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GEOCHEMICAL ASPECTS AND K/Ar-DATING OF IGNIMBRITES IN CAPPADOKIA, TURKEY

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Abstract

Neogene/Quaternary volcanic products in Cappadocia comprize at least 9 major rhyolitic ignimbrites, pyroclastic surge deposits, Plinian fallout and less evolved basaltic andesite - dacitic lava flows and cones. The ignimbrite series can be subdivided into a lower non-welded series comprizing Lower- and Upper Göreme, AkDag, and Cemilköy-Ignimbrites and an upper welded series with the Sarimaden, Kizilkaya, Incesu, and Valibaba-Ignimbrites. Subdivision is based on depositional facies, degree of welding, petrographical, and geochemical compositions. New K/Ar - dating of the ignimbrites produced ages between 9.0±0.2 and about 1.1±0.1 Ma so that, more or less constantly, every 1 Ma a major ignimbrite eruption occurred.

Geochemical analyses classified the ignimbrites as high-K calc-alkaline rhyolites having ca 4 - 6 wt.% K_2O at 70 - 77 wt.% SiO_2. The Incesu-Ignimbrite is distinctly enriched in HFSE and REE relative to the other ones. Discrimination diagrams therefore classify this unit as within-plate or A-type *"granite"* while the other ones match the fields for orogenic/volcanic arc S- and I-type *"granites"*. $^{87}Sr/^{86}Sr$ - ratios vary between 0.7069 of the Cemilköy and 0.7129 of the Kizilkaya-Ignimbrite.

The less evolved rocks of the lava flows and cones are calc-alkaline with 1 - 2 % K_2O at 55 - 65 % SiO_2. Bivariate element distribution diagrams show continuous trend lines with most ignimbrites - except for the Incesu - suggesting a differentiation relationship between both groups by fractionation of olivine, pyroxene, plagioclase ± (Ti)magnetite and apatite. The HFSE and REE - enrichment of the Incesu - Ignimbrite is explained by a coupling of the raised HFSE - content and its higher alkalinity due to the generation of the magma within a geotectonic environment transitional between *subduction* and *within-plate* setting.

The generalized petrogenetic model deduces the ignimbrite magmas from parental melts of a lithospheric mantle metasomatized by a subduction component by fractionation and assimilation of partially molten crust: their $^{87}Sr/^{86}Sr$ - ratios are too low to assume simple crustal fusion but they are also too high to neglect a significant crustal component. On the Rb/Nb vs. Rb - plot, data points follow the path generally attributed to assimilation an

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fractional crystallization (AFC). Part of the high-K - character of the ignimbrites relative to the calc-alkaline less evolved lavas may be due such crustal assimilation.

1. Introduction

The volcanic area of Cappadocia is part of the Anatolian volcanic belt between Taurus and Pontus Mountains extending W - E from the Mediterranean Sea to the Van area (Fig.: 1).

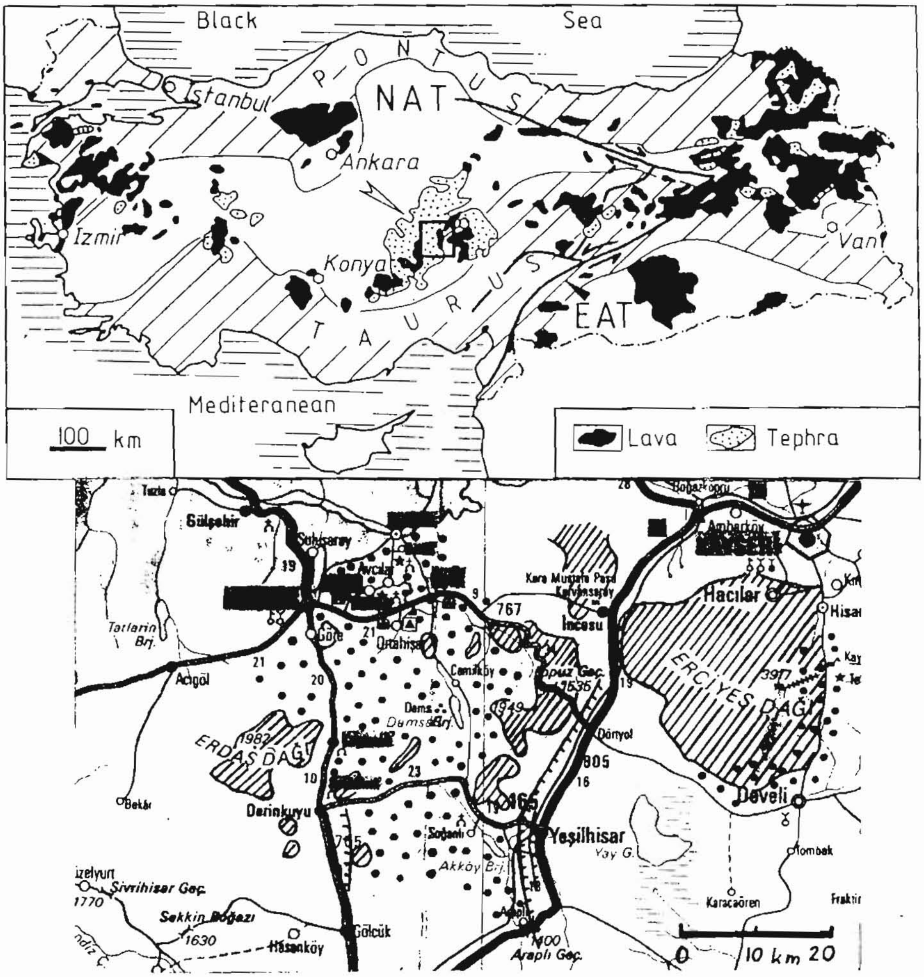


Fig. 1: (a) Location of the study area in Central Anatolia between the cities of Nevsehir, Nigde, and Kayseri. The North and East Anatolian Transform (NAT; EAT) are major strike-slipe faults along which Anatolia, beginning the the Moddel Miocene, drifted "en bloc" westward to accomodate continuing compression by the Arabian platform in the east. (b) Location map of the study area.

