THE ARCHAEAN GREENSTONE BELTS OF KARELIA (EASTERN FINLAND) AND THEIR KOMATIITIC AND THOLEIITIC SERIES

by

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Abstract

The geological and geochemical features of three greenstone belts of Eastern Finland (Suomussalmi, Kuhmo and Tipasjarvi) have been studied. We have analysed about 70 metavolcanic rocks from the low greenstone sequence for their major and trace element compositions. The field relationships between various volcanic rocks are rather obscure; but the chemical data allow us to distinguish two general magmatic series, namely, the komatiitic and the tholeiitic series. We have concluded from this preliminary geochemical study that most volcanic rocks in each may have been derived from fractional crystallization of some parental magma. The REE data, mainly presented for the rocks from the Tipasjarvi belt, provide a strong evidence for a "depleted" mantle source, a feature very similar to that of Abitibi, Canada. The REE data also suggest that not all rocks are formed by fractional crystallization; a mechanism of different degree of partial melting is called to account for some rock types.

Although the Baltic Shield is one of the first regions in which the Archaean rocks were described (Sederholm, 1897, 1932), it is only recently that the existence of greenstone belts has been clearly demonstrated (Blais et al., 1976, 1977 and in print a and b ; Bowes, 1976 ; Gaal et al., 1976 and in print; Lobach-Zhuckenko et al., 1976 ; Mutanen, 1976; Suslova, 1976).

In this contribution, the principal characteristics of the belts, which we have studied in Finland, are briefly described and we expose the present state of our petrological and geochemical research in this context.

GEOLOGICAL SETTING

The Archaean rocks crop out widely in northern and central Finland (Simonen, 1971). In this latter region, the Archaean crust comprises a gneissic basement, largely migmatised, and supacrustal formations which constitute the greenstone belts. The gneissic basement and the cover of metasediments and greenstones have undergone a common tectonometamorphic history during the time range 2.6 to 2.7 b.y. (Kuvo and Tilton, 1966 ; Blais et al., in press a).

The greenstone belts for which we presently have the most information are those of Suomussalmi, Kuhmo and Tipasjarvi, located in eastern Finland. The Suomussalmi and Kuhmo belts lie along the same approximately north-south line, extending lengthwise over 200 km, and never wider than 20 km. They were mapped by Wilkman (1924), Matisto (1958), Vartiainen (1970) and Hypponen (1973; 1976) (Fig. 1).

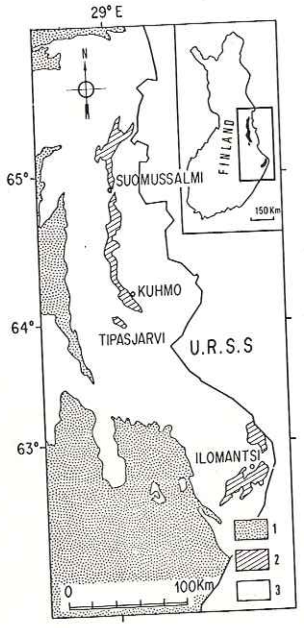

Fig. 1. Geological sketch-map of eastern Finland. 1= Karelian formations; 2= Greenstone belts; 3= High-grade metamorphic terrains (basement).

The principal characteristics of these belts are as follows:

1. Lithostratigraphy

The most complete stratigraphic column which we have found to date corresponds to the section in the northern part of the Suomussalmi belt. Its thickness is estimated at between 3000 m and 5000 m. We have distinguished three lithostratigraphic units, passing from bottom to top :

(a) An early magmatic cycle, composed initially of ultrabasic lava flows and small-scale intrusions, massive basaltic lava flows and pillow lavas flows, volcanic breccias and basic sheets.

(b) An essentially metasedimentary formation represented by pelitic mica schists, graphitic schists and greywackes, sometimes associated with quartzites, conglomerates, and volcanic rocks (mostly acidic tuffs and some minor basic lavas). The clasts of the metasediments are of mixed origin; some are derived from the greenstone belt volcanics while others show an adjacent basement provenance.

(c) A second volcanic cycle, composed of feldspathic tuffaceous rocks of intermediate composition, associated with subordinate lavas.

The members of this succession have a tectonic contact with the gneissic basement. This latter is principally composed of fine- to medium-grained grey gneisses, augen orthogneisses and migmatites, mainly heterogeneous diatexites.

2. Volcanism

The volcanism is, to a first approximation, at least bimodal in nature.

(a) The Lower volcanic sequence comprises :

i) Peridotitic komatiites ($MgO > 30\%$) which are olivine-rich cumulates; picritic komatiites ($30\% > MgO > 20\%$) in which quench and spinifex textures are sometimes preserved; picritic basalts or gabbros ($20\% < MgO < 12\%$) and basaltic komatiites ($MgO < 12\%$).

ii) Tholeiitic basalt sensu-stricto, depleted in potassium, sometimes accompanied by clino-pyroxene-bearing cumulates.

(b) The Upper volcanic sequence comprises calc-alkaline felsitic rocks, all highly sodic and of andesite to rhyolite composition.

The two sequences, tholeiitic sensu-lato and calc-alkaline, are well distinguished in the classical diagrams of Figs. 2 and 3. Their respective emplacements are clearly separated in time by the deposition of sediments.

