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EVOLUTION OF THE LOS FRAILES CALDERA, CABO DE GATA VOLCANIC FIELD, SOUTHEASTERN SPAIN

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INTRODUCTION

The Cabo de Gata volcanic field of southeastern Spain is the only extensive area of Tertiary volcanic rocks on the Iberian Peninsula. It is located southeast of a prominent left-lateral fault zone that separates the volcanic field from Paleozoic and Mesozoic sedimentary rocks of the Betic Alpine fold belt (Fig. 1). Volcanic rocks in the area of study are calc-alkaline in character and range in composition from pyroxene andesite to rhyolite and in age from about 15-7 Ma (Nobel et al., 1981; Bellon et al., 1983; and Di Battistini et al., 1987). Isolated exposures of alkaline basalts, and shosonitic and ultrapotassic rocks, are present north of the main volcanic field (López Ruiz and Rodriguez Badiola, 1980). Several calderas have been recognized recently within the volcanic field including the Los Frailes, Rodalquilar, and Lomilla calderas (Rytuba et al., 1988; 1989). The calderas all formed within a relatively short span of time (a few million years) from relatively similar processes, and evolved generally similar rocks, yet some calderas are mineralized whereas others are not. The documentation of magmatic, hydrothermal, and structural features within the calderas permits the comparison of basic data that may help understand why only some calderas contain precious metal deposits. Alunite deposits have been mined near Rodalquilar probably since Roman times. Gold, associated with the alunite, has also been mined intermittently since it was discovered a century ago, and the production in the period 1943-1966 was about 5 tonnes of gold (Sierra and Leal, 1968). The Transacción mine is being reopened as a heap-leach operation; published reserves are 650,000 tonnes averaging 2.5 grams of gold per tonne and production is expected to be over 300 kg/year of gold (Skillings Mining Review, 1988). Lead, zinc, silver, and minor gold have been produced from mines in the Cabo de Gata center, located just southwest of the Los Frailes caldera, chiefly during the last century (Fig. 1). Earlier studies in the Los Frailes area include those by Fúster et al. (1965), Bordet (1985), Pineda et al. (1981; Pineda, 1984), and Fernandez Soler and Muñoz (1988). The evolution of the Rodalquilar caldera complex is the subject of a related paper (Rytuba et al., 1989) and the preliminary results of a study of the gold-alunite deposits and associated altered rocks are in Arribas et al., (1989).

The nearly circular Los Frailes caldera, which is the oldest known caldera in the Cabo de Gata volcanic field, is about 5 km across and the center is marked by dark rounded hills surmounted by the 493 m El Fraile. The villages of San Jose, El Pozo de los Frailes, and Los Escullos are located on the perimeter of the caldera (Fig. 2). The eastern and southeastern third of the caldera has been eroded by the sea, leaving a seawall as much as 100 m high that exposes a cross section of the caldera fill.

The Los Frailes caldera formed 14.4±0.8 Ma (Rytuba et al. 1988) at the site of a cluster of older domes and stratovolcanoes made up of pyroxene-amphibole andesite lava flows, dacite domes and flows, volcanic breccia, and volcaniclastic sediments. The caldera formed in response to the eruption of a hornblende-biotite dacite ash-flow tuff. The basal outflow tuff from the

