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CRONOLOGIA DE LOS PROCESOS ERUPTIVOS Y DE MINERALIZACION EN EL CAMPO VOLCANICO DE LOS FRAILES KARIKARI, CORDILLERA ORIENTAL, BOLIVIA

CHRONOLOGY OF ERUPTIVE PROCESSES AND MINERALIZATION OF THE FRAILES KARIKARI VOLCANIC FIELD; EASTERN CORDILLERA, BOLIVIA

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The eruptive rocks of the Los Frailes Karikari Volcanic Field are located within the Eastern Cordillera of Bolivia and form a dominant part of the back arc magmatic province of the Central Andean orogen. The volcanic rocks cover an area of 8500 km^2 and represent the most important volcanic sequence of the southern part of the Eastern Cordillera. This region is one of the classical provinces where subvolcanic to volcanic magmatism is associated with important Sn-Ag(As-W-Pb-Zn-Sb-Bi-U) mineralization.

In this metallogenetic belt , vein and porphyry-type mineralization is confined to subvolcanic stocks, domes, caldera-type and ashflow volcanism.

The geological history of the volcanic field can be considered in terms of at least five distinct magmatic episodes and multiple epochs during which ore forming processes occurred. A conclusion which is based on K-Ar and fission track chronology. These dates reflect a chronological zonation of the volcanic field from its outer cupolas inwards along with increasing magmatic activity.

Such an assumption is based on 30 (+19 duplicate) analyses of biotite separates from unaltered and partly altered rocks (Schneider, 1985), on 9 (+3 duplicate) analyses of alunite gangue from the Potosi Sn-Ag deposit and on 2 fission track determinations of zircons collected from hydrothermally altered extrusive sequences (see table 1 and figure 1). Approximately 40 ages are available from earlier workers which were used to complete the chronological information (Grant et al., 1979, Mc Bride et al., 1983, Evernden et al., 1979, Baker et al., 1978, Wolf et al., 1980). (see also fig. 1).

The *initial stage* of magmatic activity can be correlated to the Lower Miocene at about 25 Ma and is represented in the volcanic field by the small intrusive of Kumurana located in the SE part of the field and most likely by the altered eruptives at Azanaques in the NW part of the volcanic field (see figure 1).

The granodiorite is a very inhomogeneous magmatic body and apart from the Azanaques granite (see next paragraph) the only intrusive known within the entire subvolcanic Sn-Ag province. This rock is composed of two feldspars, quartz, biotite, orthopyroxene and small amounts of hornblende. The normative composition shows the