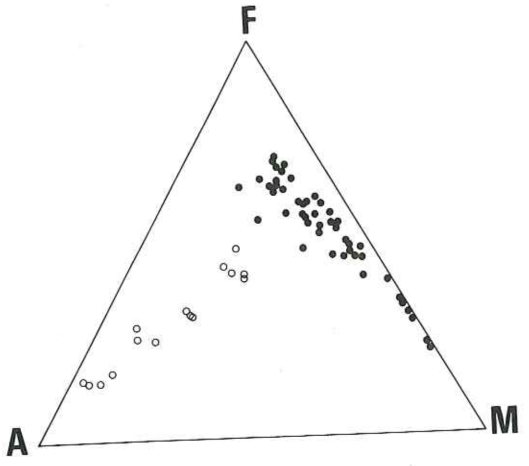

Fig. 2. Location of the two volcanic sequences in a ternary AFM diagram; filled circles = tholeiitic (s.l.) sequence; open circles = calc-alkaline sequence.

3. Structural evolution

The gneissic basement and greenstone belts of eastern Finland underwent a common structural evolution, the sequence of which in chronological order is as follows:

Phase 1 : Development of isoclinal folds deforming the volcano-sedimentary bedding of the belts and the first metamorphic banding of the basement.

Phase 2 : This is the most evident deformation in both the belts and the basement and is responsible for the general geographical distribution of the belts. Folds with subvertical axial planes and steeply plunging axes, often carry an axial planar foliation and a well-developed mineral lineation. Minor shear-zones frequently develop in the limbs of asymmetrical folds.

Phase 3 : This is a complex event, non-penetrative on the regional scale. It principally comprises early eastward thrusts, well seen in the gneissic basement, followed by major faults whose horizontal displacement components are generally sinistral. The phase 3 structures affect the Proterozoic Karelian schists and therefore are post-Archaean.

Phases 1 and 2 correspond to the end of Archaean history of the gneissic basement and greenstone belts. The tectonometamorphic banding of the basement, deformed during phase 1, corresponds to a structural evolution which predates the formation of the belts.

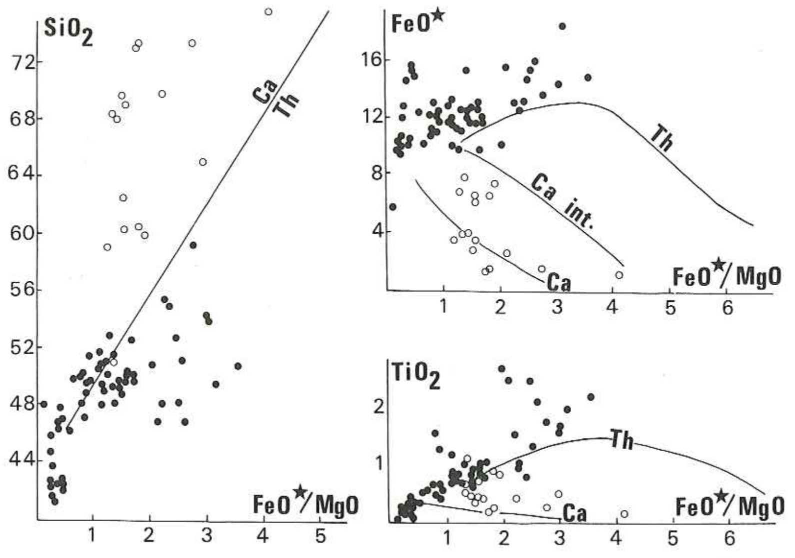

Fig. 3. Location of the two volcanic sequences in the diagrams of Miyashiro (1975); same symbols as in Fig. 2.

4. Metamorphism

All the members of the belts are affected by a regional metamorphism of weak to intermediate intensity. The most frequent paragenesis are :

(a) Quartz + biotite + muscovite + albite or oligoclase ± chlorite ± garnet in the metapelites.

(b) Chlorite + epidote + actinolite + plagioclase ± biotite ± hornblende ± garnet ± diopside in the metabasites.

(c) Antigorite ± tremolite ± chlorite ± talc ± carbonates in the meta-ultrabasites.

The rocks of the belts are all metamorphosed to at least biotite grade. According to location, they correspond to the upper greenschist facies or lower garnet amphibolite facies. This metamorphism is apparently of intermediate pressure. The analysis of deformation/blastesis relations shows that the metamorphism commences with phase 1 and reaches a maximum during phase 2.

5. Important acid and intermediate magmatic emplacement is

related to orogenic evolution of the greenstone belts. It consists of :

(a) early granodiorites, emplaced post-phase 1 and pre-phase 2. These are principally phenocrystic granodiorites, with biotite or biotite and amphibole, relatively enriched in CaO and Na_2O and poor in K_2O.

(b) late events, post-phase 2 and pre-phase 3, amongst which can be distinguished :

i) medium-grained, biotite and amphibole granodiorites and tonalites, rich in CaO and MgO and poor in SiO_2 and K_2O;

ii) fine- or medium-grained, biotite muscovite leucogranites and leucogranodiorites of a pink colour, rich in SiO_2 and poor in CaO and relatively poor in K_2O.

iii) large bodies of biotite muscovite pegmatites.