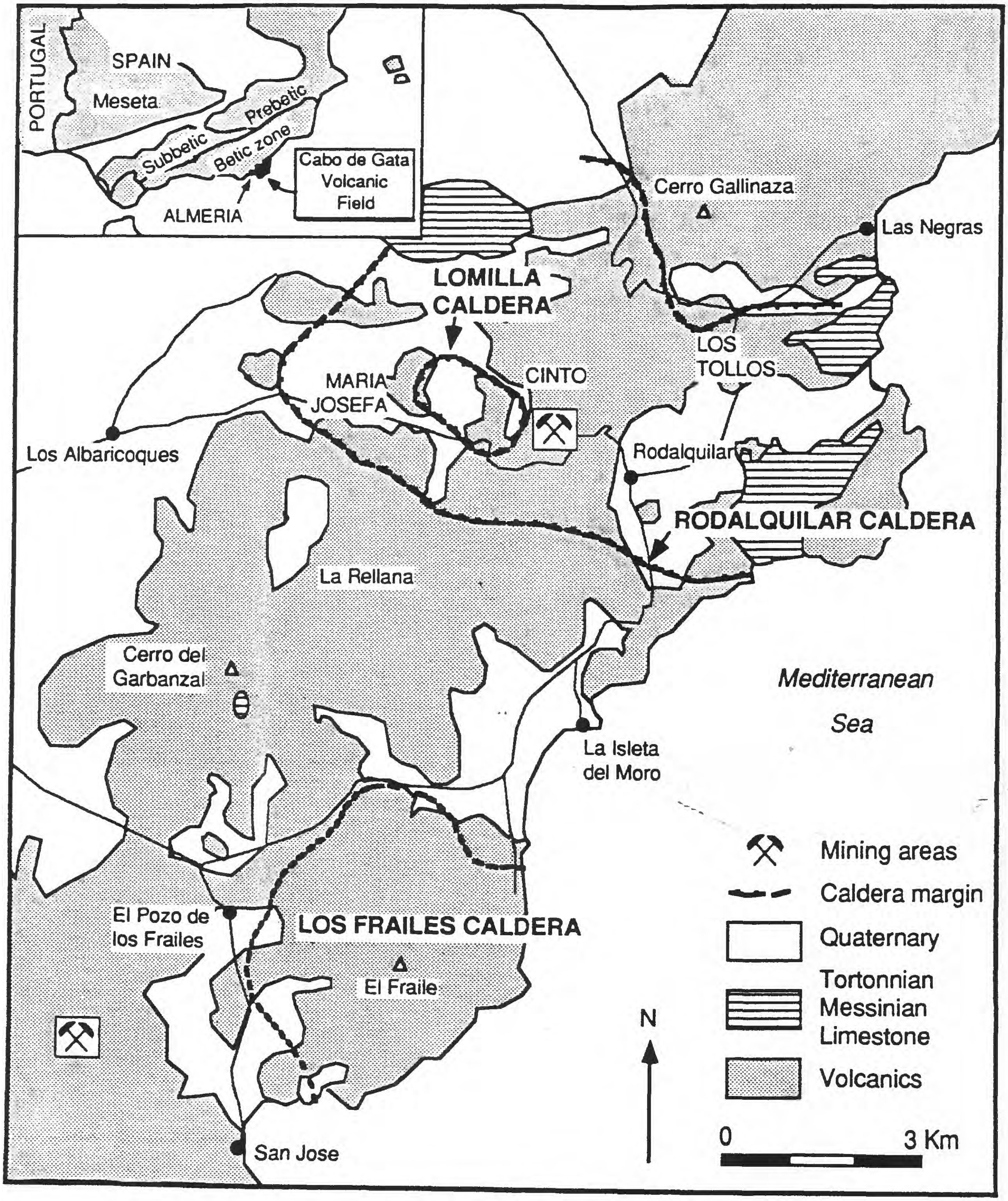

Figure 1. Index map showing location of principal geographic features, margins of calderas, and mining districts within the Cabo de Gata volcanic field.

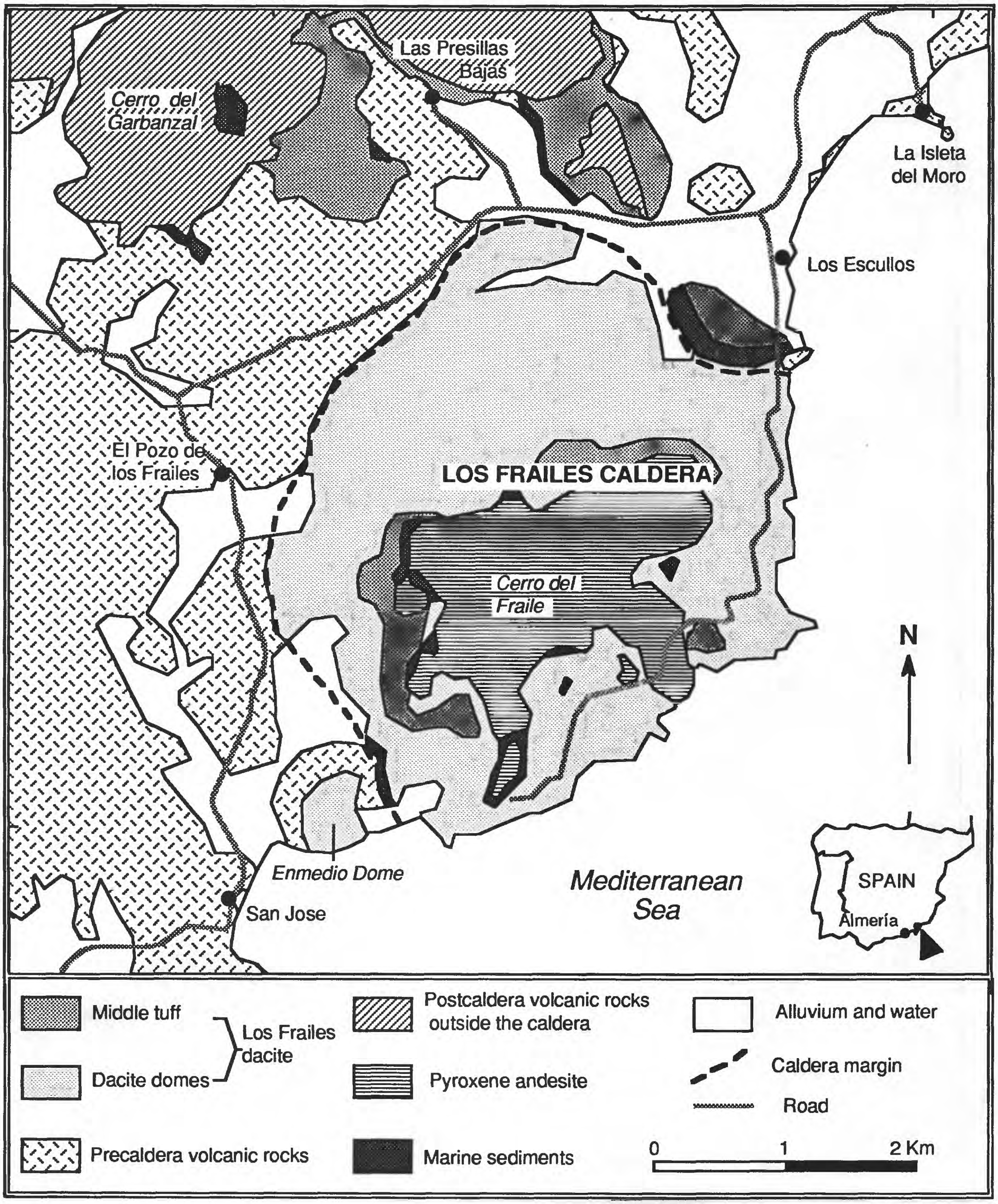

Figure 2.--Geologic map of the Los Frailes caldera and surronding area.