Volcanism resulted from the collision of the Afroarabian and Eurasian plates during Tertiary times. The collision prograded from west to east so that during the Middle Miocene the compressional regime in Western Anatolia was already replaced by post-collision extension while Eastern Anatolia just underwent high-grade compression (Yilmaz, 1990). Collision volcanism consequently migrated similarly and the Neogene activity of Central Anatolia began in the Late Miocene when actual subduction of the Tethyan ocean slab had already ceased. Instead of continuing crustal shortening in the central part, Anatolia drifted "en bloc" westward along major strike-slip or transform faults - the North Anatolian Transform (NAT) and the East Anatolian Transfrom (EAT) - at a mean rate of 0.5 cm/a to accomodate prograding compression by the Arabian platform in the east (see References in Pearce et al., 1990) (Fig.: 1). Therefore, analogus to the east (Pearce et al., 1990), the Neogene volcanic activity in Central Anatolia cannot be directly related to any subduction process because, at a mean convergence rate of the plates of 1.5 cm/a, oceanic slabs would have been subducted below the depths at which arc magmas are commonly thought to be generated. Central Anatolia is nevertheless a prominent area of calc-alkaline ignimbrite series in continental collision zones with individual units covering areas > 5000 km^2 with more than 50 km^3 of tephra. Pasquaré et al. (1988) subdivided the activity into three major phases including (a) mainly effusive activity at the beginning befor 8.5 Ma BP; (b) the main ignimbrite producing phase between 8.5 and 2.5 Ma BP; and (c) the latest period of the built-up of major stratovolcanoes. This latest period of the stratovolcano formation is here in completed by *extrusion of lavas and the built-up of spatter and scoria cones* that lasted probably until historic times (Keller & Villari, 1972; Keller, 1974).

2. Stratigraphy

The stratigraphy of the study area between the cities of Nevsehir, Nigde, and Kayseri comprises 9 non-welded and welded rhyolitic ignimbrites which are interbedded with Plinian pumice fallout, minor pyroclastic surge, and extensive reworked deposits including shallow lacustrine sediments and limestones (Fig.: 2). Additionally, blocky and scoriaceous lava occurs forming flows and cones on the plateau formed by the Kizilkaya-Ignimbrite. There is no evidence from the field that lava flows are intercalated with ignimbrites which gives rise to assume the lava flows and cones are *phase-C* extrusions sensu Pasquaré et al. (1988). The ignimbrite sequence itself can be subdivided into a lower series of the *older non-welded ignimbrites* and an upper series of the *younger welded ignimbrites* based on ignimbrite depositional facies, petrographical, and geochemical characteristics.

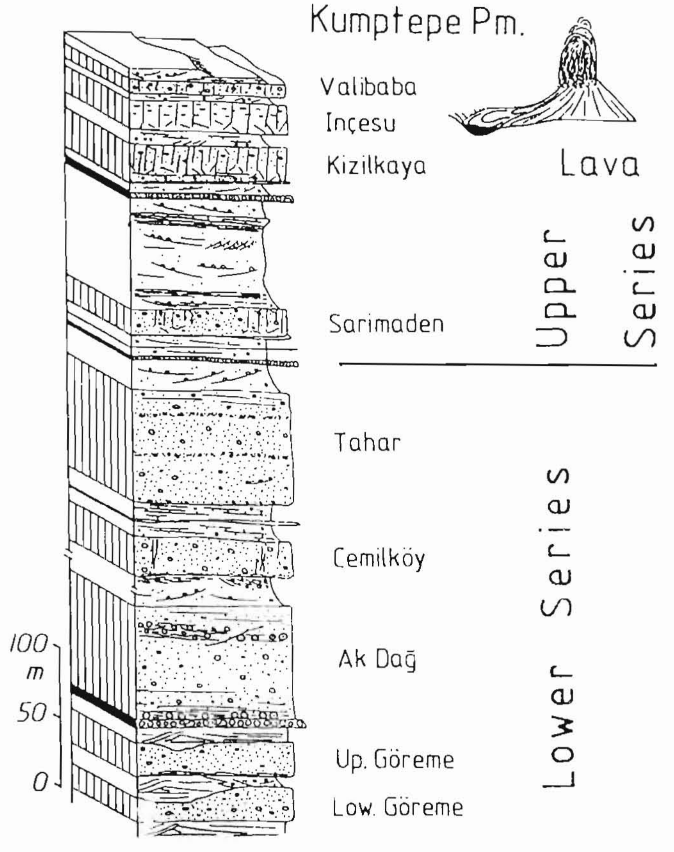


Fig. 2: Stratigraphy of the study area comprises 9 high-K calc-alkaline yolites. The sequence is subdivided into a lower series of the older non-welded ignimbrites and the upper series of the younger welded ones. Ignimbrites are interbedded with surge, fallout and extensive reworked deposits.

The lower series comprises Lower and Upper Göreme, AkDag-, Cemilköy- and Tahar-Ignimbrites, whereas the upper series comprises Sarimaden-, Kizilkaya-, Incesu- and Valibaba-Ignimbrites.

The basal part of the tephra series comprises two massive units - *Lower* and *Upper Göreme Ignimbrite* which are separated from each other in the field by pyroclastic surge deposits (Schumacher et al. 1990). *AkDag-Ignimbrite* is developed from an initial Plinian/phreato-plinian fallout throughout laminated surge deposits: individual surge layers can thicken upward until normal massive ignimbrite facies is developed. The basal fallout layer is up to 7 m thick near the village of Zelve. The forthcoming *Tahar-Ignimbrite* allows to study depositional facies relationships between a several tens of meter thick palaeovalley-fill and adjacent, thin bedded overbank facies, up to 12 m thick only. The valley-fill shows coarse lithic breccia layers forming the basal parts of flow units. The corresponding overbank facies is made up of thin-bedded, so called *incomplete flow units*: such imcomplete flow units consist only of the massive body and the upper pumice concentration zone.

The light-grey *Sarimaden-Ignimbrite* from the upper series shows a regionally inconsistent distribution of welding. This may be due to both total thickness of the deposit and distance from source. The *Kizilkaya-Ignimbrite* exhibits distinct variations in welding: the basal zone may be either welded together with the main body showing columnar jointing or the basis is non-welded loose tephra (Schumacher et al., 1990). These welding characteristics are attributed to variable cooling of the tephra during deposition. The *Incesu-Ignimbrite* is the most densly welded unit showing a basal vitrophyre. Strongly flattened pumices are concentrated in the upper part. *Valibaba-Ignimbrite*, moderately welded in the study area, looks macroscopically more like a sandstone than an ignimbrite. Disconnected outcrops are around Valibaba Tepe and in the village of Sofular N of Ürgüp.

The *Kumptepe Pumice*, a young Quaternary tephra deposit, is exposed in many quarries and road cuts between Ürgüp and Nevsehir. The several-meter-thick Plinian fallout is topped by final surge deposits locally bearing accretionary lapilli. Changes in colour of the pumices, white and light grey, may indicate the eruption from a chemically zoned magma chamber.

The young lavas comprise a wide range of composition from fine-grained dark, nearly aphyric *basaltic* flows showing locally columnar joints to grey and reddish-brown feldspar-phyric blocky and scoriaceous lava cones. Their regional distribition is chiefly concentrated along the western margin of the Sultansazligi plain, a volcano-tectonic depression confined by north - south striking faults (Fig. 1b). Crude alignment of some of the cones indicates subsurface fissure systems promoting the ascent of the magma.

