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GEOCHEMICAL AND PETROPHYSICAL CHARACTERISTICS OF PLUTONIC ROCKS FROM THE ARCHAEAN KARELIA PROVINCE IN FINLAND

by
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This study considers the geochemical and petrophysical characteristics of plutonic rocks from four terrains in the Archaean Karelia Province in central Finland: Pudasjärvi, Iisalmi, Kuhmo and Ilomantsi terrains. The samples investigated are mainly dioritic to granodioritic in composition, although some mafic intrusions have been sampled from each of the areas with the exception of the Ilomantsi terrain. The densities and magnetic susceptibilities of the samples are generally low; this reflects their relatively felsic compositions and general paucity of magnetite.

The majority of the samples show enrichment in LREE and compatible elements relative to HREE when normalized against averages calculated from nearly 3000 plutonic rock samples representing the Proterozoic and Archaean bedrock in Finland. These features are especially striking in plagioclase-rich adakitic rocks (TTGs, sanukitoids), whose chemical spectra are consistent with fractionation in the lower crust or upper mantle, at depths greater than 40–60 km. Using normalized Nd/Zr, La/Ce and Er/Lu ratios, the restitic minerals of adakitic melts can be estimated to mainly consist of clinopyroxenes, amphiboles and garnet, with lesser amounts of orthopyroxene. An important observation is the similarity of the adakitic samples from each of the terrains, suggesting similarities in their respective evolutionary history.

The evolution of adakitic rocks can be explained with respect to subduction-related magmatism and fractionation at great depth. However, when considering the wide distribution and large volume of Archaean adakitic rocks compared to those that are unequivocally interpreted as resulting from Archaean subduction processes, an alternative explanation is favoured here, involving crustal thickening by tectonic stacking, combined with underplating by anomalously hot upper mantle material. The underplating processes generated plagioclase-rich adakitic melts, leaving restites rich in compatible elements and HREE, which are locally evident as high velocity layers in the lower crust (assuming that they have not been removed by delamination).

Adakitic plutonic rocks appear to represent a continuous compositional series, from TTGs with variable Na_2O/K_2O and low Ba+Sr to sanukitoids with low Na_2O/K_2O and increasing Ba+Sr. These compositional variations can be explained by varying fractionation depths and degrees of subduction-related mantle metasomatism.

Keywords (GeoRef Thesaurus, AGI): crust, plutonic rocks, adakites, sanukitoids, geochemistry, petrophysics, tonalite-trondhjemite-granodiorite magmas, Archean, Finland

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INTRODUCTION

When studying the Tertiary lavas on Adak Island in the Aleutian arc, Kay (1978) concluded that they represented the products of slab melting. Similar magmatic rocks, subsequently known as adakites, have since been identified elsewhere and studied widely. For example Drummond and Defant (1990) and Defant and Drummond (1990) interpreted adakites as the products of partial melting of a young (< 20–30 Ma), gently dipping subducted slab. Defant and Drummond (1990) and Thorkelson and Breitsprecher (2005) summarized adakites as high-silica (SiO_2 > 56%), high-alumina (Al_2O_3 > 15%), plagioclase- and amphibole-bearing lavas with Na_2O > 3.5%, high Sr (> 400 ppm), low Y (< 18 ppm), high Sr/Y (> 40), low Yb (< 1.9) and high La/Yb (> 20). These chemical criteria were applied in selecting adakitic plutonites from the database used in the present study.

Martin et al. (2005) considered the characteristics of adakites, Archaean TTGs (tonalite–trondhjemite–granodiorites) and sanukitoids, all of which they linked to slab melting and interaction with peridotitic mantle. Late Archaean TTGs and high-silica adakites represent slab melts that have interacted with peridotite to a varying extent, whereas sanukitoids and low-silica adakites correspond to the melting of peridotite previously metasomatised by slab melt.

In his review of adakites, Castillo (2006) noted that numerous examples of adakitic rocks are not directly related to slab-melting processes in subduction environments. Moreover, the volume of adakite produced by slab melting is probably less than the amount that can be produced by other processes. In particular, slab melting is unlikely to be the most effective mechanism to produce the large observed volumes of Archaean TTGs.

Moyen (2009) defined adakites in a somewhat broader sense, placing emphasis on the high Sr/Y and La/Yb ratios as defined above. He concluded that such a signature can be generated by various processes, including: 1) melting of a high Sr/Y and La/Yb source, 2) deep melting, with abundant residual garnet, 3) fractional crystallization or AFC, or 4) interactions of felsic melts with the mantle, causing selective enrichment in LREE and Sr over HREE. He concluded that the classical model of “slab melting” provides the best explanation for the genesis of high-silica adakites, while the low-silica adakites are better explained as the products of an adakite-metasomatised mantle in the presence of garnet. Moreover, he noted that so-called “continental”, high-potassium adakites represent diverse petrogenetic processes and that most of them are different from both low- and high-silica adakites. The Archaean adakites show a bimodal compositional range, with some very high Sr/Y examples reflecting deep melting (>2.0 GPa) of a basaltic source, while lower Sr/Y rocks are formed by shallower (1.0 GPa) melting of similar sources. The Archaean TTGs are relatively heterogeneous, which is inferred to indicate a diversity of both sources and processes in their genesis.

Scaillet and Prouteau (2001 and references therein) emphasized that Archaean TTGs have been less contaminated by mantle interaction than typical Cenozoic adakites. They proposed relatively high T, low P, and possibly higher H_2O melts from gently dipping slabs as a source of Archaean TTG-type magmatism having adakitic characteristics. Smithies (2000) considered that the relatively low magnesium content of Archaean TTGs might be due to gently dipping underthrusting of oceanic plateaus, thus obviating a significant influence from the underlying peridotitic mantle.

Condie (2005) also agreed that adakites are probably slab melts, while concluding that TTGs may also be produced by partial melting of hydrous mafic rocks in the lower crust in arc systems or, in the case of Archaean tectonic settings, possibly in the root zones of oceanic plateaus. He correlated depletion in heavy REE and low Nb/Ta ratios in high-Al TTGs with the retention of garnet and low-Mg amphibole in restite in the source region, whereas moderate to high Sr values allow for little, if any, plagioclase in the restite. Thus, the melting is inferred to have occurred in the hornblende-eclogite stability field at depths of about 40–80 km and temperatures between 700 and 800 ºC.

Svetov et al. (2004) studied 3.0 Ga adakitic rocks found in basalt–andesite–dacite–rhyolite (BADR) island-arc association of the Vedlozero–Segozero greenstone belt in the Fennoscandian Shield, concluding that these rocks indicate the existence of convergent (interplate) ocean–continent transition zones and subduction-related tectonics already in the Mesoarchaean.

Kröner et al. (2011) investigated the still more ancient 3.65 to 3.53 Ga tonalitic gneisses of the Gneiss Complex in Swaziland and a 3.53 Ga felsic metavolcanic sample from the Theespruit Formation, the oldest unit of the Barberton Greenstone Belt, South Africa. They challenge the popular view that early Archaean TTGs and greenstones are principally of juvenile origin, formed in primitive arc or oceanic environments. Instead, they suggest extensive recycling of even earlier granitoid crust and mixing with juvenile material to produce successive generations of TTGs and associated felsic volcanic rocks.

Halla et al. (2009) considered granitoid magmatism in relation to Neoarchaean plate tectonics in Karelia and Kola cratons. They divided granitoids into three groups: 1–2) high- and low HREE (heavy rare earth elements) TTGs related to low- and high-angle (-pressure) subduction and 3) high Ba-Sr sanukitoids related to melting of an enriched mantle source, probably as a result of a slab breakoff following a continental collision or attempted subduction of a thick oceanic plateau or TTG protocontinent.

From the above considerations it becomes clear that the genetic link between slab melting and adakites and adakitic rocks (as well as TTGs and sanukitoids) is ambiguous. Castillo (2006) noted that adakite studies have generated confusion because the definition of adakite combines compositional criteria with genetic interpretation. Moyen (2011) emphasized that the term TTG is also imprecisely defined in much of the literature. Therefore, in this study the terms 'adakitic' or 'adakitoid' are used to refer to rocks having adakitic (or TTG or sanukitic) characteristics, as defined above, and apparently lower crust–upper mantle fractionation depths.

In the following, I consider the characteristics of 642 plutonic rock samples from four terrains of the Archaean Karelia Province in central Finland. The data used in this work are selected from the sub-group 'plutonic' of the rock geochemistry database described by Rasilainen et al. (2007). The sampling sites are indicated in Figure 1. The characteristics of the terrain samples are considered as a whole and their adakitic samples separately.

Plutonic rocks were selected for this study because it is assumed that they correspond more closely to (present) upper crustal compositions compared to supracrustal rocks that may have been more susceptible to alteration processes. It must be emphasized, however, that the sampling strategy was designed such that the number of samples per given area depends on the lithological variation seen on geological maps (Rasilainen et al. 2007). Thus, sampling density is not uniform, as is evident from Figure 1, so that calculated sample averages are only indicative of general trends and not strictly related to weighted areal averages of Finnish bedrock.

SAMPLES AND STANDARDS USED IN THIS STUDY

The Archaean terrains considered or referred to in this study are (Fig. 1): the Iisalmi terrain (IC = Iisalmi and Rautavaara complexes in Hölttä et al. (2012a), the East Finland - Kuhmo terrain (EFK = northern part of the Lentua complex), the East Finland - Ilomantsi terrain (EFI = Ilomantsi complex and the SW part of the Lentua complex), the Pudasjärvi terrain (PDj = Ranua and Siurua complexes) and the Kainuu belt (Kb), which is a Palaeoproterozoic supracrustal belt separating EFK, IC and Pdj. The subdivision and boundaries of terrains are in part adapted from Nironen et al. (2002) and modified in detail using airborne geophysical data and maps (e.g. Hautaniemi et al. 2005). A geological overview of these terrains is provided by Hölttä et al. (2012a).

The elements analysed, together with standards, units and analytical techniques are presented in Table 1. The samples have been normalized against both the C1 chondrite (Kerrich and Wyman, 1996) and the geometric mean of all Finnish plutonic rocks samples (AFP), including 3059 samples in all from both Archaean and Proterozoic terrains. The resolution of slopes and peaks in AFP-normalized 'spectra' varying around a value of one is much better compared to spectra normalized against chondrite (or MORB), for which ratios vary over many orders of magnitude, from about 0.01 to 1000. Accordingly, in this article, the main emphasis of the geochemical comparisons will be placed on the high-resolution AFP-normalized data.