caldera was mostly eroded following collapse of the caldera and incursion of the sea. The middle tuff, preserved in the center of the caldera, extends to the northwest of the caldera where it is well exposed at the base of Cerro del Garbanzal (Fig. 2). This tuff unit is moderately to poorly welded and contains about 10% phenocrysts of hornblende, plagioclase, and biotite.

Precaldera rocks consist mostly of propylitically altered, hornblende- and pyroxene-bearing andesite lava flows. In the vicinity of the caldera, volcanic breccia consisting of subrounded fragments of flow-banded intermediate composition lavas and pyroxene andesite are present in a tuffaceous matrix overlying the older andesites. The 167 m Enmedio dome (Fig. 3), which forms the central part of Cerro de Enmedio, is one of several precaldera dacite domes located just outside the margin of the caldera. It has a prominent flow foliation parallel to the margins and is bounded, and in part underlain, on the south and east by a prominent airfall tuff ring consisting of white, bedded ash and pumice lapilli tuff, which dips inward toward the dome. The dome flares markedly where it overlies precaldera propytically altered andesite lava flows on the north. The dacite that forms Enmedio dome is pervasively altered. It contains hornblende phenocrysts having centers replaced by calcite, cloudy plagioclase, and biotite, in a felted groundmass of feldspar microlites. The hornblende-biotite ratio is about 20-25:1. In contrast, the tuff in the underlying tuff ring contains abundant quartz phenocrysts, as well as brown biotite, broken fragments of plagioclase crystals, and no amphibole. This is the only rock associated with the Los Frailes caldera that contains quartz phenocrysts. The tuff also contains abundant pumice fragments in a devitrified, silicified groundmass. Another prominent precaldera dome is located at the southern intersection of the topographic wall of the caldera and the sea. This dome is characterized by a black, glassy matrix containing hypersthene and plagioclase phenocrysts.

The Los Frailes caldera is filled with interbedded marine sediments, volcanic domes, welded tuff, and lava flows. The topographic wall (Fig. 4),at the boundary between intracaldera fill and precaldera rocks, is marked by inward-dipping beach deposits consisting of pumiceous airfall tuff and fossiliferous sandstone. Talus-landslide breccias occur locally along the topographic wall and are exposed in the seawall. The lower part of the caldera fill consists of numerous dacitic volcanic domes (Figs. 4 and 5) that have intruded and overridden each other. The areas between the domes commonly contain volcanic breccia shed from the expanding carapaces of the domes and local pockets of airfall tuff. The surfaces of the domes are light brown from weathering, and the tops of many of the domes are marked by columnar joints. The dacite contains prominent hornblende and plagioclase phenocrysts, minor but variable amounts of biotite, and no quartz. The matrix ranges from microlitic to glassy. The lower domes are overlain by as much as 4 m of coquina and then by a unit of welded air-fall tuff 50 m thick. The intracaldera tuff, called the "middle tuff," is well exposed along the southwestern side of the caldera (Fig. 6) where it overlies the lower domes and is interlayered with other domes and lava flows high in the section. The tuff is poorly welded, contains large pumice fragments, locally has abundant lithic fragments, and is cross bedded. It is also present in the outflow around the northern margin of the caldera near Los Escullos, where it has been altered to bentonite that is being mined. Near the center of the caldera, a vent in the intracaldera tuff is filled with cross-bedded, airfall, altered tuff that is also being mined for bentonite. As exposed in

