A MODIFIED STRATIGRAPHY AND TECTONO-MAGMATIC MODEL FOR THE SUOMUSSALMI GREENSTONE BELT, EASTERN FINLAND, BASED ON THE RE-MAPPING OF THE ALA-LUOMA AREA

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The stratigraphic sequence of the Suomussalmi Greenstone Belt is divided into the Luoma and the overlying Saarijärvi Group. Both display polyphase deformation and low to medium amphibolite facies metamorphism.

The lowermost stratigraphic unit of the Luoma Group consists of tholeiitic volcanics. The overlying intermediate and felsic volcanics are genetically related to these early mafic rocks by various degrees of partial melting. Pre-metamorphic hydrothermal alteration caused the change in chemical composition from intermediate to felsic and the deposition of the Zn-Pb-Ag-Au sulphides. The stratigraphic lower levels are enriched in MgO, FeO* and depleted in CaO and K_2O. The upper horizons are characterized by a strong Na- K- differentiation with high K_2O/Na_2O ratios, increasing SiO_2 and FeO* contents and enrichment of ore-forming elements.

The Luoma Group deposited during an extensive rift and sag process in shallow-water, on/or in close proximity to the sialic basement.

The transition to the Saarijärvi Group is marked by a north-south trending unconformity, along which serpentinite bodies are sheared apart due to the deformation phase D_4. The intrusion of the previously peridotitic rocks was accompanied and followed by ultramafic-mafic volcanism, producing the first unit with a komatiitic affinity. The succession is terminated by felsic pyroclastic rocks which display severe HREE depletion. Thus, a geochemical and time-depending correlation with the Koivumäki Formation (Tipasjärvi Greenstone Belt), characterized by the weak depletion in HREE and slightly negative Eu-anomalies, should not be postulated any more.

Further rifting and subsequent rise of the mantle-crust boundary led to production of another mafic and felsic cycle in an oceanic rift related environment.

Key words: greenstone belts, metavolcanic rocks, stratigraphy, chemical composition, hydrothermal alteration, rifting, Archean, Ala-Luoma, Saarijärvi, Suomussalmi, Finland.

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Introduction

Detailed re-mapping of the northern part of the Archaean Suomussalmi Greenstone Belt (see Fig. 1) was carried out in summer 1988 in an attempt to solve the stratigraphic and tectono-magmatic problems related to the late Archaean regime (Windley 1981; Kröner 1981; Green 1975; Goodwin and Smith 1980) and to the ore-forming processes associated with the greenstones (Fryer

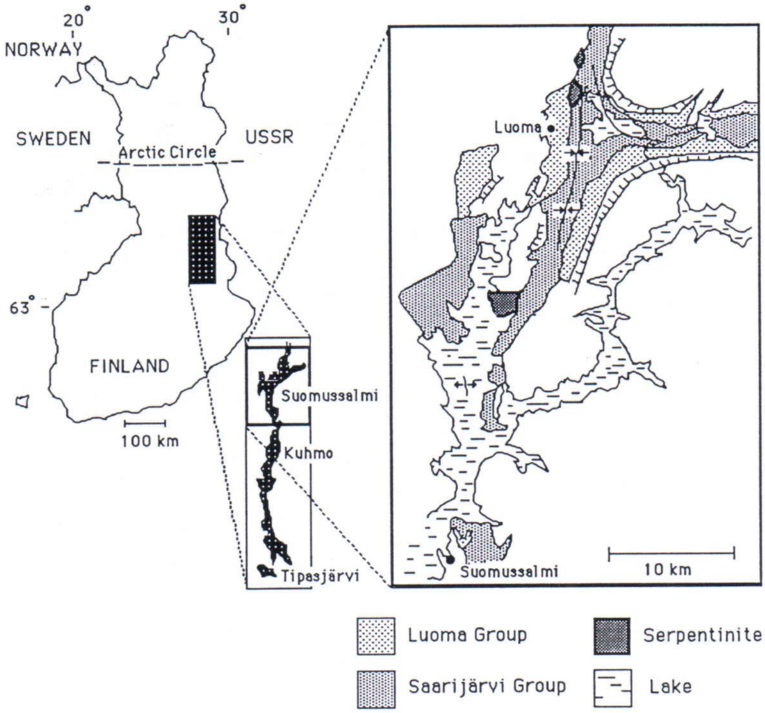


Fig. 1. Geography and regional geology (partly after Taipale and Tuokko 1981).

et al. 1979; Knuckey et al. 1978; Kopperoinen and Tuokko 1988).

The area has undergone polyphase deformation and low to medium amphibolite facies metamorphism. The most obvious instance is the extreme Na- and K- differentiation within the intermediate and felsic metavolcanics of the Luoma Group, incompatible with igneous variation patterns. Following the graphic detection and correction procedure for element redistributions in volcanic rocks by Beswick and Soucie (1978), pre-metamorphic hydrothermal alteration reactions can be distinguished from primary magmatic heterogeneities caused by differences in mantle melting, magma sources, magma segregation processes, and differential buoyancy (Turcotte 1987).

The field work was focussed on an area of about 25 km² around the Lakes Ala-Luoma and Saarijärvi (Fig. 2). This area, which is considered one of the stratigraphic type sections of the Suomussalmi Greenstone Belt (Piirainen 1985), was a target of intensive exploration by Kajaani Oy in 1975—1979. The Company put a detailed (unpubl.) lithological map at 1 : 20 000 scale at the authors' disposal. The Suomussalmi area was first mapped, at 1 : 100 000 scale by Matisto (1954; 1958).

During the last two decades the Suomussalmi Greenstone Belt has been the subject of several research programmes, particularly with reference to its petrography, structural geology, geochemistry and geochronology (Vidal et al. 1980; Blais et al. 1977; 1978; Auvray et al. 1982; Kopperoinen and Tuokko 1988; Kojonen 1981). However, more attention has been paid to the neighbouring Kuhmo and Tipasjärvi Belts (Jahn et al. 1980; Taipale et al. 1980; Taipale 1983; 1985; Querré 1985; Hanski 1980; 1988; Papunen et al. (1989); Luukkonen 1985; 1988).

Together the three belts represent a north-south trending, late Archaean greenstone terrain about 250 km long, and enveloped by an extensive granitoid basement complex (Hornemann et

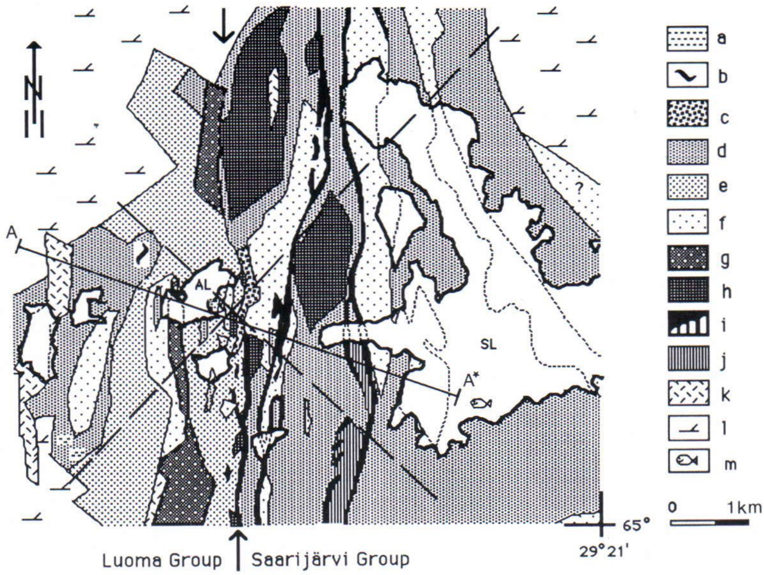


Fig. 2. Geological map of the study area. a) pelitic sediments; b) greywacke interlayers; c) ultramafic volcanics; d) mafic volcanics; e) intermediate volcanics and tuffs; f) Luoma Group, silicified volcanics; Saarijärvi Group, acid volcanics and tuffs; g) gabbroic sills; h) serpentinites; i) black schists / BIF; j) chlorite-epidote-carbonate rocks; k) meta-diabase; 1) Archaean granitoid basement complex; m) lakes; AL = Lake Ala-Luoma; SL = Lake Saarijärvi; —— —— transcurrent faults; A-A* cross-section.

al. 1988; Martin et al. 1983a; 1983b; Martin and Querré 1984).