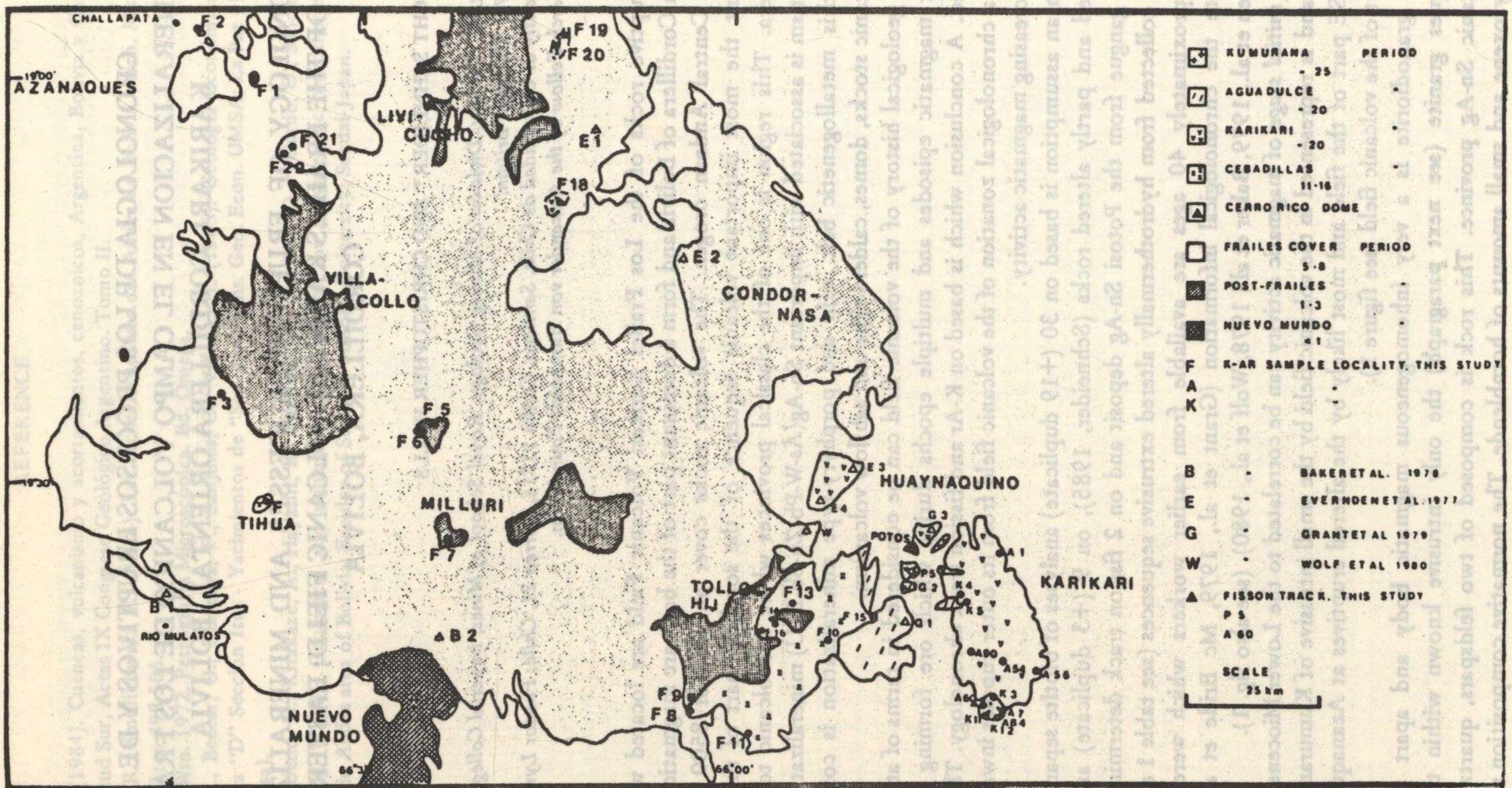

Fig.1. Los Frailes Karikari volcanic field; chronology - location map

Fig.1. Campo volcánico Los Frailes Karikari, mapa de ubicación y de cronología.

TABLE 1

K-Ar ANALYSES (CARRIED OUT AT THE BGS ISOTOPE GEOLOGY UNIT, LONDON)
ANALISIS K-Ar (REALIZADOS EN BGS, ISOTOPE GEOLOGY UNIT, LONDRES)

Sample No.	n	Vol. Rad ^{40}Ar nl/gm^{-1}	K% Alunite	Atm 40 Ar %	Age	± Error at 2σ
Pot-3a	1	2.4480	4.83	79.72	12.99	0.68
	1	2.4896	4.83	91.85	13.22	2.52
Pot-8	2	4.0923	8.49	88.52	12.36	1.23
	2	3.4231	8.49	76.09	10.35	1.04
Pot-12	2	3.0403	7.00	96.67	11.15	2.75
	2	3.1586	7.00	86.74	11.58	0.84
Pot-13	1	2.8466	7.00	59.40	10.44	0.56
Pot-15	2	3.6902	7.00	69.87	13.52	0.72
Pot-18	2	3.9273	8.00	58.01	12.59	0.57
As-137a	1	1.5516	3.50	53.92	11.37	0.53
As-147	2	6.0440	8.28	71.42	18.69	0.88
As-148	2	6.2820	8.70	59.84	18.49	1.04
			K% Biotite			
Fr-1	2	5.8886	7.19	43.85	20.96	0.71
Fr-2	2	1.4819	1.6	69.67	23.68	1.44
Fr-3	2	3.3871	6.99	58.95	12.42	0.79
Fr-4	2	2.0360	5.0	53.10	10.45	0.37
Fr-5	2	1.1043	7.3	84.38	3.89	0.38
Fr-6	1	0.5300	5,47	85.00	2.50	0.7
Fr-7	2	1.0180	7.45	71.07	3.51	0.39
Fr-8	3	3.6960	6.97	67.97	13.59	0.73
Fr-9	3	0.6497	7.59	77.11	2.06	0.30
	1	0.6991	7.59	91.05	2.37	0.23
	4	0.3664	7.59	91.97	1.24	0.13
Fr-10	2	4.3348	7.09	84.55	15.66	0.99
Fr-11	2	3.8076	7.35	49.24	13.28	0.40
Fr-13	2	2.6535	6.45	42.87	10.56	0.30
Fr-14	2	3.1045	6.91	52.09	11.52	0.42
Fr-15	2	3.3272	5.10	69.44	16.71	0.62
Fr-16	2	3.1666	6.61	51,80	12.29	0.40
Fr-18	1	2.4649	3.23	63.89	19.53	1.23
Fr-19	2	3.4339	6.25	73.42	14.09	0.55
Fr-20	1	2.9565	4.99	92.99	15.19	2.07
Fr-22	2	1.4531	7.18	70.39	5.20	0.28
KK-4-79	1	4.9610	6.14	38.62	20.68	0.71
KK-5-79	1	5.1922	6.05	44.17	21.95	0.92
As-1-81	2	4.9217	5.34	28.35	23.56	0.72
As-54	2	5.1278	6.25	50.33	20.99	0.65
KK-3-79	2	10.2609	6.14	51.90	42.51	2.20
	3	10.9869	6.14	36.32	45.48	1.38
KK-11-79	3	5.6704	5.74	50.77	25.25	0.90
	1	6.3295	5.74	58.46	28.16	1.30
KK-12-79	1	4.2250	4.1	67.51	26.33	1.12
As-7	1	5.9003	5.7	55.02	26.45	0.85
As-84	2	6.3592	6.83	65.08	23.80	0.83
As-56	2	5.9051	7.1	24.46	21.28	0.63
As-90	3	3.2200	4.5	67.54	18.32	1.00