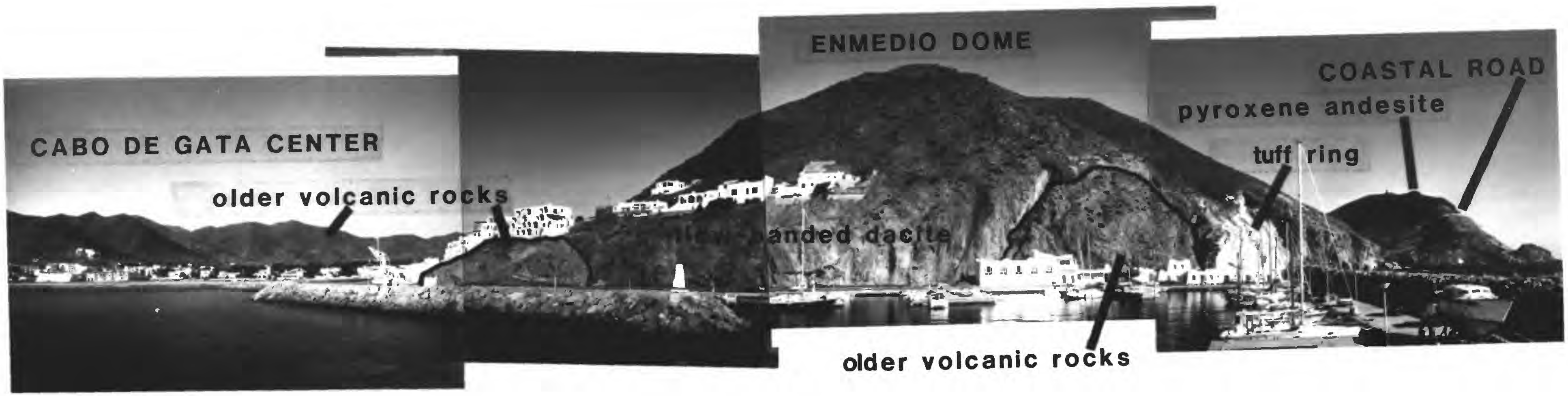

Figure 3.--Annotated view of Enmedio dome and surrounding rocks from the San Jose marina. The area where the coastal road and pyroxene andesite are shown in back of the dome, is within the Los Frailes caldera. The Cabo de Gata center is an area containing altered, mineralized domes.

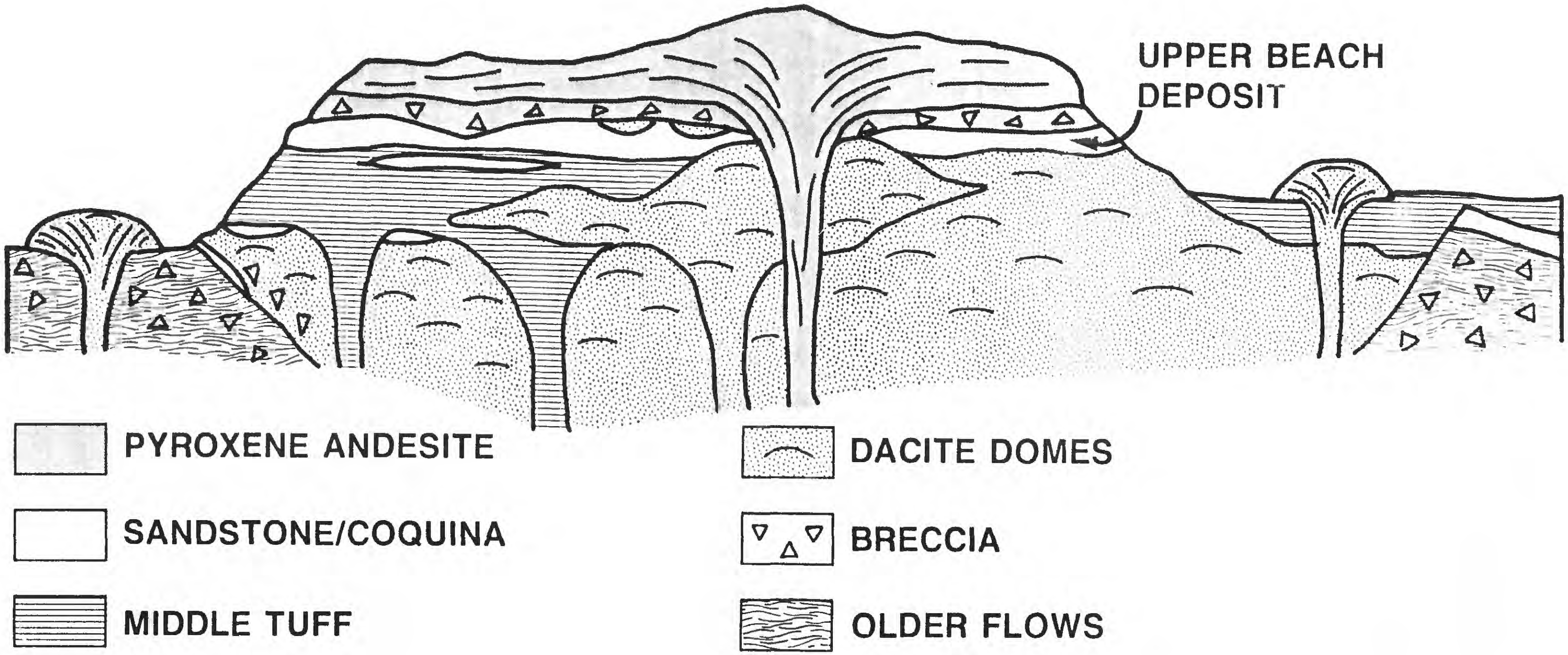

Figure 4.--Diagrammatic northeast-southwest section through the Los Frailes caldera, Spain.

Figure 5.--Intracaldera fill of the Los Frailes caldera. The light-colored, smoothly-rounded rocks in the middle are the intracaldera domes that fill the caldera. The smooth vegetated slope above the domes marks the position of the middle tuff. The bright white outcrop in the shade to the right and just below the highest peak marks the position of the upper beach deposit, and the craggy outcrops on top are the pyroxene andesite.