The different plutonic bodies appear either in the greenstone belt or at the greenstone belt/basement boundary or within the basement, close to this last. It is of note that all these plutonic rocks are allochtonous and are poor in potassium.

6. Conclusions

The geological characteristics of the greenstone belts of Eastern Finland show that they correspond to the classical model of Archaean belts. From a geodynamic point of view two fundamental stages in their evolution can be distinguished :

i) an early stage of opening of proto-oceanic rifts, during which the komatiitic and tholeiitic rocks of the Lower volcanic sequence were erupted and the sediments were deposited.

ii) a later stage of closing, during which the calc-alkaline rocks were erupted, followed by the orogeny.

Before deformation, the belts studied here may therefore have corresponded to ensimatic island-arcs, adjacent to continental areas.

DATA ON KOMATIITIC AND THOLEIITIC SERIES OF EASTERN FINLAND

The following section presents data on the komatiitic and tholeiitic components of the Lower volcanic sequence of the East Finland greenstone belts :

1. Occurrence

The following lithological units have been distinguished :

(a) Slices of schistose ultrabasites, highly serpentinized ("soapstones").

(b) Massive ultrabasites, some with magmatic layering.

(c) Massive, generally gabbroic, sometimes ultrabasic rocks with relict igneous (gabbroic), intersertal or quench (spinifex) textures, most commonly as sills, more rarely as originally discordant veins or as lava flows with occasionally scoriaceous surfaces.

(d) Fine-grained amphibolites without relict textures, corresponding to lava flows or tuff horizons.

(e) Metabasalts *sensu-lato* in which the most characteristic texture is defined by radiating tufts of fine amphibole fibres, with local relicts of vacuole structures. These represent pillow lavas whose original form is often well preserved.

The isolation of outcrops and absence of normal contacts renders the interpretation of the relationships between these various rock types difficult.

2. Petrology and geochemistry

As indicated above, the basic and ultrabasic rocks of the Lower volcanic sequence have been metamorphosed in the upper greenschist facies to lower garnet-amphibolite facies. Elsewhere, certain ultrabasic rocks have undergone metasomatic modification, some "soapstones" containing up to 20% volatiles.

Under these conditions, most of the primary minerals and glasses are no longer directly visible and this study of the magmatic evolution is rendered that much more difficult. Indeed, we are restricted to the study of a few relict minerals and the geochemistry of immobile major and trace elements of the rocks.

(a) Relict minerals : only relict minerals in rocks of cumulate texture have been observed.

The ultrabasic cumulates of the komatiitic series frequently contain residual, partially serpentinized, olivines and occasionally, clinopyroxenes and chromite. These minerals are at present the object of study.

The picritic cumulates of the tholeiitic series frequently contain clinopyroxene, the microprobe analysis of which identifies them as salite. In certain olivine-bearing cumulates of the same series, microprobe analysis shows a relative enrichment in iron (Fo_{84}).

(b) Mineral assemblages : according to their composition and degree of metamorphism, the various rock types have the following assemblages:

i) Soapstones : antigorite + talc + carbonates (breunnerite, stichtite) + magnetite with, in minor amounts, Mg - chlorite, penninite, tremolite and graphite.

ii) Massive metaperidotites : residual olivine and clinopyroxene in variable proportions + antigorite + tremolite + sulphides, and, in minor amounts, Mg - chlorite, penninite, magnesite and ± chromite ± opaques ± chrysotile in cross-cutting veinlets.

These rocks often contain olivine cumulate texture and have the normative compositions of harzburgites or lherzolites of dunite affinity.

iii) Metapicrites : tremolite + Mg-chlorite ± talc ± opaques ± carbonates ± penninite. The observed spinifex textures in these rocks demonstrate the replacement of olivine by fibrous Mg-chlorite; the spaces between the network formed by the Mg-chlorite is filled by acicular tremolite, chlorites and carbonates.

iv) Metagabbros and metadolerites: the most common assemblages are : a) actinolite + albite or oligoclase + epidote ± chlorite ± biotite ± quartz.

b) green hornblende + oligoclase or andesine ± chlorite ± epidote ± biotite ± actinolite ± garnet. In some samples, actinolite and hornblende have been observed together. Exceptionally, metamorphic associations with clinopyroxene or scapolites occur.

Certain metagabbros contain residual clinopyroxene in amphibole cores. Their chemical composition shows that, in these instances, the rocks are probably former tholeiitic clinopyroxene cumulates.

v) Fine-grained amphibolites : these present the same assemblages as the metagabbros but without relict textures. Furthermore, their plagioclase proportions are highly variable from one rock to the next; compositionally, they correspond to picritic basalts, olivine tholeiites (the most abundant) and mildly saturated tholeiites.

vi) The pillow lavas : these generally comprise fine-grained tremolite, epidote and chlorite, lack any plagioclase and have a picritic basalt composition.

