accordance with what is usual in volcanic, especially calc-alkaline suites; *i.e.* both elements increase with increasing acidity, the increase


% CaO
14
12
10
8
6
4
2
50
60
70
80 % SiO$_2$


% MgO
12
10
8
6
4
2
50
60
70
80 % SiO$_2$


%Al$_2$O$_3$
22
20
18
16
14
12
10
8
6
50
60
70
80 % SiO$_2$


%TiO$_2$
2.4
2.0
1.6
1.2
0.8
0.4
A
SA
50
60
70
80 % SiO$_2$

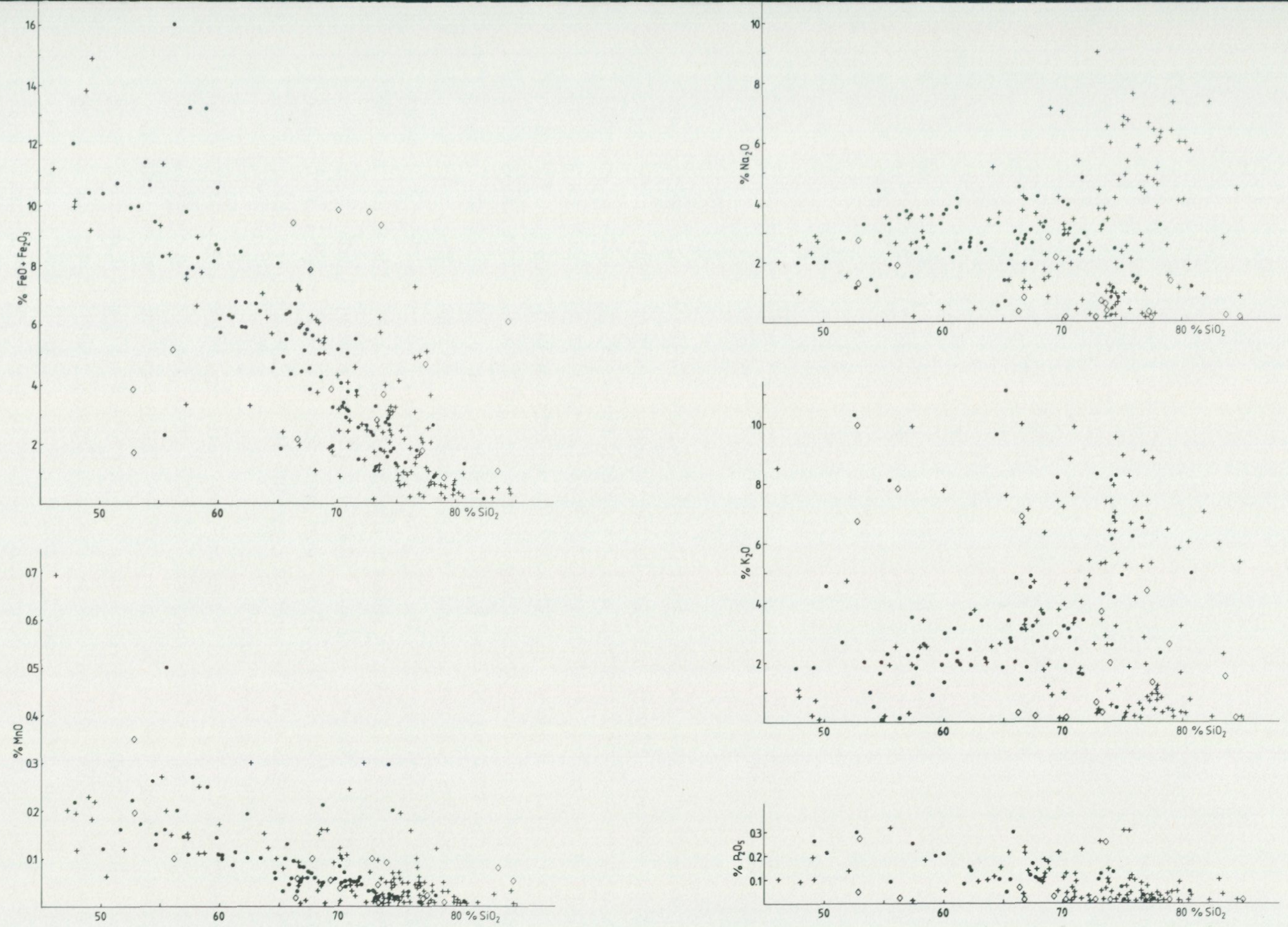


Fig. 3. Major and minor elements against SiO₂ in the metavolcanics of Central Sweden (weight %). Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks. The oblique line in the TiO₂ diagram after Whitehead and Goodfellow (1978) determines the subalkaline (SA) and alkaline (A) fields.

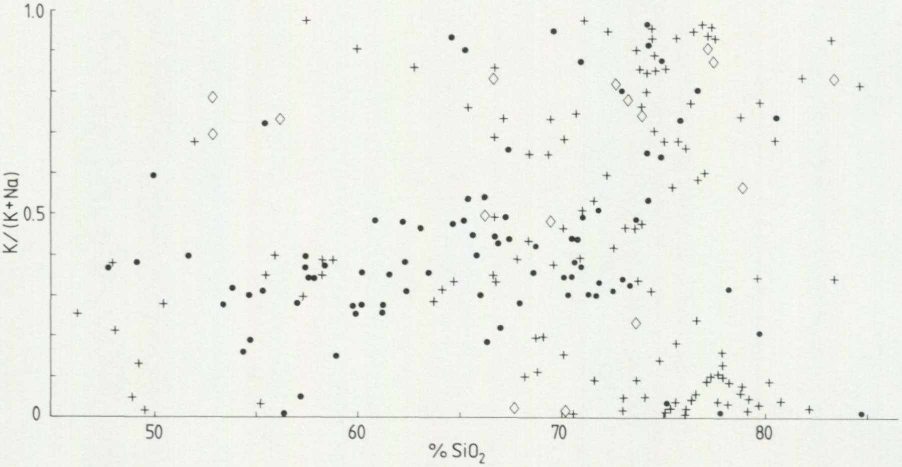


Fig. 4. Atomic ratio K/(K + Na) against weight % SiO_2 in metavolcanics of Central Sweden. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks.

being somewhat greater for potassium than for sodium. In the ore-bearing metavolcanics this pattern is largely destroyed for the rhyolitic members within which the Na and K contents vary between high and low values. However, the dacitic to andesitic members show a normal alkali distribution. A plot of the K/(K+Na) ratio (atomic %) against SiO_2 (Fig. 4) shows the tendency for an enrichment of either of the alkali elements in the ore-bearing felsic rocks. In this diagram there is a segregation of the ore-bearing rhyolites into Na- and K-rich assemblages, whereas the ore-free volcanics show a uniform increase in the ratio from low to intermediate values. The total amount of alkalies is, however, roughly the same in both types of volcanics. Fig. 5A shows that the barren volcanics contain about 5–10% Na_2O + K_2O; Fig. 5B shows that the highest contents of Na_2O + K_20 are found in the K-rich volcanics, mainly from the ore-bearing areas. Almost all analyses with more than 8% alkalies are K-rich which contrasts with most of the alkali-intermediate and the Na-rich volcanics which have a Na_2O + K_2O content of less than 6%.

As seen from Fig. 3 most of the other elements have roughly the same distribution in the ore-bearing and ore-free volcanics; in both cases the contents decrease with increasing content of SiO_2. The contents of iron, manganese, magnesium, and phosphorus in the ore-bearing metavolcanics are in part somewhat higher than in the barren metavolcanics. In the acidic members of the ore-bearing metavolcanics the extreme scatter of the iron content (bound to mafic silicates and iron oxides) is rather pronounced. That the iron and/or magnesium contents of the ore-bearing metavolcanics have been subject to redistribution is shown by the lack of relationship between the

Mg/(Mg+Fe) ratio (atomic %) and the silica content (Fig. 6). In subalkaline volcanic suites there is usually a decrease of the ratio with increasing silica content (Osborn 1979). As seen from Fig. 6 this is valid in the barren metavolcanics of Central Sweden, whereas in the ore-bearing metavolcanics there is a strong variation between low and high values for the ratio. In general the ore-bearing volcanics have a high magnesium/iron ratio indicating magnesium enrichment and iron depletion (cf. also Fig. 9).

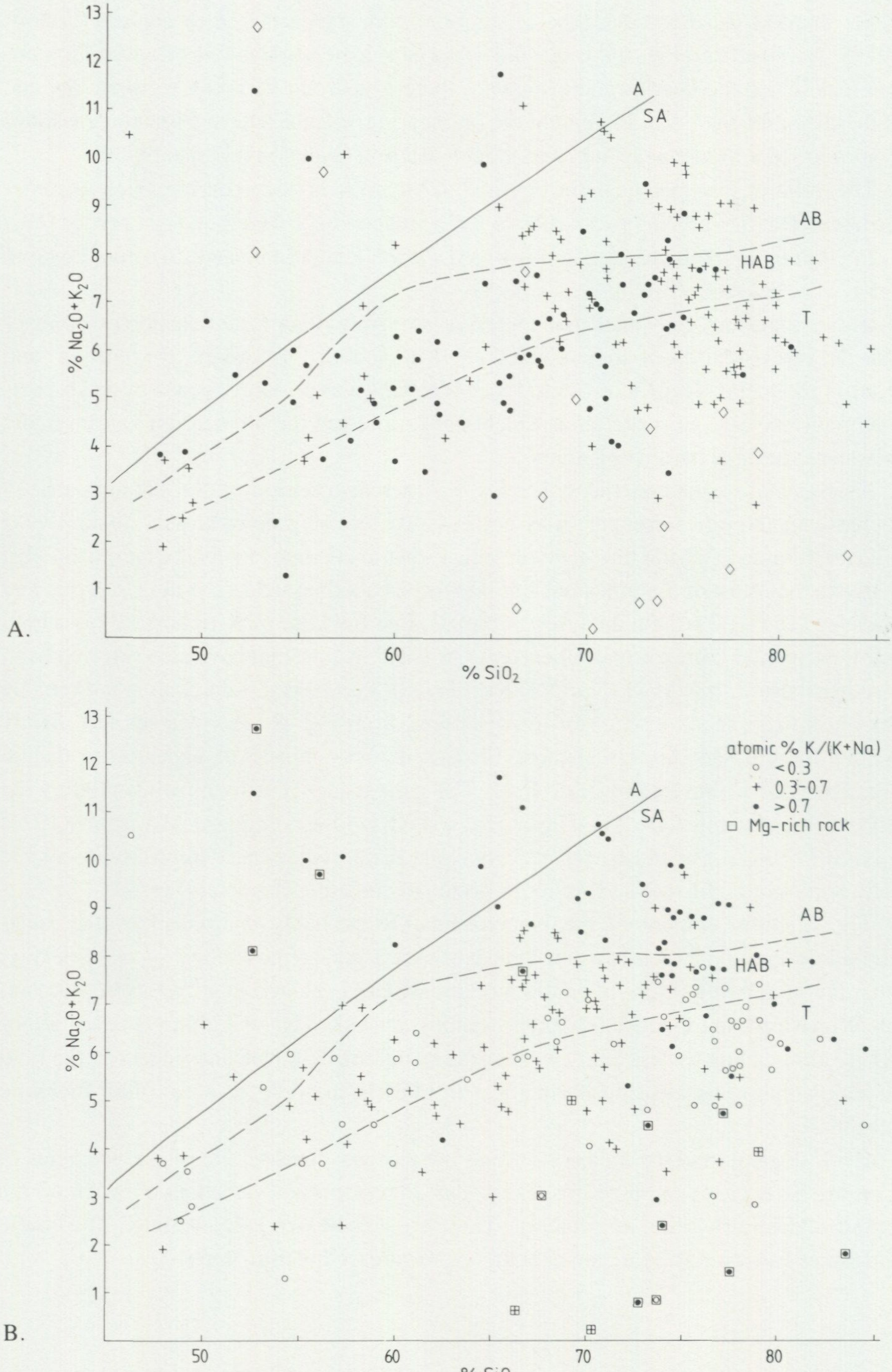
The relationship between ferrous and ferric iron in the metavolcanics is rather variable. The ore-bearing rocks show a large range of $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratios (Fig. 7) in contrast to the barren volcanics which show a less pronounced variation, being in most cases below 0.3.

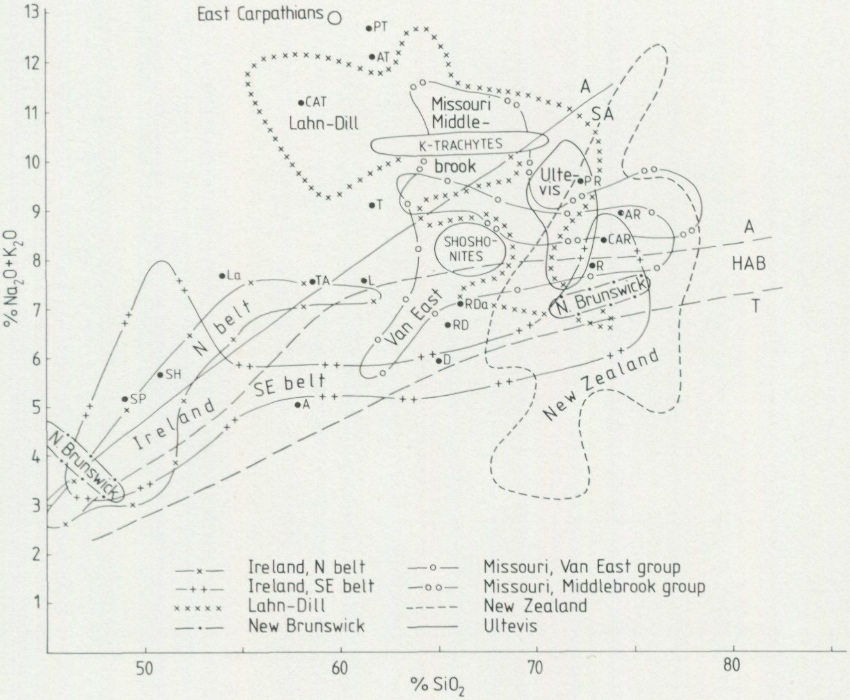
It can therefore be stated that there are strong reasons to anticipate a secondary internal redistribution of some elements (silica, sodium, potassium, magnesium, and iron) in the metavolcanics of Central Sweden. This was possibly caused by a syn-post-magmatic metasomatic alteration which mainly affected the ore-bearing volcanics and to some extent the barren volcanics.