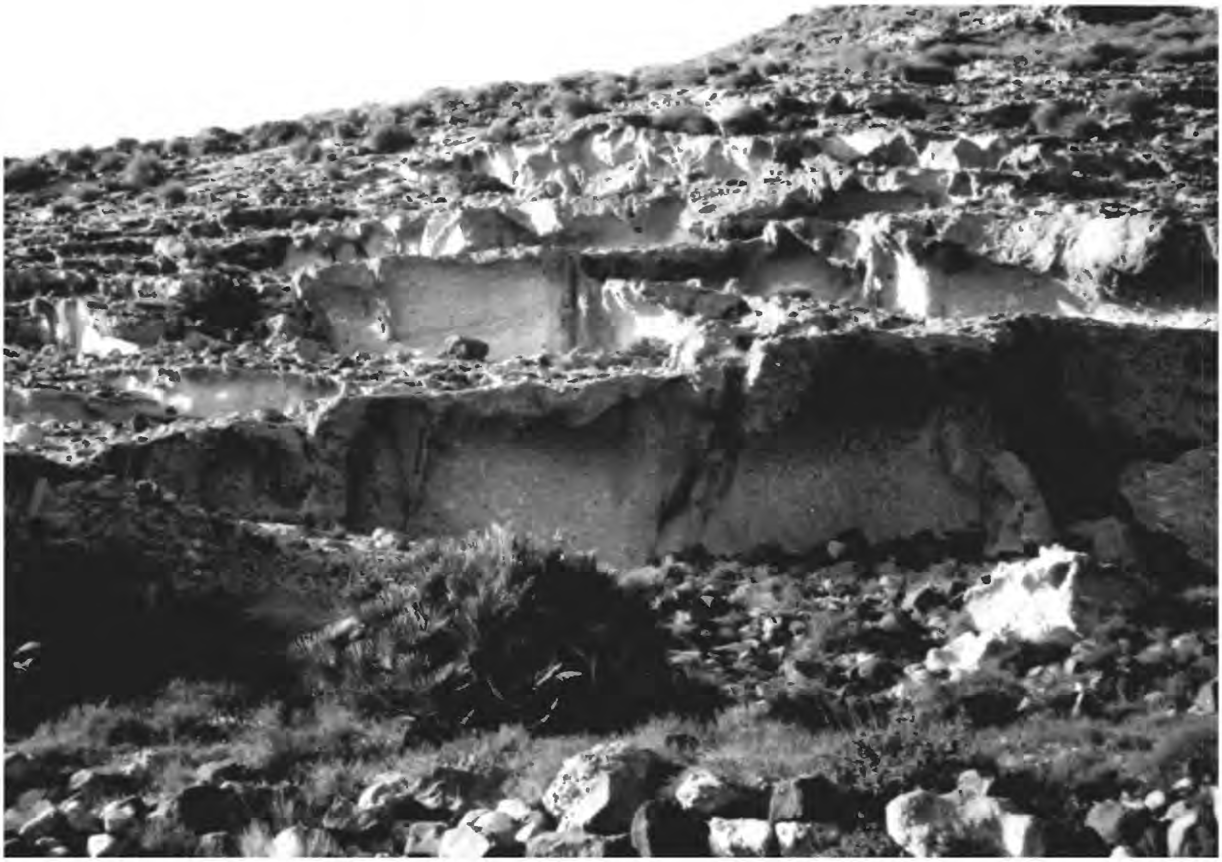

Figure 6.--Los Frailes intracaldera "middle tuff," which overlies the dacite domes that fill the lower part of the caldera.

the seawall near the southern margin of the caldera, the intracaldera tuff contains large blocks of a black, glassy precaldera dome that forms the topographic wall of the caldera in this area.

The dacite domes and middle tuff within the Los Frailes caldera are overlain by a prominent upper beach deposit that differs significantly from beach deposits at lower stratigraphic intervals within the caldera (Fig. 4). This upper beach deposit, exposed everywhere within the caldera at an elevation of about 200 m, is as much as 6 m thick, is gray, and consists mostly of quartz sand grains about 1 mm in diameter, in addition to coquina (Fig. 7). The lower part of this layer consists mainly of 2 m of fossiliferous well-sorted quartz sand from a distant source; this sand is unique within the caldera, as all other beach deposits contain calcareous material or material derived from the underlying rocks. The quartz beach sand is overlain by a 4 m thick coquina that consists of hard, white limestone that is rich in large foraminifera, bryzoa, algae, and pelecypods as much as 10 cm in diameter. The study of the planktonic assemblages of this layer indicates an early Tortonian age (Saavedra, 1966; Di Battistini et al., 1987). This coquina forms a widespread marker horizon throughout the Cabo de Gata volcanic field (Addicott et al., 1978) at a constant elevation of about 200 m. A few dacite lava flows locally overlie the sandstone layer.

The quartz sandstone and coquina layers are overlain by black, pyroxene andesite lava flows and breccias that cap the hills in the caldera. The basal part of this sequence is a volcanic breccia that increases in abundance outward from the andesite lava flow vents. The breccia consists mainly of blocks of andesite that fell into the coquina layer while it was still soft and, in places, deformed it. The breccia is overlain by a thick accumulation of pyroxene andesite lava flows that has prominent vertical flow foliations in the vicinity of vents and well-developed columnar joints peripheral to the vents. The andesite contains hypersthene and labradorite phenocrysts in a felted groundmass of plagioclase laths. These flows have been dated at 8.5 to 8.6 Ma (Di Battistini et al., 1987).