3. Petrographical Aspects

Petrographical composition of all the ignimbrites from the lower non-welded series is more or less similar, having plagioclase, quartz, alkalifeldspar, biotite, and Ti-magnetite. Crystals are frequently fragments rather than euhedral phenocrysts, and there is no evidence for dentritic growth as in units of the upper series. The fine-grained glassy matrix is chiefly composed of vesicular micro-pumices with only minor amounts of bubble-wall shards.

The phenocryst assemblage of the welded ignimbrites from the upper series varies with geochemical composition of the units: those with higher SiO_2-contents (> 72 wt.% SiO_2), Kizilkaya and Valibaba Ignimbrite, have quartz-phenocrysts. Ignimbrites with lower SiO_2-contents, Sarimaden and Incesu, (68-72 wt.% SiO_2) have no quartz, but, in contrast, significantly more clinopyroxene. The quartz phenocrysts from Kizilkaya and Valibaba show distinct *pseudo-resorption* structures and *"inclusions"* being identified as dendritic growth in samples from the *Valibaba-Ignimbrite*. Similar features are shown by plagioclases from the *Incesu-Ignimbrite*.

The andesites and dacites are plagioclase- and clinopyroxene-phyric having up to 40 vol% of crystals. If present, orthopyroxene is more abundant than clinopyroxene. Amphibole may occur in some samples instead of pyroxenes. Accessory minerals are Ti-magnetite and apatite. The very fine-grained lava flows of basaltic andesite are olivine - clinopyroxene phyric with ± plagioclase, the latter of which is generally a major constituent of the matrix. Olivines may show dendritic growth.

Plagioclase phenocrysts from the ignimbrites of the upper series were analysed by microprobe and cathodoluminiscence (CL). All samples show zonar variations of CaO, Na_2O, and K_2O within similar ranges having 30 - 43 % anorthite. However, Fe (as FeO)-content is slightly higher in those from the Incesu-Ignimbrite reflecting the generally increased Fe-content in the Incesu-magma relative to the others. CL shows light-green to yellowish-green luminiscence of the plagioclases from the Sarimaden, Kizilkaya, and Valibaba-Ignimbrites while those of the Incesu-Ignimbrite are pale-turquoise. Activator elements can be identified by spectroscopy of the luminescence showing two distinct bands centered at 695 nm - due to Fe^{3+} - and 562 nm - due to Fe^{2+} (Fig.: 3). Furthermore, the observed differeces in luminiscence are irrespective of total iron-content but are due to differences in the oxidizing state (Koberski, 1992). The Fe^{2+}/Fe^{3+} - ratio in plagioclase can be calculated from the varying intensities of the spectral bands showing a higher oxidization state of iron in the Incesu than in the other ignimbrites.

4. K/Ar - Dating

Methods

A selected series of samples from the ignimbrites were processed for K/Ar-dating. Two grain-size fractions, 125-200µm and 200-250 µm of bulk pumice samples and, if possible, biotite and feldspar concentrates were analysed. Potassium was measured by flame-photometry - the standard error corresponds to ± 1 %. Argon was measured by isotope dilution (Kirsten 1966; Dalrymple & Lanphere 1969) on a VG MM1200 mass spectrometer using a 99,9997% pure ^{38}Ar spike (Schumacher 1975).

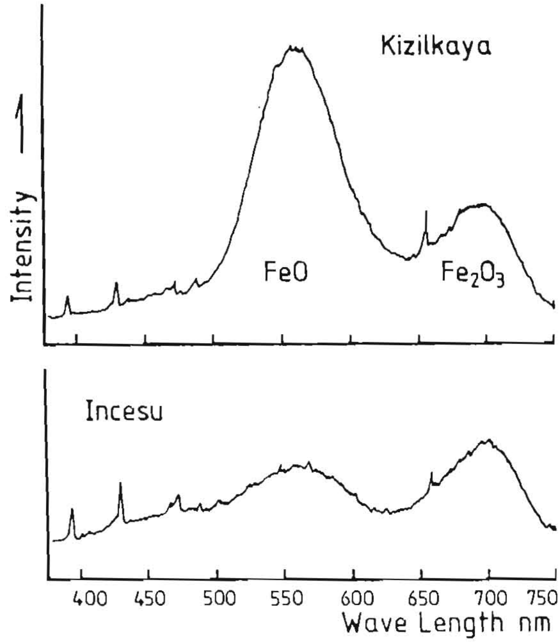


Fig. 3: Cathodoluminecence spectroscopy of plagioclase from (a) Kizilkaya and (b) Incesu-Ignimbrite shows tow distinct bands due to Fe^{3+} and Fe^{2+} activation. Varying intensities reflect different Fe^{2+}/Fe^{3+}-ratios.

For Ar-degassing, the samples were molten by a high-frequency generator in a glass high-vacuum extraction line (Flisch 1986). Extracted gas was purified on Ti- and Zr/Al-getters before being introduced into the mass spectrometer by a direct connection line. Measured differences to the mineral standard of biotite LP-6 (Flisch 1982) used in spike calibration were < 1%. Calculation of sample ages were processed using the constants of Steiger & Jäger (1977).

Results

The ages of the ignimbrites range from about 9.0±0.2 for the Lower Göreme to about 1.1±0.1 Ma for the Valibaba-Ignimbrite (Table 1). In detail, individual biotite and whole rock ages from the Lower Göreme ignimbrite show only little deviation from the mean value of about 9 Ma, while the whole rock ages for Ak Dag and Cemilköy ignimbrites vary considerably within the analytical error. Thus, an average age of about 7,6 Ma was calculated for Ak Dag and of about 6.6 Ma for Cemilköy ignimbrite. Data of the Kizilkaya ignimbrite are more complex: Due to both variable degree of alteration by weathering and welding whole rock data show a wider scatter of individual measurements.

Table 1: K-Ar-data of the ignimbrites

ignimbrite mineral	size (μm)	age (Ma)	% K ($\pm$ 1 %)	$ccm^{40}Ar_{rad}$ $10^{-6}/g$
Low. Göreme				
biotite	125-200	8.75 ± 0.18	4.12	1.404
biotite	200-250	9.17 ± 0.18	5.30	1.893
Ak Dag				
total	125-200	7.52 ± 0.16	3.72	1.089
total	200-250	7.70 ± 0.16	3.68	1.104
Cemilköy				
total	125-200	6.78 ± 0.14	4.02	1.062
total	200-250	6.51 ± 0.14	4.02	1.019
Kizilkaya				
biotite	125-500	4.27 ± 0.1	4.76	0.791
plagioclase	300-500	4.55 ± 0.1	0.61	0.108
total	125-250	4.31 ± 0.1	4.04	0.676
total	250-500	3.69 ± 0.1	4.21	0.604
Incesu				
total	500-700	2.79 ± 0.1	3.84	0.416
Valibaba				
biotite	200-250	1.10 ± 0.1	6.59	0.282

Taking into acount the mineral ages of the biotite and the plagioclase samples as well as the *older* whole rock fraction, the eruption occurred at about 4.35 Ma BP. The youngest eruptions are those of Incesu ignimbrite 2.79 Ma ago and Valibaba around 1.1 Ma ago. In summary, the data show that more or less constantly every 1 Ma a major ignimbrite eruption occurred.