As the main effect in the volcanics was a redistribution of the alkalies and an increase in the silica content, it is not possible by using conventional alkali *versus* silica diagrams to assign the metavolcanics either to alkaline or subalkaline suites. Fig. 5 shows that most of the volcanics fall into the subalkaline field according to Irvine and Barager (1971). The few analyses in the alkaline field are of K-rich rocks from both ore-bearing and barren environments. As iron and magnesium have also suffered from a redistribution, the AFM ($Na_2O + K_2O/FeO + Fe_2O_3/MgO$) diagram is not reliable for classification purposes. However, as seen from Fig. 8 the volcanics fall mainly within the calc-alkaline to alkaline field, and rocks mostly of andesitic to dacitic character fall within the tholeiitic field. The same tendency is found when plotting the SiO_2 content against the FeO^X(total iron)/MgO ratio according to Miyashiro (1974) and Gill (1981). For the barren volcanics the main evolutionary trend is calc-alkalic with the more mafic rocks exhibiting a dominant tholeiitic character (Fig. 9).

The titanium content of the metavolcanics is probably unaffected by the metasomatic alteration processes and thus provides a greater possibility of classification than the alkali-silica-iron-magnesium relationships. If plotted in a TiO_2-SiO_2 diagram by Whitehead and Goodfellow (1978) almost all volcanics of Central Sweden are of subalkaline character (cf. Fig. 3). The acid to intermediate volcanics occur in the field of calc-alkaline basalts and the mafic volcanics in the field of ocean-floor tholeiitic basalts.

Even if great uncertainties concerning the primary composition of the volçanics of Central Sweden exist, it seems likely that they represent subalkaline rocks of the basalt-andesite-rhyolite association. They are essentially calc-alkaline. The mafic volcanics however show a greater tendency towards a tholeiitic trend.


A.
% Na$_2$O + K$_2$O
% SiO$_2$
1
2
3
4
5
6
7
8
9
10
11
12
13
50
60
70
80
A
SA
AB
HAB
T
B.
atomic % K/(K+Na)
○ <0.3
+ 0.3–0.7
● >0.7
□ Mg-rich rock



C.

Fig. 5. $Na_2O + K_2O$ against SiO_2 in volcanic rocks. (Weight %.) The upper continuous line after Irvine and Baragar (1971) determines the alkaline (A) and the subalkaline (SA = tholeiitic basalt and calc-alkali) rock suites. The broken line after Kuno (1968) determines the alkali basalt (AB), the high-alumina (HAB) and the tholeiite (T) rock suites.

A. Metavolcanics of Central Sweden. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks.

B. Same as A, showing the K/(K + Na) ratio (atomic %).

C. Some volcanic rock types (average composition) and volcanic suites (several analyses).

Average compositions: CAR = calc-alkali rhyolite, AR = alkali rhyolite, PR = peralkaline rhyolite, RDa = rhyodacite, CAT = calc-alkali trachyte, AT = alkali trachyte, PT = peralkaline trachyte and La = latite from Nockolds (1954), T = trachyte, R = rhyolite, RD = rhyodacite, D = dacite, L = latite, TA = trachyandesite and A = andesite from Le Maitre (1976), SP = spilite from Vallance (1969), and SH = shoshonite from Pearce (1976).

Several analyses: shoshonites from Joplin (1968), K-trachytes from Ewart (1979); Ireland, SE belt (basalts-andesites-dacites-rhyolites) and N belt (basalts-andesites-dacites) from Stillman and Williams (1978); Lahn-Dill (keratophyres) from Lehman (1941); Missouri, Middlebrook group and Van East group (rhyolites and dacites) from Kisvarsanyi (1972); New Brunswick (mafic to felsic volcanics) from Whitehead and Goodfellow (1978); New Zealand (keratophyres) from Battey (1955) and (rhyolites-ignimbrites) from Challis (1971); Ultevis (rhyolites) from Ödman (1957).

One analysis: East Carpathians (andesite) from Radulescu (1966).

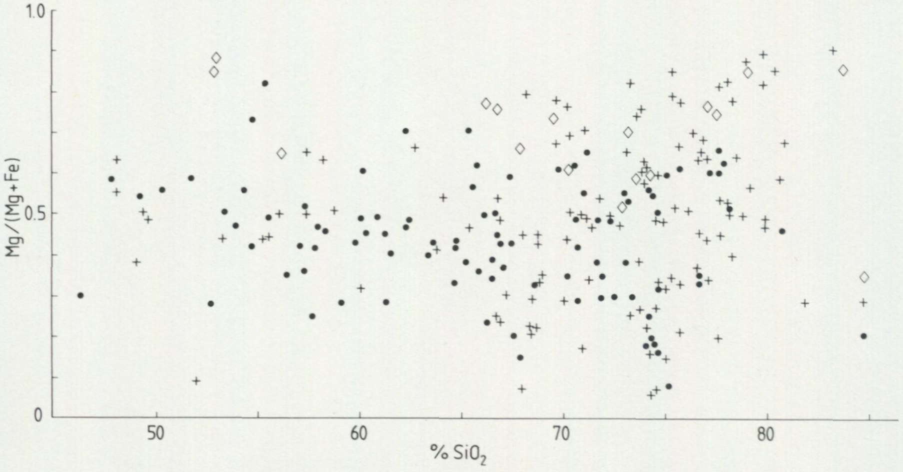


Fig. 6. Atomic ratio Mg/(Mg + Fe) against weight % SiO_2 in the metavolcanics of Central Sweden. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks.

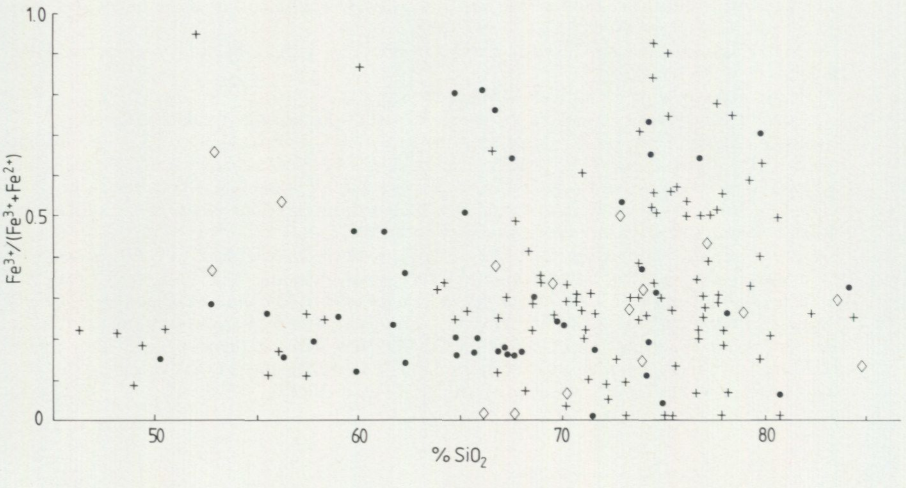


Fig. 7. Atomic ratio $Fe^{3+}/(Fe^{3+} + Fe^{2+})$ against weight % SiO_2 in the metavolcanics of Central Sweden. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks.

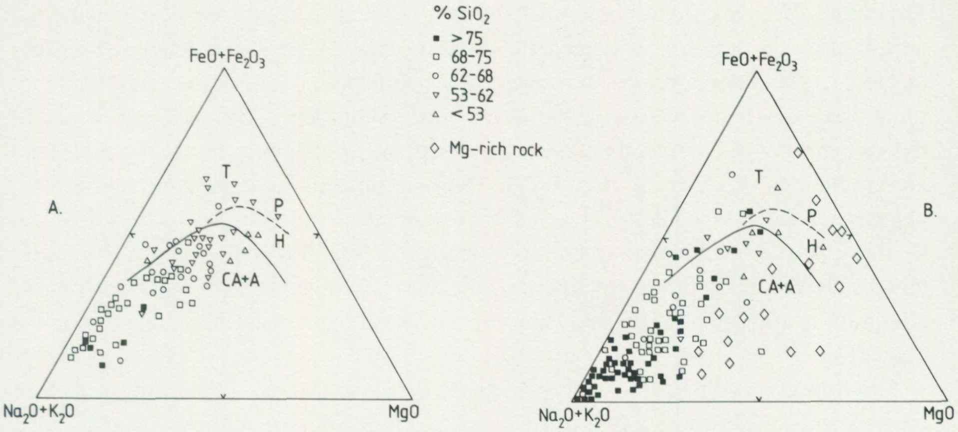


Fig. 8. AFM diagram (weight %) for the metavolcanics of Central Sweden. A. Ore-free rocks. B. Ore-bearing rocks. The continuous line after Irvine and Baragar (1971) determines tholeiitic (T) and calc-alkaline-alkaline (CA + A) rock suites and the broken line after Kuno (1968) the pigeonitic (P) and hyperstenic (H) rock suites.

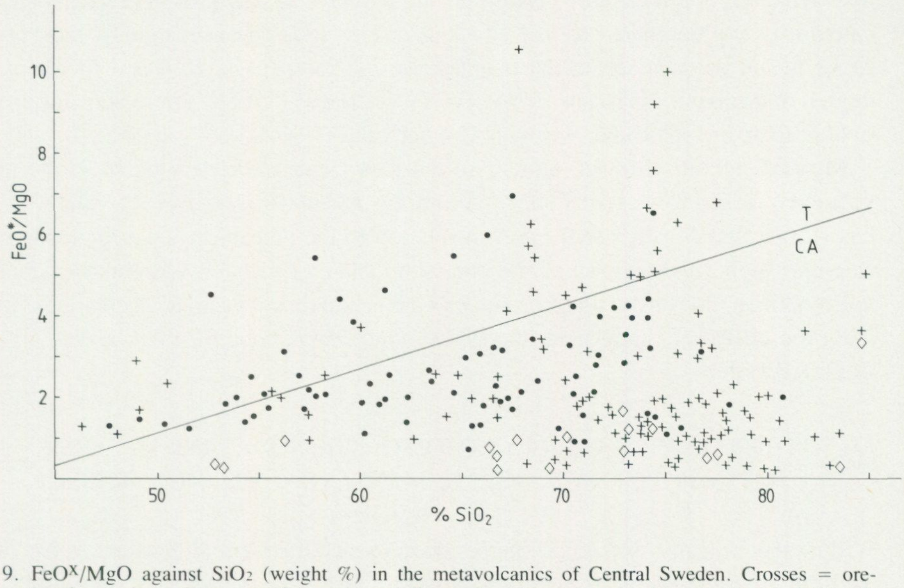


Fig. 9. FeO^{X}/MgO against SiO_2 (weight %) in the metavolcanics of Central Sweden. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks. Line dividing tholeiitic (T) from calc-alkaline (CA) compositions is after Miyashiro (1974) and Gill (1981).

CHEMICAL FEATURES OF THE Mg-RICH ALTERATION ROCKS

The sulphide ores, and also some of the iron deposits, are accompanied by a Mg-rich alteration which has given rise to minerals such as cordierite, anthophyllite and serpentine. The Mg-rich alterations have in a regional context mainly a stratabound appearance and represent a syngenetic metasomatism of the metavolcanics (Frietsch, in prep.). The alterations are, however, very restricted in comparison with the large-scale processes that gave rise to the alkali ''differentitation'' and silica enrichment in the volcanics of the ore-bearing areas. However, the age relations of the Mg-rich rocks are ambiguous (Frietsch, in prep.). The Mg-rich minerals have partly a post-tectonic appearance in the volcanics. The occurrence of local alterations, partly with sulphides, in the Early Svecokarelian plutonites (around 1 900 Ma old) and the still later metabasite dykes, both intersecting the volcanics, indicates that the Mg-metasomatic alteration is a multiphase process, however, with the main phase occurring during the volcanism.

The formation of the Mg-rich rocks involved radical changes in the composition of the volcanics. There was a loss of titanium, calcium, sodium, and phosphorus, and a gain of magnesium, whereas iron and potassium show indecisive variations (Fig. 3). A decrease for aluminium and an increase for manganese is partly obvious. The total amount of alkalies has decreased, being mostly lower than 4–5% $Na_2O + K_2O$ (Fig. 5), even if some of the Mg-rich rocks contain 8–13% $Na_2O + K_2O$. In the latter case the rocks are rich in potassium which occurs in muscovite or less commonly in biotite. Mostly there has been an increase in the content of potassium compared to sodium; the Mg-rich alteration rocks have mainly a high K/(Na + K) ratio (Fig. 4). The content of calcium is low compared to that of alkalies (Fig. 13). The formation of the Mg-rich rocks meant an increase in the magnesium/iron ratio (Figs. 6, 8 and 9) and a low degree of oxidation (Frietsch 1976). The $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratio is mainly below 0.4 but there are some analyses with a higher value (Fig. 7).

Mg-rich alteration rocks, similar to those in Central Sweden, occur in the metavolcanics in south-western Finland. From the Aijala–Orijärvi area Latvalahti (1979) has shown that Mg-rich rocks are, in relation to the volcanics, lower in sodium and calcium, higher in magnesium and potassium and partly also in aluminium. Titanium has remained unchanged and iron shows both negative and positive fluctuations. In the main the chemical changes are the same as indicated above for the Mg-rich rocks of Central Sweden.

THE STRATIGRAPHIC POSITION OF THE SODIC AND POTASSIC METAVOLCANICS AND THEIR INTERNAL RELATIONSHIPS

Within the volcanic sequence in the western part of Central Sweden it has been possible to establish a stratigraphic division based on the content of sodium and potassium; stratigraphically the Na-rich volcanics occur more frequently below the

K-rich ones (Sundius 1923, Magnusson 1925, 1940b, Hjelmqvist 1937). There is thus a common tendency that the potassic volcanics occur at high levels in the sequence, often adjacent to the synforms with greywacke–argillite metasediments (Geijer and Magnusson 1944, Pl. 1, and Frietsch, in prep.). However, this Na–K stratigraphy has many limitations which include the interlayering of the Na-rich and K-rich volcanics with rapid changes over short distances (see below) and also K-rich volcanics sometimes occurring in the lower part of the sequence. In addition there seems to be a difference in the regional distribution of the Na- and K-rich metavolcanics, for example, in the western and central parts of Central Sweden there is a dominance of Na-rich volcanics, whereas in the eastern part, along the coast, K-rich volcanites prevail. In the Nyköping area (Lundström 1976) and the Nynäshamn area (Stålhös 1979) the volcanics are almost solely potassic. In addition it has been suggested that within the metavolcanics there is an uppermost unit which consists of alkali-intermediate rocks (Geijer and Magnusson 1944). This division is, however, doubtful or very poorly developed (Lundegårdh 1949, 1974, Lundegårdh and Nisca 1978).