The best exposures of welded outflow ash-flow tuff from the Los Frailes caldera are at the southeast side of Cerro del Garbanzal near the village of Las Presillas Bajas northwest of the caldera. The village is located on propylitically altered precaldera domes capped by densely welded, quartz-bearing Cerro Cinto Tuff from the Rodalquilar caldera a few kilometers to the north. A prominent hill between the town and the caldera, marked by a quarry near the summit, is capped by outflow middle tuff from Los Frailes. The tuff wedges out against the precaldera domes that form the base of Cerro del Garbanzal. Beneath the tuff are local landslide deposits, and beneath them is a 3 m thick, well-bedded, fossiliferous beach deposit. The beach deposit overlies an eroded surface on the precaldera domes (Fig. 8), and the outcrop pattern of the beach deposit can be traced around the low hills as it dips gently away from the caldera.

A line of volcanic domes protruding above the broad valley on the north side of the caldera marks the northern edge of the caldera. The valley is underlain by middle tuff being mined for bentonite. This tuff, in turn, overlies a beach deposit exposed in quarries, and the tuff and underlying

Figure 7.--Stratigraphic sequence within the Los Frailes caldera near the southeasthern wall. The coastal road is cut on the top of intracaldera domes. The road cut exposes a quartz sand beach deposit that is overlain by a Miocene coquina (upper beach deposit) in the white outcrops above the road. The hill is capped by pyroxene andesite lava flows that have a prominent breccia at the base.

Figure 8.--A well-bedded beach deposit unconformably overlies the wave-cut tops of precaldera domes peripheral to the Los Frailes caldera. Above the area of the photograph, the beach deposit is overlain by land-slide deposits and by the outflow middle tuff member from the Los Frailes caldera. The entire sequence dips away from the caldera.

beach deposit are the same as the ones at the base of Cerro del Garbanzal. At the intersection of the caldera's northern topographic wall and the sea, near the town of Los Escullos, is an excellent exposure of these relations (Fig. 9). The middle tuff and the underlying coquina overlie dacitic domes, dip away from the caldera, and are unconformably overlain by a flat-lying Pleistocene oolite deposit.

DISCUSSION

The topographic surface at the time of the initial ash flow eruptions that formed the Los Frailes caldera must have been close to sea level because the sea repeatedly invaded the ensuing caldera. The main basal tuff was erupted onto the irregular topography of a dome field surrounded by stratovolcanoes. As this tuff was erupted, the caldera collapsed into the top of the magma chamber, and a broad area adjacent to the caldera also sagged, so that the caldera and the surrounding region were invaded by the sea. The submerged caldera was filled with domes to above sea level, and the waves cut a broad bench across the tops of the intracaldera domes, as well as across the adjacent precaldera dome field. This erosion removed the outflow lower tuff sheet adjacent to the caldera and from a platform that extended as far as a seawall at Garbanzal. Landslides from the steep seacliff at Garbanzal spread out over the beach.

The initial magmatic activity of the caldera evolved from violently erupting ash-flow tuff to passively erupting caldera-filling, viscous domes (Fig. 4) that sealed the top of the magmatic system. No volcanic activity took place while the caldera was submerged and being eroded. With time, the magmatic system restored its eruptive potential, and renewed ashflow and airfall eruptions occurred that resulted in renewed subsidence of the caldera and the filling of the upper part with more than 70 m of ash-flow tuff. Most of the vents were near the southern topographic wall and near the center of the caldera. Outflow middle tuff accumulated along the northern perimeter of the caldera; equivalent intercaldera tuff entrained large fragments of dacite domes in vents near its southern margin and ponded in several prominent vents near the center of the caldera. Domes and lava flows extruded at about the same time that the tuff was being erupted are interbedded with the tuff and are overlain by 15-25 m of tuff. The domes near the center of the caldera exhibit a wide variety of explosive, volcanic features, including tuff-filled vents, central vents within the remaining carapace of the domes, tuff rings, and at least one breccia pipe. One of these cognate domes (sample 86-SC-15) had started to solidify the roof of the dome when the interior of the dome began to vesiculate, and the carapace broke up and fell into the vesiculating interior of the dome.

As shown by the outward-dipping middle tuff and underlying coquina along the northern side of the caldera, the Los Frailes caldera and its surrounding area were resurgently domed after the eruption of the middle tuff but before the upper beach deposit was formed. The upper beach deposit formed at the time that the Cerro Cinto ash-flow tuff was being erupted from the Rodalquilar caldera about 8 km to the north. Quartz phenocrysts in the Cerro Cinto (and the volumetrically smaller Lazaras ash-flow tuff from the associated Lomilla caldera) apparently were winnowed from these tuffs or were broken from pumice that fell into the sea and was carried to the beach, to supply the sand grains for the intracaldera sandstone in the Los Frailes caldera. The entire

Figure 9.--Sequence of rock units exposed along the edge of the sea at the northern wall of the Los Frailes caldera, near Los Escullos. A Pleistocene oolite limestone unconformably overlies the middle tuff from the Los Frailes caldera. The tuff overlies a coquina that was deposited on the wave-cut top of precaldera domes. The domes, coquina, and tuff dip radially outward from the caldera, and the angular unconformity can be seen in the photograph.

region was submerged as part of the Almeria Basin during the late Neogene (Addicott et al., 1978) and then subsequently raised, because the upper beach deposit crops out at an average elevation of 200 m.