5. Geochemical Characteristics

Ignimbrites

Geochemical analyses were performed on more than 80 samples from the tephra deposits and 50 samples from lava flows and cones including Erciyes Dag stratovolcano. Data classify the ignimbrites and Kumptepe Plinian pumice as high-K calc-alkaline rhyolites with the Incesu-Ignimbrite as slightly transitional to trachytic composition due to its slightly higher alkalinity at lower silica-contents (Table 2; Fig. 4a).

Table 2a: Representative XRF-analyses of ignimbrites including Kumptepe plinian pumice. Major elements in wt.% and calculated to 100 %, traces and REE in ppm.

	Göreme	AkDag	Cemil.	Sarim.	Kizil.	Incesu	Valiba.	K-tepe
SiO_2	75.02	76.84	76.52	71.13	74.90	69.96	74.48	75.76
TiO_2	0.17	0.15	0.11	0.31	0.24	0.48	0.23	0.08
Al_2O_3	14.08	13.25	13.02	14.74	13.03	14.56	13.32	13.48
Fe_2O_{3T}	1.31	1.17	0.97	2.34	1.51	3.70	1.43	1.17
MnO	0.07	0.07	0.07	0.08	0.06	0.05	0.04	0.06
MgO	0.40	0.32	0.23	0.70	0.48	0.61	1.09	0.13
CaO	1.88	1.25	0.87	2.04	1.53	1.73	1.79	0.85
Na_2O	2.34	2.04	2.56	2.84	2.89	3.96	2.54	3.94
K_2O	4.70	4.88	5.63	5.76	5.31	4.68	4.97	4.53
P_2O_5	0.04	0.03	0.02	0.07	0.05	0.11	0.10	0.01
Rb	159	147	178	184	166	144	156	174
Sr	213	163	80	174	136	138	140	67
Ba	966	1003	776	690	689	576	634	325
Zr	98	102	89	221	138	474	136	122
Nb	11	11	8	12	10	19	9	16
Y	22	20	13.1	19.7	10.4	37.7	18	29
Na+K	7.04	6.92	8.19	8.60	8.20	8.64	7.51	8.47
Rb/Sr	0.75	0.90	2.23	1.06	1.22	1.04	1.11	2.60
Zr/Nb	8.91	9.27	11.13	18.42	13.80	24.95	15.11	7.63

Table 2b: Representative XRF-analyses lavas from Erciyes volcano and Cappadocia. Major elements in wt.% and calculated to 100 %, traces and REE in ppm.

	Erc.	Lava		Pumice	Cappa.	Lava		
SiO_2	52.46	61.64	66.21	70.09	56.84	58.31	61.13	64.02
TiO_2	1.55	0.76	0.53	0.36	1.04	0.68	0.60	0.52
Al_2O_3	18.06	17.31	16.24	15.56	16.68	17.77	17.42	16.82
Fe_2O_3	9.07	5.28	4.04	2.73	7.35	6.01	6.19	5.20
MgO	4.72	2.98	2.17	0.96	5.20	4.24	2.84	2.16
CaO	7.46	6.11	4.79	3.26	6.55	7.71	6.37	5.26
Na_2O	4.31	3.94	3.85	4.07	3.91	3.53	3.47	3.61
K_2O	1.58	1.68	1.94	2.82	2.07	1.48	1.76	2.22
P_2O_5	0.64	0.22	0.15	0.09	0.25	0.18	0.12	0.12
Rb	29	45	60	106	41	43	64	83
Sr	615	336	276	219	409	366	300	288
Ba	514	365	403	503	798	464	408	460
Zr	216	162	167	147	147	152	115	140
Nb	26	10	8	8	14	11	7	8
Y	31	30	31	26	22	22	28	27
Na+K	5.890	5.620	5.790	6.890	5.980	5.010	5.230	5.830
Rb/Sr	0.047	0.134	0.217	0.484	0.100	0.117	0.213	0.288
Zr/Nb	8.307	16.200	20.875	18.375	10.500	13.818	16.428	17.500