The use of geometric means of parameters is based on the observation that distributions of almost all elements in Finnish plutonic rocks are positively skewed (i.e. there is a long 'tail' on the maximum end of the distribution curve). In such cases, the arithmetic average would be too high – a fact that often appears to have been neglected in the literature when presenting statistics from the analysis of a large number of samples. If the distribution curve approaches the normal Gaussian 'bell shape' (i.e. 'normal' starting from zero) or is negatively skewed (with a tail on the minimum side, which is observed for SiO_2 in Finnish plutonic rocks), both averages converge upon one another.

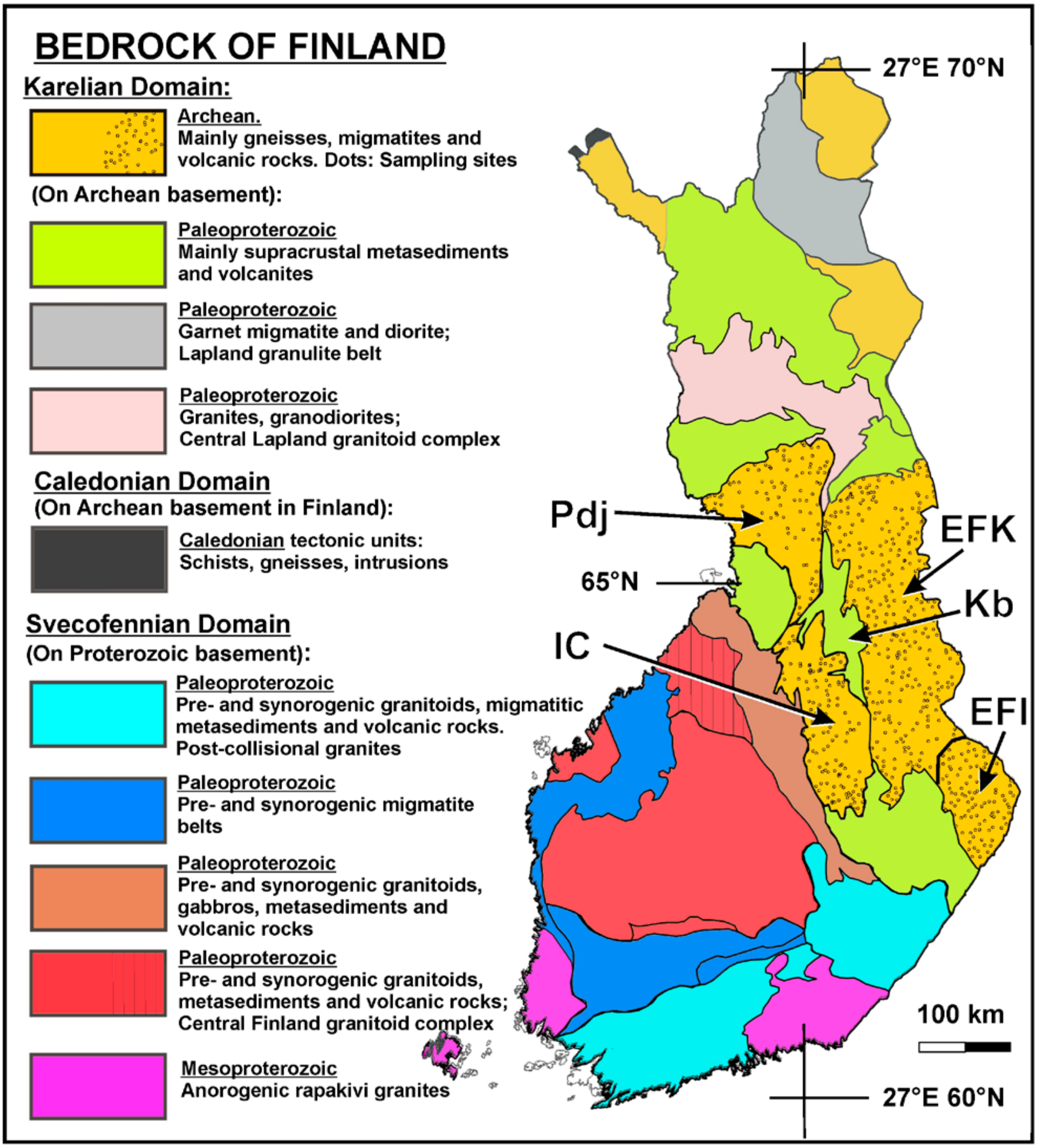


Fig. 1. Schematic map of bedrock of Finland. Modified from the map by Korsman et al. (1997). The dots indicate the sample locations. The abbreviations and names of the Archaean terrains considered or referred to in this study are:
IC: Iisalmi terrain (for simplicity, the term 'terrain' is used for the sub-areas)
EFK: East Finland - Kuhmo terrain
EFI: East Finland - Ilomantsi terrain
Pdj: Pudasjärvi terrain
Kb: Kainuu belt; Supracrustal terrain separating EFK, IC and Pdj

From Table 1 it is apparent that the abundances of some elements can vary significantly depending on the analytical method used and the position of the element in host mineral, e.g. silicates or oxides (see e.g. Sandström 1996 for more details). However, it has also been observed that the trends of element averages for given rock groups from separate terrains can share many similar characteristics, even where internal variations are substantial (see e.g. Fig. 4 and Table 3). Such variations can therefore be considered reliable and their use acceptable for the purpose of mutual comparison. The reasons behind such variations are not considered here in detail, the main emphasis being instead on the comparison of general trends and relative variations within and between various lithological terrains.

Table 1. Elements, standards, measurement units and analytical methods used in this study. Values of C1 chondrite are from Kerrich and Wyman (1996). AFP gmean = geometric mean of all Finnish plutonic rock samples. AFP nbdat = number of data used for calculation of AFP gmean. The samples have been analysed at the chemical laboratory of the Geological Survey of Finland (see Rasilainen et al. 2007).

Element	Method	Unit	AFP gmean	AFP nbdat	C1 Chondrite	Element	Method	Unit	AFP gmean	AFP nbdat	C1 Chondrite
Al	ICPAES	[ppm]	9622.43	3051	8679.70	Nd	ICPMS	[ppm]	23.37	3052	0.45
Al_2O_3	XRF	[%]	14.75	3059	1.64	Ni	ICPAES	[ppm]	11.10	2627	11000.00
Ba	ICPAES	[ppm]	89.70	2983	2.34	P	ICPAES	[ppm]	407.52	3053	1221.98
Ba	XRF	[ppm]	577.90	3044	2.34	P_2O_5	XRF	[%]	0.14	2825	0.28
Ca	ICPAES	[ppm]	3165.02	3058	9219.63	Pb	XRF	[ppm]	30.08	2982	2.47
CaO	XRF	[%]	2.56	3059	1.29	Pr	ICPMS	[ppm]	6.86	2965	0.09
Ce	ICPMS	[ppm]	54.30	3054	0.60	Rb	XRF	[ppm]	90.16	2970	2.30
Co	ICPAES	[ppm]	6.60	2921	502.00	Rb	ICPMS	[ppm]	79.45	3030	2.30
Co	ICPMS	[ppm]	9.64	2634	502.00	Sc	ICPMS	[ppm]	10.14	2542	5.82
Cr	ICPAES	[ppm]	19.22	2404	2660.00	Sc	ICPAES	[ppm]	2.88	2951	5.82
Dy	ICPMS	[ppm]	2.89	2891	0.24	SiO_2	XRF	[%]	65.28	3059	22.80
Er	ICPMS	[ppm]	1.54	2841	0.16	Sm	ICPMS	[ppm]	4.44	3003	0.15
Eu	ICPMS	[ppm]	0.88	3021	0.06	Sr	XRF	[ppm]	283.44	3051	7.80
Fe	ICPAES	[ppm]	20946.00	3056	190443.40	Sr	ICPAES	[ppm]	12.32	3033	7.80
FeO	XRF	[%]	3.10	3059	24.50	Ta	ICPMS	[ppm]	0.51	2931	0.01
Ga	XRF	[ppm]	25.16	3037	10.00	Tb	ICPMS	[ppm]	0.55	2986	0.04
Gd	ICPMS	[ppm]	3.94	3003	0.20	Th	ICPMS	[ppm]	6.39	3013	0.03
Hf	ICPMS	[ppm]	3.86	3047	0.10	Th	ICPAES	[ppm]	15.51	2272	0.03
Ho	ICPMS	[ppm]	0.54	2912	0.06	Ti	ICPAES	[ppm]		3058	437.64
K	ICPAES	[ppm]	4686.19	3055	556.21	Ti	ICPMS	[ppm]		3055	437.64
K_2O	XRF	[%]	2.55	3053	0.07	TiO_2	XRF	[%]	0.38	3054	0.07
La	ICPMS	[ppm]	28.01	3043	0.24	Tm	ICPMS	[ppm]	0.20	2958	0.02
La	ICPAES	[ppm]	24.66	2957	0.24	U	ICPMS	[ppm]	1.52	2981	0.01
Li	ICPAES	[ppm]	19.41	2872	1.50	V	XRF	[ppm]	54.63	2940	56.50
Lu	ICPMS	[ppm]	0.19	2968	0.02	V	ICPMS	[ppm]	36.60	2915	56.50
Mg	ICPAES	[ppm]	4745.62	3058	98910.04	V	ICPAES	[ppm]	25.02	2972	56.50
MgO	XRF	[%]	1.13	2946	16.40	Y	XRF	[ppm]	16.57	2909	1.56
Mn	ICPAES	[ppm]	258.64	3031	1990.36	Y	ICPMS	[ppm]	14.72	3056	1.56
MnO	XRF	[%]	0.06	2990	0.26	Y	ICPAES	[ppm]	6.73	3047	1.56
Na	ICPAES	[ppm]	772.78	3049	5000.07	Yb	ICPMS	[ppm]	1.36	2910	0.16
Na_2O	XRF	[%]	3.56	3036	0.67	Zr	ICPMS	[ppm]	141.36	3051	3.94
Nb	ICPMS	[ppm]	7.29	3045	0.25	Zr	XRF	[ppm]	157.87	3041	3.94

Analytical methods:

- XRF: X-ray fluorescence spectrometry using pressed powder pellets.
- ICPAES: Inductively coupled plasma atomic emission spectrometry after aqua regia digestion.
- ICPMS: Inductively coupled plasma mass spectrometry after hydrofluoric acid-perchloric acid dissolution and lithium metaborate/sodium perborate fusion.