In order to support the existence of the above outlined stratigraphy based on the Na- and K-dominance of the metavolcanics, a great number of partial analyses of Na, K and Ca in the volcanics from map sheet Filipstad NV, collected by the late U. Wiklander, have been plotted in Fig. 10. It shows that the division into a stratigraphically lower sodic unit and a stratigraphically higher potassic unit generally exists. Seen in detail the distribution between sodic and potassic volcanics is irregular, but in a wider context there is a tendency that the stratigraphically higher volcanics, close to the above lying metaargillites-greywackes in the central part of the basins, are dominantly potassic, whereas the volcanics farther aside, in a stratigraphically lower position, are dominantly sodic. This is evident for example west of the Saxå synform (Fig. 10) where the adjacent volcanics are potassic whilst those farther west are alkali-intermediate and sodic. Lower in the stratigraphy, in the Persberg area, the sodic volcanics dominate almost totally. Towards the north-west in the Nordmark area and still lower in the stratigraphy there is an irregular Na–K distribution, a feature already noted by Magnusson (1925). This irregular distribution is possibly due to sedimentary intercalations within the volcanics, particularly against the Nordmark quartzites farthest in north-west. In spite of these irregularities there is, however, in the Nordmark area a predominance of sodic volcanics, and the chemical composition is thus in accordance with the stratigraphic position. Eastwards from the Saxå synform towards the Grythyttan synform, the volcanics adjacent to both are potassic. Between the synforms, west of Lake Stor-Sången, the variations of sodium and potassium are rapid. On the whole the "alkali stratigraphy" holds true also for this area.

On the map illustrated in Fig. 10 are plotted analyses of the metavolcanics that contain more than 20% Ca (atomic %) of the total amount of Na, K and Ca. It is not known how much calcium is bound to carbonates and calcium-bearing silicates other than plagioclase. The distribution of the Ca-bearing samples does not show any regular traits, being scattered over the whole area. Noticeable is the fact that they are equally

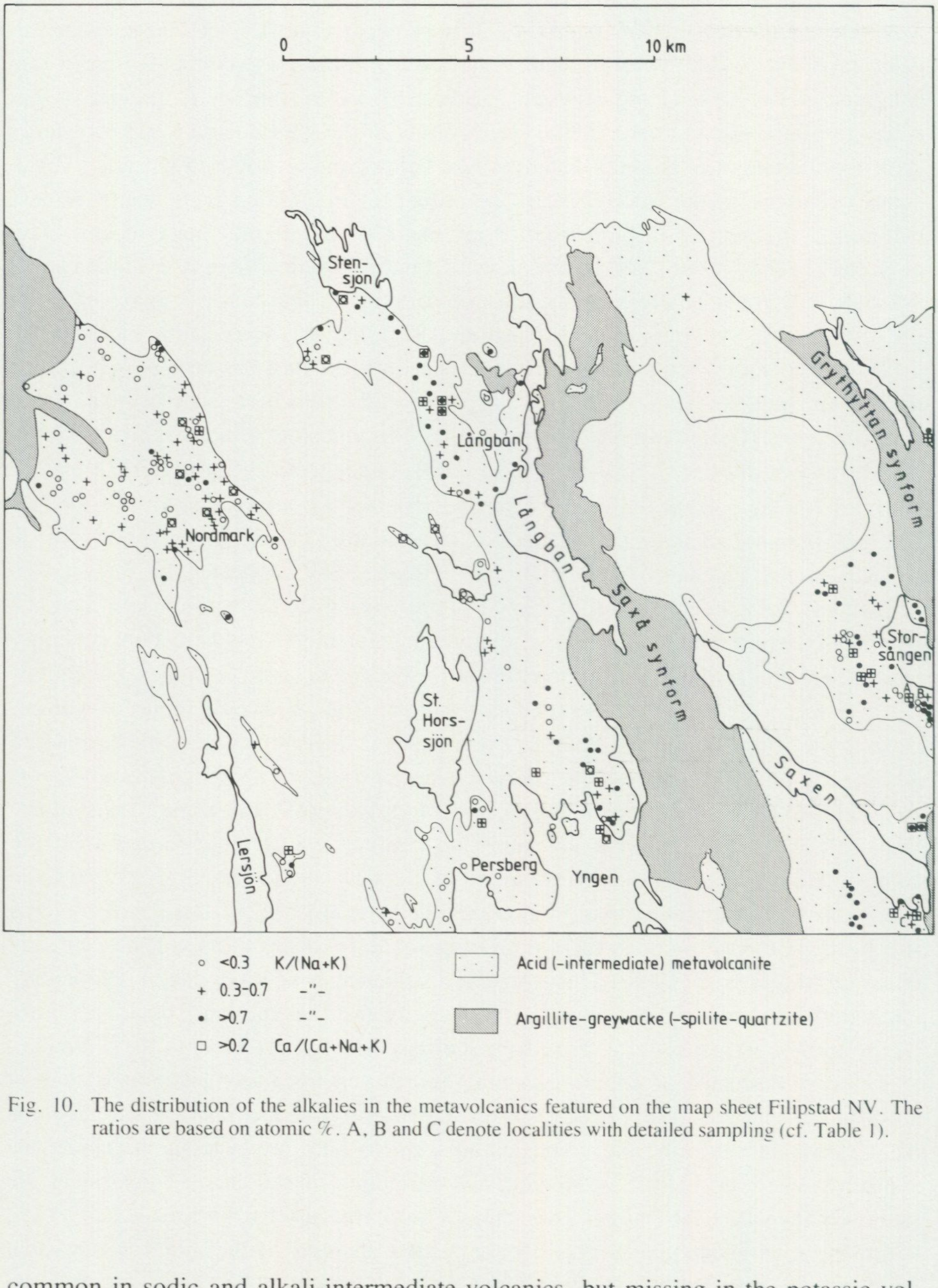


Fig. 10. The distribution of the alkalies in the metavolcanics featured on the map sheet Filipstad NV. The ratios are based on atomic %. A, B and C denote localities with detailed sampling (cf. Table 1).

common in sodic and alkali-intermediate volcanics, but missing in the potassic volcanics.

Typical for the metavolcanics of the Filipstad NV map sheet is the rapid change in the contents of sodium and potassium. At some localities (marked A, B and C in Fig.

TABLE 1. Variation of alkalies in metavolcanics from different ore-bearing areas in Central Sweden.

Locality	Weight %			Reference
	Na_2O	K_2O	CaO	
Road-cutting 500 m WSW of southern end of Lake Stor-Sången ("A" in Fig. 10)	3.8	2.4	0.6	Unpublished analyses, geological map sheet Filipstad NV
	0.4	5.2	0.1	
	2.7	2.3	2.2	
Road-cutting 500 m S of southern end of Lake Stor-Sången ("B" in Fig. 10)	6.6	1.3	0.5	,,
	1.0	5.5	0.1	
	2.1	8.2	0.3	
	0.3	7.7	0.3	
	1.0	10.8	0.3	
	0.6	7.3	5.4	
	3.1	4.5	0.1	
Road-cutting at Näset, between Saxhyttan and southern end of Lake Saxen ("C" in Fig. 10)	1.0	2.3	0.9	,,
	0.9	5.6	0.6	
	2.0	3.5	0.3	
	0.4	3.1	1.2	
	4.2	2.3	1.8	
Ryllshyttan, Garpenberg; profile length about 800 m	2.7	3.0		Lindroth (1924)
	3.3	4.7		
	3.2	2.0		
	4.4	0.5		
Långvik-Holmgruvan, Garpenberg	1.7	4.3		,,
	1.1	2.6		
	0.8	7.3		
	5.1	2.5	2.5	
Ryllshyttan, Garpenberg; intercalations in alkali-intermediate volcanite	1.5	6.4		,,
	2.0	6.6		
	3.2	0.9	5.4	
Exportfältet, Grängesberg; transition from K-rich to Na-rich volcanite at Timmergruvan	1.8	8.5		Magnusson (1938)
	3.0	4.6		
	4.0	3.2		
	6.0	1.3		
	4.8	1.2		
	6.3	0.5		
	4.6	0.7		
	6.1	0.8		
	6.6	0.8		

10) a rather detailed sampling has been made over short distances of tens of metres or less. The variation in the sodium and potassium contents is extreme in contrast to the calcium content which is usually consistently low (Table 1).

Similar rapid variations in the alkali proportions have been witnessed from other volcanic areas in Central Sweden. According to Lindroth (1922) there is in the Garpenberg area (Table 1) a change from alkali-intermediate metavolcanics in a lower stratigraphic position (Ryllshyttan) to potassic metavolcanics in a higher stratigraphic position (Långvik–Holmgruvan). Within the intermediate volcanics are intercalations of potassic and sodic rocks such as the grey Ca-rich volcanite at Garpenberg Odalfält which contains 3.2% Na_2O, 0.9% K_2O and 5.4% CaO. In the Grängesberg area where great Na-K variations are present in the volcanics of the main ore body (Exportfältet, see Table 1) and the smaller Ormberg ore, no stratigraphic division can be made (Johansson 1911, Magnusson 1938). From the Striberg ore field Hjelmqvist (1942) described an intense alternation between the dominant sodic volcanics and the less abundant potassic and alkali-intermediate volcanics, the changes over intervals of only a few metres. Rapid alternations between potassic and alkali-intermediate volcanics also occur in the Nordmark area (Magnusson 1929).

It is therefore clear from the metavolcanics of Central Sweden that there exists on a regional scale a division into a stratigraphically lower sodic unit and a stratigraphically higher potassic unit; seen more in detail there are rapid alternations between the two extremes. The transitional alkali-intermediate types are relatively subordinate but of common occurrence.

THE PROVENANCE OF THE ALKALIES IN THE METAVOLCANICS

The chemical division of the metavolcanics of Central Sweden into a Na-rich group and a K-rich group was first pointed out by Johansson (1906–1907) and considered as a magmatic feature. Later works by Johansson (1911), Sjögren *et al.* (1915), Sundius (1923), Magnusson (1925, 1930, 1940b), Geijer (1936), and Geijer and Magnusson (1944) also considered the twofold division of the metavolcanics into sodic and potassic extremes as a result of an alkali differentiation which originated in the magmatic stage. The metavolcanics should thus have a largely preserved primary chemical composition. In the opinion of Geijer (1936) the development of a magma containing considerable amounts of constituents (e.g. volatiles) which serve to lower the temperature of the magma, was a possible explanation for the formation of the sodic metavolcanics. This hypothesis was in the main followed by Magnusson (1940b). A concentration of volatiles towards the top of the magma reservoir created convection currents causing differentiation. The sodic metavolcanics were formed in the upper parts, and the alkali-intermediate and potassic magmas farther down. In the deepest parts, dacites, andesites and basalts were formed, now appearing highest in the stratigraphic sequence and being the youngest rocks.

Much interest has been devoted to the nature of the sodic metavolcanics. In a great number of investigations their primary composition has been doubted, mostly on a locally restricted scale. According to Lindroth (1916, 1922) metasomatic processes have affected the metavolcanics in the Ramhäll, Yxsjö and Garpenberg areas causing albitization with a loss calcium. This is indicated by alteration of the more anorthite-rich plagioclase (mostly in phenocrysts) into an anorthite-poor one. In the Ramhäll area a migration of constituents, mostly a loss of calcium, gave rise to the peculiar composition in the sodic metavolcanics; albitization of microcline was also described. Sundius (1923) considered low temperature metamorphism as a likely explanation for the alkaline nature of the metavolcanics; the anorthite was unstable and a decalcification took place. The possibility of such a process is however contradicted by the presence of fresh and unaltered phenocrysts of albite. Sundius (*ibid.*) also pointed out that the process not only meant an albitization by decalcification, but also a replacement of the potassium by albite.

Geijer (1936) cast some doubt on the primary nature of the alkali-extreme volcanite types, namely the great extension of the sodic rocks. The metavolcanics of Central Sweden differ in this respect from other volcanic suites and consequently the question was raised whether the sodic feldspar in the former was a result of secondary albitization.

Metasomatic alterations of the metavolcanics on a small scale have been described from some ore deposits including Nordmark (Magnusson 1929), Grängesberg (Magnusson 1938) and Kaveltorp-Ljusnarsberg (Magnusson 1940b). In the Kaveltorp–Ljusnarsberg area the metasomatic alterations meant a decrease of the alkali content and at the same time an impoverishment of potassium in preference to sodium which can be observed locally as veins of sodic volcanics in the potassic varieties. According to Magnusson (1938) there has occurred in the volcanics at Grängesberg an exchange between sodium and potassium without influencing the structure of the rock.

As suggested above the metavolcanics of Central Sweden have been affected by metasomatic solutions causing a large-scale migration of elements. The primary compositions of the rocks, especially in the ore-bearing areas, have undergone considerable alteration influencing especially the silica and alkali contents. In order to elucidate the metasomatic nature of the alteration, the relationship between Na, K and Ca has been investigated in detail.

From Fig. 11, where the Na–K proportions are plotted according to Hughes (1973), the distribution of these elements in the metavolcanics of Central Sweden can be seen to be highly erratic. The ore-bearing volcanics (Figs. 11A and 11B) cover the whole Na-K range and fall largely outside the field of the "igneous spectrum" which represents normal unaltered rocks. The distribution of the alkalies in the ore-bearing volcanics from the whole of Central Sweden and from the map sheet Filipstad NV (203 partial and 32 total analyses, collected by the late U. Wiklander) is very similar. Fig. 11A confirms the previous statement that the Na- and K-extreme rocks included within the ore-bearing volcanics have a rhyolitic composition, often with more than 75% SiO_2. Among the ore-bearing volcanics, the alkali-intermediate rocks that fall within the "igneous spectrum" are relatively few and have compositions ranging from andesite to rhyolite. The ore-free volcanics differ from the ore-bearing ones in several respects concerning the Na-K distribution. The ore-free areas show a dispersed concentration towards the potassic side (Fig. 11C) and the sodium-enriched rocks, so