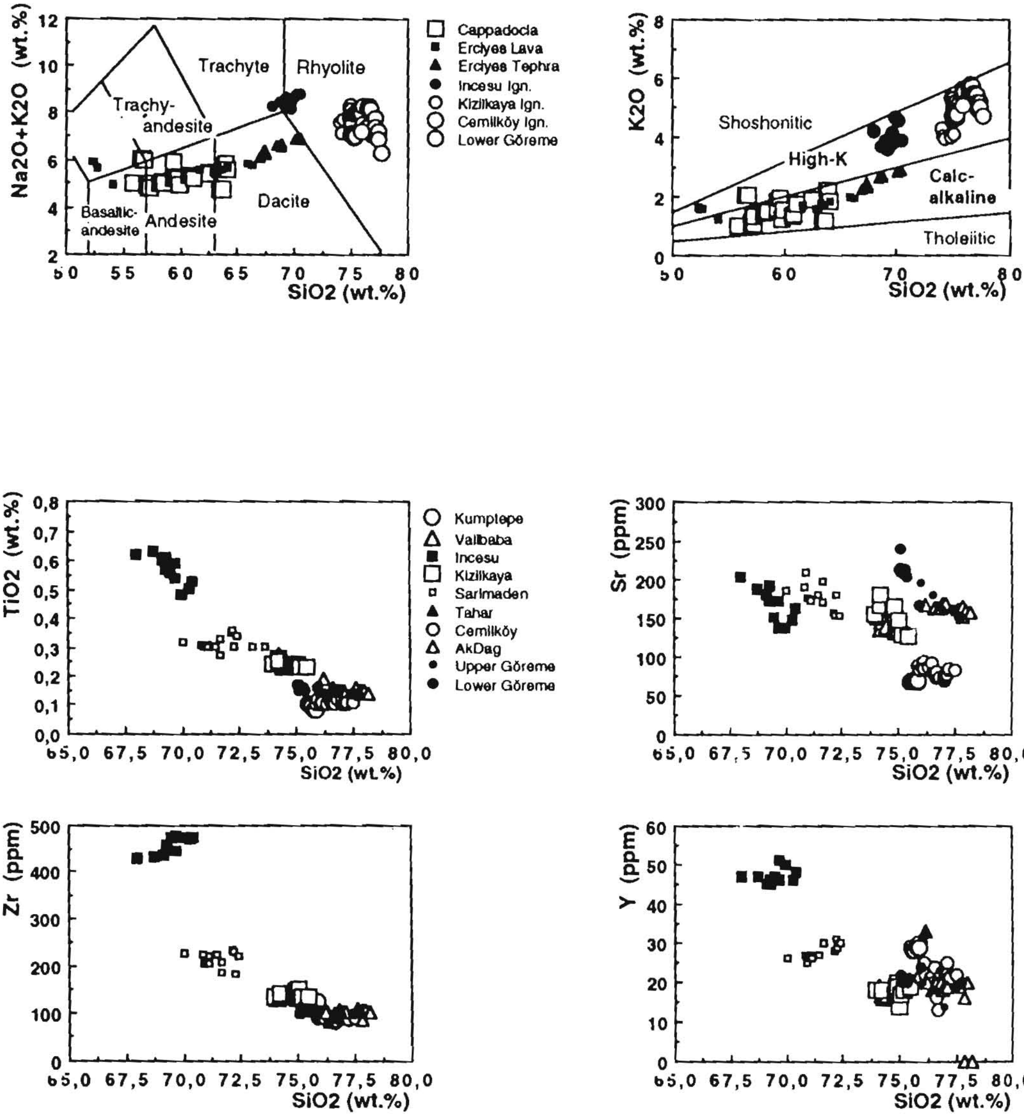


Fig. 4a: Major element abundances plotted against SiO_2 to characterize ignimbrites and other volcanic rocks including Eciyes Dag lavas and pyroclastics. Note the significant HFS-element enrichment of the Incesu-Ignimbrite. Coherent trend lines between the ignimbrites and the less evolved rocks indicates evolution by fractional crystallisation.

A set of trace element abundances including TiO_2 were plotted on Harker variation diagrams to show that the non-welded ignimbrites from the lower series are more or less homogeneous in composition while major differences occur in the upper series of the welded units (Fig. 4a).

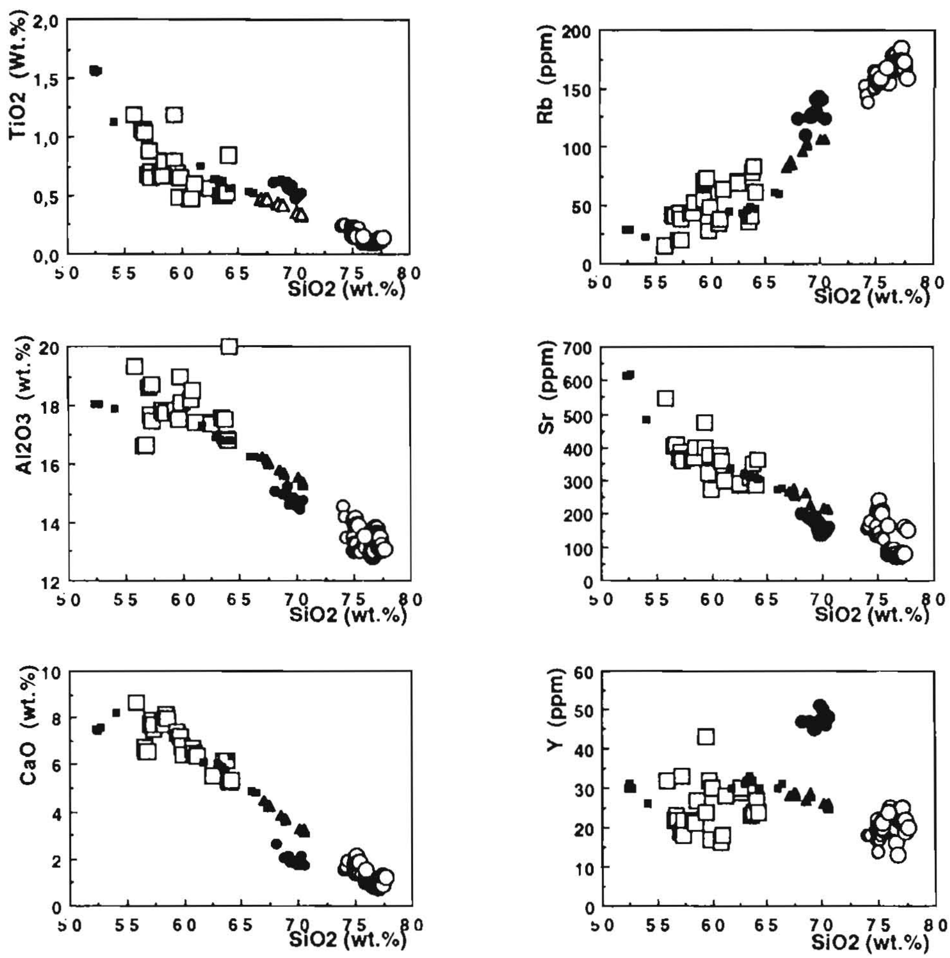


Fig. 4b: Trace element abundances plotted against SiO_2 to characterize ignimbrites and other volcanic rocks including Eciyes Dag lavas and pyroclastics. Note the HFS-element enrichment of the Incesu-Ignimbrite. For further explanations see Fig. 4a and the text.

The ignimbrites of higher SiO_2 differ from those of low SiO_2 contents with respect to HFS-element values of Ti, Zr, Y and Nb: the *siliceous ignimbrites* of the upper series are generally similar to those of the lower series; the *low-silica ignimbrites*, especially Incesu, have higher HFS-element contents. Contrasting this, all ignimbrites of both lower and upper series are similar in their LIL-element contents of Rb, Sr and Ba. Plotted on log - log diagramms Y - Nb and Rb - Y+Nb for classification of the geotectonical environment (Pearce et al., 1984) the tephra deposits of the lower series and the siliceous rhyolites from the upper series (Kizilkaya and Valibaba) are in the field for subduction related *volcanic arc granites.*