(c) Major element geochemistry : the major element composition has been measured for seventy samples, representative of the observed rock types. The average compositions are given in Table 1.

i) Classification adopted : the content of MgO, being the most variable of the oxides (4% < MgO < 46%), has been chosen as the basis for initial subdivision. The peridotites and "soapstones" have MgO contents falling between 33% and 46%. The massive peridotites divide into two groups whose MgO contents vary about

TABLE 1: Average compositions (anhydrous) of the main rock types in the Suomussalmi, the Kuhmo and the Tipasjarvi greenstone belts

	a	b	c	d	e	f	g	h	i	j
No. of analyses	3	4	9	1	5	6	19	2	2	11
SiO_2	44.12	43.25	43.74	47.84	46.85	50.21	50.54	51.15	48.00	50.90
Al_2O_3	2.27	3.93	2.66	6.86	8.08	11.77	14.80	6.29	10.84	14.04
FeO	8.86	14.88	10.56	10.73	10.75	10.74	11.87	11.90	12.59	14.94
MnO	0.14	0.25	0.09	0.20	0.17	0.22	0.20	0.27	0.21	0.24
MgO	44.27	34.23	40.89	26.67	26.01	13.91	8.06	11.84	14.77	5.63
CaO	0.13	3.08	1.90	7.21	7.45	11.01	11.21	15.28	10.11	8.90
Na_2O	-	-	-	0.01	0.18	1.23	2.14	1.65	1.00	2.81
K_2O	-	0.06	-	0.10	0.03	0.33	0.23	0.32	0.88	0.37
TiO_2	0.18	0.32	0.16	0.29	0.40	0.54	0.84	1.22	1.44	1.98
P_2O_5	-	-	-	0.11	0.07	0.07	0.09	0.10	0.14	0.19

a: peridotites (cumulate) with MgO > 40%; b: peridotites (cumulate) with MgO = 30-40%; c: soapstones; d: picritic komatiite with spinifex texture (S833); e: picritic komatiites (MgO = 20-30%); f: picritic basaltic komatiites (MgO = 12-20%); g: basaltic komatiites (MgO < 12%); h: tholeiites with clinopyroxene cumulates; i: tholeiites with possible olivine cumulates; j: tholeiites. Total iron oxides as FeO.

Analyst: F. Vidal, Centre Armoricain d'Etude Structurale des Socles, Univ. de Rennes.

44% and 34%, corresponding to two types of cumulates of different olivine proportions. The MgO content of the picrites falls between 21% and 28%, with an average close to 26%. We have grouped the basalts and picritic gabbros whose MgO content is between 12% and 16%. Some of these rocks are clinopyroxene cumulates, others are gabbros probably enriched in olivine. Finally, we have considered a very extensive group of rocks, whose MgO content lies between 4% and 12%, to be basalts.

ii) Magmatic series : the basaltic rocks have compositions of oceanic affinities. These are ocean-floor basalts and low-K tholeiites; however, it is not possible at present to discriminate between those rocks of ridge and those of island-arc types. As is often the case in the Archaean belts (Arndt et al., 1977) and recent oceanic environments (Clarke, 1970 ; Dietrich et al., 1977), the rocks studied correspond to two series of distinct composition and evolution characterized in particular by different TiO_2 concentration. Thus, the components of the Lower volcanic sequence of the belts in Karelia can be subdivided into a komatiitic series and a tholeiitic series.

The komatiitic series includes a fairly continuous series of rocks passing from peridotites to basalts, characterized by high CaO/Al_2O_3 ratio at constant MgO and low alkalis and titanium contents.

The tholeiitic series is, albeit, exclusively composed of basalts with associated rare clinopyroxene and perhaps olivine cumulates. Compared with the previous series, the tholeiitic series, though relatively poor in potassium, is richer in alkalis, relatively depleted in CaO and MgO and is especially characterized by a great iron and titanium abundance.

Fig. 4 shows the discrimination between these two series on a TiO_2 versus Al_2O_3 diagram. Except for minor details, these series are very similar to those of South Africa (Viljoen and Viljoen, 1969 a,b), Ontario (Arndt et al., 1977) and Western Australia (Naldrett and Turner, 1977) which are well known.

iii) Trend of crystallization : the representative points of the rock compositions of the two series plotted on oxide versus oxide diagrams show trends attributable to magma fractionation. Taking account of these trends and of the measured or estimated composition of the residual minerals, we can make the following observations.

<ins>Tholeiitic series</ins> (Fig. 5) : the principal diagrams in terms

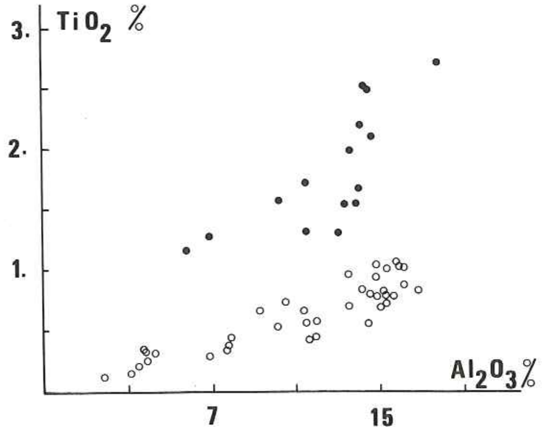

Fig. 4. TiO_2 vs Al_2O_3 diagram showing the opposition between tholeiites (s.s.) and komatiites; filled circles = tholeiites, open circles = komatiites.

of MgO and SiO_2 show that, except for the cumulates, rocks of the tholeiitic series present a unique linear differentiation trend. This trend is characterized by the regular decrease of Al_2O_3, FeO, MgO and CaO and the increase of SiO_2 and Na_2O during the crystallization.