Pot, As - 137a, As - 147, As - 148: Potosi Dome altered extrusive, alunite age represent tne final gangue stage of the mineralizing event.
Fr-2: Azanaques, altered extrusive, Kumurana Episode
KK – 3 – 79, As – 7
KK - 11 + 12 – 79, As – 84: Kumurana granodiorite
As – 54 + 56 + 90 + 1, KK – 4 + 5 – 79: Karikari extrusive + Episode
Fr – 1: Azanaques granite, Karikari Episode
Fr – 3: Torko, Upper Cebadillas
Fr – 4: Tihua Dome, Upper Cebadillas
Fr – 5: Jhanko Khollu, Post Frailes
Fr – 6: Cerro Chico Paya "
Fr – 7: Milluri, "
Fr – 8: NE of Jalsuri, Upper Cebadillas
Fr – 9: NE of Churata, Post Frailes
Fr – 10: NE of Río Negro, Lower Cebadillas
Fr – 11: Cerro Apo Porco, Upper Cebadillas
Fr – 13: Tollochij, Upper Cebadillas
Fr – 14: Tollochij, Upper Cebadillas
Fr – 15: SW of Potosi, Lower Cebadillas
Fr – 16: NE of Torre Mayo, Upper Cebadillas
Fr – 18: Cruce Ventilla, Karikari Episode
Fr – 19: SW of Pumpuri, Lower Cebadillas
Fr – 20: " "
Fr – 22: Barbara district, Frailes Cover Episode
n: number of aliquots measured at single argon extraction
open space below samp. no.: duplicate measurements mass spectrometer used: AEI – MS 10
mass spectrometer used: AEI – MS 10

TABLE 1 CONTINUED, FISSION TRACK ANALYSES

Sample N°	Irradiation	N° of crystals cd.	N° of spont. tracks, ps.	N° of ind. tracks, pi.
Pot –5–79	FTD–120	25	3613	5725
As – 60	FTD–124	28	4863	6704

ps/pi	Zeta-CN2	Zeta – CN1	pd in (x 10E5 t/cm^2)	Age (in Ma)
0.631	126	115	7.28	12.0 ± 0.4
0.726	–	–	6.25	25.0 ± 0.8

cd: counted spont.: spontaneous ind.: induced
pd.: mica count per area
Pot–5–79 : Potosi Dome, altered rocks
As – 60: Altered rhyolitic dyke associated to the Kumurana intrusive

presence of diopside and thus a metaluminous source. Its initial Sr ratio of 0.7072 is typical for crustal interaction during magma genesis but may also point towards a component of mantle derived magma (Schneider, 1985).