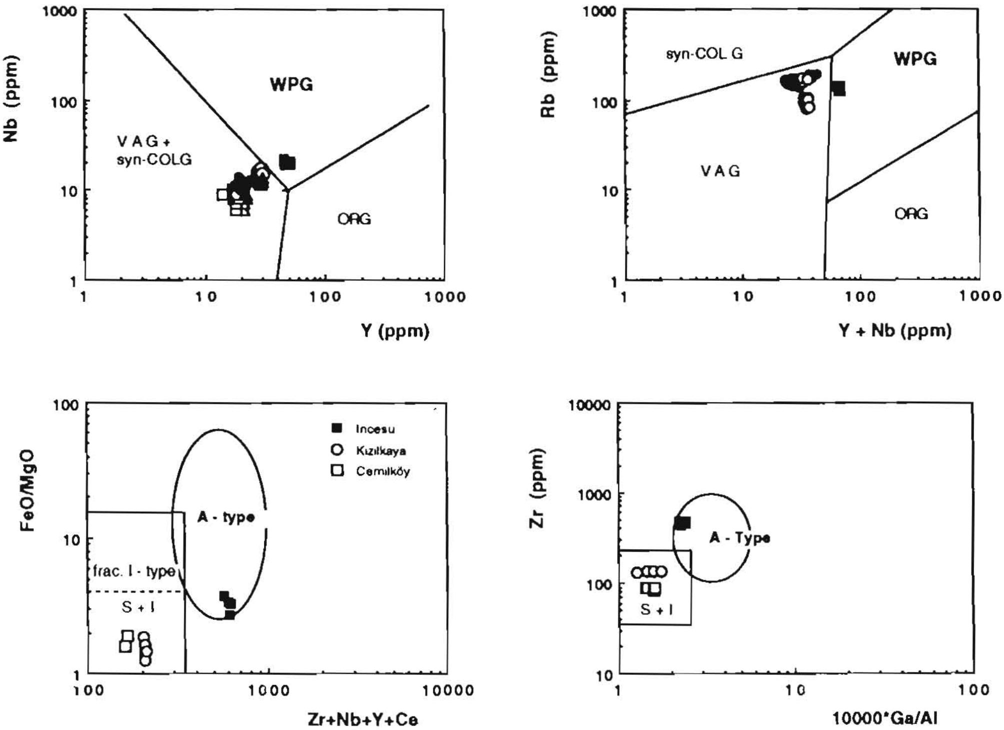


Fig. 5: Discrimination diagrams after Pearce et al. (1984) and Whalen et al. (1987) classify the Incesu-Ignimbrite as HFS-element enriched within-plate (WPG) or A-type granite while the other units match the fields for volcanic arc (VAG) S- and I-type granites. Kizilkaya-Ignimbrite represents a high silica unit from upper and Cemilköy-Ignimbrite of the lower series.

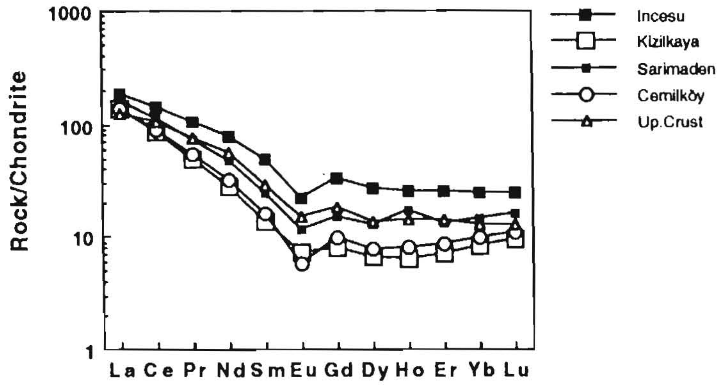
Table 2c: REE-analyses with ICP of selected ignimbrites.

	Cemilköy	Sarimaden	Kizilkaya	Incesu
La	33.00	39.00	33.00	44.20
Ce	55.10	68.90	52.30	86.40
Pr	5.11	6.91	4.72	9.96
Nd	15.00	22.00	13.30	36.10
Sm	2.45	3.77	2.06	7.46
Eu	0.33	0.66	0.42	1.30
Gd	1.99	3.12	1.64	6.90
Dy	2.00	3.21	1.66	7.00
Ho	0.45	0.69	0.36	1.44
Er	1.42	2.19	1.15	4.30
Yb	1.68	2.49	1.41	4.13
Lu	0.27	0.40	0.24	0.61
Y	13.1	19.7	10.4	37.7
Sc	1.8	3.1	1.7	7.0

The Incesu-Ignimbrite, however, matches the field for *within plate granites* due to its HFS-element enrichment (Fig. 5).

REE - data and "spidergrams"

Chondrite-normalized REE patterns of Cemilköy, Sarimaden, Kizilkaya and Incesu-Ignimbrites exemplify the steep slope of LREE enrichment with normalized $(La/Sm)_N$ - ratios of 3.8 - 10.3 and a flat HREE distribution having $(Sm/Yb)_N$ - ratios of 2.0 - 1.6 (Fig. 6). Additionally, a negative Eu - anomaly typical of high-silica feldspar fractionated rocks occurs. Sarimaden-Ignimbrite holds an *intermediate position* between Kizilkay+Cemilköy and the Incesu-Ignimbrite.



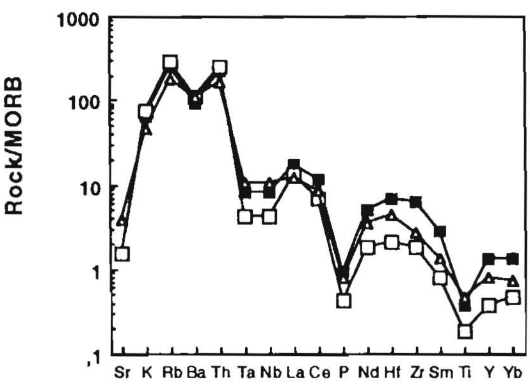


Fig. 6: Chondrite-normalized REE (a) and MORB-normalized trace element variation patterns (b). Notably, patterns parallel that of average upper continental crust although Incesu shows increased and Kizilkaya and Cemilköy ignimbrites depleted values in HFS-elements contents relative to crustal value. Normalizing values from **Sun & McDonough (1989)**; crustal values from **Taylor & McLennan (1985).**

MORB - normalized trace element variations (after Pearce, 1983) show only slight enrichment in the HFS elements in the Kizilkaya and Cemilköy ignimbrites and a much stronger one in the Incesu ignimbrite relative to the MORB - value but a distinct selective enrichment in the LIL - elements Sr - Th which produces negetive Ta-Nb anomalies typical of subduction related volcanic rocks. Surprizingly, the Incesu pattern parallels that of the former units although displaced to higher HFSE - abundances. When compared to average upper continental crust, post-Archaean sediments and greenshist and amphibolite facies metamorphic rocks (Taylor & McLennan, 1985; McLennan, 1990; Grauch, 1990), REE and MORB-normalized trace element distribution patterns are closely similar.

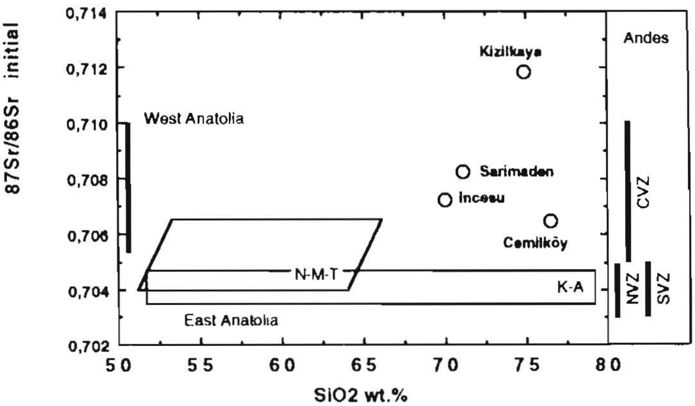
Rb - and Sr - isotopes

^{87}Rb - and $^{87}Sr/^{86}Sr$ - data are available for Cemilköy, Sarimaden, Kizilkaya, and Incesu Ignimbrites having initial $^{87}Sr/^{86}Sr$ ratios between 0.7069 for Cemilköy and 0.7129 for Kizilkaya (Tab. 3). When plotted on a normal $^{87}Sr/^{86}Sr$ vs. $^{87}Rb/^{86}Sr$ diagramm data points for Incesu, Sarimaden, and Kizilkaya Ignimbrites form a line of positive correlation of both ratios (Fig. 7). The Cemilköy Ignimbrite, however, is displaced due to its high $^{87}Rb/^{86}Sr$ ratio. The isotope ratio thereby reflects the high Rb/Sr trace element ratio of about 2 relative to the other units which generally do not exceed 1.5. It may be further worthwhile noting that the initial $^{87}Sr/^{86}Sr$ ratio of the Sarimaden Ignimbrite falls between the values of Incesu and Kizilkaya. A similar *intermediate* position is already known from the normalized REE distribution patterns.