If we consider that the rocks richest in MgO and poorest in SiO_2 are close to the primary liquid composition, this magmatic evolution is therefore mainly controlled by plagioclase and clinopyroxene fractionation. However, the primary liquid being relatively depleted in SiO_2 compared to the plagioclase-clinopyroxene mixtures, some small quantities of olivine and opaque minerals must also have played a role, at least in the early stages of the differentiation. The role of an opaque mineral rich in iron is confirmed by the fact that all of the tholeiitic series rocks are richer in total iron than mixtures plagioclase + clinopyroxene + olivine.

The observed cumulates belong to two types. Some are cumulates with evident clinopyroxene, their chemical composition confirming the textural and mineralogical observations; others are probably early cumulates, lightly enriched in olivine and clinopyroxene, as deduced from their chemical composition, but without microscopic evidence.

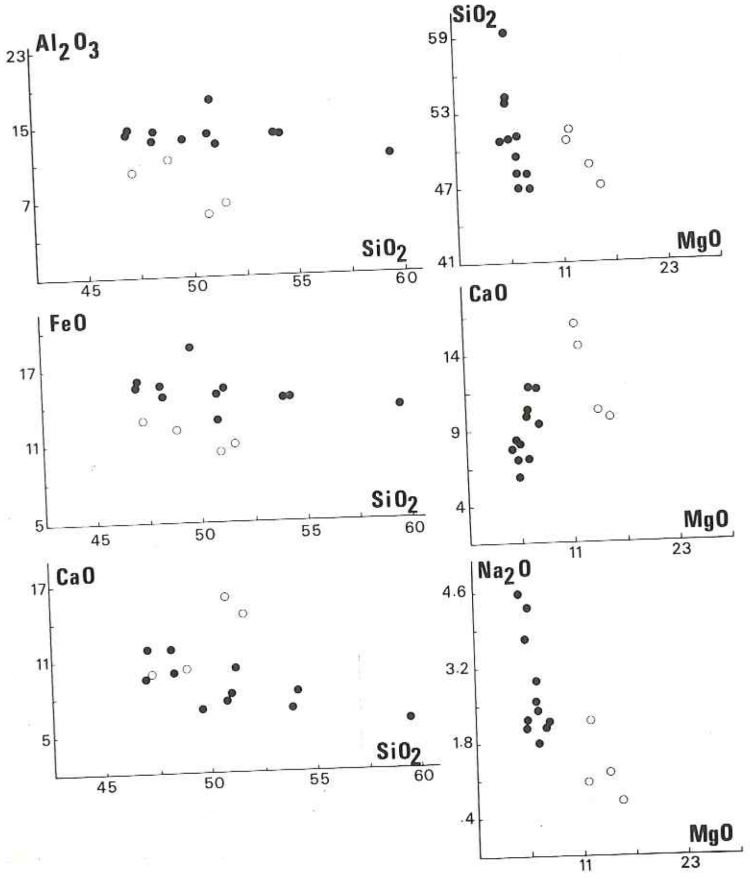

Fig. 5. Different oxides vs MgO and SiO$_2$ diagrams in the tholeiitic series. Filled circles = tholeiites without cumulate textures; open circles = cumulates.

Komatiitic series (Fig. 6) : the crystallization trend of the komatiitic series is much more complex. Here, the diagrams include all the rocks of Suomussalmi, Kuhmo and Tipasjarvi belts whereas the trends specific to each belt may present some slight differences. For the moment, our observations only constitute a first approximation.

The diagrams, oxide versus MgO, show continuous and regular enrichment in SiO$_2$, Al$_2$O$_3$ and CaO for MgO values between 45 and 15%. This enrichment suggests that the fractionation of this part

