Rare-earth and trace element abundances of the Neogene volcanism of the Farellones Formation and the WE Montenegro-Cerro Manquehue Lineament (Central Chile)

Nicole VATIN-PERIGNON[1], Sergio RIVANO G.[2], Mario VERGARA M.[2]
and Francine KELLER[1]

[1] Université Joseph-Fourier de Grenoble, UFR de Géologie & Laboratoire de Géodynamique des Chaînes Alpines UPRES -A 5025 CNRS, 15, rue Maurice Gignoux, 38031 Grenoble cedex, France

[2] Facultad de Ciencias Fisicas y Matematicas, Departamento de Geología y Geofisica, Universidad de Chile, Casilla 13518, correo 21, Santiago, Chile

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INTRODUCTION

Miocene volcanics of the *Farellones Formation* are located at the north of the río Aconcagua, east of the Oligocene-Miocene magmatic belt and west of the present volcanic arc in the Central Chilean Andes (Vergara *et al.*, 1988; Rivano *et al.*, 1990; Rivano & Sepúlveda, 1991). Deposits of this period form a N/S trending chain of 400 km long to 25-65 km wide between 31°30 and 34°S. This segment of the calc-alkaline magmatic arc is cross-cutted by an equivalent age localized mafic to intermediate magmatism forming a *W/E Lineament* with a discordant orientation. The stratigraphy and detailed chronology established for this Formation have been given by Beccar *et al.* (1986), Rivano *et al.* (1990, 1993) and the isotopic character of lavas by López-Escobar *et al.* (1991). More recently, Stern and Skewes (1995) show that lower and upper plate parameters may have the same importance for producing spatial and chemical segmentation of the Andean arc.

Miocene Farellones activity is characterised by calc-alkaline volcanic rocks ranging from basalt through andesite and dacite to high-silica rhyolite. The *Montenegro-Cerro Manquehue Lineament* provides outstanding exposures of lava necks and domes ranging from basalts to dacites, extruded during the same period and commonly aligned along a W-E fault zone. We use trace element and rare earth element (REE) abundances, petrography and mineral chemistry to « fingerprint » eruptive products and to describe the compositional distinctions between the volcanic series. The purpose of our contribution is to clarify the relationships between ignimbrites, andesites and the transversal basaltic lineament.

GEOLOGIC SETTING

The volcanic sequences at Cerro La Gloria (type locality) can be divided into two major episodes. The *Lower Member* is composed mainly of rhyolitic welded and non-welded ignimbrites and air-fall deposits interbedded with lacustrine sediments and its thickness varies from 1 m to about 300 m. $^{40}Ar/^{39}Ar$ ages indicate an age of about 26.7 Ma for the oldest phase of the *Farellones Fm.* (Rivano & Vergara, 1996). The well defined history of multiple eruptions begins about 20 Ma. The *Upper Member* consists mostly of andesitic to dacitic lavas (up to 1500 m) with minor dacitic tuffaceous beds, erupted between 19 and 8 Ma, and associated with several riodacitic domes and dykes extruded during this period.

Basaltic necks and dacitic domes of the *W/E Montenegro-Cerro Manquehue Lineament* are part of isolated Miocene volcanic rocks and plutons which intruded the foothills of the Central Chilean Andes. The basaltic neck of Cerro Huechún has been dated at 20.2 and 20.3 Ma and the dacitic dome of Chacabuco at 18.4 Ma by K-Ar method (Rivano *et al.*, 1993).

The Portezuelo del Azufre unit is formed by small dacitic to rhyodacitic intrusions which are Miocene in age (18 Ma, Rivano *et al.*, 1993) and in relation with volcanics of the *Upper Member* of the Farellones Fm.

PETROGRAPHY AND MINERAL CHEMISTRY

Rhyolites (70-75% SiO_2) represent about 95% of the total eruptives of the *Lower Member* and are variably porphyritic with plagioclase (oligoclase-andesine) as dominant phase and quartz usually present. The greatest petrographic variation lies in the subordinate assemblage of biotite ± hornblende ± Fe-Ti oxides.

The most mafic rocks of the *Upper Member* are basalts and basaltic andesites but plagioclase-two-pyroxene andesites make up the dominant group. Basalts and basaltic andesites are variably porphyritic and generally contain phenocrysts of plagioclase and clinopyroxene in a granular to subophitic groundmass of plagioclase, pyroxene and magnetite. Olivine (Fo_{55-62}) and plagioclase (An_{73-75}) occur as phenocrysts and microphenocrysts in the most primitive lavas (<5o wt% Sio_2). Augites show relatively little compositional variation (Wo_{40-42} En_{41-42} Fs_{15-18}). Plagioclase phenocrysts often display core to rim zonations (An_{81-46}) and augite (Wo_{45-47} En_{41-45} Fs_{10-20}) and pigeonite (Wo_3 En_{74} Fs_{22}) increase in relative abundance. In more evolved compositions, andesites contain hornblende, biotite and glomerocrysts.