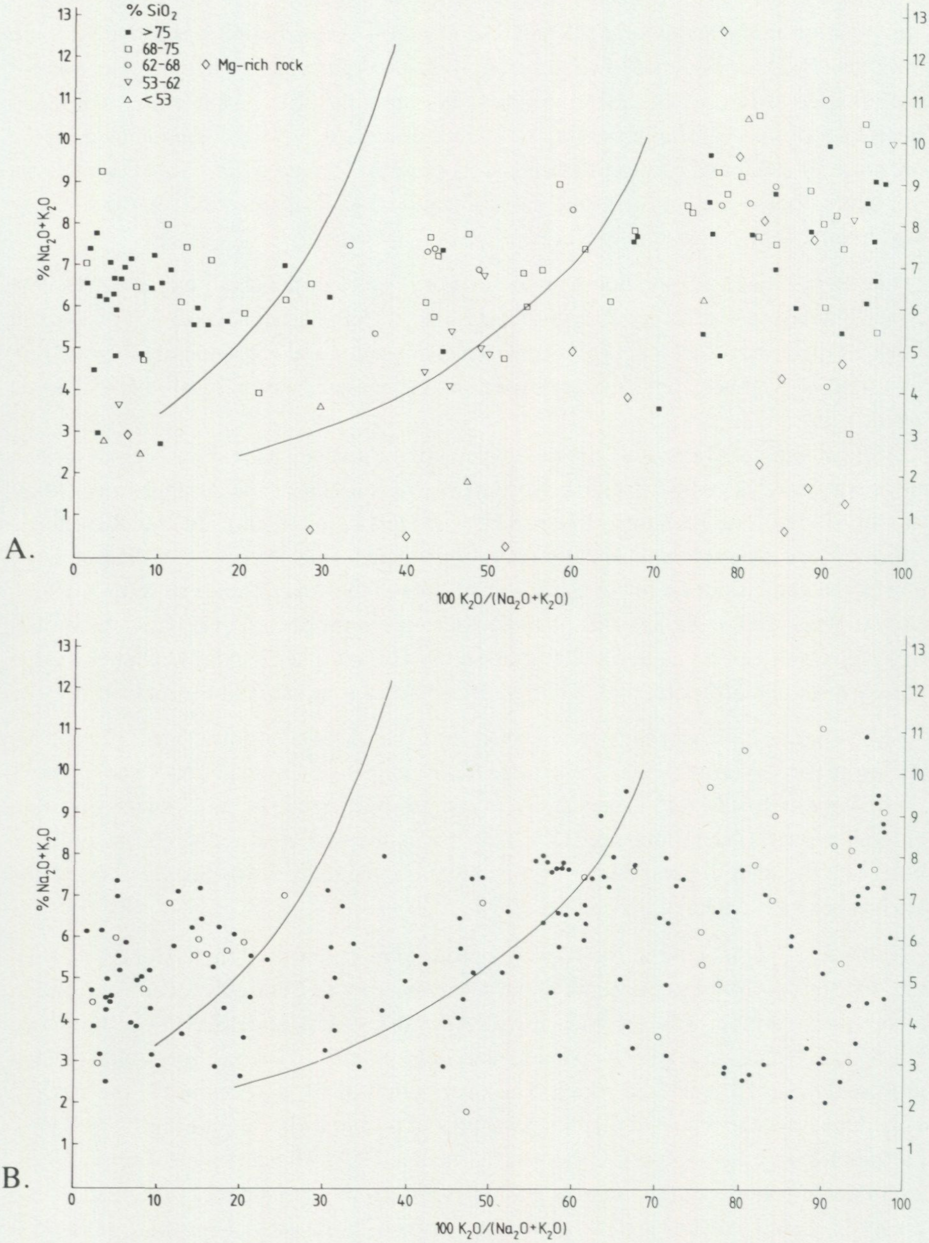
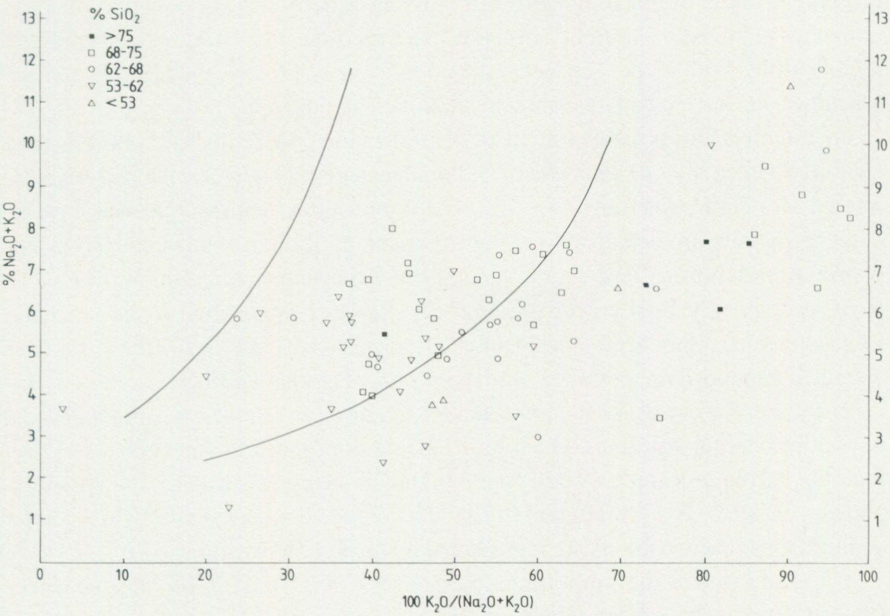


Fig. 11. The relationship between alkalies and potassium expressed as (weight %) $Na_2O + K_2O$ against 100 $K_2O/(Na_2O + K_2O)$ according to Hughes (1973). The field limited by heavy lines indicates the ''igneous spectrum'' by Hughes (ibid.).

A. Ore-bearing metavolcanics in Central Sweden.

B. Ore-bearing metavolcanics on the map sheet Filipstad NV. Points denote partial analyses and circles total analyses, the latter the same as shown in Fig. 11A.



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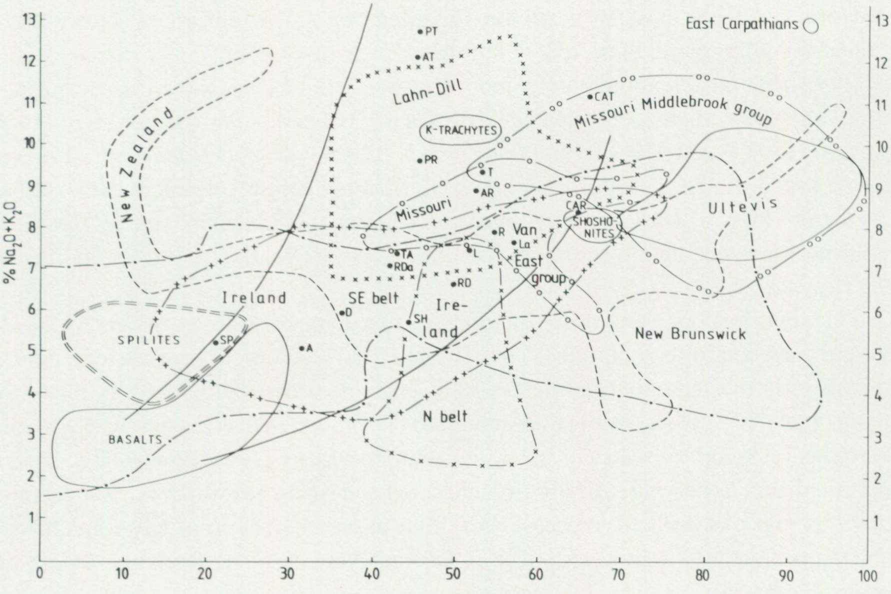

D.

C. Ore-free metavolcanics in Central Sweden.

D. Some volcanic rock types (average composition) and volcanic suites (several analyses). For abbreviations and references see Fig. 5. The composition of spilites is from Hughes (1973) and that of basalts from Stephens (1980).

prominent in the ore-bearing areas, are missing. The K-rich rocks within the ore-free volcanics are mostly "normal" rhyolites with less than 75% SiO_2. Alkali-intermediate rocks falling within the "igneous spectrum" are relatively abundant in the barren volcanics and have mostly a dacitic to andesitic composition.

To establish the possible extent of "spilitization" affecting the metavolcanics of Central Sweden, *i.e.* to what extent sodium has replaced calcium, the rocks have been plotted in a Na-Ca diagram (Fig. 12). The figure shows that the volcanics have a low content of calcium and partly a high content of sodium compared to the Na-Ca distribution in normal unaltered volcanics (cf. the average compositions in Fig. 12C). It is consequently highly probable that the present composition of the volcanics of Central Sweden has been developed by spilitization. Here again the difference in chemical composition between ore-bearing and barren volcanics is obvious. In the latter the trend towards a calcium-deficient composition is much less pronounced than in the ore-bearing volcanics which have, in addition, much higher contents of sodium than the barren volcanics. A trait found in the ore-bearing volcanics, but absent in the barren volcanics, is a low content of calcium combined with a similarly low content of sodium; these compositions are represented by the K-rich rhyolites.

In Fig. 13 where the proportions between Na, K and Ca in the metavolcanics of Central Sweden have been plotted and related to the silica content of the rocks, it is obvious that there exist all transitions between Na- and K-rich rocks. However, for volcanics with more than 75% SiO_2 there is a discontinuity area between those analyses rich in sodium and potassium. This discontinuity, characterized by a paucity of alkali-intermediate metavolcanics, was already pointed out by Sjögren *et al.* (1915), Sundius (1923) and Magnusson (1940b). Fig. 12 shows that besides the "differentiation" into Na- and K-rich members among the ore-bearing volcanics, there is also a "calcium loss". Rocks with a substantial amount of calcium among the barren volcanics are much more common than among the ore-bearing volcanics, particularly the rhyolitic types.

This abnormal distribution of the alkalies in the metavolcanics of Central Sweden favours a metasomatic origin. The division into sodium and potassium extreme members is most pronounced in the ore-bearing rhyolites, particularly in those with more than 75% SiO_2, and less pronounced in the ore-free volcanics where sodium extreme rocks are absent and potassium extreme rocks are relatively few. Instead, intermediate Ca-bearing volcanics (dacites and andesites) are common. It is therefore obvious that metasomatic processes resulting in an enrichment of silica and alkalies and an antipathetic impoverishment in calcium have been most intense in the ore-bearing volcanics.

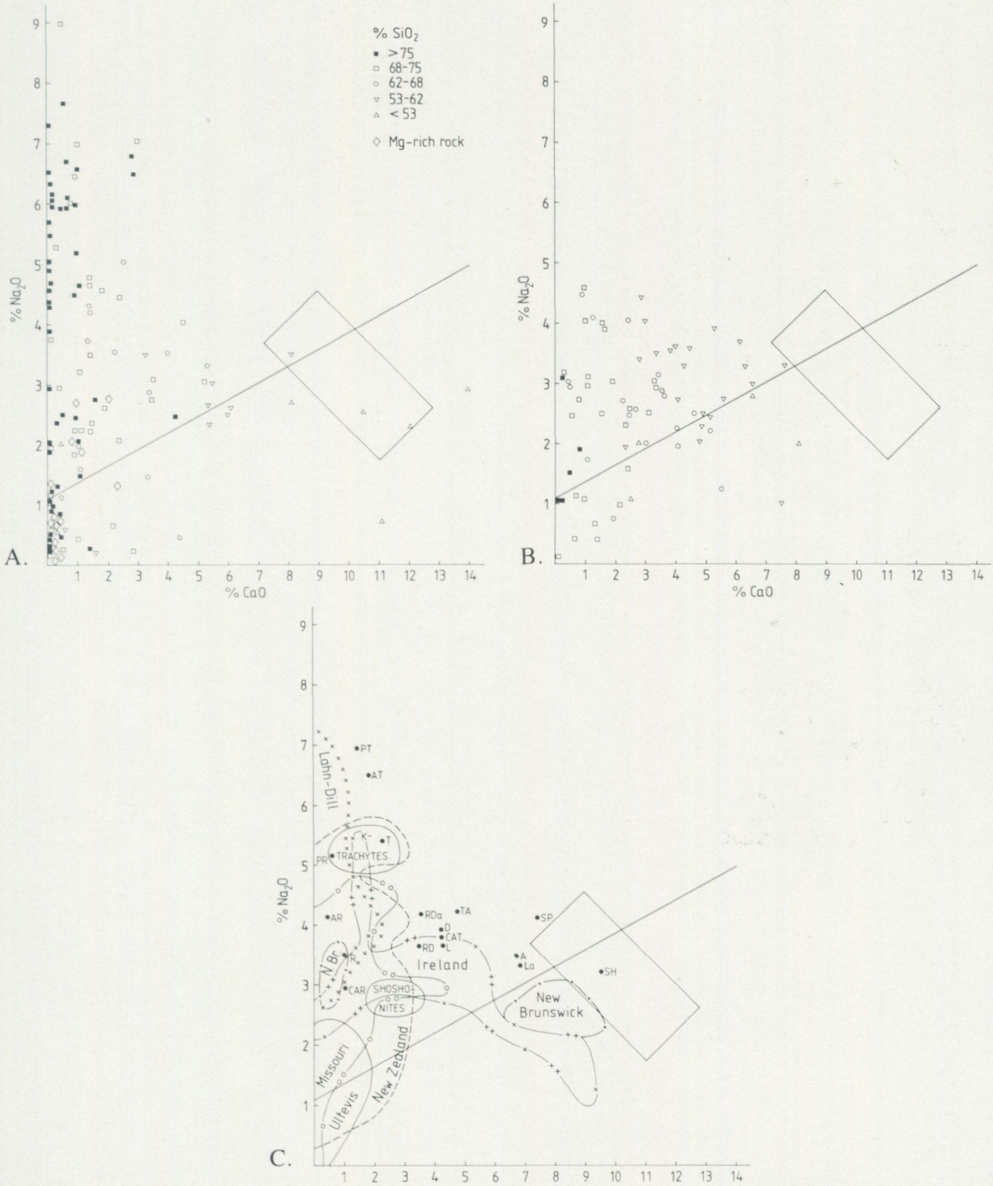

Fig. 12. The relationship between (weight %) Na_2O and CaO. Straight line separates high-Na_2O and low-Na_2O rocks according to Graham (1976). Box outlines normal, unaltered basalts according to Stephens (1980).

A. Ore-bearing metavolcanics in Central Sweden.

B. Ore-free metavolcanics in Central Sweden.

C. Some volcanic rock types (average composition) and volcanic suites (several analyses.) For abbreviations and references see Fig. 5.