For detailed descriptions of the analytical methods, see Sandström (1996) and Rasilainen et al. (2007).

CLASSIFICATION AND GROUPING OF THE SAMPLES

In this study, the lithological ('lithogeochemical') classifications of the samples are based on the Na_2O+K_2O vs SiO_2 diagram of Cox et al. (1979) and the R1-R2 diagram by De La Roche et al. (1980), as illustrated in Figure 2. Moreover, samples are classified by the incompatible – compatible diagrams proposed by Pearce and Peate (1995), as shown in the diagrams in Figure 4, where the geochemical 'spectra' of samples are presented as values normalized against both C1 chondrite (Kerrich & Wyman 1996) and the geometric averages of all Finnish plutonic rocks (AFP), whose values are given in Table 1. The diagrams in Figure 4 were prepared separately for all plutonic rocks in each terrain, and also separately for adakitic plutonic rocks, which will be considered in more detail below. The relative variations of sample densities and susceptibilities are demonstrated by the diagrams in Figure 3.

GEOCHEMICAL CHARACTERISTICS OF THE TERRAINS

The classifications of adakitic rocks, and also of all plutonic rock samples using the Na_2O+K_2O vs SiO_2 diagram of Cox et al. (1979) and the R1-R2 diagram of De La Roche et al. (1980) are presented in Figure 2. From the diagrams, it can be seen that the samples from the East Finland – Ilomantsi terrain (EFI) are exceptionally felsic and mainly granitic - monzogranitic. Granitic and granodioritic rocks also dominate in the Pudasjärvi area (Pdj), while in the Kuhmo (EFK) and Iisalmi (IC) terrains the relative proportion of more mafic rocks is higher. In the Cox diagrams, the adakitic samples mainly plot in the sub-alkaline field with the exception of the Ilomantsi area, where the samples are more alkaline. In the tectonomagmatic De La Roche diagram, the adakitoids of the Ilomantsi terrain mainly plot in the post-collision – late-orogenic fields, while in other sub-areas the sample distribution is less distinct, ranging from pre- to post-collisional samples. From the De La Roche diagrams it also appears that adakitic rocks tend to cluster in the dioritic – granodioritic fields and that 'granitic' adakitic rocks are less common.

PETROPHYSICAL CHARACTERISTICS OF THE SAMPLES

Figure 3 illustrates the cumulative distributions of densities and susceptibilities of all plutonic rock samples from each of the sub-areas. From this figure, it is evident that the densities of the more felsic rocks in the Pudasjärvi (Pdj) area are lowest while those of the Iisalmi terrain (IC) are highest, due to the large number of more mafic samples. In addition, samples from the Ilomantsi (EFI) and Kuhmo (EFK) areas are less dense than the Finnish average (AFP). The susceptibilities of samples are mainly below the Finnish average reflecting the low abundance of magnetic minerals (mainly magnetite) in Finnish Archaean rocks. The low paramagnetic susceptibilities (below 1000 [$SI*10^6$]) of the Kuhmo (EFK), Ilomantsi (EFI) and Pudasjärvi (Pdj) terrains is a consequence of the relatively low iron contents of mafic minerals (e.g. Puranen 1989).

CHARACTERISTICS AND CORRELATIONS OF PEARCE-PEATE DIAGRAMS FOR EACH OF THE TERRAINS

Incompatible → compatible diagrams proposed by Pearce and Peate (1995) are presented in Figure 4 for each of the terrains. The diagrams essentially describe the preferential tendency or compatibility of elements to reside in restitic, more mafic minerals (e.g. garnet, pyroxenes and amphiboles) at higher pressures and can thus be used in analysing the genesis and evolution of rocks and minerals.

From the diagrams in Figure 4 it can be seen that the LREE-HREE slopes of the adakitic series 'spectra' (red curves) are much steeper than those for all samples (including adakitic rocks; black curves). The high Ba, Eu, Sr and Sr/Y

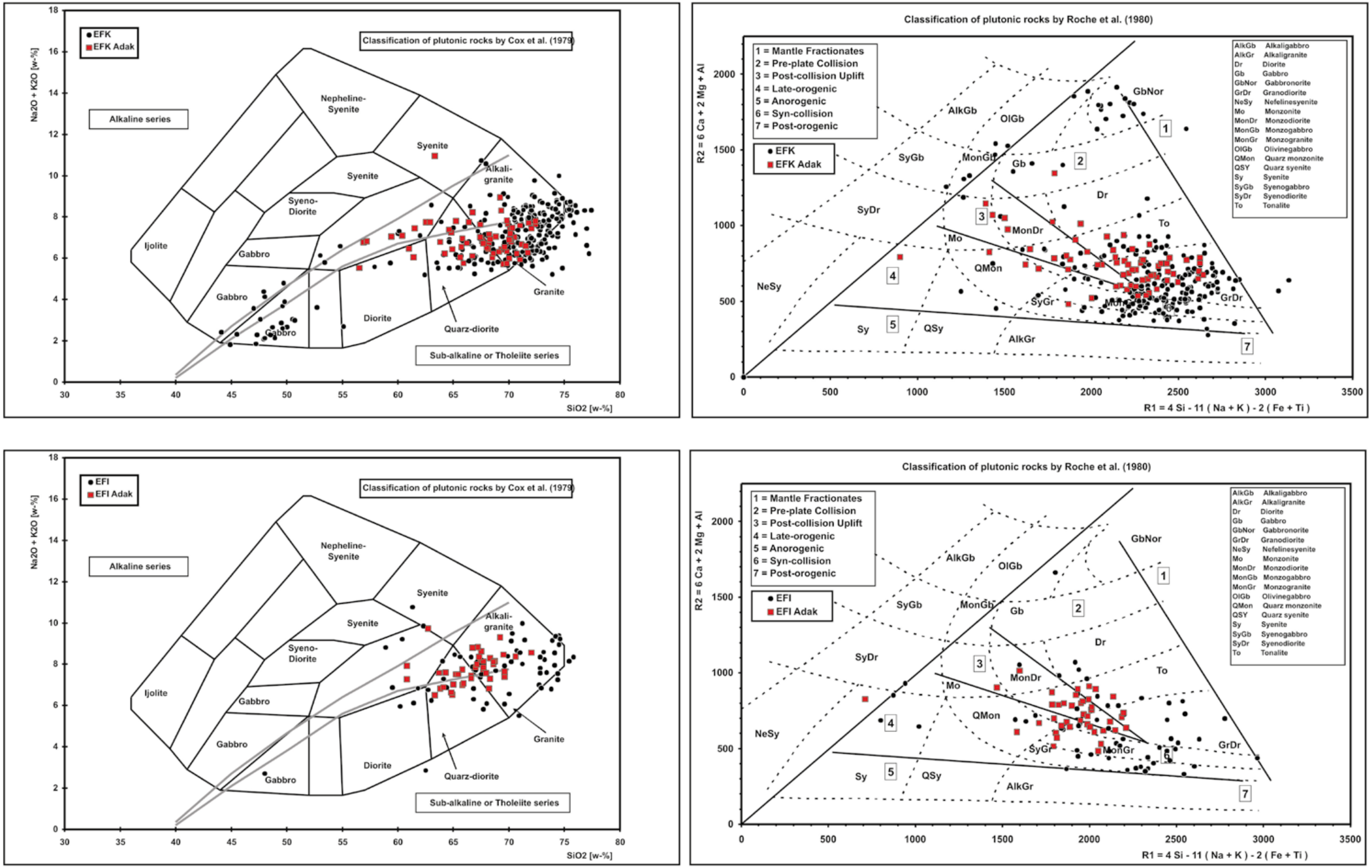


Fig. 2. Lithological classification of samples for each terrain according to the Na_2O+K_2O vs SiO_2 diagram of Cox et al. (1979) and the R1-R2 -diagram of De La Roche et al. (1980). The tectonomagmatic fields have been adopted from Batchelor and Bowden (1985) and rock type boundaries have been digitized from Rollinson (1993). The alkaline / sub-alkaline boundary zone in the Cox diagram (which is not precisely located – hence two curves) has been adopted from Rickwood (1989). The red boxes in the diagrams refer to adakitic samples.