Phenocryst assemblages of basaltic andesites of the *W/E Lineament* are characterised by plagioclase (An_{92-75}), orthopyroxene (Wo_{2-3} En_{53-70} Fs_{27-40}), clinopyroxene (Wo_{40-45} En_{43-45} $Fs_{9.15}$), magnetite and rare olivine. Microlites (An_{50-57}) and intersertal groundmasses change in composition. Dacitic domes are sparsely porphyritic with plagioclase (An_{40-47}), augite (Wo_{42} En_{37} Fs_{21}), pigeonite, Fe-Ti oxides and contain vesiculated mafic inclusions.

RARE-EARTH AND TRACE ELEMENT GEOCHEMISTRY

Contents of REE and trace elements in representative Farellones and W/E Lineament lavas are given in Table 1.

Chondrite-normalized rare-earth-element (REE) profiles for the rhyolites of the *Lower Member* and for andesites of the *Upper Member* are very similar. Andesites and rhyolites have evolved patterns and show low LREE/HREE factionation (La/Yb_n = 5 - 7) and negative Eu anomalies increasing with differentiation. These characteristics are consistent with lavas formed mainly through crystal fractionation. Basaltic andesites of the *Upper Member* are comparable with those of the *W/E Lineament* showing less evolved and regular REE patterns and only a slight enrichment of LREE relative to the HREE.(La/Yb_n = 2 - 3). The relative parallelism of their patterns confirm their genetic relationship. Dacites exhibit maximal variations in REE abundances and have no Eu anomalies. These lavas are characterized by higher LREE/HREE fractionation and have among the highest La/Yb_n (14-19) of all Farellones lavas.

Table 1. Major and trace element analyses of representative Farellones samples

N°	1	2	3	4	5	6	7	8	9	10	11	12	13
sample	*CH95-13*	*1801-B*	*CH95-16*	*CH95-14*	*CH95-9B*	*2801-09*	*15-14*	*CH95-18*	*CH95-3A*	*CH95-4*	*CH95-1*	*1301-04*	*2801-01*
SiO2	70,33	75,52	49,82	51.24	56,86	59,10	61,55	62,54	50,26	50.39	51,51	62,80	63,92
TiO2	0.26	0,28	1,53	1,41	1,11	0,96	0,76	0,64	0,89	0,90	0,61	0,56	0,64
Al2O3	13,14	11,89	19,43	19,02	19,36	16,51	16,99	17,82	18,46	18,51	19,04	15,67	17,04
Fe2O3t	1,48	1,41	9,00	8,35	6,16	7,19	5,24	4,55	8,90	8,84	7,92	2,67	3,37
MnO	0.06	0.03	0,14	0.18	0,11	0,14	0,11	0,05	0,13	0,13	0,13	0,08	0,06
MgO	0,26	0,16	4,04	3,24	1,76	3,16	1,79	1,59	4,84	4,74	6,32	0,31	1,81
CaO	2,54	2,35	8,86	8,05	4,97	4,93	4,65	4,15	9,48	9,43	10,68	7,90	4,32
Na2O	1,68	1,59	3,48	3,83	4,46	2,96	4,15	5,85	3,08	3,11	2,64	3,74	4,62
K2O	5,19	3,77	2,20	2,32	3,31	1,59	1,87	1,39	0,84	0,85	1,11	1,74	1,96
P2O5	0,01	0,04	0,32	0,31	0,28	0,11	0,16	0,07	0,36	0,37	0,08	0,06	0,10
L.O.I.	4,06	3,60	1,68	0.99	1,75	3,85	2,18	1,29	2,50	2,47	0,77	4,85	1,31
Total	99.01	100,64	100,50	98,94	100,13	100,50	99,45	99,94	99,74	99,74	100,81	100,38	99,15
Ba	473	335	323	382	512	515	380	331	314	323	266	830	581
Rb	173	187	42	59	85	45	65	21	17	21	11	58	53
Sr	45	128	496	455	469	318	441	544	749	784	752	586	658
Y	26	22	33	32	31	20	19	8	18	18	13	10	8
Zr	179	207	215	239	306	157	193	170	92	96	55	131	112
Nb	10	7	9	12	15	5	5	3	5	5	2	5	4
Cs	4,13	11,20	1,94	1,89	3,52	1,54	1,55	0,55	0,65	0,89	0,64	8,85	2,19
Hf	6,54	6.45	5,93	6,85	8,52	4.35	5.26	2.01	2,34	2,38	1,59	3,18	2,99
Ta	0.85	0,81	0,59	0,75	0,94	0,40	0,46	0,23	0,30	0,31	0,08	0,40	0,40
Th	21,00	24,20	5,44	7,10	8,31	6,21	11,10	2,18	2,56	2,53	1,43	5,31	4,54
U	5,35	5,58	1,53	1,82	2,14	1,88	3,44	0,53	0,79	0,80	0,45	1,66	1,44
La	21,14	24,73	21,07	23,08	28,21	15,89	17,85	10,24	16,09	16,39	6,78	24,33	18,39
Ce	49,12	54,42	49,33	53,26	66,76	35,18	37,47	22,31	35,01	36,82	16,43	47,76	38,35
Pr	5,92	6,51	6,59	6,99	8,80	4,70	4,77	2,83	4,60	4,71	2,32	5,62	4,72
Nd	22,43	23,96	28,26	29,48	36,24	19,75	19,69	11,00	18,78	18,81	10.27	20,11	18,75
Sm	4,88	5,06	6,41	6,48	7,73	4,53	3,89	2,02	4,18	4,17	2,57	3,61	3,55
Eu	0,72	0,51	1,62	1,59	1,76	1,22	0,96	0,64	1.27	1,32	0,88	0,96	1,02
Gd	3,98	4,13	6,11	6,13	6,81	3,86	3,39	1,80	3,41	3,58	2,32	2,63	2,55
Tb	0,65	0,67	0,91	0,90	0,97	0,62	0,55	0,23	0,54	0,55	0,36	0,36	0,31
Dy	4,00	3,71	5,28	5,23	5,38	3,56	3,13	1,21	3,34	3,24	2,16	1,92	1,63
Ho	0,83	0,87	1,09	1,08	1,07	0,79	0,71	0.24	0,69	0,70	0,47	0,37	0,31
Er	2,45	2,23	3,02	2,97	2,90	1,89	1,66	0,64	1,72	1,78	1,30	0,99	0,76
Yb	2,73	2,63	2,77	2,71	2,64	1,88	1,82	0,62	1,84	2,00	1,31	0,99	0,67
Lu	0,41	0,42	0,42	0,41	0,39	0,28	0,29	0,10	0.26	0,26	0,20	0,16	0,09