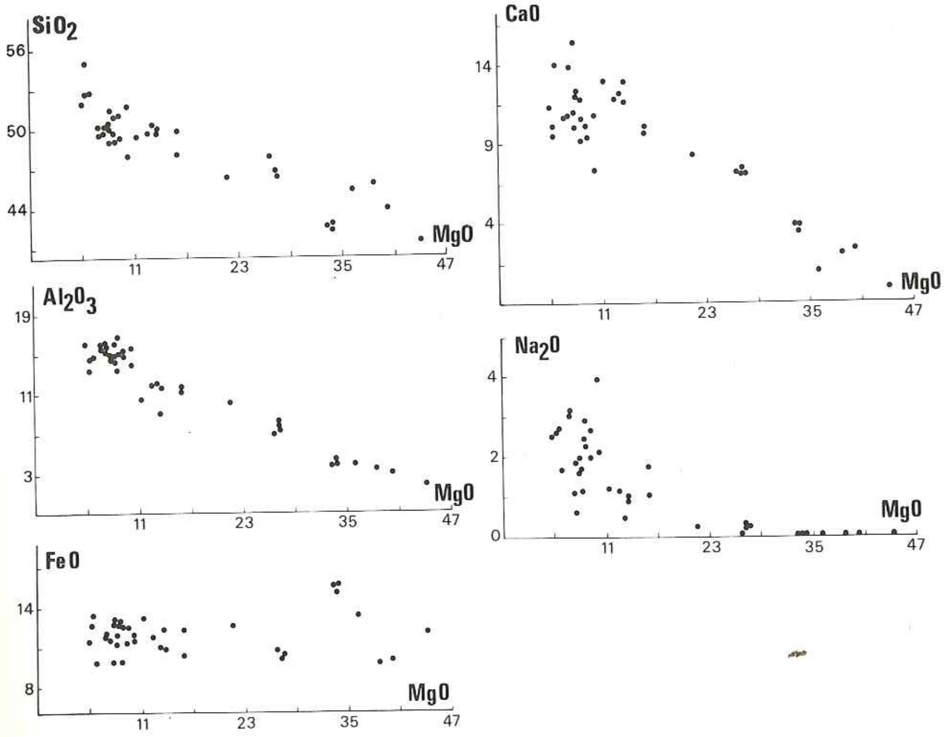

Fig. 6. Different oxides vs MgO in the komatiitic series. Cumulates are not distinguished in these diagrams.

of the suite was essentially controlled by olivine, starting from a primary liquid situated at about 26-27% MgO, a composition that corresponds to the micro-spinifex rocks. The FeO content being quite stable during the early crystallization, described above, it is possible that a small quantity of opaque iron ores crystallized at the same time as the olivine.

Between 15% and 10% of MgO, the contents of SiO$_2$, Al$_2$O$_3$, FeO and Na$_2$O are generally constant, while the CaO content increases somewhat, corresponding to a concomitant fractionation of olivine and clinopyroxene.

From about 11% MgO the general trend splits, principally into three micro-trends, mainly corresponding to liquids depleted in clinopyroxene and plagioclase and to liquids lightly enriched in clinopyroxene or clinopyroxene and plagioclase.

As may be seen, the major element geochemistry in the komatiitic series of eastern Finland is compatible with simple mechanisms of fractional crystallization. The trends agree with the experimental data of Arndt (1976).

(d) Geochemistry of some transition elements : only fragmentary data for trace elements is available (Ni, Co, V, Cr, Zr, Y), the only systematic study being that of the Tipasjarvi belt.

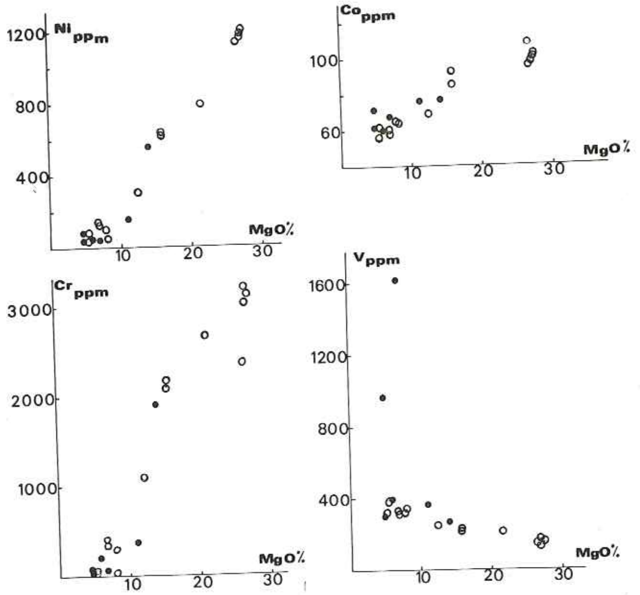

Fig. 7. Transition-elements (Ni, Co, V, Cr) vs MgO diagrams in the volcanites of Tipasjarvi greenstone belt. Filled circles = tholeiites; open circles = komatiites.

In Fig. 7, the Ni, Co, V and Cr values have been plotted vs the MgO content, this latter being considered as an index of degree of differentiation. Concerning the komatiitic rocks, Ni, Co and Cr show a good positive correlation with MgO, and this seems to indicate that they are mainly concentrated (especially Ni and Cr) during the first stages of crystallization (incorporation in olivine and perhaps, also, in opaque phases, oxides or sulphides). On the other hand, V shows a strong negative correlation; it seems to be concentrated in the residual liquid with advancing fractional crystallization. From this point of view V appears to be a more incompatible element than Ni, Co or Cr.

Correlations are less clear cut for the rocks belonging to the tholeiitic series, and this can be explained by the concomitant crystallization of several phases (clinopyroxene, plagioclase, olivine and opaques).

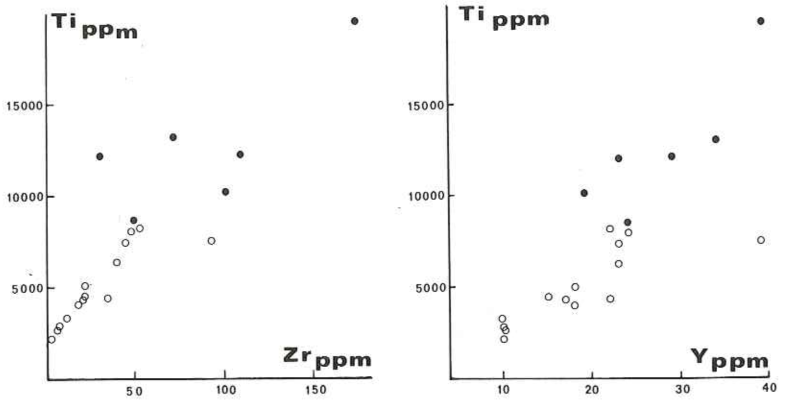

Fig. 8. Ti vs Zr and Ti vs Y diagrams in the volcanites of Tipasjarvi greenstone belt. Same symbols as in Fig. 7.