The *second stage* marks a period of increasing magmatic activity which led to magma extrusion from local cupolas clustered mainly along the NE parts of the volcanic field. These eruptive pulses formed the dominant Karikari Caldera (Francis et al., 1981, Schneider, 1985); other smaller ring complexes formed the Agua Dulce volcanics and fissure and vent controlled extrusions gave rise to minor ashflow sheets and lavas like the Mondragon Formation and the eruptives at Cruce Ventilla. High level intrusions like the small cupolas of the Azanaques granite and the shallow level laccolith of Huaynaquino also belong to this period which can be assigned to the time around 20 Ma. The prominent volcanic feature of this stage is the Karikari-trapdoor caldera, which was constructed during the eruption of approximately 550 km^3 of ashflow material from a weakly zoned 'monotone' magma chamber. Its three units range in composition from that of a high-K-andesite to a high-K-toscanite and finally to a high K-rhyodacite. The peraluminous character of this magma chamber is indicated by its phenocryst mineralogy (garnet-orthopyroxene-biotite-cordierite-plagioclase-alkalifeldspar-quartz) which reflects the alumina oversaturation of these melts, also shown by their corundum normative character. The initial Sr ratios of 0.7105 are indicative for increasing involvement of crustal componets into the source of this magma chamber.

During the *third stage*, between 10-17 Ma, the eruptive activity shifted into the central zones of the Los Frailes Karikari Volcanic Field.

The oldest eruptives in this sequence belong to the Lower Cebadillas Episode. They crop out at Pumpuri and in areas SW of Potosi.

The upper Cebadillas Episode is characterized by local ashflows, domes and stocks which host important metal deposits. The entire distribution of this volcanic period is largely obscured along the western margin of the volcanic field and in its central parts by the extensive ashflow eruptions of the fourth stage which formed the Los Frailes Meseta. The eruptives are also peraluminous, but a characteristic peraluminous mineralogy is absent. Initial Sr ratios vary between 0.707-0.712. The relatively large time interval between 10-18 Ma may be indicative for multiple and heterogeneous igneous subcycles within this magmatic episode. The wide distribution of eruptives related to this period along the eastern flank of the volcanic field and occasional inliers beneath the Frailes Meseta may also be an indication of other pulses of Cebadillas eruptives in the central areas of the volcanic field.

The clearly separate *fourth stage* between 5-8 Ma in which the Frailes Cover was formed marks an important change in the style of igneous activity in the Eastern Cordillera. During this time the rate of volcanic activity increased dramatically and the volumetrically huge meseta-forming ashflows were erupted from multiple centres which are now covered by their own ejectas. These rocks have very similar geochemical features as those related to the Cebadillas Episode.

The vast increase in magma production could coincide with the start of eastward spreading from the East Pacific Rise in the Upper Miocene (Noble et al., 1974), which could have triggered the rise of a large volumen of magma into higher levels beneath the Los Frailes Meseta.

The *fifth stage* is that of the Post Frailes Episode which took place between 4-1 Ma, even though data belonging to this period are still very limited. Especially the large resurgent structures which compose the Cerro Toro and the Villacollo Dome were not dated so far. The rocks related to this stage are in general the most evolved types present within the volcanic field and are high-K-rhyolites with initial Sr ratios similar to the Cebadillas stage (0.712).

A change towards increasing bimodality of volcanism terminated the evolution of the volcanic field, which is seen in the appearance of high-K-rhyolites and that of basaltic andesites in central and marginal parts of the volcanic field. This bimodal stage continued at least into the Pleistocene.

Youngest Pleistocene volcanism in the superimposed Nuevo Mundo province which overlies the Los Frailes magmas in its southern parts reflects a shift of recent volcanic activity towards the South, but absolute ages from its rocks are, as yet, not available.

Mineralization within the volcanic field is related to 4 of the 5 magmatic stages, but is of different styles and intensity. High temperature tin-tungsten ores are related to the Kumurana granodiorite and the older eruptives at Azanaques, where the high temperature vein type mineralization is followed by zoned Zn-Pb-Ag mineralization.

Economic base-metal, Ag and Sn mineralization is found in the Karikari Caldera. Here ore-forming processes are related to three stages of caldera evolution. The most important Episode of mineralization is that coinciding with the Upper Cebadillas Episode at about 14-11 Ma. Here mineralization is associated with local subvolcanic stocks, domes and lava flows which contained high grade Sn-Ag-Zn-Pb and minor Bi and U vein and porhpyry-type mineralization.