XRF analyses for major elements (in wt.%) and ICP-MS analyses for trace elements (in ppm) at the Geological Department of the University Joseph-Fourier of Grenoble.
Analytical procedures for trace element and REE concentrations following those of Barrat et al. (1996).
Farellones Fm: lower Member: anal. 1 to 2, upper Member: anal. 3 to 8, Montenegro-Cerro Manquehue lineament: anal. 9 to 12. Miocene dacitic intrusion (Portezuelo del Azufre) associated with the Farellones volcanics: anal. 13.

On a multi-element diagram normalized to N-MORB, rhyolites of the *Lower Member* and andesites of the *Upper Member* show typical patterns for evolved subduction related magmas with marked enrichment of the large-ion lithophile (LIL) elements (e.g. K, Rb, Th) with the exception of Ba and Sr (and Eu) indicating the effects of feldspar and accessory mineral fractionation. The negative anomaly of Ba may be also an indication of a refractive mineral phase, possibly phlogopite, in the source material. Ti and P show marked negative anomalies for rhyolites, this is general for all the analysed rhyolites and is very typical for arc magmas indicating the early fractionment of ilmenite or

Ti-magnetite and apatite. Nb also least some of the magma is of mantle origin. Decreases of Zr and Ba in these rocks may be explained by fractionation of biotite. Rhyolites have patterns much like those of high-silica rhyolites with Nb and Ti depleted relative to the REE and a pattern of high field strengh (HFS) elements (Ta, Nb, Zr, Hf) typical of arc magmas. Basaltic andesites of the *W/E Lineament* are the most mafic compositions erupted and display a low range in concentrations including the relative enrichement of the LIL elements and depletions of HFS elements relative to the REE. their patterns are different of those of basaltic andesites of the *Upper Member*, especially one basaltic andesite (CH95-1) in having all the elements depleted . Dacites are enriched in Ba and in common with Yb, Y decreases and the overall decrease in these elements may be probably due to hornblende fractionation.

All of the lavas have a high Th/Ta ratio: 25-35 for rhyolites, 15-24 for dacites, 10-15 for andesites and 8-9 for basaltic andesites. In general, Th vs Ta trends are very coherent for basaltic andesites and andesites of the *Upper Member* and the *W/E Lineament* whereas rhyolites of the *Lower Member* and dacitic domes are very different. Compositional variations show also coherent trends for basaltic andesites and andesites on binary element-element diagrams for a number of other elements (e.g. Zr vs Hf, Yb vs Ce) and show that these lavas have the same parental magma and their evolution may be largely dominated by crystal fractionation. The differences in REE and trace element compositions for rhyolites and dacitic intrusions may be attributed to source heterogeneity of lavas.

CONCLUSIONS

The volcanism of the *Farellones Fm.* and the *W/E Lineament* is characterized by the relative enrichments of the LREE accompanied by. enrichments of LIL elements. Mafic magma of the *W/E Lineament* and andesites of the *Upper Member* of the Farellones Fm. can be related to each other by crystal fractionation. REE and trace element concentrations show coherent trends which may reflect a relatively homogeneous magma source. Compositions of rhyolites and ash flow tuffs of the *Lower Member* and dacitic intrrusions are very different and may reflect large components of continental crust formed or reworked in a subduction-related environment.

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