Table 3: Rb-Sr isotopic data of four ignimbrites.

	SiO_2 %	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial
Cemilköy	76.52	170.82	78.35	6.307±16	0.70725±09	0.70689
Sarimaden	71.13	184.66	169.50	3.152±06	0.70837±11	0.70819
Kizilkaya	74.90	178.29	134.14	3.847±52	0.71317±19	0.71291
Incesu	69.96	141.65	140.20	2.923±06	0.70762±11	0.70746

Compared with other Sr-isotope data of Western and Eastern Anatolia, our data show higher initial ratios than subduction related calc-alkaline rocks from the Kars - Ararat region but they are similar in their variation to those of alkaline rocks from the Nemrut-Mus-Tendürek region in Eastern Anatolia The Kars - Ararat values vary between 0.7035 and 0.7045 irrespective of their degree of differentiation indicated by the silica-content (Pearce et al., 1990) (Fig. 7). The Nemrut - ratios range from 0.7035 to 0.7065 and show distinc positive correlation with SiO_2 - content that is attributed to assimilation of crustal material during magma - ascent through thickened continental crust. West Anatolian calc-alkaline volcanic rocks, andesitic - dacitic in composition, have Sr-isotope ratios between 0.705 and 0.709 while the "granitic" suites are > 0.710 (Yilmaz 1990). There is also positive correlation with SiO_2 - content attributed to their *"hybrid character" in terms of crustal and mantle components* (Yilmaz 1990).



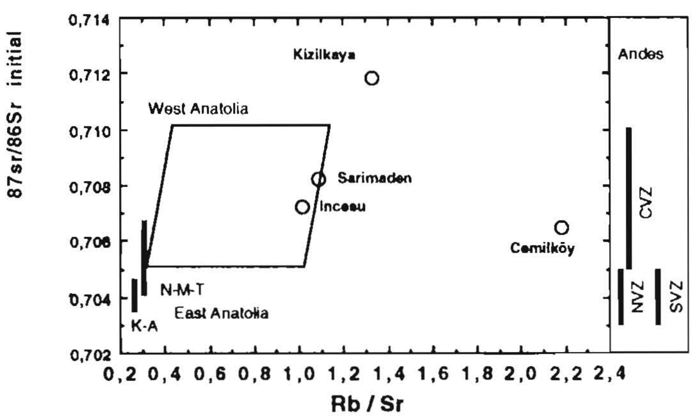


Fig. 7: $^{87}Sr/^{86}Sr$ - ratios of ignimbrites compared to other subduction zone volcanic rocks from Western and Eastern Anatolia and the Andes Data from **Yilmaz (1990)**; **Pearce et al. (1990)** and **Thrope et al. (1984)**. Note the positive correlation of the Sr-isotope ratio and SiO_2 - content which is attributed to assimilation of crustal material.

Futhermore, compared to other subduction zones, our Sr-isotope ratios roughly match the variation field of the Central Volcanic Zone (CVZ) of the Andes (Fig. 7). Thrope et al. (1984) document a considerable variability of Sr-isotope ratios depending on both the degree of differentiation and degree of crustal contamination. Mainly, processes of assimilation and fractional crystallization (AFC) are adressed to explain the observed compositional variations.

Extrusive rocks

Geochemical data classify the extrusive rocks including those samples collected from Erciyes Dag as calc-alkaline (Fig. 4a). The variation ranges from basaltic andesites, andesites, and dacites to the rhyodacites of the latest Erciyes Dag pumice eruption. The set of trace element abundances plotted against SiO_2 futher illustrates the similarity between the Erciyes Dag volcanic rocks and the lavas erupted in the area between Nevsehir and the Sultansazligi plain.

When compared to the ignimbrites, data points continue the coherent trend lines with most of the tephra units suggesting a fractionation of the siliceous tephra from the more primitive lavas (Fig. 4b). Element co-variations, however, do not explain the composition of the Incesu magma with its HFS-element enrichment.

6. Interpretation and Discussion

The geochemical data imply to a number of interpretations and considerations about the magmatic and volcanic activity of Central Anatolia. To begin with, the similarity between Erciyes Dag lavas and those erupted in the area between Nevsehir and the Sultansazligi plain gives rise to assume both lava *"suites"* represent the same volcanic period after the main ignimbrite phase and are thus all interpreted as *phase C* volcanic rocks in the sense of Pasquaré (1988). This is in concordance with the stratigraphy of the area for there was found no evidence in the field for intercalation of lavas and ignimbrites up to the Kizilkaya unit (interbedding of lavas with ignimbrites younger than Kizilkaya is still uncertain).

Coherent trend lines between the basaltic andesites - dacites and most of the rhyolites on bivariate element variation diagrams suggest a relationship of fractionation between lavas and ignimbrites although the latter are high-K calc-alkaline in their character (instead of the simply calc-alkaline lavas). Ti, Fe, Ca, P, Sr, Rb vs. SiO_2 account for a *standard* fractionation of olivine, pyroxene, plagioclase ± (Ti)magnetite and apatite. Amphibole may has also played a role in magma evolution indicated by the near-constant Y - values (Fig. 4b) (cf. Pearce et al., 1990). Fractionation, however, does not explain the HFSE- and REE - enrichment in the Incesu magma which can be classified as an A-type "granitic" magma:

The observed HFSE- and REE-enrichments of Incesu- and, to a minor extent, of Sarimaden-Ignimbrite are typical for A-type granites which are not only restricted to within-plate settings but may also occur in a post-collision environment above a former subduction zone (Whalen et al., 1987; Eby, 1990). Zr, Nb, Ce, Y, Yb and the Ga/Al - ratio are particularly informative in discriminating the A-type from other types of granitic magmas. Log-log plots of the FeO/MgO-ratio vs. Zr+Nb+Y+Ce and Zr-contents in variation of the Ga/Al-ratio identify the Incesu-Ignimbrite as A-type while the siliceous Kizilkaya- and Cemilköy-Ignimbrites (the latter representing the lower series) match the field of S- and I-type granites (Fig. 5).