The greenstone belt volcanics constitute a mafic (ultramafic) to felsic cyclic succession ranging from MgO-intermediate komatiitic to rhyodacitic and rhyolitic in composition. The greenstone belt also includes pelitic sediments. Piirainen (1985) divided the stratigraphic succession into the Luoma Group and the overlying Saarijärvi Group. Querré (1985) and Martin (1989) argue that the Luoma Group volcanics were generated by partial fusion of the gneissic basement and represent the youngest extrusives of the Kuhmo-Suomussalmi Greenstone Belt.

Megascopic and structural observations

The field work was based on the lithological map compiled at 1:20 000 scale by Kajaani Oy. Observations on the bedrock were made at about 100 outcrops, and tectonic elements were measured at 60 localities. Rock types were determined on the basis of textural features and mineral composition. Further microscopic investigations together with XRF-, AAS-, DCP-, INAA-, and wet-chemical analyses led to production of the modified geological map for the area around Lake Ala-Luoma presented here (Fig. 2). In nature, however, the geological situation is more complex, and because of the Quarternary glacial cover and the spot-like distribution of the outcrops, an interpolation had to be made on the basis of the aeromagnetic map (Geol. Surv., sheet 4513, 1977).

The most prominent tectonic feature in the outcrops is foliation (D_3 axial planes according to Luukkonen 1988) which trends uniformly north to south and dips steeply to east. However, statistically there is a difference in dip angles between the Luoma and Saarijärvi Groups. In the field this tectonic borderline can be observed by following the sill-like serpentinite bodies. The serpentinites are easily recognized by the strong positive anomalies they leave on magnetic maps. The difference in dip angles between the two rock groups is about 6°, from 77° E in the Luoma Group to an average of 83° E in the Saarijärvi Group (see Fig. 3). On a regional scale, the isolated occurrence of the serpentinites is not interpreted as a boudinage structure, as in the Moisiovaara area in the north of the Kuhmo Belt (see

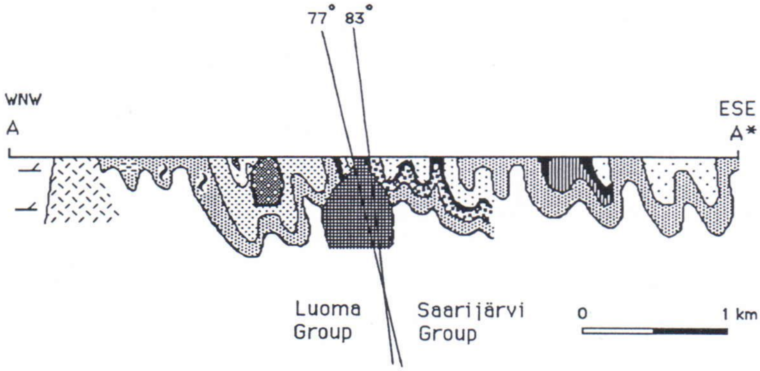


Fig. 3. Idealized cross-section. For position and legend see Fig. 2. From WNW to ESE there is more or less continuous decrease in altitude A: 240 m, A*: 202 m above sea level.

Luukkonen 1988); for this, a north-south acting tensional stress would have been necessary. The fracturing of the serpentinites is more likely due to strike slip faults, corresponding to deformation phase D_4 (see Fig. 5), that can be traced into the Archaean basement as described in detail by Luukkonen (1988). Apart from the unconformity, the main tectonic elements in the area are the transcurrent faults and the dominant, large scale isoclinal folding F_3, with subvertical north-south trending axial planes and steeply plunging axes. The structural interpretation leads to an approximately orthogonal grid of major lineaments. Combined with the north-south trending unconformity, a point of intersection occurs about 200 m west from the south shore of Lake Ala-Luoma (see Fig. 2). The isoclinal type of folding can not be recognized in single outcrops; only ptygmatic overprinted segments are visible (see Fig. 6). Owing to the short amplitude of the isoclinal folds, individual lithological layers appear much thicker than in reality (see Fig. 3).

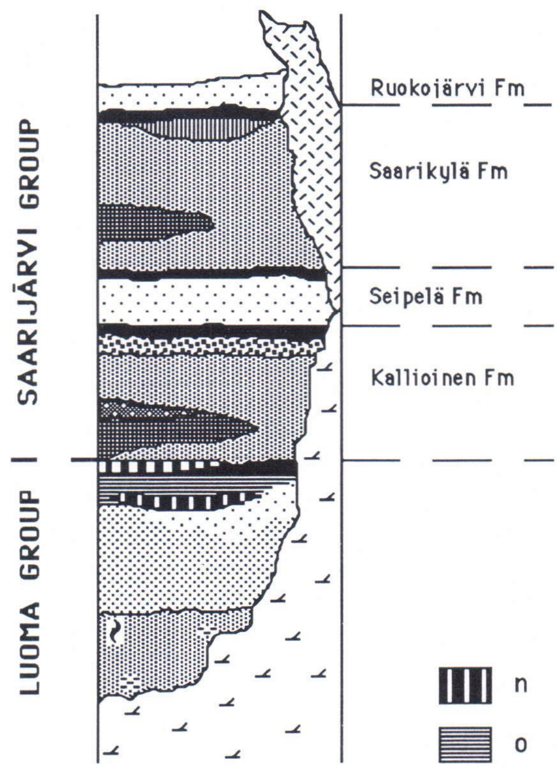


Fig. 4. Lithostratigraphic profile of the Ala-Luoma area. Legend as in Fig. 2. Additional patterns: n) Zn-Pb-Ag-Au mineralization; o) mica schists.

Rock types and stratigraphy

A stratigraphic profile is given in Fig. 4. The lowermost stratigraphic unit of the Luoma Group occurs in the west of the research area in vicinity of the basement contact.

The unit is represented by mafic volcanics. Metasedimentary rocks, ranging from arkositic quartz-feldspar schists to pelitic greywackes, occur as interlayers within the mafic volcanic rocks. Resembling erosion products of a probably sialic basement and/or felsic volcanics, they also contain mafic components and plagioclase phenocrysts from an early mafic volcanic event.

Petrographically the metapelites are composed of detrital and recrystallized quartz, plagioclase, mainly albite, but also polytwinned grains with sericite-bearing cores, brownish biotite, muscovite, very little sphene and zircon. Some assemblages contain chlorite and/or epidote as well as garnet, cordierite and tschermakitic hornblende. Disseminated pyrrhotite and minor chalcopyrite follow the main layering.

Pb-Pb and Rb-Sr systematics by Vidal et al. (1980); Martin and Querré (1984); Martin and Barbey (1988) reveal that the whole volcanic sequence of the Suomussalmi Greenstone Belt has been emplaced in a very short period at about 2630 Ma. However lead isotope ratios for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ have been determined on an arcositic rock at the eastern border of the Suomussalmi Greenstone Belt and on a sericite schist exposed in the western part of the schist belt, suggesting model ages (Stacey and Kramers 1975) for the galenas of 3020 Ma (G33), 3036 Ma (G305) and 2766 Ma (G306) (see GSF Ann. Rep. 1974 and Vaasjoki 1981). The arcositic rocks are presumed to represent weathering products of acid and intermediate volcanics of the Luoma Group (Taipale et al. 1980). The most recent lead isotopic determinations by Vaasjoki (1989) show that the Ala-Luoma galenas contain a lead component as old as 3600—4000 Ma. Because the host rocks of the sulphides were dated much younger, we suggest that the metal ions have been partly leached from the old, probably sialic, crust below, or from eroded crustal material.