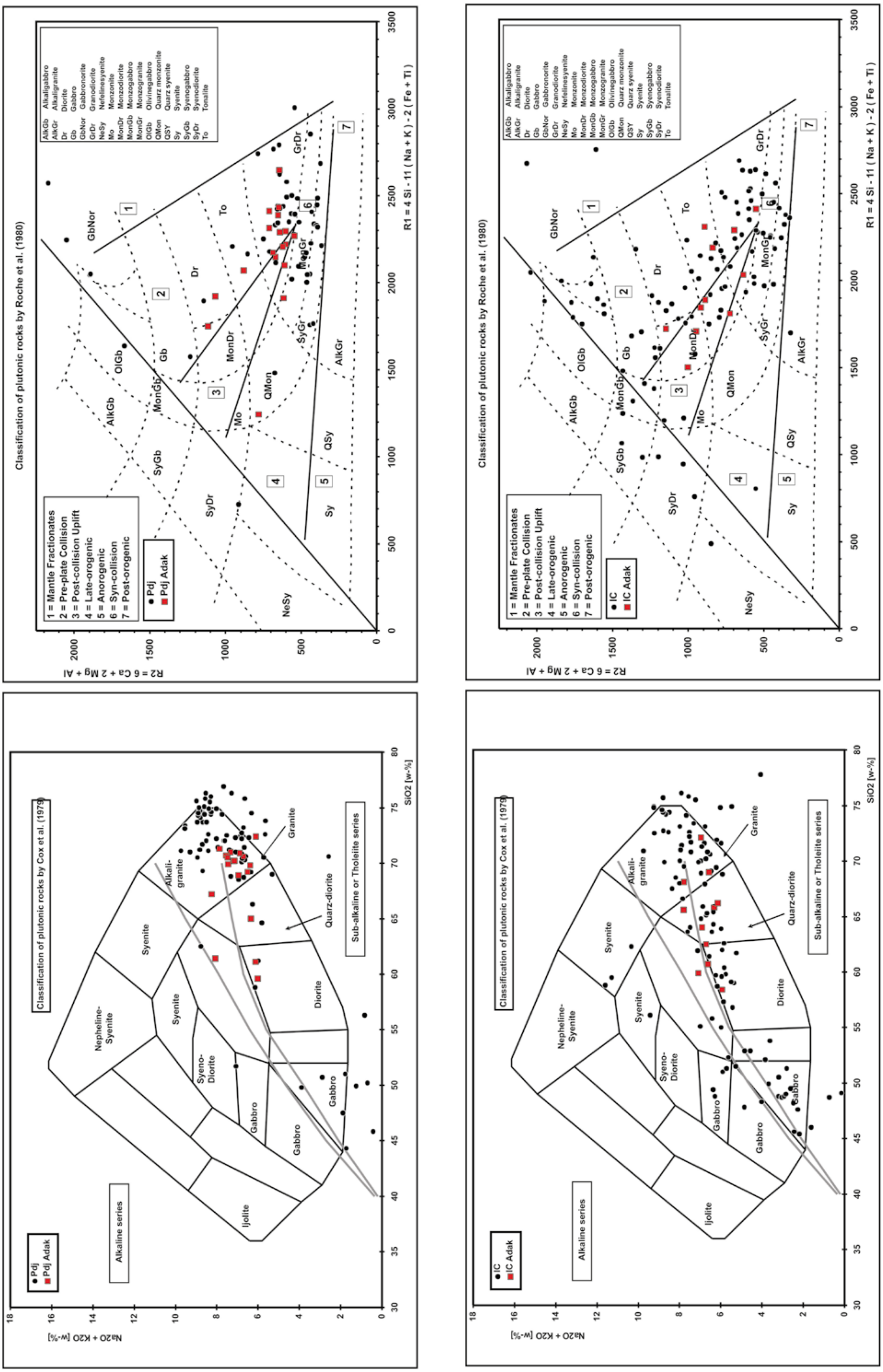

Classification of plutonic rocks by Roche et al. (1980)
1 = Mantle Fractionates
2 = Pre-plate Collision
3 = Post-collision Uplift
4 = Late-orogenic
5 = Anorogenic
6 = Syn-collision
7 = Post-orogenic
Pdj
Pdj Adak
R1 = 4 Si - 11 (Na + K) - 2 (Fe + Ti)
R2 = 6 Ca + 2 Mg + Al
AlkGb Alkaligabbro
AlkGr Alkaligranite
Dr Diorite
Gb Gabbro
GbNor Gabbronorite
GrDr Granodiorite
NeSy Nefelinesyenite
Mo Monzonite
MonDr Monzodiorite
MonGb Monzogabbro
MonGr Monzogranite
OlGb Olivinegabbro
QMon Quarz monzonite
QSY Quarz syenite
Sy Syenite
SyGb Syenogabbro
SyDr Syenodiorite
To Tonalite
Classification of plutonic rocks by Cox et al. (1979)
Alkaline series
Sub-alkaline or Tholeiite series
Na2O + K2O [w-%]
SiO2 [w-%]
Nepheline-Syenite
Syenite
Syeno-Diorite
Gabbro
Ijolite
Alkali-granite
Granite
Quarz-diorite
Diorite
IC
IC Adak

Fig. 2 cont.

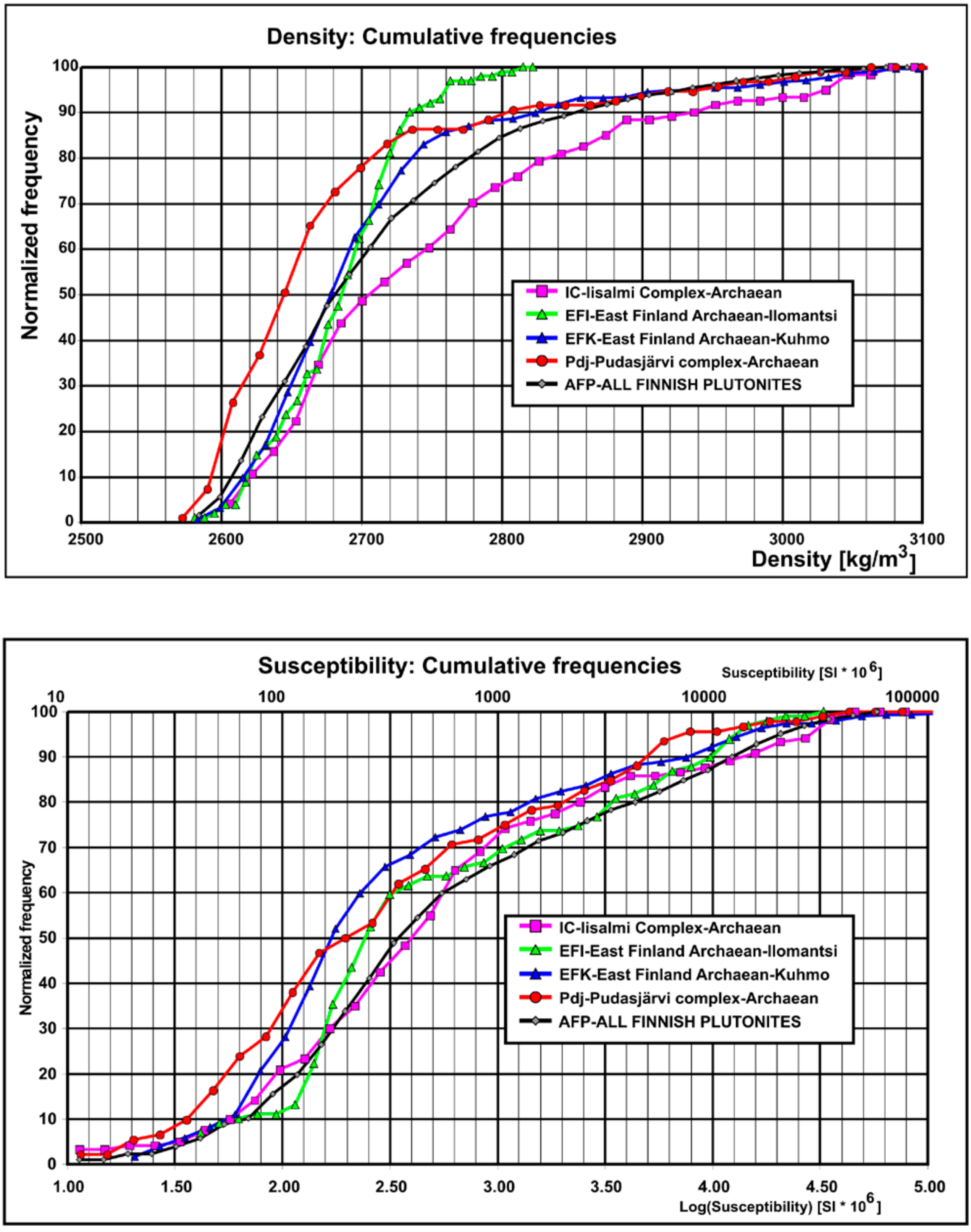


Fig. 3. Cumulative distributions of densities and susceptibilities of the sub-areas compared with all Finnish plutonite (AFP) distributions.

and steep increase in abundance of compatibles relative to HREE all signify lower crust – upper mantle fractionation depths, where plagioclase is unstable. A possible mantle component is discernible in the marked increase in V, Mn, Fe and Mg (but high Cr and Ni are only observed in the Ilomantsi (EFI) samples). It must be noted that the amplitude scale in the diagrams is highly variable, particularly because of the constant sum effect due to varying values of SiO_2 (see e.g. Wilson 1989 and Rollinson 1993). Thus, in the following discussion, the main emphasis is not on absolute values, but on relative amplitudes and trends of chemical variations.

Table 2 provides the number of samples in each of the terrains. The total number of plutonic rock samples from the Iisalmi terrain is 123, of which 11 samples (about 9%) are classified as adakitic, based on the definitions given above by Defant and Drummond (1990) and Thorkelson and Breitsprecher (2005). The number of samples from the Eastern Finland terrain (EFK) is 317, of which 66 samples (about 21%) are classified as adakitic. Of the 104 samples from the Ilomantsi (EFI) terrain, as many as 41 samples (39%) classify as adakitic. The total number of plutonic rock samples from the Archaean Pudasjärvi terrain (Pdj) is 98, of which 18 samples (19%) are adakitic. Thus, with the exception of Iisalmi terrain, the Archaean terrains are characterized by abundant adakitic rocks.

The cross-correlations of the Pearce-Peate spectra shown in Figure 4 for all samples and for adakitic samples separated according to terrain are provided in Table 3. From the table it can be seen that the correlation between Kuhmo and Ilomantsi terrains (EFK and EFI) is very high when considering the entire dataset and slightly less with the Pudasjärvi terrain (Pdj). The Iisalmi terrain correlates significantly with the Kuhmo data, while correlations between Ilomantsi and Pudasjärvi data are weak. These correlations indicate that EFK, EFI and Pdj terrains form a relatively homogeneous group of Archaean terrains, while IC is more 'exotic', possibly due to the complex structure of the terrain (e.g. Hölttä et al. 2000) and the effect of Proterozoic overprinting, as described by e.g. Sorjonen-Ward and Luukkonen (2005). It must also be noted that Figure 3 indicates that the densities of the Iisalmi terrain rocks are highest and that susceptibilities are also high. These features, as well as the fact that the Iisalmi terrain samples have lowest observed concentrations of incompatible elements in the whole data spectrum in Figure 4, can be attributed to the relatively high mafic component in these rocks.

Table 2. Number of all samples and adakitic samples in the sub-areas.