Pyroxene-andesite lava flows, dated at about 8.5-8.6 Ma (Di Battistini et al., 1987), in the upper part of the Los Frailes caldera fill were erupted from several vent areas near the center of the caldera (Fig. 4). The underlying volcanic breccia formed as the result of solidified blocks at the edges of the flows being overridden by the main lava flows. The Miocene upper beach deposits (Fig. 4) were still soft and were deformed by the lava and breccia of these eruptions. The pile of andesitic lavas extended well above sea level and, therefore, ended marine deposition within the caldera.

The chemical composition of the rocks that are spatially and genetically related to the Los Frailes caldera are shown in Tables 1 and 2. Precaldera rocks are represented by sample 86-SC-08 from the summit of the Enmedio dome and sample 86-SC-04 from the tuff ring on its southeast side. The Enmedio dome is composed of dacite that is similar in major element chemistry to the slightly younger, intracaldera dacite domes (samples 86-SC-01 and 86-SC-15); however, comparison of the trace-element chemistry indicates some significant chemical differences. The Enmedio dome has distinctly higher K_2O (11.2%); Rb (679 ppm), As (313 ppm), and Sb (60 ppm) and lower Na_2O (0.50%) and CaO (2.22%) contents than the younger domes. These differences in abundances probably resulted from hydrothermal alteration and metasomatism of the dome. Although the trace elements arsenic and antimony, commonly associated with gold, are enriched, precious metals have not yet been found in the dome. The tuff ring shows a marked depletion in most major elements, except SiO_2 (81.4%), which is enriched; this enrichment verifies observations that the tuff ring has been silicified, probably during devitrification.

The composition of the dacitic rocks genetically related to the caldera is best represented by the analyses of three intracaldera domes. Sample 86-SC-01 is from an intracaldera dome in the lower dome field on the south side of the caldera, sample 86-SC-13 is from the black glassy dome where the southern topographic wall is cut by the seacliff, and sample 86-SC-15 is from the cognate fragments in a dome in the center of the caldera. The dacite domes, lava flows, and tuff associated with the Los Frailes caldera appear to be part of the same magmatic system. Major and trace element chemistry (Tables 1 and 2) show them to be normal dacites. Rare earth element patterns (Fig. 10) indicate that plagioclase crystallization and Eu fractionation were not important factors in magma evolution. The mineralogical variations in precaldera domes, such as the presence of hypersthene and the marked vertical stratification within individual domes (in some to the extent that abundant quartz phenocrysts formed in the apex), suggests these domes represented periodic tapping of a larger, evolving magmatic system.

The composition of the black pyroxene-andesite flows that cap the intra-caldera fill (Fig. 4) and form the summit of El Fraile are represented by sample 86-SC-10. This sample was collected from a massive, black lava flow exposed in a quarry on the south side of Cerro del Marchal.

The location of major eruptive centers for the pyroxene andesite in the center of the Los Frailes caldera shows that the pyroxene andesite used the same

Table 1.--Major-element X-ray fluorescence analysis of rocks related to the Los Frailes caldera, Spain

LAB NO.		W-237255	W-237256	W-237257	W-237258	W-237259	W-237260
FIELD NO.		86-SC-01[1]	86-SC-04[2]	86-SC-08[3]	86-SC-10[4]	86-SC-13[5]	86-SC-15[6]
SiO_2	%	60.4	81.4	62.4	52.6	60.4	61.9
Al_2O_3	%	15.9	8.94	14.2	18.6	15.7	15.8
Fe_2O_3[7]	%	4.70	0.45	3.96	9.73	5.44	5.10
MgO	%	3.15	0.93	1.48	5.10	2.99	2.46
CaO	%	5.58	0.76	2.22	10.1	5.06	5.45
Na_2O	%	2.67	1.62	0.50	2.07	3.12	3.08
K_2O	%	1.72	1.32	11.2	0.63	2.04	2.16
TiO_2	%	0.49	0.08	0.43	0.74	0.61	0.50
P_2O_5	%	0.13	<0.05	0.15	0.14	0.15	0.13
MnO	%	0.06	<0.02	0.13	0.15	0.07	0.07
LOI	900°C	5.08	3.77	2.60	0.54	2.27	2.65
TOTAL	%	99.88	99.34	99.27	100.40	97.85	99.30
FeO	%	2.0	0.16	0.16	5.8	3.4	2.3
H_2O^+	%	2.2	1.7	0.87	0.59	2.1	1.8
H_2O^-	%	2.4	1.7	0.37	0.29	0.43	0.69
CO_2	%	0.02	0.19	1.5	0.04	0.02	0.02
Cl	%	0.11	0.16	0.015	0.065	0.19	0.24
F	%	0.064	0.031	0.056	0.023	0.045	0.050

Field No.

[1] Dacite dome in lower part of Los Frailes caldera.
[2] Enmedio dome tuff ring.
[3] Enmedio dome.
[4] Pyroxene andesite in upper part of Los Frailes caldera.
[5] Black, glassy, dacite dome on south margin of Los Frailes caldera.
[6] Dacite dome from the center of the Los Frailes caldera.
[7] Total iron as Fe_2O_3.