The mafic volcanic rocks display a tholeiitic rather than a komatiitic chemical trend for the first lithostratigraphic unit (Table 1, Fig. 10, Fig. 11 and compare Blais et al. 1978). These mafic rocks are composed of hornblende, actinolite-tremolite, plagioclase, chlorite and occasionally also of epidote and carbonate. Quartz is very often an additional constituent and biotite is present in varying amounts. Sphene, zircon, pyrrhotite and chalcopyrite are accessories.

The intervening of the mafic volcanics and early sedimentary rocks and the probability that some of these volcanics have been eroded, together with the fact that both are situated close to the basement contact, indicate the stratigraphic beginning of the Suomussalmi Greenstone Belt. From this we can conclude that the earliest volcanic products of the Luoma Group are of basic, and not intermediate or felsic composition as described by Taipale et al. (1980) and Kopperoinen & Tuokko (1988).

Volcanic layers of intermediate chemical composition are encountered east of this lowermost stratigraphic unit. The structural features range from massive volcanic flows to fragmental and agglomeratic tuffites. Actinolite, albite and a few

Fig. 5. Fracturing due to D_4 in a serpentinite intrusion north of Lake Ala-Luoma.

Fig. 6. Ptygmatic folding in a slightly agglomeratic intermediate volcanic rock of the Luoma Group, SE of Lake Ala-Luoma.

Fig. 7. Agglomeratic intermediate volcanic rock with elongated fragments and quartz-calcite bearing veinlets. South of Lake Ala-Luoma.

Fig. 8. Sill-like intrusion of a gabbroic amphibolite on the SE shore of Lake Ala-Luoma.

Fig. 9. Chlorite-epidote-carbonate rock with irregular, folded carbonate veins containing sulphide minerals. Roadcut at Portinvaara.

plagioclase phenocrysts with An_{35-42} and epidote are the main constituents. Hornblende and biotite are much less common than in the mafic volcanics. They reflect a higher quartz content and chlorite occurs in various amounts. Accessories are zoisite, clinozoisite, zircon and sphene. The agglomeratic type is characterized by foliated, elongated and often sheared fragments with variable composition. The structure is clearest recognized in the outcrops, where the fragments have a brighter colour compared with the intermediate grey of the matrix. A further attribute of the intermediate volcanics are lenses of different shapes and veinlets, ranging from a few mm to several cm in thickness (see Fig. 7). They contain mostly medium to coarse grained quartz, carbonates, minor prehnite and clinozoisite and often display narrow, irregular folding, probably a combination of D_3 and D_4.

A more detailed study of the intermediate volcanic rocks was made possible by drill-core investigation. As reported by Kopperoinen & Tuokko (1988), the upper pyroclastic part shows pronounced sericitization and the rock turns into a quartz-sericite schist with minor concentrations of albite, chlorite and carbonate. This is the host rock for the Zn-Pb-Ag-Au sulphide mineralization. The ore minerals are disseminated and follow the main layering, but they also occur in fracture-fillings associated with quartz-carbonate

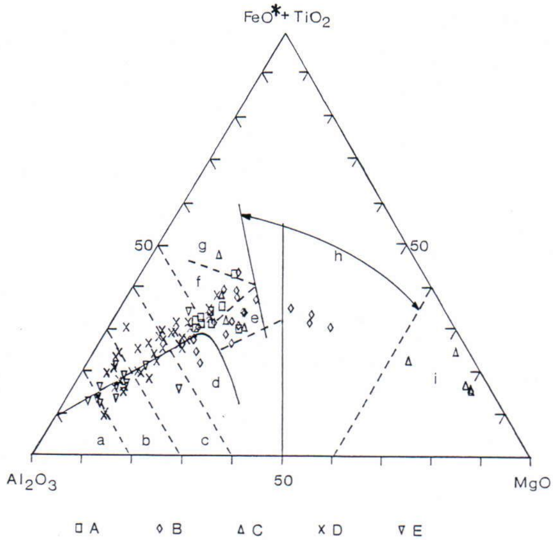


Fig. 10. Jensen cation plot. a—d) calc alkalic field; a) rhyolite; b) dacite; c) andesite; d) basalt; e) Mg-rich tholeiitic basalts; f) normal tholeiites; g) Fe-rich tholeiitic basalts; h) komatiitic basalts; i) komatiites; A) mafic Luoma volcanics; B) mafic Saarijärvi volcanics and chlorite-epidote-carbonate rocks; C) gabbroic amphibolites and serpentinites; D) intermediate Luoma volcanics; E) felsic volcanics, Luoma- and Saarijärvi Group.

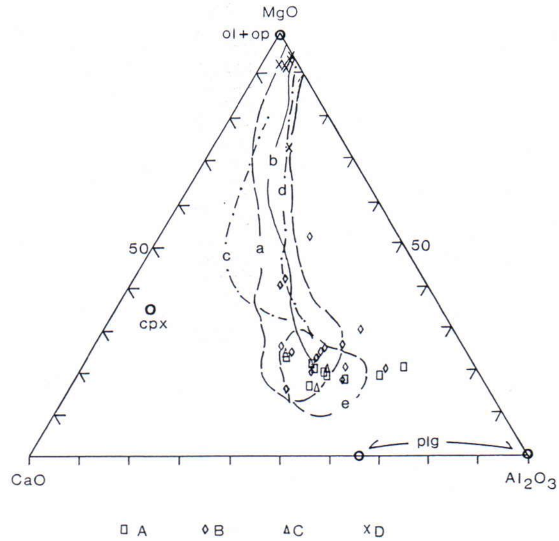


Fig. 11. Ca-Mg-Al diagram. a) Suomussalmi-, Kuhmo-, Tipasjärvi-trend; b) Olivine fractionation trend after Marston and Groves (1981); c) Barberton trend; d) Munro Township trend; e) tholeiites. A) mafic Luoma volcanics; B) mafic Saarijärvi volcanics; C) gabbroic amphibolites; D) serpentinites.

gangue. The mineralization is capped by thin layers of iron sulphides. The change in chemical composition from intermediate to felsic is complex. In comparison with Fig. 10 (Jensen cation plot), it becomes evident that one part of the intermediate and felsic metavolcanics plots into the tholeiite field, whereas the rest seems to form a calc-alkaline series. Further remarkable are the Na/K ratios (compare Table 1), which show a systematic K increase in the upper sericitized intermediate unit, incompatible with igneous variation patterns. On a regional scale Si, Mg, Fe, Ba and Rb also increase. However, depletion of Na, Ti and Ca can be noted in intermediate rocks with low to moderate K values (Table 1). These variations show that pre-metamorphic metasomatic alteration is very possible. Thus the data distribution of the intermediate and felsic rocks in Fig. 10 does not necessarily reflect the existence of two different magmatic series. Another important aspect is the linear increase/decrease of Rb and K (see Fig. 12) between K/Rb = 200 and K/Rb = 500. Intermediate metavolcanics with low to moderate K- and Rb contents plot between the compiled values for Andesite (I) and Andesite (II) (see Condie 1981). K and Rb, both soluble elements under seawater based hydrothermal alteration (Mottl 1983), are proportionally enriched in the upper sericitized levels (Fig. 12). Although they show very similar K/Rb ratios with the Arola Granite (compare Querré 1985) this fact can not be interpreted as a proof for the same genetic evolution of these two rock types and consequently not as a proof that the Luoma Group would be the stratigraphic top of the Suomussalmi Greenstone Belt. The Zr/TiO_2*10^4 and Nb/Y ratios (Fig. 13) show the extent of secondary alteration, as these elements are not usually mobile in aqueous solutions (Winchester and Floyd 1977). In the SiO_2 en-

Table 1. Chemical Analyses (calculated averages) of the Luoma and Saarijärvi rocks. 1) mafic volcanics Luoma Group; 2) gabbroic amphibolites; 3) mafic volcanics Saarijärvi Group; 4) serpentinites; 5) felsic volcanics Luoma Group; 6) felsic volcanics Saarijärvi Group; 7) chlorite-epidote-carbonate rocks; 8) carbonate-rich intermediate volcanics Luoma Group; 9—12) intermediate volcanics Luoma Group; 13) sericitized intermediate volcanics Luoma Group. FeO* as total Fe content SiO_2-CO_2 wt.%; Cu-Lu ppm.