	EFK	**EFI**	**Pdj**	**IC**
All	317	104	98	123
Adakitoids	66	41	18	11

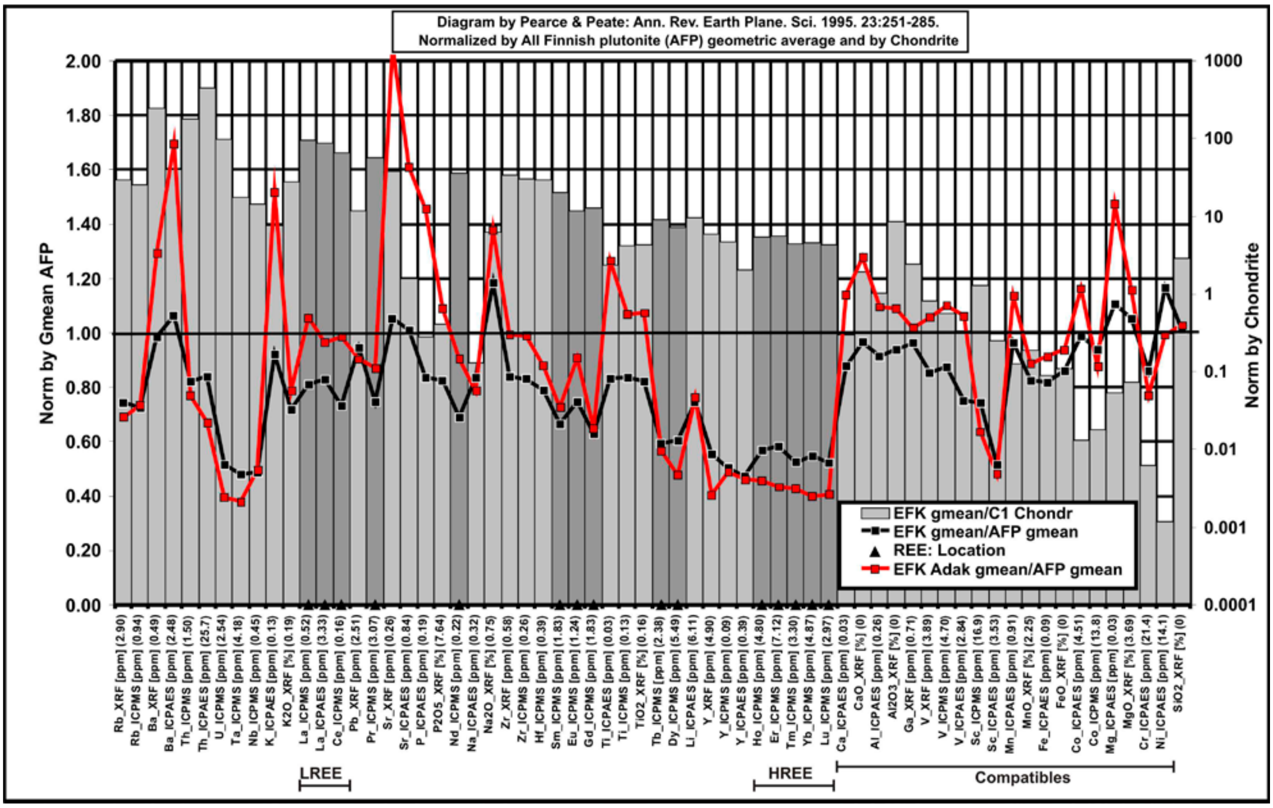
Table 3. Correlations of the AFP-normalized element values for each terrain.

ALL DATA	**EFK**	**EFI**	**Pdj**
IC	**0.65**	0.43	0.34
EFK		**0.84**	0.79
EFI			**0.69**
ADAKITOIDS	**EFK Adak**	**EFI Adak**	**Pdj Adak**
IC Adak	**0.88**	**0.78**	**0.87**
EFK Adak		**0.89**	**0.94**
EFI Adak			**0.86**

In Table 3, the correlation between the adakitic samples from each of the terrains, including the Iisalmi Complex, is significant, which strongly suggests a similar evolution of adakitoids, independent of their location in the respective terrains. From the table it can be concluded that the Archaean terrains in central Finland form a relatively coherent group, with the slight exception of the more complex Iisalmi terrain (IC), even though the Eastern Finland Terrain is separated from the Iisalmi and Pudasjärvi terrains by the supracrustal Kainuu belt.

Table 4 contains geometric averages of SiO_2 values, densities and susceptibilities of all samples and the subset of adakitic samples from each terrain. In addition, the table gives the LREE/HREE and compatibles/HREE ratios (* see box below) of the group averages of their Pearce-Peate spectra (see Figure 4). These ratios can be assumed to correlate with the degree of increasing fractionation (depth) and the role of the upper mantle, respectively. It is evident from the table that the average SiO_2 contents of the samples from each terrain are relatively high, corresponding to granitic – granodioritic – tonalitic compositions. In the rock geochemistry database described by Rasilainen et al. (2007), plutonic rock samples having densities between 2685–2755 kg/m^3 are mainly granodioritic (371/759 samples = 42%), tonalitic (144/759 = 19%) and granitic (89/759 = 12%). These samples have low susceptibilities and are paramagnetic, due to the low abundance of magnetite, with iron mainly being concentrated in mafic silicates.

In Table 4 the LREE/HREE and compatibles/HREE ratios of the adakitic group averages are



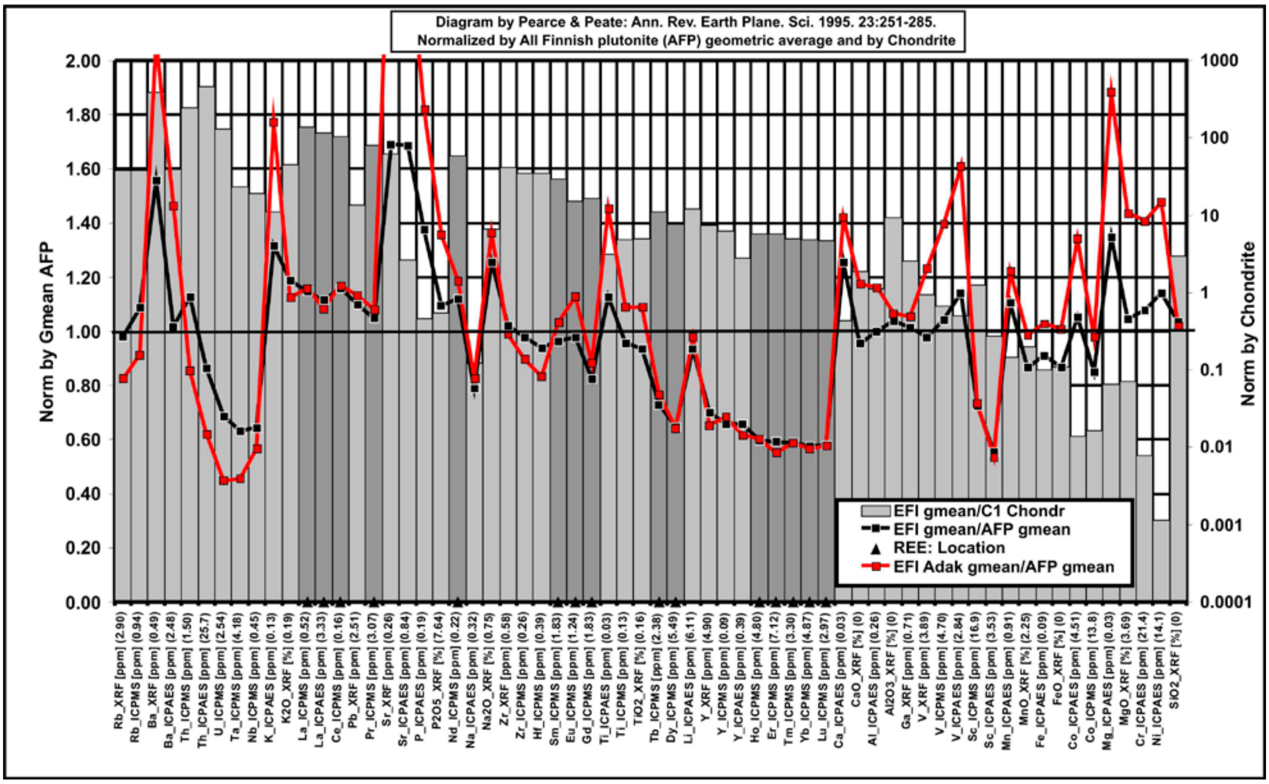


Fig. 4. Classification of the samples of sub-areas using the incompatible-compatible diagram of Pearce and Peate (1995); compatibility increasing from left to right (excluding the SiO_2 value at furthest right). The black curve represents the geometric average of the elements normalized by the geometric averages of all Finnish plutonic rocks (AFP; left vertical axis; see Table 1). The red curve shows corresponding variations for adakitic-only plutonic samples from each terrain. The grey bars give the element values of all samples normalized by C1 chondrite (Kerrich & Wyman 1996; right vertical axis). The darker grey bars and triangles indicate the location of rare earth elements (REE). The location of Light REE (LREE), heavy REE (HREE) and compatible elements considered in the text have been emphasized in the diagrams for the EFK. The last number in the element names in parentheses () gives the % of rejected samples (mainly due to values below detection limits).