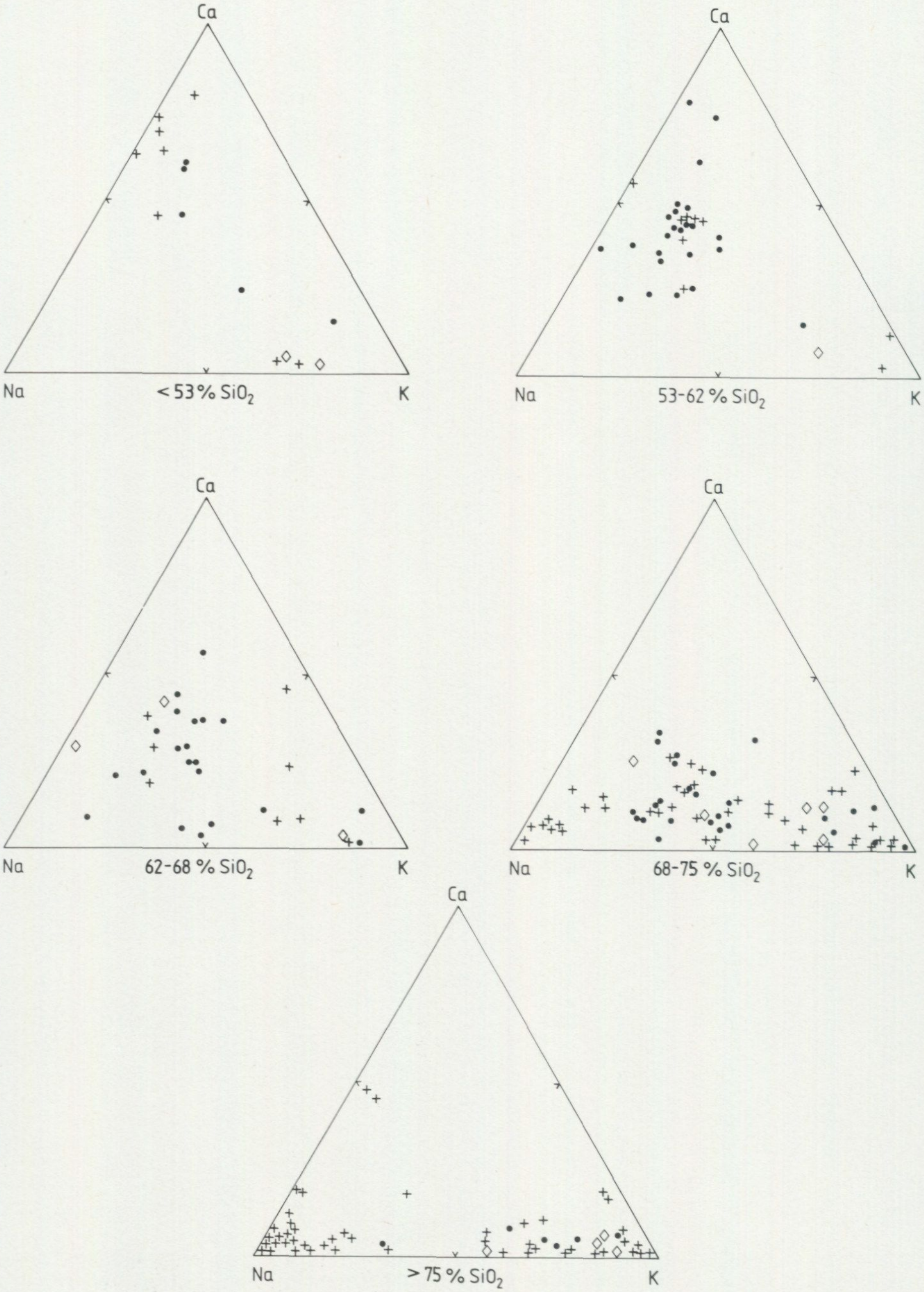

Fig. 13. The relationship between Na, K and Ca (atomic %) for the metavolcanics of Central Sweden. In analyses with more than 0.1 weight % CO$_2$ an equivalent amount of Ca has been deducted as calcite. Crosses = ore-bearing rocks, points = ore-free rocks and diamonds = Mg-rich rocks.

ALKALI ENRICHMENT IN OTHER VOLCANIC SUITES

There are volcanic suites from other localities abroad which are similar to the described volcanic rocks of Central Sweden in their concentration of sodium or potassium, mainly in the acidic members. The content of sodium, potassium and calcium and the internal relationship between these elements in the volcanics abroad is shown in Figs. 5C, 11D, 12C, and 14. The enrichment of sodium or potassium is often due to metasomatic processes, but represents in some localities a primary magmatic feature.

Battey (1955) showed that the New Zealand keratophyres, occurring in a typical spilite-keratophyre association, were originally glassy flow-rocks and breccias comparable with young volcanic areas. The keratophyres are composed of quartz, albite and potash feldspar in widely varying proportions. Alkali metasomatism has altered some of the rocks to become rich in sodium (up to 6.6% Na_2O) and others in potassium (up to 10.3% K_2O) so that their compositions are symmetrically disposed around that of a primary rhyolite magma with roughly equal amounts of alkalies. In part albite is replaced by potash feldspar. The variations in the alkali ratio, with an antipathetic relation between soda and potash in the different parts of the same lava, are very rapid, occurring on the decimetre scale.

Stillman and Williams (1978) described Ordovician volcanics from south-eastern Ireland among which rhyolites dominate making up more than 60% of the total, with basalts, andesites and dacites making up the rest. The distribution of the SiO_2 content is similar to that of the volcanics of Central Sweden; *i.e.* the proportion basalt: andesite: dacite: rhyolite is 12: 18: 9: 62. The south-eastern Irish rocks are largely subaqueous volcanoclastics containing intercalated clastic sediments which have been altered as a result of syn- or immediately post-emplacement submarine weathering and local hydrothermal metasomatism (spilitization). The effect of the burial metamorphism has been active to greenschist facies. The rhyolites have been strongly affected by late magmatic and hydrothermal fluid migration contributing to the observed extreme mobility of alkalies within the rock mass; instances have been recorded in which rhyolite composition varies from 13% K_2O, 2% Na_2O to 5% K_2O, 7% Na_2O over a distance of less than 10 m. Average contents of two different types of rhyolites range from 2.3% Na_2O, 6.4% K_2O to 5.4% Na_2O, 1.3% K_2O.

In the volcanic rocks of the Lower Palaeozoic Tetagouche group at Bathurst, New Brunswick in Canada, dacitic to rhyolitic pyroclastics and lavas dominate contributing up to 67% of the total (Whitehead and Goodfellow 1978). Mafic rocks are relatively abundant whereas intermediate members are quite subordinate. The frequency distribution of SiO_2 is typically bimodal with maxima around 72% and 50%. Among the acidic rocks are ''augen schists'' with 65–77% SiO_2, 2.7% Na_2O and 4.7% K_2O; the high potassium content is attributed to potash metasomatism. In addition there are rhyolites which are more alkali-intermediate with 3.6% Na_2O and 3.5% K_2O. The erratic distribution of sodium and potassium in these acidic rocks is possibly a result of alkali metasomatism; the majority of the analyses fall outside the boundary of normal, unaltered rocks according to Hughes (1973).

In the Lahn-Dill spilite-keratophyre association most of the rocks are alkali-intermediate or sodium-dominated, potassic members being rare (Lehman 1941, Juteau and Rocci 1974). The Na_2O and K_2O contents reach 5–6% and their sum is often 9–10%. These rocks are considered to have a primary magmatic origin.

In the above volcanic suites the distribution of the alkalies is bimodal. Examples of unimodal volcanic suites with a potassium dominance are, however, not uncommon. Normal, unaltered magma suites do not contain the high potassium contents found in the metavolcanics of Central Sweden.

The shoshonite series described by Joplin (1968) are composed of potassium-rich rocks of basaltic to more acidic composition. The content of potassium is above average compared to common volcanite associations, but even in the more acidic members (toscanites, quartz latites, latites, and liparites with up to 67% SiO_2) the content does not exceed 5–6% K_2O. The sum of alkalies in the acidic shoshonites is around 8% $Na_2O + K_2O$. It is suggested by Joplin (*ibid.*) that the shoshonite association is a primary magma series. Furthermore, Jakeš and White (1972) considered the tholeiitic, calc-alkaline and shoshonitic association occurring in island arcs as closely related in space and time. In this sequence the most important variations are the increase of the K_2O content at a given SiO_2 content and the increase of the K_2O/Na_2O ratio.

In addition to the shoshonites, similar high potassium contents are found in the potassic trachytes published by Ewart (1979) which contain 62–70% SiO_2 and 4.8–5.5% K_2O; the sum of alkalies is around 10% $Na_2O + K_2O$.

Fiala (1974) held the view that the potash-spilites (6–8% K_2O) of the Algonkian volcanism of the Bohemian massif were primary and formed by magma differentiation. Moreover Marinelli and Mittempergher (1966) considered the potassium-rich magmas in the recent volcanism of central Italy as formed by a pneumatolytic differentiation from a sialic-anatectic magma.

In the view of modern development of plate tectonics there seems to be a general opinion that the potassium-rich volcanics, in comparison with the sodic volcanics, are formed at a deeper level in a subduction zone. For example, there is a positive correlation between the potash content and the depth of the seismic (Benioff) zone below the volcanoes (Hatherton and Dickinson 1969, Zonenshain *et al.* 1974, Clark *et al.* 1976, Gill 1981). This is supported by an increase of the potassium content in magmatic rocks as the distance from the continental margin increases. Other examples include the high-potassium (5–6% K_2O, 1–3% Na_2O) rhyolites reported by Baskina (1978) from Sikhote in East-Asia URSS which are thought to be formed by deep-seated sources of ore-bearing magmas. Ninkovich and Hays (1972) considered high-potassic volcanics to have originated by dehydration of oceanic crust, the released water working its way to the surface and scavenging potassium and other alkalies on the way. According to Pearce (1976) the high potash (2.5% K_2O) basalts have originated along continental rifts and in an ocean island setting associated with ''hot-spots''; or, in a volcanic arc setting a considerable distance behind the trench or, possibly, following a continental collision at a converging plate boundary.

Even if an enhanced potassium content in volcanics is thought, in many cases, to be of primary nature, there are examples which indicate that metasomatic reactions have been responsible for potassium enrichment.

Radulescu (1966) envisaged the high potassium content of some Neogene volcanics in the East Carpathians as of secondary origin. The existence of the ultrapotassic rocks is believed to be associated with channels which have provided access to the migration of ascending solutions rich in potassium. There are rhyolites with 70–78% SiO_2 which are sericitized, kaolinized and adularized, containing 3.5–7.5% K_2O. Potassium-rich mafic rocks are also encountered best exemplified by an andesite which contains 12.0% K_2O, possibly the highest potassium content ever reported in a volcanite (Fig. 14).

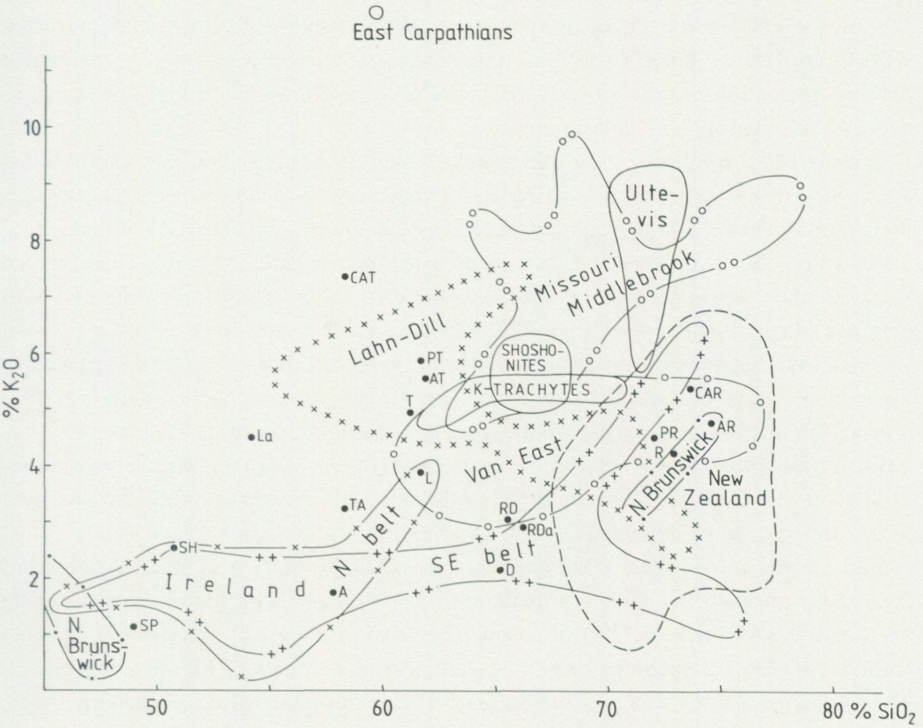

Fig. 14. K_2O against SiO_2 (weight %) in some rock types (average composition) and volcanic suites (several analyses). For abbreviations and references see Fig. 5.

According to Kisvarsanyi (1972) some of the Proterozoic (1 300–1 400 Ma) volcanics of Missouri are extremely potassium-rich. This concerns especially the stratigraphically lower Middlebrook group which contains 4.9–9.8% K_2O and 0.1–4.5% Na_2O. In the stratigraphically higher Van East group more alkali-intermediate (3.8–6.9% K_2O and 2.4–4.5% Na_2O) volcanics are encountered. According to Kisvarsanyi (*ibid.*) the high potassium contents might indicate anomalous magma types, but may on the other hand due to the (partly) high silica content, be post-magmatic. The rocks might have attained their present composition through leaching and subsequent removal of sodium and calcium and a relative enrichment of potassium. Several factors may have been responsible including hydrothermal alterations, potassium metasomatism, and assimilation.

At Ultevis in Northern Sweden there are Precambrian rhyolitic volcanics mostly developed as porphyries, and to a smaller extent as tuffites (Ödman 1947). Locally there is a rapid change between tuffitic sediments, tuff agglomerates and porphyries. The rocks are potassium-rich (5.7–9.1% K_2O, 0.2–2.5% Na_2O) and characterized by the dominance of microcline; quartz and albite are present in small amounts. In the tuffitic sediments there are both bedded manganese oxide-silicate ores and jaspilitic iron ores which are considered as syngenetic chemical sediments formed in connection with the tuffites. Ödman (*ibid.*) envisaged metasomatic processes being involved in the ore formation which affected the wall rock resulting in differences in colour between ore-bearing and barren volcanics.

Compared to the above volcanic suites, which all are enriched in sodium and/or potassium, the metavolcanics of Central Sweden are in many respects unique with their combination of high contents of $Na_2O + K_2O$ and SiO_2 (Fig. 5). Similar high alkali-silica contents are present in the volcanics from Ireland (SE belt), Ultevis, New Zealand and Missouri, although only in the two latter regions do volcanics with extreme silica contents (more than 75% SiO_2) occur. The same intense scatter between low and high contents of sodium and potassium recorded from the volcanics of Central Sweden is found in the volcanics from New Brunswick and New Zealand. In both regions the volcanics cover the whole range between sodic and potassic members (Fig. 11D). Potassium extreme volcanics also occur at Ultevis and in the Middlebrook group at Missouri with both rock suites showing the same enrichment in potassium and silica as the ore-bearing volcanics of Central Sweden (Fig. 14).

Fig. 12 shows that most of the ore-free metavolcanics of Central Sweden fall within the Na/Ca area where other intermediate to acid volcanics are found. In contrast the ore-bearing volcanics of Central Sweden are extraordinary in their spread between sodium-rich and -poor rocks, a feature similar to that reported from the volcanics of New Zealand. Furthermore, sodium-enriched/calcium-depleted rocks as found in the ore-bearing areas of Central Sweden are also represented by the Lahn-Dill keratophyres. Sodium-depleted (that is K-rich) rocks as those in Central Sweden are common to these found at Ultevis and in New Zealand occurrences.