	1	2	3	4	5	6	7	8	9	10	11	12	13
SiO_2	49.98	47.71	50.62	41.12	73.34	81.44	43.54	56.70	55.82	60.10	61.85	69.50	56.54
TiO_2	0.92	1.01	0.74	0.10	0.56	0.14	0.84	0.83	0.91	0.73	0.72	0.55	0.76
Al_2O_3	15.42	14.03	14.20	1.76	12.38	9.16	12.82	14.70	16.98	15.42	18.0	13.20	19.59
FeO*	10.52	13.10	9.75	8.43	3.27	1.50	11.66	6.65	9.38	5.93	6.81	5.49	6.80
MnO	0.21	0.19	0.20	0.09	0.06	0.04	0.18	0.16	0.18	0.14	0.16	0.10	0.13
MgO	6.18	7.40	7.86	35.10	1.56	1.22	10.35	3.60	5.61	4.54	4.43	0.72	3.87
CaO	9.12	10.42	8.98	1.43	2.37	0.53	6.80	10.51	4.14	4.63	0.92	0.89	1.80
Na_2O	2.49	2.33	2.74	0.01	2.41	1.33	0.08	1.55	2.27	2.79	0.52	0.97	1.69
K_2O	0.40	0.29	0.28	—	2.21	2.51	0.03	2.86	1.30	2.52	2.56	3.90	4.68
P_2O_5	0.18	0.07	0.10	0.01	0.07	0.03	0.07	0.21	0.17	0.25	0.15	0.15	0.10
LOI	2.50	2.30	2.10	9.80	1.10	0.90	6.40	1.10	2.35	2.50	2.30	2.85	3.20
CO_2	0.04	0.08	1.60	0.75	0.10	0.05	8.10	0.65	0.15	0.05	0.03	0.04	0.01
Cu	119	109	36	2	26	11	85	59	59	66	64	160	74
Ni	101	107	140	2069	56	29	121	96	137	67	50	38	123
Co	56	51	44	22	20	10	55	32	48	25	14	18	34
Zn	23	70	81	7	52	38	172	87	83	185	200	1400	746
Pb	<2	<2	<2	<2	26	11	10	20	12	21	80	1000	27
Cr	397	380	410	2360	230	66	347	275	279	149	130	77	264
V	256	281	277	19	74	27	281	126	175	101	100	56	151
Ag	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	1	<0.5	<0.5	2.5	0.9
As	<2	<2	<2	<2	3	2.5	3	<2	2	3	<2	2	8
Sb	<0.2	<0.2	0.4	<0.2	<0.2	1.5	<0.2	<0.2	0.2	0.2	0.2	4.5	0.4
Bi	<0.2	<0.2	<0.2	<0.2	3.3	<0.2	n.d.	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Rb	25	<10	14	<10	52	56	<10	83	47	56	87	101	121
Sr	172	124	105	<10	146	75	99	343	144	160	200	10	75
Ba	88	130	45	<10	772	428	42	1210	305	455	630	1613	1053
Zr	87	40	47	<10	122	82	43	144	93	129	120	104	98
Y	12	10	<10	<10	19	<10	14	17	18	14	17	<10	18
Nb	14	<10	<10	<10	17	<10	<10	10	13	11	16	20	14
Mo	n.d.	<5	n.d.	n.d.	<5	<5	n.d.	<5	<5	<5	<5	<5	<5
Sn	n.d.	<100	n.d.	<100	<100	<100	<100	<100	<100	<100	<100	<100	<100
W	n.d.	<5	n.d.	n.d.	n.d.	n.d.	n.d.	<3	<3	<3	<3	<3	<3
Pt	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Cl	194	377	215	<100	102	80	<100	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Th	0.9	<0.5	0.65	n.d.	6.8	10.9	n.d.	<0.5	2	7	10	11	9
U	0.7	5	<0.5	<0.5	1.1	2.5	<0.5	2.5	2.7	3.1	1.9	3.5	2.3
Cs	1.3	12.5	1.0	<0.5	<0.5	2.05	1.6	<0.5	2.5	2.2	1.3	2.1	3.6
La	4.8	17.5	7.4	n.d.	32	27.5	3.9	20	25	32	30.9	37	25
Ce	11.3	22.5	13.5	n.d.	46	48	11	70	51	56	63	68	45
Ta	<1.0	2.5	<1.0	n.d.	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1	<1	1.3
Nd	14	n.d.	5.7	n.d.	16.5	17.6	8	n.d.	16	19	27	26	19
Sm	4.25	n.d.	1.7	n.d.	3.25	2	2.3	n.d.	3.4	3.5	2.9	4.2	3.9
Eu	1.12	n.d.	0.4	n.d.	0.8	0.75	0.7	n.d.	0.8	1.2	0.9	0.7	0.9
Tb	0.6	n.d.	0.56	n.d.	0.7	0.25	<0.5	n.d.	0.5	0.6	<0.5	<0.5	0.6
Yb	2.3	n.d.	2.16	n.d.	0.25	0.65	1.2	n.d.	2.1	2.0	1.8	1.5	2.1
Lu	0.35	n.d.	0.33	n.d.	0.09	0.14	0.17	n.d.	0.3	0.4	0.3	0.3	0.4

riched intermediate to felsic metavolcanics, the Zr/TiO_2*10^4 ratios are below the average of Archaean andesites/dacites (compare Condie 1981), due to the relatively high TiO_2 contents. Within the ore-element and sulphur enriched horizons, Y is depleted and Nb is enriched. The ana-

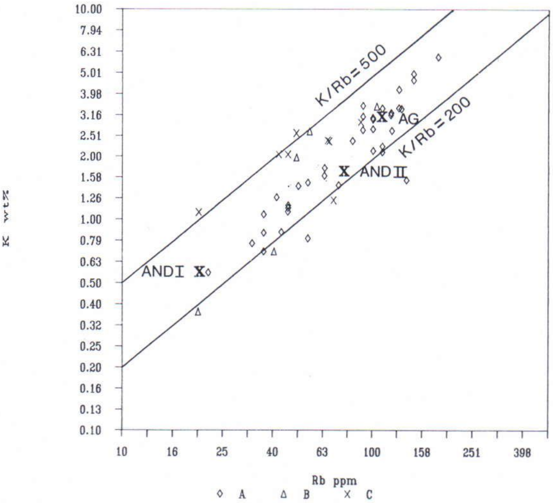


Fig. 12. K-Rb diagram. AND I = Andesite I; AND II = Andesite II (Condie 1981); AG = Arola Granite (Querré 1985). A) intermediate Luoma volcanics; B) felsic Luoma volcanics; C) felsic Saarijärvi volcanics.

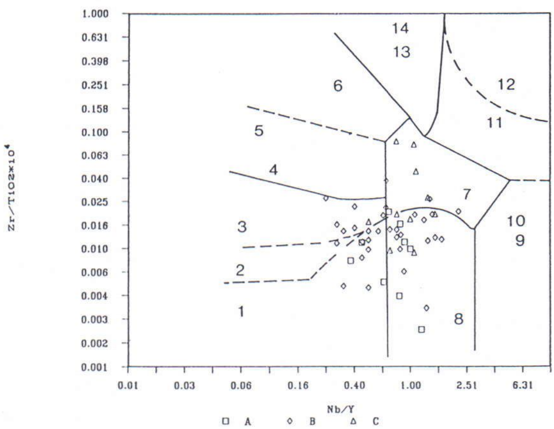


Fig. 13. Zr/TiO_2*10^4 vs. Nb/Y diagram. 1) sub-alkaline basalt; 2) andesite/basalt; 3) andesite; 4) dacite; 5) rhyodacite; 6) rhyolite; 7) trachyandesite; 8) alkali-basalt; 9) nephelinite; 10) basanite; 11) trachyte; 12) phonolite; 13) pantellerite; 14) comendite (Winchester and Floyd 1977). A) mafic Luoma volcanics; B) intermediate Luoma volcanics; C) felsic Luoma volcanics.

lyses therefore plot in the alkali-basalt field (see Fig. 13).