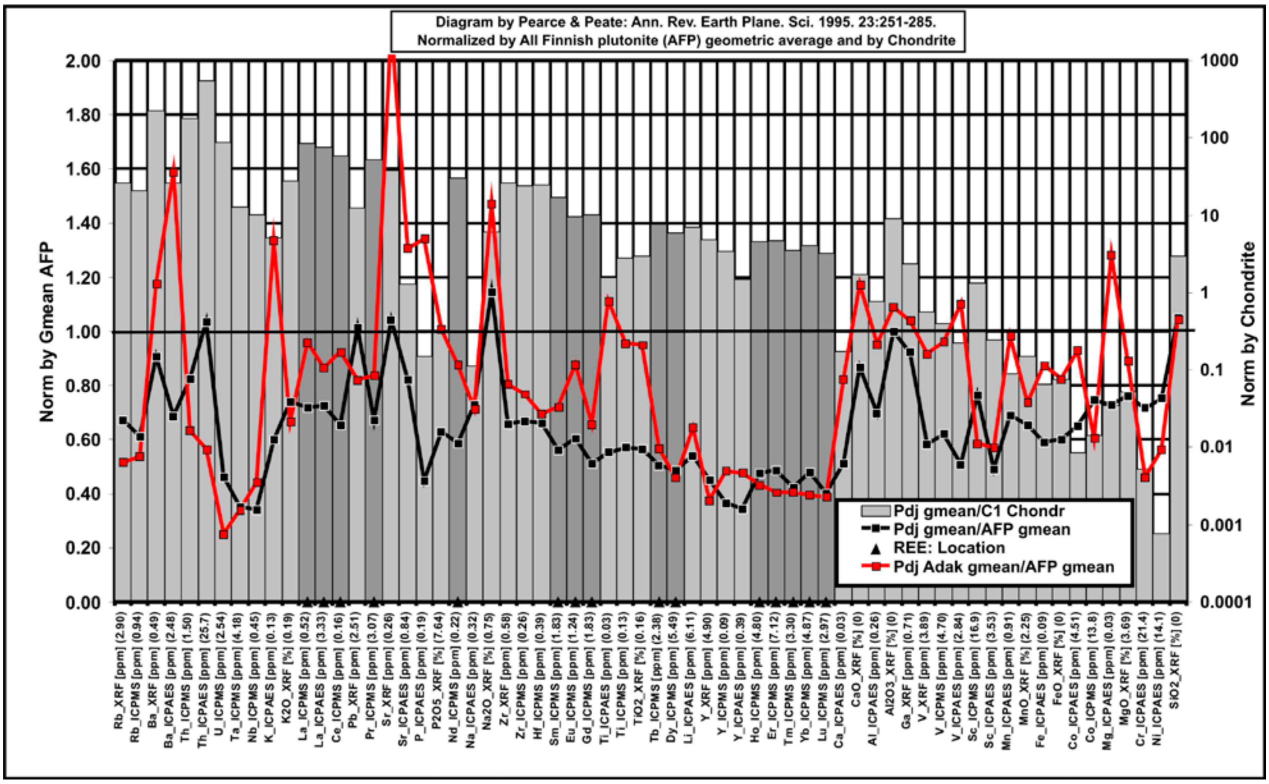
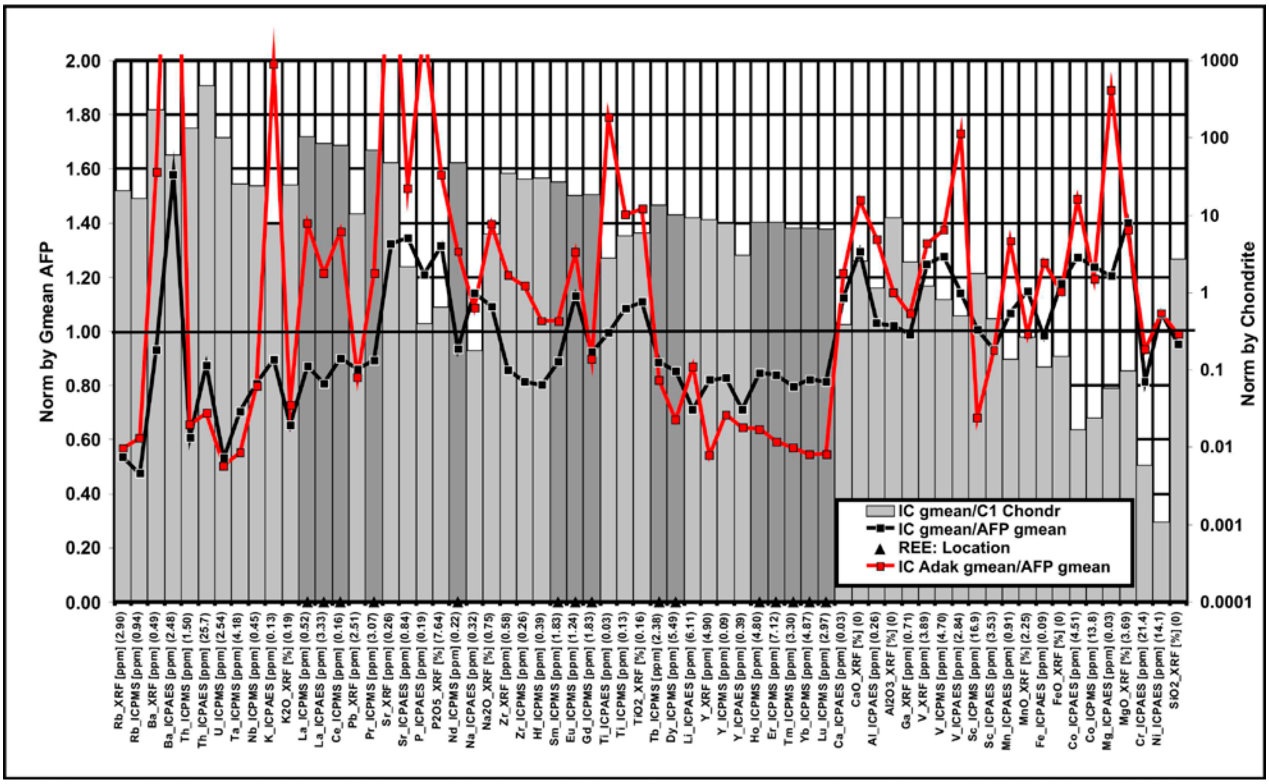


Diagram by Pearce & Peate: Ann. Rev. Earth Plane. Sci. 1995. 23:251-285.
Normalized by All Finnish plutonite (AFP) geometric average and by Chondrite
Norm by Gmean AFP
Norm by Chondrite
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1000
100
10
1
0.1
0.01
0.001
0.0001
Pdj gmean/C1 Chondr
Pdj gmean/AFP gmean
REE: Location
Pdj Adak gmean/AFP gmean
Rb_XRF [ppm] (2.90)
Rb_ICPMS [ppm] (0.94)
Ba_XRF [ppm] (0.49)
Ba_ICPAES [ppm] (2.48)
Th_ICPMS [ppm] (1.50)
Th_ICPAES [ppm] (25.7)
U_ICPMS [ppm] (2.54)
Ta_ICPMS [ppm] (4.18)
Nb_ICPMS [ppm] (0.45)
K_ICPAES [ppm] (0.13)
K2O_XRF [%] (0.19)
La_ICPMS [ppm] (0.52)
La_ICPAES [ppm] (3.33)
Ce_ICPMS [ppm] (0.16)
Pb_XRF [ppm] (2.51)
Pr_ICPMS [ppm] (3.07)
Sr_XRF [ppm] (0.26)
Sr_ICPAES [ppm] (0.84)
P_ICPAES [ppm] (0.19)
P2O5_XRF [%] (7.64)
Nd_ICPMS [ppm] (0.22)
Na_ICPAES [ppm] (0.32)
Na2O_XRF [%] (0.75)
Zr_XRF [ppm] (0.58)
Zr_ICPMS [ppm] (0.26)
Hf_ICPMS [ppm] (0.39)
Sm_ICPMS [ppm] (1.83)
Eu_ICPMS [ppm] (1.24)
Gd_ICPMS [ppm] (1.83)
Ti_ICPAES [ppm] (0.03)
Ti_ICPMS [ppm] (0.13)
TiO2_XRF [%] (0.16)
Tb_ICPMS [ppm] (2.38)
Dy_ICPMS [ppm] (5.49)
Li_ICPAES [ppm] (6.11)
Y_XRF [ppm] (4.90)
Y_ICPMS [ppm] (0.09)
Y_ICPAES [ppm] (0.39)
Ho_ICPMS [ppm] (4.80)
Er_ICPMS [ppm] (7.12)
Tm_ICPMS [ppm] (3.30)
Yb_ICPMS [ppm] (4.87)
Lu_ICPMS [ppm] (2.97)
Ca_ICPAES [ppm] (0.03)
CaO_XRF [%] (0)
Al_ICPAES [ppm] (0.26)
Al2O3_XRF [%] (0)
Ga_XRF [ppm] (0.71)
V_XRF [ppm] (3.89)
V_ICPMS [ppm] (4.70)
V_ICPAES [ppm] (2.84)
Sc_ICPMS [ppm] (16.9)
Sc_ICPAES [ppm] (3.53)
Mn_ICPAES [ppm] (0.91)
MnO_XRF [%] (2.25)
Fe_ICPAES [ppm] (0.09)
FeO_XRF [%] (0)
Co_ICPAES [ppm] (4.51)
Co_ICPMS [ppm] (13.8)
Mg_ICPAES [ppm] (0.03)
MgO_XRF [%] (3.69)
Cr_ICPAES [ppm] (21.4)
Ni_ICPAES [ppm] (14.1)
SiO2_XRF [%] (0)


Norm by Gmean AFP
Norm by Chondrite
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1000
100
10
1
0.1
0.01
0.001
0.0001
IC gmean/C1 Chondr
IC gmean/AFP gmean
REE: Location
IC Adak gmean/AFP gmean
Rb_XRF [ppm] (2.90)
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Ba_XRF [ppm] (0.49)
Ba_ICPAES [ppm] (2.48)
Th_ICPMS [ppm] (1.50)
Th_ICPAES [ppm] (25.7)
U_ICPMS [ppm] (2.54)
Ta_ICPMS [ppm] (4.18)
Nb_ICPMS [ppm] (0.45)
K_ICPAES [ppm] (0.13)
K2O_XRF [%] (0.19)
La_ICPMS [ppm] (0.52)
La_ICPAES [ppm] (3.33)
Ce_ICPMS [ppm] (0.16)
Pb_XRF [ppm] (2.51)
Pr_ICPMS [ppm] (3.07)
Sr_XRF [ppm] (0.26)
Sr_ICPAES [ppm] (0.84)
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Na_ICPAES [ppm] (0.32)
Na2O_XRF [%] (0.75)
Zr_XRF [ppm] (0.58)
Zr_ICPMS [ppm] (0.26)
Hf_ICPMS [ppm] (0.39)
Sm_ICPMS [ppm] (1.83)
Eu_ICPMS [ppm] (1.24)
Gd_ICPMS [ppm] (1.83)
Ti_ICPAES [ppm] (0.03)
Ti_ICPMS [ppm] (0.13)
TiO2_XRF [%] (0.16)
Tb_ICPMS [ppm] (2.38)
Dy_ICPMS [ppm] (5.49)
Li_ICPAES [ppm] (6.11)
Y_XRF [ppm] (4.90)
Y_ICPMS [ppm] (0.09)
Y_ICPAES [ppm] (0.39)
Ho_ICPMS [ppm] (4.80)
Er_ICPMS [ppm] (7.12)
Tm_ICPMS [ppm] (3.30)
Yb_ICPMS [ppm] (4.87)
Lu_ICPMS [ppm] (2.97)
Ca_ICPAES [ppm] (0.03)
CaO_XRF [%] (0)
Al_ICPAES [ppm] (0.26)
Al2O3_XRF [%] (0)
Ga_XRF [ppm] (0.71)
V_XRF [ppm] (3.89)
V_ICPMS [ppm] (4.70)
V_ICPAES [ppm] (2.84)
Sc_ICPMS [ppm] (16.9)
Sc_ICPAES [ppm] (3.53)
Mn_ICPAES [ppm] (0.91)
MnO_XRF [%] (2.25)
Fe_ICPAES [ppm] (0.09)
FeO_XRF [%] (0)
Co_ICPAES [ppm] (4.51)
Co_ICPMS [ppm] (13.8)
Mg_ICPAES [ppm] (0.03)
MgO_XRF [%] (3.69)
Cr_ICPAES [ppm] (21.4)
Ni_ICPAES [ppm] (14.1)
SiO2_XRF [%] (0)

Fig. 4. cont.