Fig. 8 demonstrates the good correlation, for the komatiitic rocks, both between Ti vs Zr and Ti vs Y ; this is a general feature of Archaean komatiites (Nesbitt and Sun, 1976). Another common characteristic of the Archaean rocks is the scattering of the plots of tholeiitic rocks in such diagrams and this is well observed for Tipasjarvi. Nesbitt and Sun (op. cit.) explained this scattering by the influence, in the tholeiitic rocks, of both the clinopyroxene and the opaque minerals; it is likely that the same interpretation applies equally to the case studied here. Lacking accurate data on the content of trace elements of minerals involved in the evolution of komatiitic and tholeiitic series, it is, for the moment, impossible to identify more accurately the mechanisms of behaviour of trace elements during fractional crystallization of the two series. However, in respect of their amount and trends of evolution, trace elements in the Tipasjarvi greenstone belt show features very similar to those described in volcanic rocks of other Archaean greenstone belts (for example, see Nesbitt and Sun, op. cit.; Arndt et al., 1977; Naldrett and Turner, 1977).

(e) Rare-earth element characteristics : the REE abundances in 35 basaltic rocks from the three belts (Tipasjarvi, Kuhmo and

Suomussalmi) were determined by the isotopic dilution method at Universite de Rennes. Because the rocks from the Tipasjarvi belt possess most of the features characterizing the evolutionary processes and the source natures, only the results obtained for this belt are discussed. A more detailed account for the REE geochemistry on all three belts will be reported elsewhere (Jahn et al., in prep.). In the following, the REE concentrations have been normalized against the chondritic values determined by Masuda et al. (1973), but further divided by a factor of 1.2 and the results are plotted in the conventional REE variation diagrams (Fig. 9).

In the komatiitic series of the Tipasjarvi belt, three types of REE patterns are recognized :

i) REE patterns with strong LREE depletion, $(La/Sm)_N$ = 0.27 - 0.68, but essentially flat HREE, $(Ga/Yb)_N \sim 1.0$; HREE are 4 to 12 times chondritic abundances. This type of pattern has been found for some Archaean volcanic rocks from the Munro Township, Ontario (Arth et al., 1977) and from Noranda, Ontario (Jahn, unpublished).

ii) REE patterns with slight to moderate LREE depletion but with sloping HREE, $(Ga/Yb)_N$ = 1.2 to 2.0. These two types may be related to each other with a similar mantle source characteristic, i.e. the source has previously undergone a severe LREE depletion. However, type (i) rocks, with flat HREE, seem to be derived by partial melting of the source in which no garnet remained in the residue. In contrast, type (ii) rocks, with sloping HREE and smaller degree of LREE depletion, require that they be derived from a similar source but with garnet in the residue. For type (i) rocks, the four patterns may be derived by various degrees of partial melting. However a crystal fractionation model can equally be applied. Using proper distribution coefficients for REE in basaltic melt, it can be estimated that 30% of olivine removal is required to produce rock S 831 from a melt of composition equivalent to rock S 847. In turn, 60% of fractionation of olivine and pyroxene (1:1 ratio) is required to produce rocks S 818 and S 828 from S 831. Plagioclase separation, if any, is rather insensitive in increasing the HREE abundances. Moreover, the role of plagioclase is probably insignificant because both S 818 and S 828 have smaller negative Eu anomalies than both S 831 and S 847. For type (ii) rocks, because of their similar MgO contents (13.5 and 12.5%) but very different REE abundances, a model of different degree of partial melting can better explain the results.

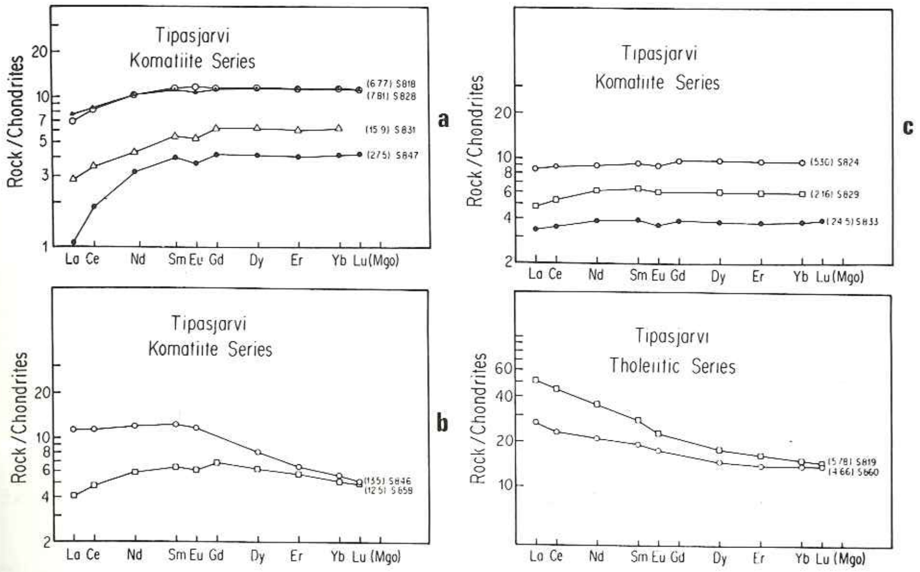

Fig. 9. Chondrite normalized rare earth distribution patterns for komatiitic and tholeiitic rocks from the Tipasjarvi greenstone belts.