The Luoma stratigraphic sequence itself is terminated by metasediments such as mica schists, black schists and BIF. These mark the transition from the Luoma Group to the Saarijärvi Group in the Ala-Luoma area which can be recognized in the field by the above mentioned unconformity and the occurrence of sill-like serpentinite bodies. The serpentinites were originally peridotitic in composition, uralite porphyrites together with gabbroic amphibolites occur within the Luoma Group (see Table 1, Fig. 8, 10 and 11). The amphibolites have subconformable contacts with the Luoma volcanics. Kopperoinen & Tuokko (1988) interpreted them as feeder channels for the tholeiitic volcanics of the Saarijärvi Group.

The intrusion phase was accompanied and supplemented by mafic and ultramafic volcanism, producing the lowermost volcanic rocks of the Saarijärvi Group with komatiitic affinity. Although chemical analyses implied a pyroxenitic composition for the volcanics east of Lake Ala-Luoma (Fig. 2, 10 and 11), spinifex or other quench textures have not been recognized. Tremolite, chlorite, antigorite, talc, carbonates and magnetite are present in variable proportions; residual olivine and pyroxene do not exist.

This stratigraphic unit, termed the Kallioinen Formation of the Saarijärvi Group (Taipale 1985), is capped by a thin layer of black schist. In the Ala-Luoma area, the lithostratigraphic sequence of the mafic and ultramafic volcanics of the Kallioinen Formation is not visible. A contact between komatiitic basalts and the black schists occurs south, in the Kallioinen type area, indicating that the mafic volcanics extruded first.

Towards the east the black schist is in contact with the acid pyroclastic rock of the overlying Seipelä Formation (see Fig. 2, and compare Taipale 1985 and Piirainen 1988), assumed to be recrystallized felsic tuffs. The mineral assemblage consists of quartz, plagioclase (An_{26-29}) and orthoclase with minor microcline, biotite, sericite and sphene. Epidote, calcite, limonite and pyrite are accessories. In comparison with the silicified volcanics of the Luoma Group, they show a significant higher SiO_2 content (Table 1). According to their REE distribution, they also belong to the rhyolite (F II type) of Condie (1981). A thin layer of black schist overlying the Seipelä Formation marks the third interruption in volcanic activity.

Large volumes of mafic volcanic rocks with a well preserved pillow structure in several outcrops exist in the adjacent Saarikylä Formation. Compared with the mafic volcanics of the Luoma Group, the Saarikylä volcanics have a conspicuously low plagioclase, and a higher actinolite, tremolite and chlorite content. Together with antigorite and talc they demonstrate that the Saarikylä volcanics were primarily rich in mafic silicates (olivine and pyroxene). Accessory minerals are zircon, magnetite, pyrrhotite and chalcopyrite. Chemically most of the volcanics plot in the field of normal and MgO-rich tholeiites according to their MgO, FeO*, TiO_2 and Al_2O_3 contents (Figs. 10 and 11). However low TiO_2 and high Cr and Ni concentrations suggest a relationship to a komatiitic source (compare Auvray et al. 1982), in this case the easternmost serpentinite of the mapped area (see Fig. 2).

An intervening chlorite-epidote-carbonate rock enveloped by a partly sheared band of black schists crops out within the mafic volcanics. From its appearance in the field, but particularly because the chemical data are comparable with those of the mafic volcanics of the Saarikylä Formation (Table 1, Figs. 10 and 11), we suggest that the chlorite-epidote-carbonate rock is the uppermost lithological unit of this volcanic sequence and may represent an alteration product of the Saarikylä volcanics. Carbonate veins and lenses with minor quartz containing the sulphide minerals pyrrhotite, pyrite, chalcopyrite and sphalerite in particular, are widely and irregularly distributed (see Fig. 9). The host rock itself is composed of chlorite, epidote, actinolite, carbonate quartz and plagioclase. The An-rich cores of poikiloblastic plagioclase show clinozoisite, calcite and little sericite.

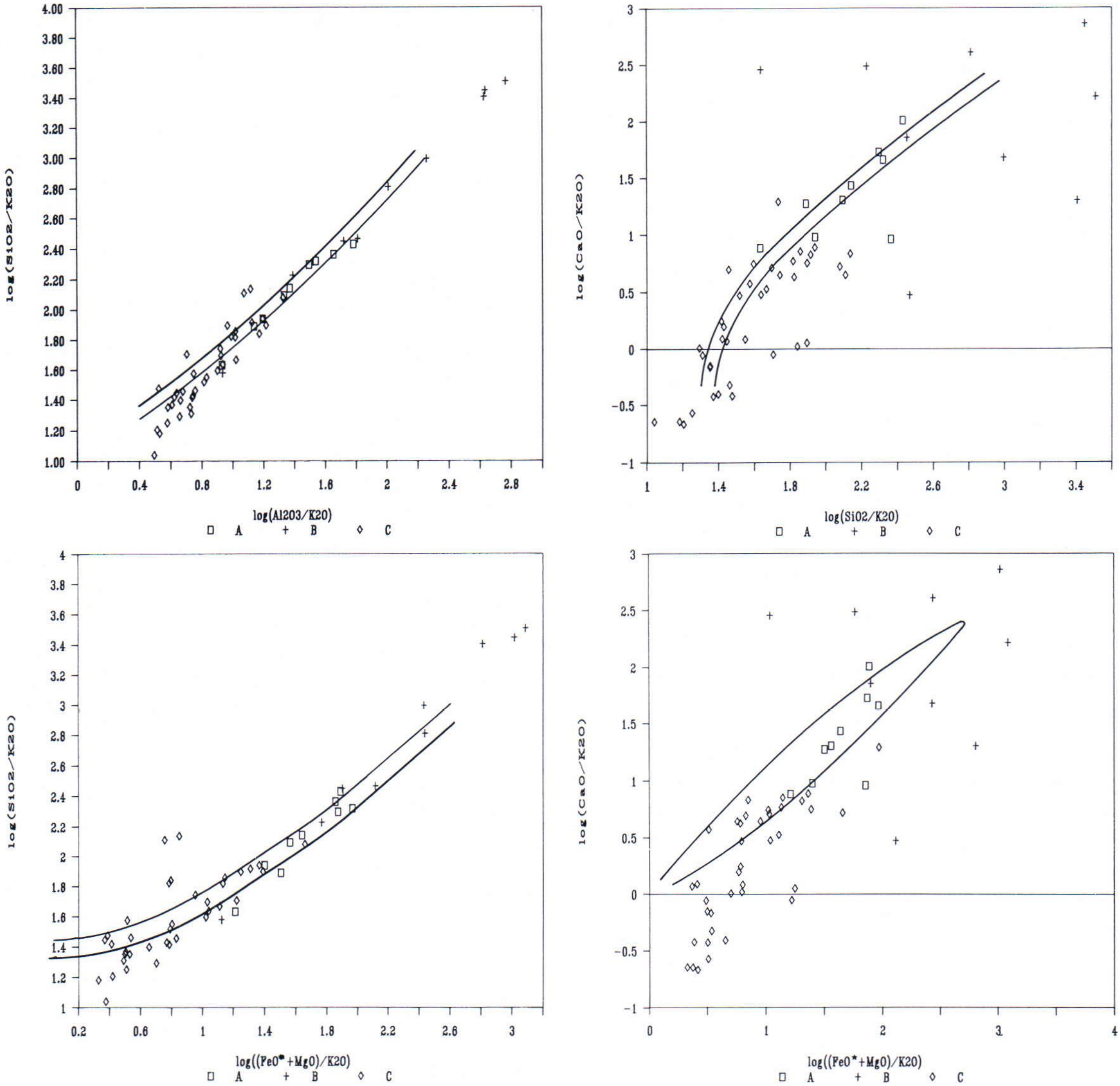
The Saarijärvi Group ends with the felsic pyroclastic rocks that make up Ruokojärvi Formation (Taipale 1985), which is very similar to the above mentioned Seipelä Formation.