THE PRIMARY COMPOSITION OF THE METAVOLCANICS

The ore-bearing metavolcanics of Central Sweden are distinguished from the barren varieties by the following petrochemical features: 1, the high content of SiO_2, largely exceeding 75%, 2, the extreme division into Na- and K-rich members; alkali-intermediate rocks being relatively rare, 3, the low content of Ca (bound to silicates such as plagioclase and amphibole), and 4, the paucity of intermediate to basic rocks. All these features are possibly caused by one and the same metasomatic alteration which was coeval or directly subsequent to the volcanism.

In Central Sweden there is a relationship between the different types of iron and manganese ore, their stratigraphic position and the composition of the volcanic host rock (Frietsch 1981 and in prep.). The manganese-bearing ores (manganiferous skarn iron ore, manganese oxide-silicate ore of the Långban type and Fe-Mn silicate-bearing eulysite) occur in the stratigraphically higher K-rich volcanics. Quartz-banded iron ores are found both in the K-rich and the Na-rich volcanics. The non-manganiferous skarn iron ores occur mostly in the stratigraphically lower Na-rich volcanics.

The difference in composition between the ore-bearing and the ore-free volcanics, combined with the connection between specific ore types and a specific alkali composition of the volcanics, indicates a common genesis for the ore-formation and the regional metasomatic alteration of the volcanics. A genetic link between the formation of the alkali extreme volcanics and the ores, particularly the iron-bearing ones, has previously been noted. Johansson (1906–1907) emphasized that the sodium-rich volcanics have a large extension within the ore-bearing formations. The alkali ''differentiation'' of the ore-bearing volcanics was pointed out by Johansson (1911) and Sjögren *et al.* (1915). In these investigations the chemical composition of the volcanics was considered as a primary feature formed by the differentiation of the magma. Magnusson (1940b) postulated a simultaneous formation of the ore-bearing solutions and the volcanics, *i.e.* during magmatic differentiation into the Na- and K-rich volcanics, the solutions rich in manganese accompanied the potassic rocks whereas those poor in manganese accompanied the sodic rocks. This differentiation thus resulted in iron ores rich in manganese in the upper K-rich volcanics whilst iron ores poor in manganese were confind to the lower Na-rich volcanics. A more metasomatic view was given by Geijer (1921) when discussing the genetic relationship between the volcanics and the skarn iron ores. The importance of the sodium extreme volcanics was pointed out and it was suggested that the composition of these was due to large-scale chemical re-arrangements in connection with the ore formation.

As a consequence of the hypothesis postulated by the present author in that the chemical alteration of the volcanics and the related ore-formation belong to the same syngenetic-post-volcanic metasomatic process, two questions arise: 1, what was the original composition of the metavolcanics of Central Sweden and 2, what kind of solutions were active?

Concerning the original composition of the volcanics, it should be emphasized that the problem could not be solved by simply assuming that the ore-free volcanics represent the original high-temperature differentiate. These volcanics, even if less altered than the ore-bearing ones, scarcely have their primary chemical-mineralogical composition preserved. The metasomatic alteration process was so extensive that most of the volcanic terrain of Central Sweden was affected. The barren volcanics show similar traits, but much less pronounced, of chemical changes such as silica enrichment and alkali partitioning as in the ore-bearing volcanics. An indication of the original composition of the volcanics may, however, be given by the relative distribution between mafic and felsic rocks. The paucity of intermediate to basic rocks in the volcanics of Central Sweden is a remarkable feature, previously pointed out by Sundius (1923), Geijer and Magnusson (1944) and Geijer (1963). In most other volcanic suites of the world basalts and andesites dominate, the more acid rocks being subordinate or of little importance. In Central Sweden the amount of mafic rocks (andesites to dacites) is much greater in the barren volcanics than in the ore-bearing volcanics (Fig. 2). If the formation of the felsic members in the volcanics of Central Sweden is the result of a metasomatic alteration, there are thus good reasons to believe in a more basic to intermediate composition of the original rocks. It should also be emphasized that the mafic volcanics of Central Sweden never host iron ores and sulphide ores. In addition they are barren in limestones and dolomites. This strengthens the hypothesis of the mafic volcanics reflecting pre-alteration rocks which to-day represent remnants of (basaltic to) andesitic to dacitic lavas, having originally a much larger extension. The main part was subsequently altered to a felsic composition by the large-scale metasomatic processes in which the ore-forming solutions played an important role.

The transition of the original high-temperature pre-alteration volcanics into the present composition involved not only an enrichment in silica and a partition into alkali extreme members but also a removal of calcium. The altered ore-bearing volcanics thus have a low content of calcium compared to the barren volcanics (Figs. 12 and 13), a fact which is further reflected by the mineralogy, *i.e.* the ore-bearing volcanics do not have the anorthite member in the plagioclase whereas in the barren volcanics the anorthite content is relatively high being represented by andesine and labradorite. If the volcanics of Central Sweden contain secondary quartz and albite, the latter having replaced a more calcic plagioclase, the original high-temperature magmatic rocks may have had a more mafic composition comprising dacites and andesites characterized by a more calcic plagioclase (andesine or labradorite).

The mafic volcanics in the ore-free areas show, in spite of metasomatic alteration to a greater or lesser extent, preserved chemical traits typical for magmatic suites. The metal oxide *versus* silica variations in the ore-free mafic volcanics of Central Sweden are similar to those found by Gill (1981) for medium-K (0.8–1.6% K_2O) and high-K ($>$ 1.6% K_2O) orogenic andesites. The similarity is confined to the behaviour of aluminium, titanium, iron, and potassium, whereas the contents of calcium and sodium are somewhat lower in the volcanics of Central Sweden; in the 53–63% SiO_2 interval they contain 8–4% CaO and 2–3.5% Na_2O compared to 9–6% CaO and 3–5%

Na_2O in the orogenic andesites (Gill, *ibid.*, Figs. 5.2 and 5.3). Still more convincing evidence for a primary composition of the ore-free volcanics in Central Sweden is the decrease of the Mg/(Mg + Fe) ratio with increasing silica content, this feature being typical for many magmatic rock suites (Fig. 6 and p. 14). The mafic volcanics of Central Sweden occupy in a FeO^X/MgO diagram the same area as the calc-alkaline medium- and high-K andesites according to Gill (*ibid.*). In spite of their alteration the mafic volcanics of Central Sweden have preserved their primary trend of alkalies in accordance with what is usual in magmatic suites, *i.e.* with increasing silica content there is an increase of potassium and sodium, the increase being somewhat greater for potassium than for sodium (Fig. 4).

The hypothesis that the felsic volcanics are formed from the andesites and dacites by metasomatic processes necessitates the existence of intermediate stages. Gradual changes in composition between pre-alteration rocks and totally altered rocks should therefore be expected. Transitions between the mafic and felsic volcanics do occur, but seem not to be common. Such features can be exemplified from the Garpenberg area (p. 9) where mafic volcanics pass into felsic, alkali-intermediate ones. Intercalations of intensely banded mafic volcanics with oligoclase to andesine, biotite and hornblende occur in the K-rich felsic volcanics west of the Ställdalen synform (Magnusson 1940b). Further west in the same area, the stratigraphycally lower Na-rich volcanics are locally rich in narrow intercalations of mafic volcanics. East of Ludvika, in the eastern limb of the Stollberg synform, there are in the K-rich felsic volcanics layers rich in dark minerals and plagioclase. These layers, which are folded and resembling remnants, pass gradually into the felsic volcanics. Hjelmqvist (1937) also described similar conformable layers of mafic volcanics in the felsic ones around the Stollberg synform. All the occurrences described here are in ore-bearing areas, and the amount of mafic volcanics is consequently low. In the barren Norrköping region there is characteristically rapid alternation between silica-intermediate and basic volcanics, locally with gradual transitions (Wikström 1975). In addition there is a common occurrence of mafic volcanics within the felsic volcanics.

THE NATURE OF THE ALKALI METASOMATIC PROCESS

The metasomatic process that gave rise to the felsic volcanics of Central Sweden was extensive and occurred para-contemporaneously with the volcanism or shortly after its cessation. Whether the alteration is due to late-magmatic hydrothermal fluids associated with the volcanic activity, or due to meteoric-connate waters heated by adjacent volcanic centra, is an open question. Possibly the fluid flow that changed the chemistry of the volcanics was in part caused by hot, in part metal-bearing, brine solutions which were common in the ore-bearing volcanic areas. A great number of investigations have shown that volcanic suites elsewhere have been subject to chemical alterations after the volcanic activity, mainly during diagenesis and burial metamorphism. In most cases the process is considered as being metasomatic caused by hydrothermal solutions of magmatic origin or by heated connate-meteoric water (Battey 1955, Radulescu 1966, Hughes 1973, Schermerhorn 1973, Graham 1976, Stillman and Williams 1978, Whitehead and Goodfellow 1978, Stephens 1980). More rarely this alteration is due to submarine weathering (Stillman and Williams 1978) or to hydration (Stewart 1979). A common feature for all these studies is a change in the distribution of the alkalies which tend to be very mobile and migrate easily in solution. In most cases there has been an increase of sodium (''spilitization'') and often albite is replacing a (somewhat) more calcic plagioclase.

Hydrothermal alteration and chemical redistribution within the volcanics of Central Sweden which began during diagenesis and attributed mainly to low-grade, non-deformative metamorphism, has previously been envisaged by Levi and Malmqvist (1979) and Levi *et al.* (1980). This hypothesis is based on the differences in chemistry (distribution of Ba, Rb, Sr, Na, and K) in the Cu-Pb-Zn- Fe sulphide mineralization at Svärdsjö and the wall rock. Magnesium leached from the volcanic rocks was precipitated in limestone intercalations causing dolomitization in these and in the rocks surrounding them (''magnesia metasomatism''). Cu, Pb, Zn, and S were redistributed in a similar way. Barium and alkali metals, especially sodium, were deposited far away from the limestone thus giving rise to the sodium-rich acid rocks.

As a consequence of the theory postulated by the present author involving metasomatic alteration as a source for the alkali enrichment in the volcanics of Central Sweden, it thus follows that the sodic or potassic nature of the rocks used as a base for stratigraphic division in fact represents a chemical zonation in the volcanic pile with enrichment of sodium in the lower part and an enrichment of potassium in the higher part of the sequence. This zonation is however often disturbed locally, and in some cases regionally.

The mechanism that caused the partition of the volcanics of Central Sweden into Na- and K-rich members is obscure. The difficulties to be surmounted involve not only the reason for such a general division, but also why the potassic volcanics in comparison to the sodic are of such restricted extent. A possible explanation for the latter feature is that the K-rich volcanics, stratigraphically overlying the Na-rich varieties, have been eroded to a much greater degree so that denudation has consequently resulted in a preponderance of the Na-rich volcanics.

The intimate link between specific ore composition and Na- or K-rich volcanics, such as manganese-bearing iron ores with Zn-Pb-Fe-(As) sulphides in K-rich volcanics and non-manganiferous skarn iron ores with Cu-Fe sulphides in Na-rich volcanics, indicates a genetic connection between the ore formation and the post-magmatic alteration of the volcanics. The ores were deposited coevally with the alteration although the different types of ore have been deposited under different conditions. It has been suggested (Frietsch 1981 and in press) that there was a decrease in the temperature and redox potential coupled with an increase in basicity from the more marginal (stratigraphically lower) parts of the depositionary basins to the more central (stratigraphically higher) parts. Thus the manganese-bearing skarn iron ores and the iron-manganese-silicate-bearing eulysites were deposited in the more central part of the basins at a greater water depth in a reducing, alkaline and low temperature environment. The non-manganiferous skarn iron ores were formed at an oxidation potential somewhat below zero, whereas the quartz-banded iron ores, which occur relatively high in the stratigraphy both in Na-rich and K-rich volcanics, were deposited under relatively oxidizing conditions. The Långban ore type which is a formation intermediate between the quartz-banded iron ores and the manganiferous skarn iron ores, was deposited under conditions varying from oxidizing to reducing.

It is an open question as to whether the above described metal zonation in the depositionary basin can be explained solely by differences in the physico-chemical conditions. Possibly there was a change through time of the composition of the metal- and sulphur-bearing fluids, resulting at a late stage in the potassic volcanics with their Fe-Mn-Zn-Pb-(As) assemblages.

Possibly there were additional factors other than differences in the physico-chemical condition of deposition and in the composition of the ore-bearing solutions contributing to the alkali partition of the volcanics. The nature and degree of the metasomatic alterations formed in a post-magmatic stage in a volcanic sequence are largely controlled by the chemical composition and the temperature of the circulating fluid phase, the composition and texture of the flow beds and the minerals that first nucleate after devitrification.

Generally lava flows are highly permeable and make good aquifers (Fyfe *et al.* 1978), but tuffs should be even more efficient in this respect. The water permeability is naturally dependent on the degree of compactness and one of the major controlling influences rendering some flows more permeable and prone to alteration than others is exerted by the character and the amount of original interstitial glass (Smith 1974). During hydration-leaching of glassy material in lavas, caused by meteoric-connate waters at a late-magmatic stage or by weathering, there occurs a change in the partition between sodium and potassium.

According to Scott (1966) deuteric alterations during cooling of ignimbrites resulted in a redistribution of sodium and potassium in the more welded zones, whereas leaching of sodium by weathering greatly affected the less welded zones. Noble (1967) showed that natural silicic glasses have undergone secondary hydration and thus contain lower amounts of sodium and silica than primarily crystallized ones. These rocks have lower Na/K ratios than the non-hydrated glasses and there has been an absolute increase in the potassium content. A similar point of view was expressed by Steward (1979) who found that hydration by meteoric waters of glassy rocks brought about a relative potassium enrichment; hydrogenium ions replaced cations at different rates. The interaction of glassy siliceous rocks and meteoric water will tend to produce large volumes of highly potassic glasses until devitrification intervenes. In the chemical changes of obsidian with the meteoric water there is a selectivity sequence with $2H^+ > 2\,K^+ > 2\,Na^+ > Ca^{2+} > Mg^{2+}$. A continued passage of water through the glassy rock causes a gain in the glass of K^+ and H_2O and a loss of Na^+. A positive correlation thus exists between increasing hydration and increasing potassium/sodium ratio. According to Battey (1974) the high alkali content of keratophyres (associated with spilites) is due to alkali migration during conditions of burial metamorphism with the concentration of potassium in the originally glassy parts and of sodium in the originally crystalline parts.

The alkali partition of the volcanics of Central Sweden could therefore be related to fundamental differences in the lithological-textural composition at the time of the deposition. The stratigraphically upper potassic unit is predominantly composed of banded to layered rocks of which both tuffaceous sediments and pyroclastic flows are common; minor amounts of chemically decomposed material may be present. According to Sundius (1970) the potassic volcanics, with the exception of some larger quartz porphyry occurrences, form a transitional series to the overlying greywacke metasediments. With the exception of some locally restricted coarser fragment-bearing rocks, the sodic volcanics show a less pronounced layering or banding, being often homogeneous. Porphyritic rocks are here more common than in the potassic volcanics.