(iii) REE patterns of about 4-10 x chondrites with very slight LREE depletion, $(La/Sm)_N$ = 0.75 to 0.90, and essentially flat HREE $(Ga/Yb)_N \sim 1.0$; included in this group is the rock S 833 in which a microspinifex texture is found. In a crystal fractionation model, to produce rock S 824 from S 829, 40% of fractionation of olivine + clinopyroxene (1:1 ratio) is required, and from S 833 to S 829, 40% of olivine fractionation. As in the case of types (i) and (ii), type (iii) rocks could also be derived from different degrees of partial melting from a mantle source with slight LREE depletion; further, garnet has not remained in the residue.

In the tholeiitic series, the REE patterns are characterized by the enriched LREE and sloping HREE $(La)_N$ = 26-52 x, $(Lu)_N$ = 14-15x. These are comparable to the results of Abitibi tholeiites (Arth et al., 1977). If the two rocks are related by crystal fractionation, clinopyroxene probably played the dominant role. Olivine fractionation is not important because the MgO contents of the liquids are low (MgO = 4.7 and 5.8%); plagioclase separation is not possible because it would cause the $(La/Lu)_N$ ratio to decrease from S 860 to S 819, whereas the opposite is observed. The production of tholeiitic melt could be through the partial melting of a mantle source of relatively undepleted nature.

Arth et al. (1977) formulated a unified model in which the tholeiitic and the komatiitic series of Munro Township are thought to be genetically related simply because of their intimate spatial relationship. Almost exactly the same conclusion has been obtained from the present work. The greenstone belt of Tipasjarvi has a long dimension of about 10 km and all samples were collected within a distance of about 5 km. Most of the tholeiitic rocks from this and the Kuhmo belt have $(La/Sm)_N$ and $(Ga/Yb)_N$ ratios greater than 1.0. Early extraction of tholeiitic liquids from a mantle source characterized by a flat chondritic REE pattern would leave the residue strongly depleted in LREE and $(Gd/Yb)_N$ slightly less than 1.0. This residual mantle may serve as the source for some komatiitic rocks of types (i) and (ii) described earlier. Subsequent melting of this residue, involving garnet or not in the second generation residue, produces the variance in the REE patterns of types (i) and (ii).

It is important to note that the highly LREE-depleted nature of the mantle source is found for only the second time in Archaean greenstone belts, the first case being the Abitibi (Arth et al., 1977; Sun and Nesbitt, 1977 ; Jahn, unpublished). Whether this type of depletion is world-wide remains to be explored.

However, the significance of this depletion must be emphasized. If the depletion is world-wide and large scale, this phenomenon may have to be related with the known and tremendous production of granitic liquid from the mantle sources. The granitic basement rocks surrounding the greenstone belts are emplaced penecontemporaneously (Vidal and Blais, 1977). If the belts and granitic basement are genetically related, the depletion nature is then due to the earlier separation of granitic liquids, rather than from the extraction of tholeiitic liquids as mentioned before.

The depletion nature of the mantle source has another aspect of importance. It clearly indicates that the mantle heterogeneity has existed ever since at least 2.7 b.y. ago. The available Sr isotopic data show that the initial Sr^{87}/Sr^{86} ratios in the 2.7 b.y. terrains are variable. This suggests that the mantle heterogeneity was already created at least 3.5 b.y. ago (see Jahn and Nyquist, 1976).

CONCLUSIONS

The study of Archaean greenstone belts in eastern Finland, initiated three years ago, is still very fragmentary and the comparison between the interpretations based on the major element geochemistry and the rare earth element geochemistry may occasionally be contradictory, as in the case of the tholeiitic series.

However, even at this early stage, it is possible to present certain conclusions : the Archaean greenstone belts reported as such in the Baltic Shield in 1976 are the first so identified in Europe; they are very similar in many respects to the other Archaean greenstone belts described in Africa, North America, Australia and India (Windley, 1973; Hunter, 1974; Anhaeusser, 1975; Glikson, 1976 and others). The formation of the Finnish greenstone belts appears to be compatible with a model combining the proto-oceanic rift model of Windley (1973) and the ensimatic island-arc model of Anhaeusser (1973). However they show features which distinguish them from more classical greenstone belts : the regional metamorphism is of higher grade than in the other belts, and the erosion seems to have been deeper than in other greenstone belts because the lower sequence constitutes the essential part of the outcrops. In consequence, the Finnish greenstone belts may provide a better chance for the study of deeper levels of the Archaean greenstone belts.

Another important characteristic is that these belts are the super-structure of vast orogens, at least on the scale of the Baltic Shield. The fact that the gneissic basement and the belts themselves all formed within about 100 m. y. of each other is evidence for the extreme rapidity of geodynamic processes. Finally, it is clear that in Finland the mantle showed an important heterogeneity, at least 2.7 b. y. ago or earlier.

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