Table 4. Geometric averages of petrophysical parameters and some characteristic ratios of Pearce-Peate diagrams for each of the terrains. For LREE, HREE and compatible elements, see the EFK diagram in Figure 4. 'D' denotes density and 'K' magnetic susceptibility.

ALL Data:	IC	EFK	EFI	Pdj
SiO_2 [%]	62.24	66.35	67.00	68.59
D [kg/m^3]	2755	2713	2692	2685
K [*10^{6}SI]	526	396	500	192
LREE/HREE	1.04	1.55	1.57	1.54
Compatibles/HREE	1.36	1.74	1.51	1.53
Adakitoids:	**IC Adak**	**EFK Adak**	**EFI Adak**	**Pdj Adak**
SiO_2 [%]	64.63	67.03	66.73	68.22
D [kg/m^3]	2715	2714	2697	2690
K [*10^{6}SI]	1071	412	599	679
LREE/HREE	2.29	2.33	2.04	2.26
Compatibles/HREE	2.16	2.42	2.09	2.14

much higher than those obtained by combining all samples from each of the terrains, which clearly indicates the effectiveness of fractionation processes and the possible involvement of mafic, upper mantle material in the sources of adakitic melts. The highest and lowest LREE/HREE and compatibles/HREE ratios of EFK and EFI adakitoids may refer to deepest and lowest fractionation depths of these blocks, respectively.

The Pearce-Peate diagram characteristics can be summarized as follows:

- The adakitic groups have higher LREE, lower HREE and higher compatible element abundances than corresponding values for the group combining all samples. The adakitic population can be distinguished from the combined sample data in the Pearce-Peate spectra for most groups.
- In the Iisalmi terrain (IC), the difference between adakitoids and the combined data for all samples is strongest. For example, the ratio (LREE/HREEAdak) / (LREE/HREEAll) is highest in this terrain, presumably reflecting the complex structure of the terrain. In contrast, the data for the Ilomantsi terrain (EFI) are much closer, which is attributed to the predominantly adakitic composition of the terrain as a whole.
- Adakitic rocks typically have elevated Ba, Sr, (Sr/Y) and Eu, all of which can be related to the presence of plagioclase (and fluid) in the melt phase and thus fractionation at depths greater than the plagioclase stability field (about 40 – 80 - … km). Lower crustal or upper mantle processes are also implicated by low values of Rb, Th, Nb, U and Y. It is also interesting to note the high K (ICPAES) values relative to K2O (XRF) in adakitic rocks. This can be explained by biotite being more abundant relative to potassium feldspar (see e.g. Tarvainen et al. 1996). Moreover, low Sc and Cr in adakitic rocks can be attributed to the presence of clinopyroxene, and low Ni to olivine in the restite (e.g. Stosch 1981).
- Thus, it is apparent that adakitic magmas have fractionated at greater depths where garnet ± amphiboles ± pyroxenes, which have affinities for HREE, are stable and where an excess of mafic material is available during melting.

(*) Elements used for ratios:

$LREE_{ave}/HREE_{ave}$ =

Average [$La_{(ICPMS)}$, $La_{(ICPAES)}$, $Ce_{(ICPMS)}$] / Average [$Ho_{(ICPMS)}$, $Er_{(ICPMS)}$, $Tm_{(ICPMS)}$, $Yb_{(ICPMS)}$, $Lu_{(ICPMS)}$]

($Compatibles_{ave}/HREE_{ave}$) =

Average [$Ca_{(ICPAES)}$, $CaO_{(XRF)}$, $Al_{(ICPAES)}$, $Al_2O_{3\ (XRF)}$, $Ga_{(XRF)}$, $V_{(XRF)}$, $V_{(ICPMS)}$, $V_{(ICPAES)}$, $Sc_{(ICPMS)}$, $Sc_{(ICPAES)}$, $Mn_{(ICPAES)}$, $MnO_{(XRF)}$, $Fe_{(ICPAES)}$, $FeO_{(XRF)}$, $Co_{(ICPAES)}$, $Co_{(ICPMS)}$, $Mg_{(ICPAES)}$, $MgO_{(XRF)}$, $Cr_{(ICPAES)}$, $Ni_{(ICPAES)}$,] / Average [$Ho_{(ICPMS)}$, $Er_{(ICPMS)}$, $Tm_{(ICPMS)}$, $Yb_{(ICPMS)}$, $Lu_{(ICPMS)}$]

DETERMINATION OF RESTITE MINERALOGY FOR ADAKITIC ROCKS

The characteristics of restite remaining in the lower crust / upper mantle after removal of the adakitic melt fraction is evaluated using ratios of partition coefficients for basaltic and basaltic andesite liquids, whose values have been summarized by Rollinson (1993). Table 5 lists the relative ratios for the coefficient pairs used here. For simplicity, it can be said that if the value of the ratio is less than one, the denominator dominates in the restitic mineral, and vice versa. For example, if orthopyroxene dominates in the restite, Zr is more likely to be retained in the mineral phase and Nd in the adakitic melt phase. Hence, the AFP-normalized Nd/Zr ratio of adakitic samples should be relatively enriched in Nd.

It must be emphasized that the estimated values of partition coefficients can vary widely, and their relative effect on the concentrations of elements in melt and the remaining restite fraction can thus only roughly be evaluated. Therefore, the results given in the maps in Figure 5 must be taken as indicative only.

Assuming that clinopyroxene, orthopyroxene, garnet and amphibole represent the most probable restite phases for preferential retention of the compatible elements, the possible enrichment of elements in adakitic melts can be defined as follows from the AFP-normalized ratios of adakitic rocks:

Table 5. Ratios of mineral/melt partition coefficients for basaltic and basaltic andesite liquids using coefficients summarized by Rollinson (1993 and references therein).

Restite:	opx	cpx	hornblende	garnet
Nd/Zr	<1	>1	<1	<1
La/Ce	>1 (*)	<1	<1	<1
Er/Lu	<1	>1	>1	<1
(*) = evaluated for andesitic liquids				

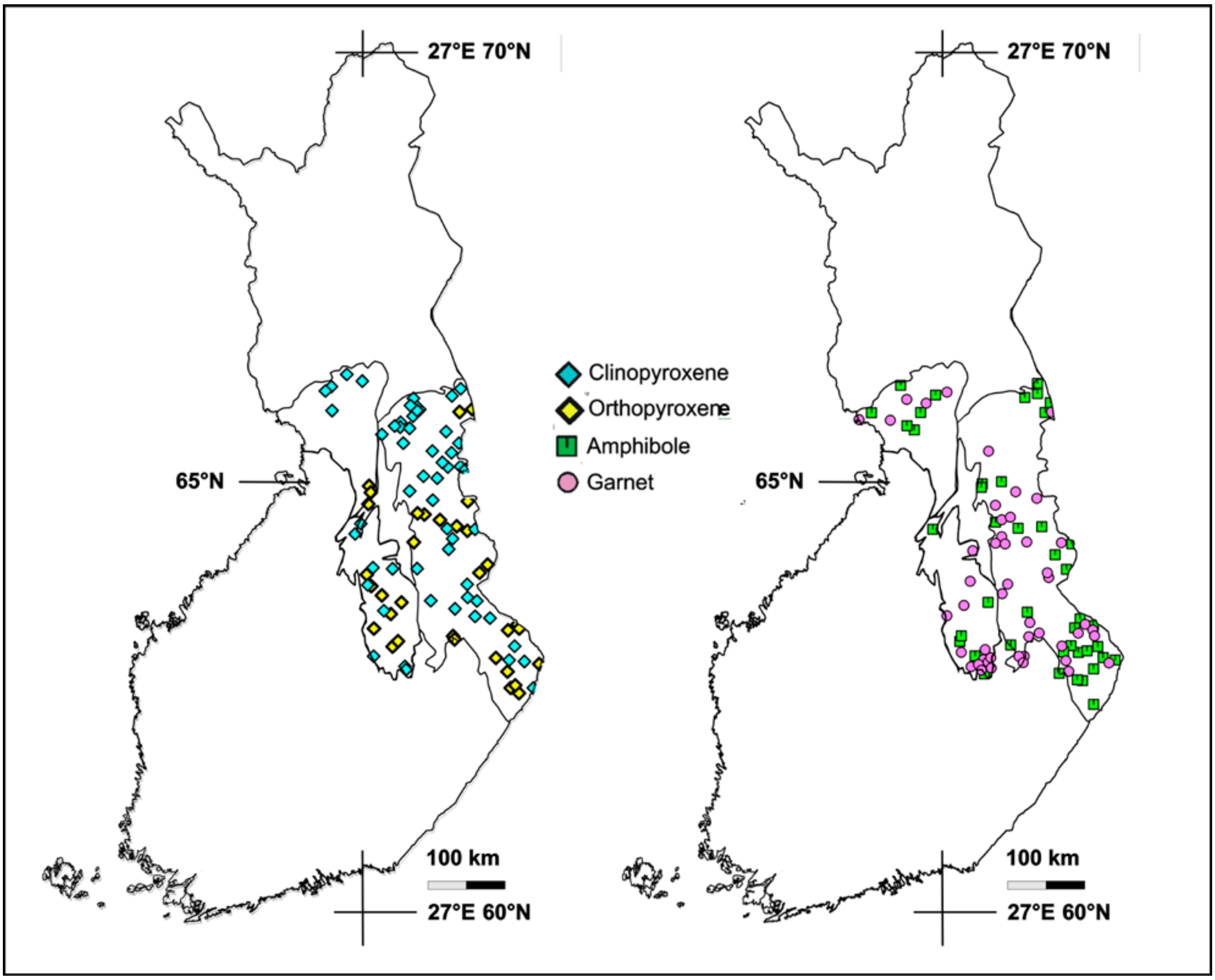

Fig. 5. Modelled restite mineralogy of the adakitic plutonic rocks in the study area.