There are thus differences in the structural development of the two types of alkali volcanics. The potassic ones are richer in sedimentary material and consequently comprise a less cohesive unit than the sodic ones. The potassic volcanics would therefore have accomodated more readily to the movement and transport of the solutions active. There was in all probability a rapid flow of water through the unconsolidated rocks promoting, in the glassy volcanic units, the diffusion of sodium in preference to potassium with the resultant increase of the potassium/sodium ratio. A selective diffusion of the alkalies within the more ''sedimentary'' volcanics in the higher stratigraphic position could thus explain the formation of the potassic rocks.

The large extension of the sodic volcanics in Central Sweden is enigmatic. The differential leaching and later deposition of the alkalies with a concentration of sodium, as outlined by Levi and Malmqvist (1979) and Levi *et al.* (1980), cannot be generally applied to the formation of the alkali extreme rocks, in particular why the greatest part of the volcanics of Central Sweden are sodic. It seems more plausible to suppose that the sodium-rich character was founded at an early stage of the syn-post-magmatic metasomatic process, being brought about by sodium-rich fluids such as saline, connate water or brines. Alternatively, the enrichment of sodium may also be due to a lower amount of glass present in the primary lava. As mentioned above, crystalline parts of the lava are often characterized by sodium concentrations, whereas in the originally glassy parts there tends to be a concentration of potassium.

However, the partition among the volcanics of sodic and potassic rocks may also be due to a mineralogical control during the metasomatic alteration. The minerals formed at an early stage of the hydrothermal metasomatism and metamorphism have probably been of crucial importance. The heated solutions acting on the volcanic glass brought about during devitrification the formation of clay minerals and micas which are capable of fixing the alkalies, particularly potassium. According to Grimm (1968), the clay minerals associated with hot springs and fumaroles in volcanic terrains, include kaolinite, halloysite and smectite. Illite seems to be associated with hydrothermal alterations at higher temperatures. Of these minerals illite and smectite concentrate potassium. Sodium is fixed in the clay minerals only to a small degree as long as other ions are present.

Considerable information regarding the compositional changes incurred during interaction between heated sea-water and basalts has been gained by laboratory investigations, simulating the action of sea-water that continuously circulates and reacts with basalts along active ocean ridges (Bischoff and Dickson 1975, Seyfried and Bischoff 1977, 1979, Mottl and Holland 1978, Mottle *et al.* 1979). The results show that at 200–500°C, 500 bars and a high water/rock ratio, the basalts are changed to smectite; less common alteration products are tremolite-actinolite, talc, albite, analcime, and anhydrite. In the basalts there is a general gain of Mg and a loss of Ca and SiO_2 during the alteration, which are consistent with field observations. According to Hart (1973) the action of sea-water on primary basalts of the oceanic crust implies the formation of K-rich smectite in a low-temperature weathering process, whereas chlorite is formed during retrograde metamorphism and albite-actinolite during greenschists metamorphism. In the Reykjanes geothermal system the basalt is altered to montmorillonite, anhydrite and calcite at a lower temperature (below 200°C) and chlorite, epidote and prehnite at a higher temperature (230–280°C; Tómasson and Kristmannsdóttir 1972, Kristmannsdóttir 1976). In general, similar alteration products occur in silicic volcanics in the Wairakei geothermal area in New Zealand. From low rank to high rank alteration, K-montmorillonite/albite, calcite, micaceous and chloritic clays/K-feldspar and quartz are found (Clayton and Steiner 1975, Steiner 1977). Potassium has been fixed in the micaceous clay and iron in the chloritic clay.

According to Mottl and Holland (1978) the crystallinity of the basalt is an important factor in determining the mineralogical and chemical changes which occur. During greenschist metamorphism glassy parts of marine flows are commonly altered to chlorite, whilst more crystalline basalts may be altered to a more typical greenschist facies assemblage of albite, actinolite, epidote, chlorite, and sphene. Experimental studies by these authors showed that the crystallinity of basalt had an influence on the formation of tremolite-actinolite and talc at high temperatures (400–500°C). According to Seyfried and Bischoff (1979) basalt glass in laboratory studies reacted more extensively at 150°C than diabase, reflecting the relative resistance of the crystalline minerals to alteration.

During the sea-water alteration of basalts either potassium or sodium may be concentrated in the rock. In most cases alteration involved a depletion of potassium in sea-water, the element bound to smectite in basalt. According to Bischoff and Dickson (1975) basalt can remove up to 30% dissolved K from sea-water at 25°C. On the other hand Seyfried and Bischoff (1977) reported a slight loss of sodium when basalt at 500°C was transformed to smectite.

As earlier stated the division into sodic and potassic volcanics in Central Sweden may have been brought about by varying degrees of hydration, *i.e.* with increasing fluid activity there was an enrichment of potassium relative to sodium resulting in potassic rocks. From the laboratory investigations cited above, it seems likely to suppose that the primary mafic volcanics at low temperatures were altered to smectite and at higher (moderate) temperatures to albite-actinolite. The formation of smectite served to fix the potassium, and through later prograde metamorphism was then subsequently changed to K-feldspar and K-mica.

OTHER ORE-BEARING VOLCANIC SUITES WITH ALKALI METASOMATIC ALTERATIONS

The hypothesis, relating to a genetic connection between the regional metasomatic alteration of the metavolcanics of Central Sweden and the ores contained in them, has many practical prospecting implications. The ores ought to be restricted to volcanics where the silica enrichment and the alkali ''partition'' is most pronounced. Alkali-intermediate rocks with less than 75% SiO_2 should be less promising and areas with greater amounts of mafic rocks (andesites to dacites) should be barren.

In the ore-bearing province of south-western Finland, the same volcano-sedimentary complex as in Central Sweden is present. However, in south-western Finland the distribution between felsic and mafic volcanics is different. Between the felsic volcanics in the stratigraphically lower part of the sequence and the argillite to greywacke metasediments in the upper part of the sequence, there are intermediate to basic volcanics (lavas, agglomerates and tuffs) which constitute a relatively great part of the complex. Iron ores and sulphide ores are scarce. The main deposits are Aijala, Metsämonttu and Orijärvi. The acidic volcanics in which the ores occur contain 71.2–77.6% SiO_2 and are alkali-intermediate with 0.7–3.9% Na_2O and 0.7–3.2% K_2O (Latvalahti 1979). The content of calcium is fairly high: 2.5–4.9% CaO. The mafic volcanics consist of basalts with 47.7–50.9% SiO_2 and are alkali-poor (less than 3% $Na_2O + K_2O$) and calcium-rich (7.6–12.6% CaO). In a $K_2O/(Na_2O + K_2O)$ diagram such as in Fig. 11 the felsic as well as the mafic volcanics lie within the field of normal, unaltered rocks (the ''igneous spectrum'' by Hughes 1973). This concerns especially the mafic volcanics which all fall within the field of basalts. In a Na/Ca diagram such as in Fig. 12 all volcanics show only a low degree of spilitization, *i.e.* the Na/Ca ratio is fairly low.

The data presented indicate that the metavolcanics of south-western Finland have been subjected to a relatively restricted metasomatic alteration. Mafic volcanics are still largely preserved. In the felsic volcanics the silica enrichment and the division into alkali extreme rocks is barely pronounced and consequently there are few ores. Potassium-rich volcanics are missing and there was no formation of manganese-bearing ores.

Hydrothermal alteration of the wall rock accompanies many ore deposits, in particular sulphide-bearing ones (*e.g.* porphyry copper ores). This process implies a propylitic, argillic, sericitic, or potassic alteration caused by chemical changes such as hydrogen and potassium metasomatism. It is, however, of very restricted extent, mostly confined to the nearest hundred metres of wall rock adjacent to the ore. Regional metasomatic alterations of ore-bearing volcanics are on the contrary rare. Counterparts to Na-K metasomatically volcanics with their sulphide, iron and manganese ores of Central Sweden and south-western Finland, are scarcely found elsewhere in the world. Possibly the best exception is the previously described (p. 31) Tetagouche group in the Bathurst-Newcastle area in New Brunswick, Canada. Here the volcanics, partly of acid composition and with Na-K metasomatic alterations, contain massive sulphide ores and iron formations, the latter being in part manganese-bearing (Boyle and Davies 1963, Stockwell and Tupper 1966, Rose *et al.* 1970, Lusk 1972, Whitehead 1973, Skinner 1974, Goodfellow 1975, Graf 1977). Over 30 deposits with sulphide ore are known consisting mainly of stratabound bodies of pyrite with Pb, Zn and Cu sulphides and mostly occur within or adjacent to the rhyolitic ''augen schists''. There is a close association between the sulphide ores and the iron formations lying in the same stratigraphic horizons. Locally, as in the Brunswick No. 12 deposit, there are alterations of the foot wall to about 500 m below the sulphide ore (Goodfellow 1975). Towards the ore Mn, Mg, Fe, and K increase whereas Ca decreases and the Na/K ratio shows a distinct decrease; the potassium enrichment is, however, moderate. From unaltered to intensely altered foot wall the contents are 1.4–1.5–0.6% Na_2O and 4.5–9.3–3.2% K_2O which are less intense when compared to the alterations in Central Sweden. It is interesting to note that in the Brunswick No. 12 mine there is an enrichment of manganese and potassium associated with Zn-Pb sulphide ore, a feature similar to that in the potassic volcanics of Central Sweden.

In the Ordovician volcanics of south-eastern Ireland, which show pronounced Na-K metasomatic changes partly with a preference for potassium (p.31), there are only the copper-bearing pyrite ore deposits at Avoca. Associated are sub-economic mineralizations of sphalerite, chalcopyrite and galena (Pointon 1980, Sheppard 1980).

In other alkali metasomatically altered volcanic suites containing sulphide deposits associated with acidic volcanics, the alterations have mainly affected the sodium contents mostly producing an increase whereas changes in the potassium content are of restricted importance. At Stekenjokk in the Swedish Caledonides there is an intimate link between the formation of massive sulphide deposits and the spilitization of basalts, basaltic andesites and especially dacites to rhyodacites (Stevens 1980). The dacites to rhyodacites have undergone substantial alteration to quartz keratophyre. The volcanic pile was enriched in sodium and depleted in a number of elements such as aluminium, iron, magnesium, and potassium. In the Iberian pyrite belt, the ores occur in felsic volcanics comprising rhyolites, quartz-latites and potassic quartz keratophyre (Schermerhorn 1970). Both albite and microcline seem to replace each other. The Rio Tinto deposits occurs in sodic felsic volcanics. A regional alteration of silicic volcanics in connection with the formation of sulphide mineralization is found at Mt. Lyell, Tasmania (Cox 1981) where hydrothermal alteration resulted in sodium depletion and enrichment of potassium into mica and feldspar. Potassium-enriched ore-bearing volcanics of rhyolitic composition are encountered at Ultevis, Northern Sweden (p. 34). The potassic rhyolites are, as is common with those in Central Sweden, the carrier of manganese oxide-silicate ores and jaspilitic iron ores.

THE TECTONIC SETTING OF THE METAVOLCANICS

The general tectonic setting of the volcano-sedimentary complex of Central Sweden has been recently reviewed by several authors, notably Löfgren (1979), Loberg (1980a, 1980b) and Boström (1980). They considered the volcanics to occur in a major arc-shaped structure, the centre of this semi-circle being north-east of Stockholm. Inside this arc-structure extensive granitoid diapirism has taken place (Stephansson 1975). Löfgren (1979) considered the volcanics, due to their calc-alkaline composition, to represent an island-arc formed at a subduction zone. Boström *et al.* (1979) concluded on a geochemical basis that the Långban manganese oxide ore was deposited at a spreading centre or at a subduction zone in an island-arc basin. The basic volcanics, which occur in inferior amounts within the volcanic unit, are according to Loberg (1980a) basalts both of ocean floor type and volcanic arc type; the occurrence of both types is due to tectonic mixing in a subduction zone, dipping towards the East.

In the opinion of the present author the magma-tectonic environment giving rise to the volcanics of Central Sweden is not unequivocally determined. The present knowledge of the tectonic and stratigraphic features in Central Sweden is too sparse to allow a proper assessment concerning the geological evolution of the area. The existence of a subduction zone is not fully elucidated and the presence of calc-alkaline volcanics is not in itself sufficient proof for a formation by subduction processes, even if it is a well-known fact that these rock-types are mainly found at active continental margins and with island arcs. One of the main features in a calc-alkaline rock suite is the abundance of basalts and andesites, acidic rocks being subordinate. In Central Sweden, andesites and basalts represent minor lithological constituents compared to the acidic volcanics. The mafic volcanics form scattered occurrences at Riddarhyttan, Norberg, Larsbo, and Garpenberg in the western part of Central Sweden, and appear in increasing amounts towards the east and south-east along the coast of the Baltic sea. Large amounts of basic volcanics additionally occur in the area north of Västervik which is situated at the southern periphery of what is considered as Central Sweden. The nature and origin of these mainly amphibolitic rocks, apparently consisting of both extrusive and igneous members, is not very well known. Wikström (1980), however, considered the rocks to be extrusive and mostly basaltic in character, possibly forming the lower part of the Svecokarelian supracrustal sequence. Whether these amphibolites belong to the volcano-sedimentary complex of Central Sweden is therefore uncertain. In the eastern extension of the complex, in south-western Finland, sediments dominate but among the volcanics basalts and amphibolites are more abundant than the acid volcanics (Simonen 1980). The basic and intermediate volcanites seem mainly to form a distinct stratigraphic unit overlying the acid volcanics and underlying the argillite to greywacke sediments (Latvalahti 1979).

Island belts tend to be characterized by basic or intermediate volcanics. Baker (1968) showed that the principal rock in young arcs is basalt and in the older more mature arcs andesite becomes dominant. Ringwood (1974) pointed out that the first stage of island arc volcanism is marked by a tholeiitic series represented by basalt and basaltic andesites, and in the later stage of volcanism by a calc-alkaline series characterized by andesites. According to Miyashiro (1974) the most common rocks comprising immature island arcs are usually basalts and basaltic andesites of the tholeiitic series, whereas those in well-developed island arcs, associated with a thick continental-type crust, are andesites and dacites of the tholeiitic and calc-alkaline series. In contrast the main volcanic rocks found at continental margins are andesites, dacites and rhyolites of the calc-alkaline series.

Examples of acid-dominated rocks associated with calc-alkaline volcanism in folded belts are few in the world. Acidic volcanites in the eastern Pacific Cordillera occur relatively abundantly together with Palaeozoic and Mesozoic volcanism, but are subordinate to the basaltic to andesitic lavas extruded during the full range of the orogenic epoch (Windley 1977, p. 267). In the Northern Andes the main products of the youngest eruptions are rhyolites (Carmichael *et al.* 1974, p. 531). Furthermore, dacite to rhyolite ignimbrites of large areal extent occur in New Zealand.