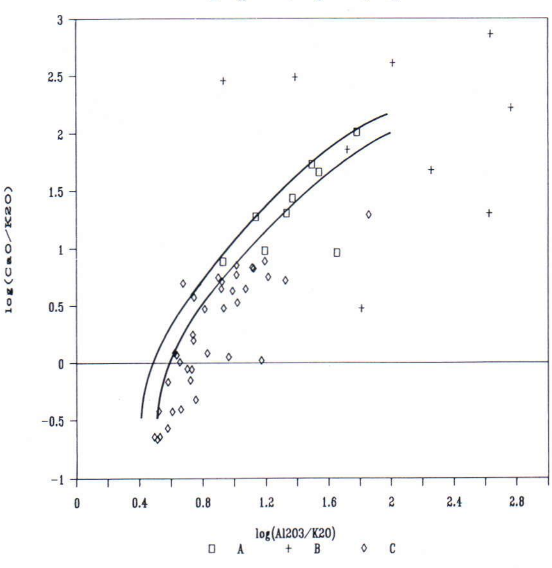
Implications for a secondary alteration

Redistribution of the major oxides, in particular the strong Na- K- differentiation and SiO_2-increase observed in the intermediate and felsic sequence of the Luoma Group and the occurrence of secondary hydrous minerals, carbonates and sulphides indicate a pre-metamorphic hydrothermal alteration. Beswick and Soucie (1978) developed a method to examine the compositional relationships in metasomatically altered rocks in terms of oxide molecular proportion ratios. The analyzed data are plotted in form of log (X/Z) vs. log (Y/Z) (LMPR plots). For post-Mesozoic unaltered rocks, well defined trends are obtained if the rationing oxides are K_2O or Na_2O irrespective of whether the suite is tholeiitic, calc-alkaline or alkaline. Hanski (1988) applied this graphic procedure to the Kuhmo, Tipasjärvi and Karelia Greenstone Belts. In addition he could demonstrate the element redistribution for the intermediate to felsic volcanics, in comparison with the compiled data for Tertiary to Recent andesites to rhyolites from Ewart (1979).

Using the same method, secondary alteration patterns can also be shown for the Ala-Luoma area of the Suomussalmi Greenstone Belt. To distinguish the mafic, intermediate and felsic volcanic rocks, different symbols are used in Figs. 14a—e, Figs. 15a, b and Figs. 16a—d. In general, 'X' metasomatism will cause a displacement parallel to the log (X/Z)-axis, 'Y' metasomatism parallel the log (Y/Z)-axis and 'Z' metasomatism is responsible for a displacement of the original composition along the line with 45° slope (see Beswick and Soucie 1978).

For log (SiO_2/K_2O) vs. log (Al_2O_3/K_2O) (Fig. 14a) the mafic Luoma volcanics plot on the trend line. A displacement along the 45° slope towards the lower left is due to a steady but minor K_2O





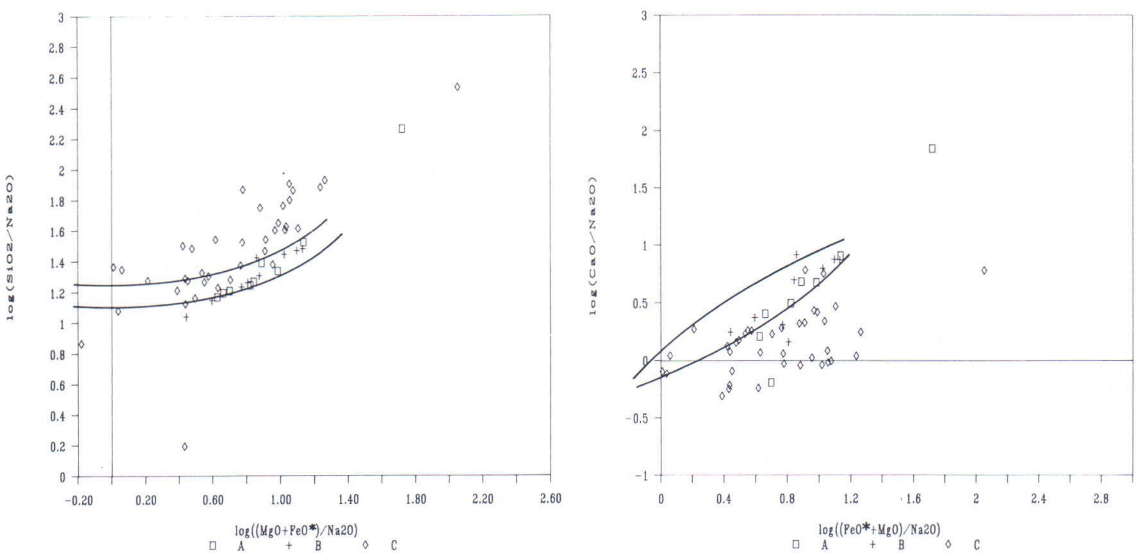
Figs. 14a—e. Logarithmic molecular proportion plots (LMPR), with K_2O as denominator. Trend lines for post-Mesozoic volcanic rocks by Beswick and Soucie (1978). a) SiO_2 vs. Al_2O_3; b) SiO_2 vs. ($FeO^* + MgO$); c) CaO vs. Al_2O_3; d) CaO vs. SiO_2; e) CaO vs. ($FeO^* + MgO$). A) mafic Luoma volcanics; B) mafic Saarijärvi volcanics; C) intermediate Luoma volcanics.

increase. The mafic volcanics of the Kallioinen Formation (Saarijärvi Group) plot at the elongation of the modern trend in direction of a strong K_2O loss. However in the Saarikylä Formation, K_2O tends to increase. The sericitized intermediate Luoma volcanics plot outside the lower end of the trend line, according to a strong K_2O increase, but also due to the excess of Al_2O_3 and low SiO_2 values. Intermediate volcanics with a moderate K_2O content deviate above the modern trend, caused by the excess of SiO_2.