Orthopyroxene: Nd/Zr > 1, La/Ce < 1, Er/Lu > 1
Clinopyroxene: Nd/Zr < 1, La/Ce > 1, Er/Lu < 1
Hornblende: Nd/Zr > 1, La/Ce > 1, Er/Lu < 1
Garnet: Nd/Zr > 1, La/Ce > 1, Er/Lu > 1

These results can be expressed in a more simplified form, demonstrating the uniqueness of the combinations:
Orthopyroxene: (1,0,1)
Clinopyroxene: (0,1,0)
Hornblende: (1,1,0)
Garnet: (1,1,1)

These combinations now allow us to evaluate the distributions of all these restite minerals in the study area. These ratios were calculated for AFP-normalized samples, and the locations of adakitic rocks containing any of these four restite-phase minerals were plotted on the maps in Figure 5. It is evident from the maps that the most evenly distributed restite minerals appear to be clinopyroxene, amphiboles and garnet. Orthopyroxenes are also present but in lesser amounts, and mainly south of 65°N.

It must be noted, that the method gives only one apparently dominating mineral in the restite. Their relative combinations could be possibly evaluated by considering e.g. paired groups of the ratios above. Moreover, analyses for some samples were incomplete. Thus, it was not possible to determine the restite-phase elements for all samples using this method.

The method was also tested using normalization by geometric means of all Finnish adakitic samples, which gave results very similar to the AFP normalization used here. It must be emphasized that these minerals are assumed to dominate in restitic rocks deep in the lower crust – upper mantle, not in outcrops at the present erosion level

RELATIONSHIPS BETWEEN ADAKITOIDS, TTGS AND SANUKITOIDS

During this study I also tested the distribution of sanukitoid plutonic rocks in the database using the criteria applied by Halla (2005 and references therein): SiO_2 = 55–60%, Mg numbers > 0.6, Ni

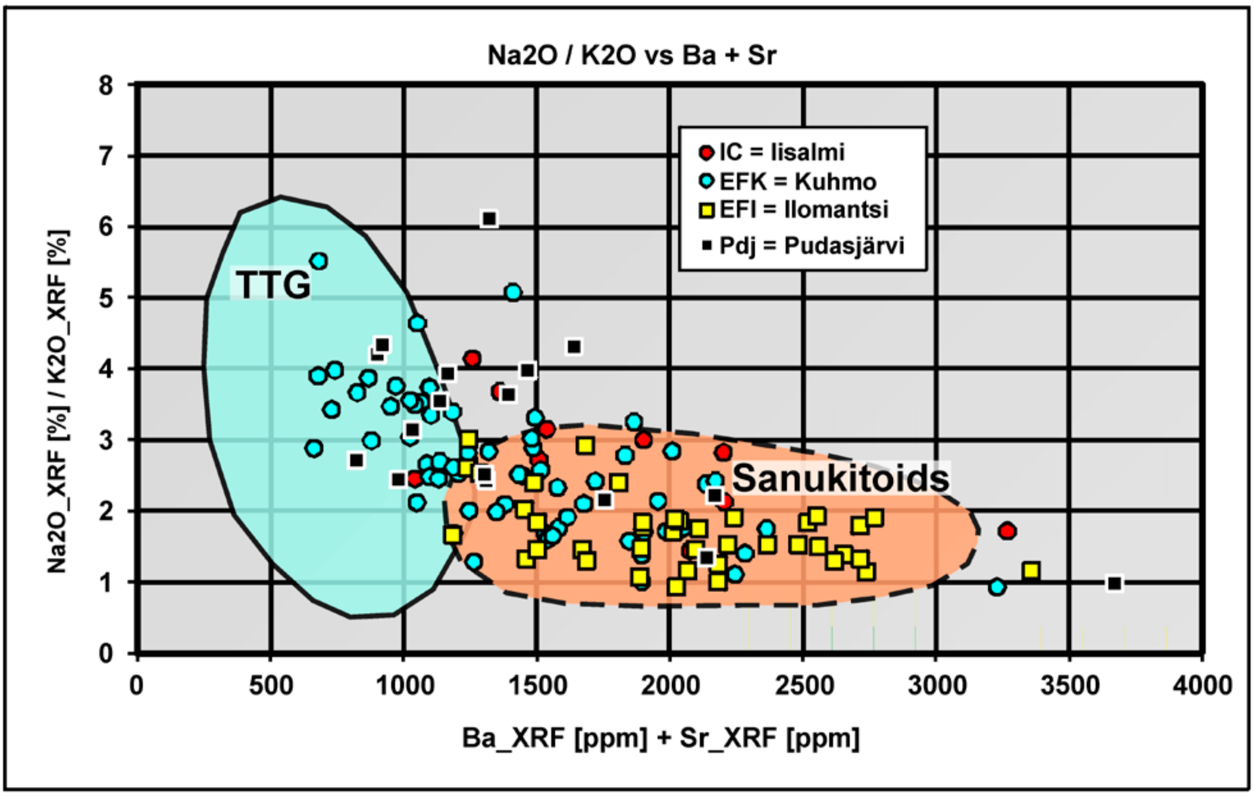

Fig. 6. Na_2O/K_2O vs. Ba + Sr plot for discriminating the high Ba–Sr sanukitoid group from the TTG groups. The hypothetic source end members are enriched mantle (high Ba + Sr, low Na_2O/K_2O) and primitive basalt (low Ba + Sr, high Na_2O/K_2O). Adopted from Halla et al. (2009).

>100 ppm, Cr > 200 ppm, K_2O > 1%, Sr and Ba > 500 ppm and Rb/Sr ratios < 0.1. However, very few 'sanukite-like' plutonic rocks were found using their criteria. Later, it was observed that using broader definitions given by Heilimo et al. (2010), many of the Archaean adakitic rocks in Finland are also sanukitic.

Figure 6 presents all Archaean adakitic rock samples considered here on a Na_2O/K_2O vs. Ba + Sr diagram adopted from Halla et al. (2009). It is apparent from the diagram that the adakitic samples considered in this study represent a continuum from TTGs to sanukitoids. It is therefore difficult to discriminate between potential primitive basaltic and enriched mantle sources on the basis of this diagram. Although this makes attempts at classification somewhat arbitrary, all samples from the Ilomantsi terrain (EFI) classify as sanukitic. The Kuhmo terrain (EFK) contains both TTG and sanukitic plutonic rocks, while the samples from the Iisalmi and Pudasjärvi terrains show more random scatter within and around the TTG and sanukitic fields.

DISCUSSION

This study considered four separate terrains in the Archaean crust in central Finland: the Iisalmi terrain (IC), East Finland - Kuhmo 'terrain' (EFK), East Finland - Ilomantsi 'terrain' (EFI) and Pudasjärvi terrain (Pdj). Each of these areas is characterized by predominantly felsic, dioritic to granodioritic plutonic rocks. Some mafic plutons were also sampled, except from the Ilomantsi area, where almost all samples are from felsic rocks. Petrophysically, the plutonic rock samples are relatively low in density and magnetite poor.

A characteristic feature of the samples is that they are relatively enriched in LREE and compatible elements relative to HREE (compared to the reference group of 'all Finnish plutonic rock samples', AFP). These features are especially striking in plagioclase-rich adakitic rocks, whose chemical spectra probably record fractionation at lower crustal or upper mantle depths, i.e. at depths greater than ca. 40–60 km. Using normalized Nd/Zr, La/Ce and Er/Lu ratios, the restitic minerals of adakitic melts can be estimated to predominantly consist of clinopyroxenes, garnet and amphiboles, with lesser amounts of orthopyroxene. The high potassium contents in adakitic rocks may be a result of high-pressure melting of phlogopite in the source material. Moreover, low Sc and Cr contents can be attributed the presence of clinopyroxene and low Ni to olivine in the restite. The chemical spectrum of adakitoids is broad, forming a continuum from TTGs to sanukitoids, thus indicating complex melting processes and diverse primary sources, ranging from a primitive basaltic source to enriched mantle.

An important observation is the compositional similarity between the adakitic samples from the various terrains, resulting in a high degree of statistical correlation. For example, even though the correlation of the combined data for all plutonic rocks is relatively poor between the Iisalmi terrain and the other terrains, the Iisalmi adakitic rocks nevertheless correlate strongly with adakitic rocks from the other terrains.

The evolution of Archaean adakitic rocks has been interpreted in terms of subduction processes by Svetov et al. (2004). Subduction results in partial melting of the overriding plate, thus producing enriched magmas contaminated by mantle material. O'Brien et al. (1993) and Hölttä et al. (2012, this volume) noted that calc-alkaline volcanic rocks, crustal signatures in the geochemistry of ultramafic rocks and high abundances of volcaniclastic greywackes in the sanukitic Ilomantsi belt (here 'terrain') are consistent with arc-type tectonic settings, and hence may indeed be related to subduction processes.

However, there is still an apparent contradiction between the considerable volume of Archaean adakitic plutonitic rocks and the relatively small proportion of rocks that can be unequivocally interpreted as being related to subduction. Therefore, an alternative explanation, preferred here for most Archaean adakitic / TTG terrains lacking direct indications of 'modern type' subduction is crustal thickening due to collision-related stacking and melting by underplating and mixing with hot upper mantle material. Underplating processes could be expected to generate high-velocity layers in the lower crust, which may still be evident in deep seismic sections. However, much of the lower crust has apparently been eroded or delaminated during later processes, as modelled by Kukkonen et al. (2008) for the Svecofennian crust in western Finland.

This type of process can be linked with a model proposed by Kröner et al. (2011), who suggested extensive recycling of early-formed granitoid crust and mixing with juvenile material to produce successive generations of TTGs and associated felsic volcanic rocks. Thus, in the model introduced here, the repeated stacking corresponds to the recycling concept of Kröner et al. (2011) and underplating represents the mixing of juvenile material in their model. It must, however, be emphasized that Archaean subduction-related collision and stacking processes are not excluded by this model. Moyen (2011) also commented that crustal recycling was already a rather prominent process in the Archaean, because sizeable portions of grey gneiss complexes have old model ages, pointing to a long term continental history.

Thus, a comprehensive answer to these questions needs to be addressed by isotopic analysis of carefully selected samples: A wide range of ages in sampled zircons may refer to multi-stage stacking / recycling processes instead of relative rapid 'single-stage' subduction-related crustal growth.

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