If the volcanics of Central Sweden are to be explained by an island arc model, the dominance of rhyolites thus necessitates special attention. The magmas may have formed below a thick continental crust. Miyashiro (1974) showed that large amounts of acidic volcanics within the calc-alkaline suites are formed at an active continental margin where the crust is thick. Supporting evidence is given by Stillman and Williams (1978) who have suggested that the calc-alkaline volcanics found in east and south-east Ireland are erupted products formed at the margins of a continental plate which thickened in general towards the south-east above a subduction zone. The dominance of rhyolites in the south-east with only minor occurrences of dacites, andesites and basalts, is here considered as due to the thickening of the crust.

The present hypothesis involving a large-scale metasomatic alteration of mafic volcanics into the present felsic composition would however give a satisfactory explanation for the ''abnormal'' proportions between mafic and felsic rocks in the calc-alkaline volcanics of Central Sweden without recourse to crustal thickening.

According to Garcia (1978) the most reliable criteria for an island-arc formation include the presence of 1, a paired metamorphic belt, 2, predominant pyroclastic texture of the volcanites and 3, thick sequences of greywackes and mudstones interbedded with pyroclastic volcanic rocks. These requirements are in the main fulfilled in Central Sweden. The volcanites are in the main pyroclastics. A N–S-oriented subduction zone in south-western Sweden has been proposed by Lundqvist (1979) who based this opinion on the existence of a pair of metamorphic belts exemplified by the occurrence of highly metamorphic granites and gneisses to the west of the so-called Protogine zone and the less affected Svecokarelian rocks to the east. In Central

Sweden there is also an intermingling of volcanics and sediments on a regional scale. However, in many of the ore-bearing island arcs, such as the Tertiary one in Japan, or the Palaezoic one in Spain-Portugal, volcanics and sediments are more intimately mixed, often with a repetition of intercalated sediments at different stratigraphic levels.

In summary it is therefore still an open question if the volcanics of Central Sweden represent an island arc situation, and furthermore it is even doubtful if the volcano-sedimentary complex forms an arcuate structure open to the east. The arc-shaped form has been outlined by many authors but seems to be only based on a visual interpretation of maps such as that illustrated in Fig. 1. If the distribution of the volcano-sedimentary complex is carefully scrutinized, it becomes obvious that the arc-structure seems to reflect convention rather than being based on real facts. For example, the supracrustals cover an area much larger than the inferred arc and even if the delineation is not easy, the same rocks are found more or less continuously about 100 km north and south of the area shown in Fig. 1. In addition the Early Svecokarelian supracrustals and plutonics, which are partly similar to those in Central Sweden, occur even further to the south in an isolated area between Vetlanda and Oskarshamn. The supracrustals, which comprise basic to intermediate volcanics, argillites and minor acid volcanics, are intruded by granodiorites about 1 800 Ma old (Röshoff 1975, Welin 1979). Towards the west, the volcanics of Central Sweden are mainly bordered by post-Svecokarelian volcanics and granites dated to about 1 500–1 750 Ma old. The central part of the inferred arc-structure is occupied be Early Svecokarelian granitoids. In this ''batholith of Uppland'' there are rather extensive belts of volcanics orientated approximately NE and E–W. It is conceivable that a large part of the area covered by the plutonics was originally built up of supracrustal rocks now largely assimilated by the plutonics, a feature which further discredits an inferred arc-structure. Probably the whole eastern part of Sweden, between Hudiksvall and Oskarshamn, along a length of 500 km in N–S direction, was covered by Svecokarelian volcanics equivalent to those in Central Sweden. If this volcanic sequence was generated in a subduction zone, it would most likely have a straight N–S orientation as outlined by Lundqvist (1979); an arc-structure thus being highly unlikely. The existence of the ring-formed structure in the region north of Stockholm (cf. Fig. 1) is only a relatively minor feature in a regional context being due possibly to differences in competency in accordance with what has been outlined by Stålhös (1981). The Early Svecokarelian plutonites, covering the central part of this structure, have during the Svecokarelian orogeny acted as a tectonically competent body around which the volcano-sedimentary complex was subsequently folded and cross-folded.

As previously outlined by the present author (Frietsch 1981 and in prep.) the main tectonic structure in the ore-bearing area of Central Sweden is isoclinal folding trending NE to NNE. In the westernmost part, as in the Grythyttan and Saxå synforms, NW directions are prevalent. There is thus in the western part of Central Sweden, just east of Filipstad, a large-scale regional ''break'' in the geological structures which remains unclear, although it may be tied to some deep-seated inhomogeneity in the crust. It should be emphasized that Geijer (1967), Sundius (1970) and Welin *et al.* (1980b) have attributed important differences in the geological evolution of Central Sweden to a boundary occurring in the western part, roughly close to the above described ''break'' in the regional structures. Geijer (1967) stressed the importance of a boundary extending from Ludvika to Guldsmedshyttan which was assumed to have developed during the later stages of the volcano-sedimentary complex. The most important feature is that the sediments of the Larsbo formation and dacitic volcanics, both high up in the stratigraphical succession, occur only to the east of the boundary, in contrast to the western area where the upper part of the complex is made up of argillites and greywackes with minor spilites. Sundius (1970) also indicated the existence of a similar N–S boundary although somewhat to the west of that postulated by Geijer. Sundius considered this line of great importance for the geological development of the area; *i.e.* the Early Svecokarelian plutonics only occur to the east of the line. Moreover there was to the west of the boundary a subsidence of the volcanics which resulted in the deposition of the argillite and greywacke sediments in basins. Welin *et al.* (1980b) considered the change in metamorphic facies in the Grythyttan region, from greenschist facies in the west to amphibolite facies in the east, as due to a tectonic boundary. In common with Sundius (1970), the absence of synkinematic plutonites in the westernmost part of the region was stressed. Welin *et al.* (*op.cit.*) also considered the Grythyttan volcanic sequence on the basis of a potassic rhyolite dated radiometrically to 1 862 Ma, as younger than the main volcanic sequence of Central Sweden. The present knowledge of the relationships between the volcanics in different parts of Central Sweden is incomplete, and it is therefore not possible to comment if this statement is valid over a great extent. However, on the basis of the tectonic-stratigraphic appearance of the different types of iron and manganese ores, there appears to be no substantial difference in the nature of the volcanism from area to area, the ore formation follows the same general pattern over the whole region. The only exception occurs in the westernmost part in the Grythyttan and Saxå areas where the amount of manganese oxide ores of the Långban type is greater than in the rest of Central Sweden. This can be adequately explained by different conditions during ore deposition rather than necessitating a separate phase of volcanism.

SUMMARY

The Early Proterozoic (> 1 900 Ma) metavolcanics of Central Sweden are dominantly felsic, quartz-feldspar rocks (rhyolites) which show a division into Na- or K-rich members, often with an extremely high silica content. The associated mafic volcanics, being subordinate in amount, are mainly dacites to andesites and occasionally include basalts. Among the felsic volcanics there is a tendency that the Na-rich rocks occur in a lower stratigraphic position than the K-rich rocks. This division, however, is by no means always clearly distinguishable. The alternation between sodic and potassic rocks is on a local scale very rapid, and alkali-intermediate rocks are not uncommon. In the western and central part of Central Sweden Na-rich volcanites dominate, whereas in the eastern part there is a preponderance of K-rich volcanites. The mafic volcanics which cover restricted areas, have an uncertain position within this stratigraphic scheme.

The felsic volcanics and intercalated limestones and dolomites contain syngenetic volcanogenic deposits of iron, manganese and sulphide ore. There are petrochemical differences between the volcanics in ore-bearing and ore-free areas. The ore-bearing volcanics differ from the barren volcanics by 1, the high content of SiO_2, often exceeding 75% (average 72.7%), 2, the extreme division into Na- and K-rich rocks; alkali-intermediate rocks being relatively rare, 3, the low content of Ca bound to silicates, and 4, the paucity of mafic members. There are thus strong reasons to anticipate a secondary, internal re-arrangement of the chemistry of the volcanics with the ore-forming process. The main effect has been an increase of the silica content and a redistribution of the alkalies. In the most acidic members the range of Na_2O or K_2O is mostly 5–9%. The total amount of alkalies is, however, roughly constant. The K-rich volcanics have the highest $Na_2O + K_2O$ totals usually exceeding 8%. The erratic distribution of the alkalies is evident from the K/(K + Na) diagrams which show that the ore-bearing volcanics cover the whole Na-K range and fall largely outside the field of normal unaltered magma rocks. In addition the ore-bearing volcanics show typical traits of spilitization exemplified by a high sodium/calcium ratio. The chemical alteration of the ore-bearing volcanics is further shown by an irregular variation of the Mg/(Mg + Fe) ratio in relation to the silica content; in normal magmatic suites there is a decrease with increasing acidity.

In the ore-free volcanics, comprising both rhyolites and subordinate dacites to andesites, more normal chemical features are prevalent. The SiO_2 content seldom exceeds 75%, the average is 65.1%. The alkali ''partition'' is less developed; sodium extreme rocks are absent and potassium extreme rocks are relatively few. Instead alkali-intermediate Ca-bearing volcanics are common which show a (slight) increase of the alkali content and a (slight) decrease of the Mg/(Mg + Fe) ratio with increasing silica content, relations being in accordance with those in normal magmatic suites.

There is a distinct relationship between the stratigraphic position and the composition of the host rock volcanics and the different types of iron and manganese ores with associated Zn-Pb-Fe-(As) sulphides. The Mn-bearing ores (manganiferous skarn iron ore, manganese oxide-silicate ore of the Långban type and the Fe-Mn silicate-bearing eulysites) occur in the potassic volcanics which also encompass part of the quartz-banded iron ores. The remaining quartz-banded iron ores and the main part of the non-manganiferous skarn ores with associated Cu-Fe sulphides occur in sodic volcanics. The difference in composition between ore-bearing and barren volcanics, together with the relationship between specific ore types and specific alkali composition of the volcanics, indicates a common genesis for the ore-formation and the regional metasomatic alteration of the volcanics.

The volcanics of Central Sweden have been altered, mainly in the ore-bearing areas, by a metasomatic process coeval or directly subsequent to the volcanism. Whether the alteration is due to late-magmatic hydrothermal fluids associated with the volcanic activity or due to meteoric-connate waters heated by subadjacent volcanic centres, is still an open question. The primary high-temperature pre-alteration volcanics have been andesitic to dacitic in composition having originally had a large areal extension. It is noticeable that relatively unaltered mafic volcanics lack intercalations of limestones and dolomites and never contain ores. The main part of the mafic rocks were altered to felsic compositions with enrichment of silica, redistribution of alkalies and impoverishment of calcium. The plagioclase in the mafic volcanics is andesine to labradorite (mostly as phenocrysts) and in the felsic volcanics albite to oligoclase. The altered nature of the volcanics hampers a precise classification of the magma type, but alkali-SiO_2, AFM, FeO^x/MgO, and TiO_2-SiO_2 diagrams indicate that they essentially have a calc-alkaline character; the mafic volcanics however show a trend towards tholeiitic compositions.

The mechanism that caused the division of the volcanics into Na- and K-rich members is obscure. The physico-chemical conditions of deposition and the composition of the alterating ore-bearing solutions may have been different. The Mn-Fe-Zn-Pb association in the potassic volcanics indicates formation at low Eh and relatively high pH, whereas the Fe-Cu association in the sodic volcanics indicates more oxidizing and acidic conditions. Differences in composition and texture of the lava flows may also have influenced the development of the alkali extreme members, for example the K-rich volcanics are richer in clastic sedimentary material thus being more porous than the Na-rich volcanics. The K-rich volcanics were consequently more reactive for the solutions active during the alteration; with an increased degree of hydration there was an enrichment of potassium relative to sodium giving rise to the potassic rocks. The Na-K partitioning process may also have been governed by the minerals that were first to form after devitrification of the volcanics. At low temperature the volcanics were altered to clay minerals (mainly smectite) which subsequently changed to K-feldspar and K-mica during prograde metamorphism giving rise to the potassic rocks. At a higher (but still moderate) temperature there was an early formation of albite resulting in the sodic rocks.

The sulphide ores and part of the iron ores are commonly accompanied by Mg-rich rocks containing minerals such as cordierite, anthophyllite and serpentine. They are regionally stratabound and represent alterations of the volcanics, mainly coeval with the ore formation. The formation of the Mg-rich rocks, which have a very restricted extension compared to the regional Na-K-metasomatic altered volcanics, required a gain of magnesium, and loss of titanium, calcium, sodium, and phosphorus, whereas iron and potassium show no systematic variations; the total alkali content has decreased. The age relations of the Mg-rich alterations are however ambiguous. Locally the alteration minerals have a post-tectonic appearance in the volcanics. In addition there are local alterations, partly associated with sulphides, of the Early Svecokarelian plutonites and still later metabasite dykes. These features indicate that the Mg-rich alteration is a multiphase process with the main phase occurring during the volcanism.

Other volcanic suites with regional alkali metasomatic alterations similar to those in Central Sweden are few, being found only in New Zealand, south-eastern Ireland, New Brunswick, and Missouri. They are dominated by acidic members and show a great range in alkali content with an antipathetic behaviour of sodium and potassium. The volcanics of Central Sweden are outstanding in that they are characterized by a high content of $Na_2O + K_2O$ (mostly exceeding 6%) combined with a high content of SiO_2 (mostly exceeding 75%). Regional distributions of Na-K-altered volcanics hosting iron, manganese and sulphide ores are rarely found outside Central Sweden. In south-western Finland where there is a direct continuation of the volcanics described above for Central Sweden, metasomatic alteration is considerably less. Here the mafic volcanics occupy a relatively large part of the sequence and the felsic volcanics, in contrast to Central Sweden, show a silica content which is mostly below 75%. The content of Na_2O and K_2O is mostly less than 4% and the content of CaO is fairly high (8–13%) indicating a low degree of spilitization. As a direct consequence, the amount of iron and sulphide ore is low, the K-rich volcanics are missing and thus also the Mn-bearing ores. A counterpart to the ore-bearing volcanics of Central Sweden and south-western Finland is found in New Brunswick, Canada. Here the volcanics of the Tetagouche group are regionally alkali-altered and contain massive sulphide ores and iron formations, the latter in part Mn-bearing.

It has been suggested that the ores and volcanics of Central Sweden were formed in a subduction zone, however, the volcanics are dominantly acidic in contrast to most island-arc systems which are built up of basic and intermediate volcanics. The acidic nature of the volcanics, if formed in an island-arc environment, would necessitate formation by subduction below a thick continental crust. The present postulated metasomatic alteration of extensive primary andesitic to dacitic volcanics offers an alternative explanation for this specific feature. The previous hypothesis of an arc-shaped structure open towards east must be abandoned. The volcanics occur extensively in eastern and south-eastern Sweden and occupy a N–S aligned area much larger than the inferred arc.

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