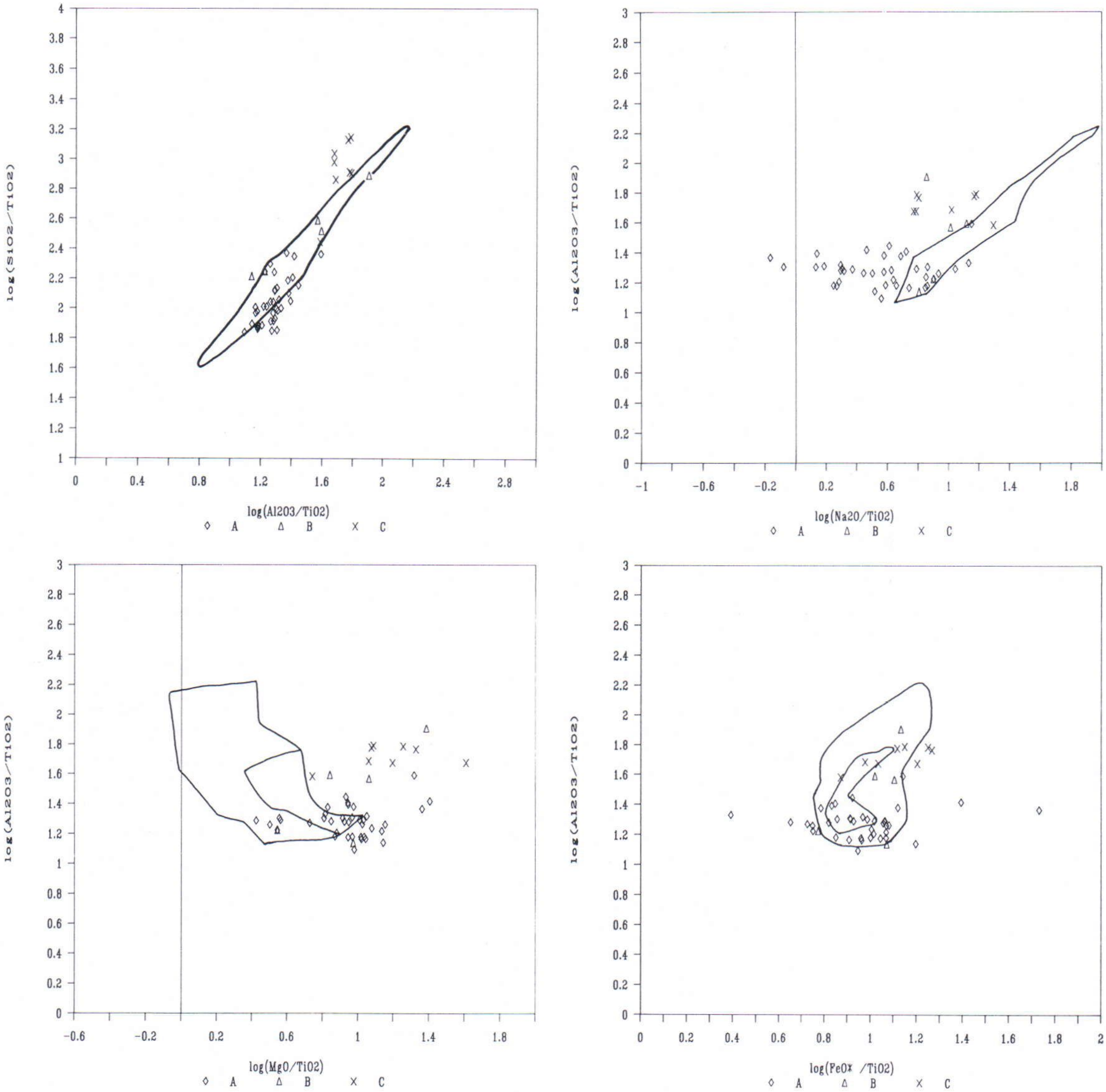
When (FeO^* + MgO) is substituted for Al_2O_3 on the x-axis (Fig. 14b), no major changes occur for the mafic Luoma- and Saarijärvi volcanics. The scattering of some intermediate rocks is due to the irregular variation of (FeO^* + MgO).

In Fig. 14c, with log (CaO/K_2O) vs. log (Al_2O_3/K_2O) and Fig. 14d, with log (CaO/K_2O) vs. log (SiO_2/K_2O) it is possible to compare the behaviour of CaO versus Al_2O_3 and versus SiO_2. Both diagrams show nearly identical element distributions for the mafic metavolcanics. Only two of the mafic Luoma volcanics plot below the trend line. According to Fig. 14a, where all mafic Luoma volcanics plot on the modern trend, the only explanation must be a CaO loss. For the same reason, the mafic Saarijärvi Group volcanics show considerable CaO decrease and increase. This metasomatic CaO variation is reflected also in Fig. 14e, with log (FeO^* + MgO) for all mafic samples. CaO variation within the intermediate Luoma volcanics is best visible in Fig. 14c, where nearly all data plot below the trend line and therefore indicate a CaO decrease.

When Na_2O is the rationing oxide to SiO_2 and (FeO^* + MgO), we can use the information of the nominator variations obtained from Fig. 14a—e, to deduce changes in the Na_2O contents. The mafic Luoma and Saarijärvi volcanics do not show a significant Na_2O metasomatism, all analyses plot on the trend line (Fig. 15a). This is different for the intermediate volcanics. A positive displacement along the 45° slope and above the trend line is the combination of a SiO_2 increase, accompanied by a strong Na_2O decrease. Furthermore, low (FeO^* + MgO) values in the sericitized intermediate volcanics cause an additional movement parallel the x-axis to the left. A combined Na_2O and CaO decrease is the major reason for the displacement below the modern trend line in Fig. 15b.



Figs. 15a and b. LMPR plots with Na_2O as denominator. Trend lines for post-Mesozoic volcanic rocks by Beswick and Soucie (1978). a) SiO_2 vs. (FeO^* + MgO); b) CaO vs. (FeO^* + MgO). A) mafic Luoma volcanics; B) mafic Saarijärvi volcanics; C) intermediate Luoma volcanics.



Figs. 16a—d. LMPR plots with TiO_2 as denominator. Compiled trend fields for Tertiary-Recent andesites to rhyolites by Ewart (1979). a) SiO_2 vs. Al_2O_3; b) Al_2O_3 vs. Na_2O; c) Al_2O_3 vs. MgO; d) Al_2O_3 vs. FeO*. A) intermediate Luoma volcanics; B) felsic Luoma volcanics; C) felsic Saarijärvi volcanics.

LMPR plots with TiO_2 as denominator (Figs. 16a—d) are applied to check for metasomatic variations with the intermediate and felsic Luoma and felsic Saarijärvi volcanics. They are drawn against a reference field of unaltered Tertiary to Recent andesites to rhyolites, including volcanics of the high-K, calc-alkaline and low-K series of the compiled data from Ewart (1979). Displacement along the 45° slope due to TiO_2 metasomatism is only of major importance for the felsic Luoma volcanics which plot over a wide range on the reference field (Fig. 16a). However displacements parallel the x- and y-axes are more likely due to the nominator variations. A decreasing TiO_2 content of the silicified intermediate volcanics compensates the displacement, caused by high SiO_2 values (compare Fig. 14a), so that they plot not above, but within the modern field. The most obvious displacement however can be observed for the felsic Saarijärvi volcanics. In comparison with the average of high silica rhyolites, the SiO_2/TiO_2 ratios are too high (see Table 1). This suggests a clear SiO_2 enrichment. With log (Al_2O_3/TiO_2) vs. log (Na_2O/TiO_2) in Fig. 16b, the strong Na_2O metasomatism is well documented. Na_2O decrease is obvious for the intermediate and felsic metavolcanics. MgO and FeO* are plotted separately in Fig. 16c and Fig. 16d. With regard to the described metasomatic variations of TiO_2, the Al_2O_3 contents (Figs. 16a and 14a) and the constant sum effect, an increase of MgO becomes evident for the silicified intermediate and felsic Luoma and Saarijärvi volcanics. This is different for the sericitized intermediate volcanics with low MgO contents. With a displacement parallel the x-axis to the left, they still plot on the relatively broad modern field. Metasomatic variations of FeO* are difficult to interpret because most of the analyzed samples plot on the modern field. Considering only the calc-alkaline sector of the modern field, the intermediate volcanics show increase as well as decrease of the total iron content, the felsic volcanics instead show only FeO* enrichment.

Discussion and conclusions

Re-mapping of the Ala-Luoma area, together with the structural, petrographical, geochemical and available geochronological data, suggests a different stratigraphy and tectono-magmatic model for the Suomussalmi Greenstone Belt, compared with the interpretation by Blais et al. (1977); Vidal et al. (1980); Martin and Querré (1984); Martin (1989) and supplements the observations from Taipale (1981); Kopperoinen and Tuokko (1988).