The Frailes Cover Episode brought an end to the mineralizing events, even though some young Sb ores are known from the Central parts of the meseta at Milluri and Jhanko Khollu.

The general trend is from early-formed high temperature tin-tungsten ores at Kumurana, followed by largely tin-silver and then base-metal ores (e.g. at Potosi, Porco, Tihua, Tollochij, Karikari) which were finally followed by the above mentioned Sb mineralization. This trend follows that of the level of exposure of the eruptive units.

A similar situation occurs on a larger scale in the relationship with depth of erosion and the change in the style of the mineralization in the Northern Tin Belt, where Sn-W mineralization is associated with granodioritic intrusives.

Thus the general situation of the Southern Tin Belt shows a transition from high to moderate to lower temperature mineralization: (W-Sn), (Sn-Ag) (Pb-Zn-Ag-Sb-Bi-Sn-U). Deep-seated mineralization in the terrains beneath the youngest volcanism may thus possibly occur. This applies especially to the Milluri and the Jhanko Khollu alteration zones and to several vein-controlled Ag-Pb-Zn occurrences along the western flank of the Karikari Cordillera. (see figure 2).

The multiple stages of magmatism identified in the Los Frailes Karikari Volcanic Field may also be recognizable in the general distribution of igneous occurrences in the Southern Volcanic Mineral Belt outside the Los Frailes Karikari region.

The early Kumuana-Karikari stages are also represented by local stocks, domes and small volcanic centres or calderas North of the volcanic field which are also strongly mineralized (Colquechaca, Llagua, San Pablo).

During the Cebadillas Episode the important mineralized domes and stocks in the South of the volcanic field (Tatasi, Chocaya, Chorolque, Tasna, Atocha) and in the North (San Jose Dome at Oruro) were formed.

The major change in the volcanic activity and the style of emplacement during the Frailes Cover Episode marked the end of the important mineralizing events. This stages has also counterparts in the Morococala Meseta and in the extensive but little studied ashflows in South Bolivia.

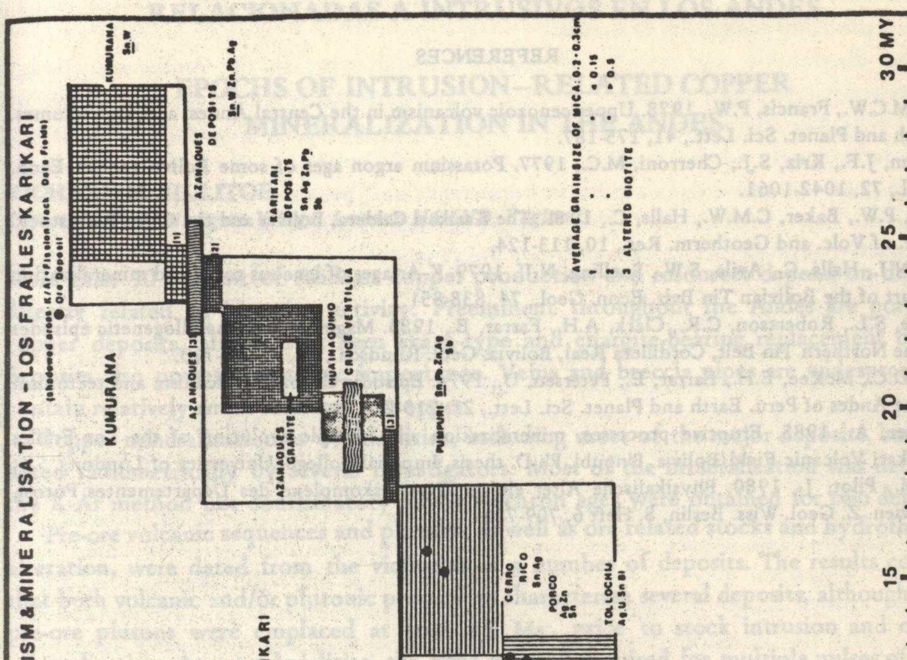

Fig.2. Main periods of magmatism & mineralization Los Frailes Karikari.
Fig.2. Principales períodos de magmatismo y mineralización – Los Frailes Karikari

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