A-type granitic melts may be of various origin such as fractionation from a mantle derived parent, mantle metasomatism, and two-stage melt extraction from crustal anatexis. Fractionation of the Incesu magma from a mantle derived parent, apart from the above reason of no coherent trend lines with the more primitive lavas on bivariate element distribution diagrams, is also ruled out by the relatively high Y/Nb - ratio of > 2-3 (Eby, 1990) and the relatively high $^{87}Sr/^{86}Sr$ - ratio of 0.7075.

Two-stage melt extraction from curstal anatexis is also invalid to explain the A-type characteristic of the Incesu magma unless special circumstances are involved, e.g. partial fusion of intermediate meta-igneous rocks (references in Whalen et al., 1987). Moreover, the $^{87}Sr/^{86}Sr$ ratio of 0.7075 of the Incesu ignimbrite is by far too low to assume pure crustal origin although the older Kizilkaya ignimbrite deposited underneath could well represent the first melts extracted: the model of two-stage melt extraction includes first melt which are wet, minimum-T melts concentrating the LIL - elements and which generally match the fields for S- and I-type granites. The second melts are dry ones generated at elevated temperatures from the same source concentrating higher HFSE - values out of the former residue. Kizilkaya ignimbrite would fulfill these requirements having amphibole and mice as hydrouos phases (only mica in the Incesu unit), LILE-enrichment and HFSE-depletion relative to Incesu and a significantly higher Sr-isotopic ratio of 0.7129 which may indicate a crustal origin.

Towards an explanation of the HFSE and REE - enrichments of the Incesu magma, Central Anatolia may be compared with the volcanic zones of the Andes. Alkaline rocks in addition to the normal calc-alkaline and high-K magmas extruded above and to the east of South American subduction zone and were documented from the northern and southern volcanic zones (Thrope et al., 1984). They exhibit derivation from a mantle enriched in within-plate components by their chemical and isotopic characteristics. Alkaline rocks are thus not only restricted to intra-plate settings. It is further known that the HFSE (and REE) abundance correlates with the alkalinity of volcanic rocks. For the Incesu magma shows slightly higher alkalinity than the others having about 8 wt.% Na_2O+K_2O at 68-70 wt.% silica relative to ca. 8 wt.% alkalies at 75% SiO_2 of the Kizilkaya ignimbrite the relative HFSE and REE - enrichment of the former correlates with its sightly higher alkalinity. Consequently, on the basis of the HFS - elements the Incesu-Ignimbrite matches the fields for within-plate or A-type granites in a narrow way close to the field boundaries in the diagrams. The occurrence of granitic melts bearing an A-type or within-plate component above the Central Anatolian subduction zone is therefore not strictly exceptional - not even with respect to the tectonic environment of some other A-type granites: according to Whalen et al. (1987) palaeozoic A-type magmas from the North American Caledonides occur closely related with transcurrent strike-slip-faulting. Applied to Central Anatolia the Incesu ignimbrite was erupted - on the basis of the time estimates of Pearce et al. (1990) - after active subduction has already ceased and Central Anatolia drifted westward along the North and East Anatolian transform faults - hence, a tectonic environment which is transtional between "subduction" and "within-plate".

To summarize a petrogenetic model in brief, we deduce the Central Anatolian high-K calc-alkaline ignimbrite magmas from partial fusion of lithospheric mantle metasomatized by a subduction zone component. These parent melts further experienced fractional crystallization and assimilation of partially molten continental crust.

Derivation of parental melts from lithospheric mantle is based on the Sr - isotopic ratios varying between 0.7069 and 0.7129 which are generally too low to assume crustal fusion for the generation of ignimbrite melts alone. Metasomatism by a subduction zone component - fluids released from the subducted slab - prior to the melting is indicated by the *spidergrams* showing the enrichment of LIL - elements relative to MORB typical of subduction related volcanic rocks. This LIL - element pattern does not necessarily imply enrichment by subduction zone fluids alone but may also be due to assimilation of crustal material or a combination of both processes. We cannot quantify either process here and suppose a combination of both for there is clear evidence of assimilation of crustal material by the $^{87}Sr/^{86}Sr$ - ratios being intermediate between *pure molten crust* (> 0.71) and *pure derivate of fractional crystallization* from a mantle parent (< 0.705). The combination of fractional crystallization and assimilation is evidenced by the Rb/Nb vs. Rb plots (Fig. 8). Data points generally follow the diagonal AFC - path while simple assimilation (and subduction zone enrichment) would cause horizontal trends and simple fractional crystallization would cause vertical trends. AFC - processes are also evidenced by the Sr - isotope ratios and their positive correlation with fractionation index - SiO_2 of Rb/Sr. Yilmaz (1990) stated crustal assimilation during rise of the magma through thicked continental crust with wide zones of high-grade metamorphism and anatexis. Similarly, Pearce et al. (1990) and Thrope et al. (1984) document AFC for magmas the $^{87}Sr/^{86}Sr$ and SiO_2 correlate positively passing through thickened crust below the Nemrut-Mus-Tendürek region and the Central Andes respectively.

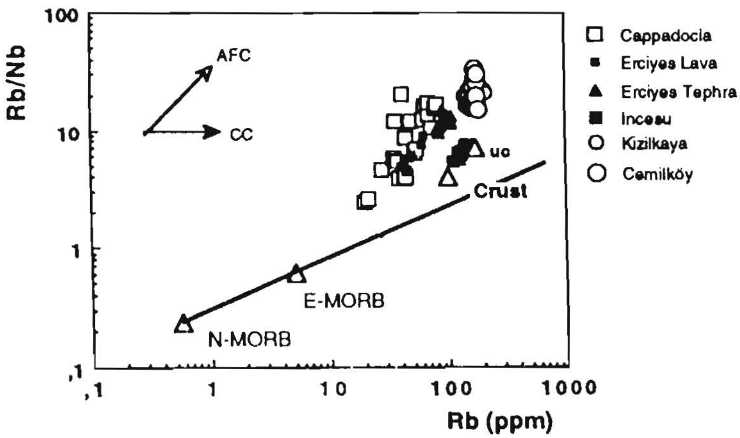


Fig. 8: Log-log plot of Rb/Nb - Nb being generally indicative of crustal contamination illustrates an (hypothetica?) AFC-path of assimilation - fractional crystallization of the rhyolithes except for the Incesu-Ignimbrite matching the value of upper crust.

Assimilation of crustal material may also be the appropriate process to explain part of the high-K character of the siliceous rhyolites relative to the "simply" calc-alkaline less evolved magmas. Additionally, mixing may have occurred in regard of the Sarimaden-Ignimbrite composition being strictly *intermediate* between the Incesu and the Kizilkaya compositions although no streaky pumices are yet reported. In turn, according to Sparks & Marshall (1986) magmas of similar viscosities mix within short after thermal equilibrium is reached so that occurrence of streaky pumices seems nor necessary.

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