Despite a few sedimentary interlayers, the lowermost stratigraphic unit in the Ala-Luoma area consists of mafic volcanic rocks with a tholeiitic affinity. The mineral assemblage and geochemistry of these mafic volcanics of the Luoma Group are indicative of an isochemical metamorphic element redistribution; on LMPR plots they show no major element exchanges. Furthermore they can be connected with the overlying intermediate volcanics according to the model of Condie (1981), who suggests a relationship between TH1 tholeiites and andesite types I and II. TH1 tholeiites are produced, like basaltic komatiites, by partial melting of an undepleted lherzolite source, and the andesite melts by garnet and/or amphibole crystallization from the TH1 magma. Alternatively the TH2 tholeiites are partial melts of eclogite, garnet-amphibolite or amphibolite, and the andesites are produced in a similar manner by smaller degrees of melting. The major oxide chemistry of the mafic Luoma volcanics indicate a TH1 tholeiite type. However the REE patterns do not allow this clear discrimination between a TH1 and possible TH2 source. Because both tholeiite types are considered to generate andesitic melts, convergent plate boundary models whether fore-arc or back-arc, with subduction and remelting of oceanic crust, are not necessary to explain the coincidence of mafic with intermediate volcanics in the Luoma Group.

In terms of Archaean constraints, the development of the Suomussalmi Greenstone Belt could have started with crustal attenuation and fissuring in response to small-scale convection patterns in the mantle (see Lambert 1981), collecting detrital and shallow-water sediments and the first derived mafic lavas, produced by a high degree of pressure-released melting in the subcrustal mantle (compare Kröner 1981).

Intervening sedimentary layers and the lack of oceanic environmental features, especially pillow lavas, indicate that the sequence of the Luoma Group deposited in shallow-water on/or in close proximity to old sialic basement.

Metavolcanic rocks of intermediate chemical composition rest on this first stratigraphic unit and vary from massive volcanic flows to agglomeratic and fragmental tuffites. The upper pyroclastic part shows pronounced sericitization and turns into the quartz sericite schist that is the host rock of the Zn-Pb-Ag-Au sulphide mineralization (Kopperoinen & Tuokko 1988).

The intermediate metavolcanics exhibit extreme Na-K-differentiation with high K_2O/Na_2O ratios underneath the ore-bearing horizon. Many parts of the volcanics are silicified, showing a positive SiO_2 displacement on various LMPR plots. Furthermore for the stratigraphic lower parts, SiO_2 and CaO decrease, variable FeO* values, together with low tenors of Cu, Zn, Pb, Ag and Ba and a slight MgO increase can be noted. Seawater based hydrothermal alteration could have been responsible for the leaching of Si^{4+}, Ca^{2+}, Fe^{2+}, Cu^{2+}, Zn^{2+}, Pb^{2+} and K^+, Rb^+ while slightly basic Na-Mg-Cl-SO_4- enriched seawater changed to a slightly acidic Na-Ca-Cl- solution. Removal of Mg^{2+} from seawater in form of a $Mg(OH)_2$-component and uptake of Mg into secondary silicates would explain the MgO increase on the LMPR plots of these volcanics. Contemporaneously the pH of the solution drops because of the remaining of H^+. Depending on the seawater/rock mass ratio, the acidity of the solution and the p/T-relations (see Mottl 1983), the Mg^{2+} and possibly Na^+ removal from the solution is balanced largely by the leaching of Ca^{2+} from the volcanics. This coincides well with the observed CaO decrease on the LMPR plots. However, Fe^{2+} and total Fe are lost and gained. The incorporation of some Fe together with Mg into chlorite could be one reason for the Fe uptake by the volcanics, while the rest remains in solution. When returning to the surface, the hydrothermal fluids lost some of their Ca^{2+}, SO_4^{2+}, Fe^{2+} and Si^{4+}. K^+, Rb^+ and most of the ore-forming elements remained in solution until the fluids cooled down.

Enrichment of K and depletion of Na are favoured at temperatures below 150° C (Bloch and Bischoff 1979). This explains why the K-rich sericitized intermediate volcanics occupy the upper stratigraphic levels.

The pattern of tectonic lineaments seen on a regional scale, displays a nearly orthogonal grid of transcurrent faults. They represent zones of weakness, along which the ore-bearing solutions may have risen. The north-south trending unconformity and the faulting along NE and NW directions show several points of intersection. One of them occurs within the sericitized intermediate volcanics, about 500 m south of the area where most of the drilling was performed.

Extreme caution should be exercised when making direct analogies between Archaean and modern andesitic rocks on the basis of REE systematics. The REE patterns do not permit a distinction to be made between the island-arc and the above mentioned mantle-source model for a 2 : 1 mixing of mafic and felsic end-members (Taylor & McLennan 1985). However, the intermediate volcanic rocks of the Luoma Group have a higher Ni and Cr content than andesitic rocks produced by modern island-arc volcanism.

In the Luoma Group, the complex change from intermediate to felsic in chemical composition is influenced by hydrothermal alteration. Silicification and high TiO_2 contents of the volcanics are the most obvious instances.

The association of sulphide minerals with the intermediate and felsic pyroclastic rocks in the Ala-Luoma area and the felsic pyroclastic rocks of the Taivaljärvi Ag-Zn deposit in the Tipasjärvi Greenstone Belt prompted Taipale (1988) to compare these two deposits with a Kuroko-type ore formation in an island-arc environment. Despite geochemical similarities with felsic island-arc volcanism, the felsic volcanics of the Luoma Group have very fractionated REE patterns (Taipale 1988) with severe HREE depletion. The REE distribution patterns are indicative of conversion of mafic parent material to garnet-bearing or eclogitic rocks at mantle depths, where garnet is a stable residual phase.

After the extensive rift and sag process during which the rock sequence of the Luoma Group deposited, the lithosphere must have been considerably stretched and thinned. This raised the mantle-crust boundary and caused mantle-derived magma to pile up high into the crust, forming the ultrabasic sill-like intrusions of the Saarijärvi Group. They were accompanied and followed by the deposition of the mafic and ultramafic volcanic rocks of the Kallioinen Formation. These environmental features, deduced from the stratigraphic succession of the Ala-Luoma area, support the tectono-magmatic model proposed by Goodwin (1977).

Felsic pyroclastic rocks (Seipelä Formation) overlie the Kallioinen Formation. The LMPR plots display SiO_2, MgO and FeO* enrichment. In the stratigraphic correlation of the Suomussalmi and the Tipasjärvi Greenstone Belts by Taipale (1985), the Seipelä Formation corresponds to the much thicker Koivumäki Formation, which is the stratigraphic base and hosts the Taivaljärvi Ag-Zn deposit (Papunen et al. 1989). The felsic volcanics of the Koivumäki Formation are characterized by a weak depletion in HREE and negative Eu anomalies (Taipale 1988; Papunen et al. 1989). They may be derived either through a higher degree of partial melting at crustal depth or by late stage fractional crystallization. The fact that the felsic volcanic rocks are the first extrusive phase in the early stage of greenstone belt development in the Tipasjärvi area may be attributed to the formation of magma at a shallow crustal level by the thermal effect of rising, mantle-derived mafic magma. Because of the F I-type character of the Seipelä Formation, with severe HREE depletion, a correlation with the F II-type Koivumäki Formation (Taipale 1985) should not be considered (see also Condie 1981).

A second interruption in volcanic activity of the Saarijärvi Group is marked by the occurrence of black schists. Further rifting could have led to the decoupling of crustal blocks to establish an oceanic crust related rift system, producing the large volumes of mafic volcanic rocks of the Saarikylä Formation which is next in succession. This can be correlated with another intrusion phase, the easternmost serpentinite body in the Saarijärvi Group.

The uppermost lithological unit of the Saarikylä Formation is a chlorite-epidote-carbonate rock. Together with the sulphide mineralization, it represents a secondary altered product of the mafic lavas. Unlike the mineralization in the intermediate and felsic volcanics of the Luoma Group, which is interpreted as the result of premetamorphic hydrothermal alteration, the enrichment in transition metals and a slight enrichment in Au can also be related to retrograde metamorphic alteration, resulting in carbonatization and sericitization of the previous mafic rocks.

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