Table 2.--Minor-element instrumental neutron activation analysis of rocks related to the Los Frailes caldera, Spain

LAB NO.	W-237255	W-237256	W-237257	W-237258	W-237259	W-237260
FIELD NO.	86-SC-01[1]	86-SC-04[2]	86-SC-08[3]	86-SC-10[4]	86-SC-13[5]	86-SC-15[6]
Na	2.05 ±2%	1.31 ±3%	0.44 ±3%	1.65 ±3%	2.47 ±3%	2.46 ±3%
K	1.12 ±17%	0.82 ±18%	7.1 ±11%	<1	1.31 ±18%	1.29 ±18%
Ca	4.2 ±9%	<2	1.6 ±22%	7.0 ±10%	4.1 ±14%	3.9 ±13%
Fe	3.53 ±2%	0.343 ±3%	2.84±2%	6.91±2%	3.99±2%	3.56±2%
Sc	18.0 ±2%	1.83 ±3%	13.00 ±2%	31.4 ±3%	20.2 ±2%	16.1 ±3%
Cr	14.4 ±6%	2.3 ±21%	13.8 ±8%	31.3 ±5%	21.7 ±14%	12.1 ±10%
Co	10.96 ±2%	<0.6	8.37 ±3%	24.4 ±3%	14.0 ±3%	10.8 ±4%
Ni	<150	<50	<140	<200	<160	<140
Zn	63 ±12%	9.1 ±14%	67 ±5%	84 ±15%	81 ±11%	56 ±21%
As	13.1 ±4%	6.6 ±6%	313 ±3%	3.4 ±13%	22.5 ±5%	17.8 ±5%
Rb	115 ±6%	116 ±4%	679 ±4%	37 ±26%	161 ±7%	152 ±5%
Sr	250 ±20%	128 ±23%	<400	350 ±24%	350 ±15%	300 ±21%
Zr	134* ±21%	87* ±20%	<250*	<300	230 ±22%	140* ±24%
Sb	1.15 ±9%	7.8 ±7%	59.7 ±3%	<0.6	1.49 ±12%	0.80 ±11%
Cs	13.27 ±2%	5.37 ±3%	6.75 ±4%	2.67 ±8%	13.6 ±3%	12.8 ±3%
Ba	250 ±8%	102 ±10%	460 ±6%	234 ±10%	360 ±9%	311 ±10%
La	19.7 ±3%	21.2 ±3%	16.5 ±3%	8.5 ±4%	20.8 ±3%	20.1 ±3%
Ce	37.7 ±2%	39.9 ±4%	33.1 ±3%	19.0 ±5%	42.2 ±4%	39.4 ±4%
Nd	16.5 ±7%	14.6 ±7%	12.1 ±10%	10.8 ±10%	18.0 ±7%	16.2 ±8%
Sm	3.71 ±3%	2.84 ±4%	2.85 ±3%	3.13 ±3%	4.84 ±3%	3.53 ±3%
Eu	0.85 ±4%	0.486 ±5%	0.643 ±4%	0.84 ±5%	0.976 ±3%	0.976 ±3%
Gd	<6	<2	<5	<7	<4	<3
Tb	0.537 ±5%	0.447 ±6%	0.47 ±7%	0.48 ±7%	0.67 ±6%	0.54 ±6%
Tm	<0.4	<0.2	<0.3	<0.3	<0.2	<0.3
Yb	1.57 ±7%	1.52 ±6%	1.11 ±7%	1.59 ±8%	1.65 ±5%	1.48 ±5%
Lu	0.253 ±7%	0.238 ±6%	0.201 ±7%	0.255 ±6%	0.279 ±5%	0.245 ±5%
Hf	3.54 ±8%	2.13 ±6%	3.08 ±6%	1.75 ±6%	3.74 ±3%	3.59 ±4%
Ta	0.69 ±8%	0.62 ±11%	0.556 ±5%	0.274 ±5%	0.55 ±9%	0.623 ±4%
Au	<13	<9	<13	<13	<12	<13
Th	9.55 ±3%	9.60 ±3%	8.9 ±4%	2.21 ±12%	8.09 ±3%	9.67 ±3%
U	4.11 ±3%	3.65 ±4%	4.24 ±4%	1.08 ±13%	3.99 ±4%	4.11 ±4%
La/CHOND	63.9	68.6	53.4	27.62	67.4	65.1
Ce/CHOND	46.8	49.8	41.1	23.55	52.3	48.9
Nd/CHOND	27.60	24.44	20.25	18.04	29.99	26.96
Sm/CHOND	19.00	14.55	14.61	16.05	24.83	18.08
Eu/CHOND	11.52	6.63	8.75	11.44	13.29	10.95
Tb/CHOND	11.55	9.61	10.14	10.38	14.51	11.53
Yb/CHOND	7.56	7.33	5.35	7.65	7.92	7.11
Lu/CHOND	7.88	7.40	6.26	7.96	8.68	7.62

Na, K, Ca, and Fe in percent, all other elements in ppm. Error limits are one standard deviation based on counting statistics alone.
Normalizing data based on CI-chondrites (Anders and Ebihara, 1982: GCA 46, 2363-2380) X 1.31

Normalizing data are: La= 0.309, Ce= 0.807, Pr= 0.122, Nd= 0.599, Sm= 0.195, Eu= 0.073, Gd= 0.258
Tb= 0.047, Dy= 0.321, Ho= 0.072, Er= 0.210, Tm= 0.032, Yb= 0.208, Lu= 0.032

Field No.

1 Dacite dome in lower part of Los Frailes caldera.
2 Enmedio dome tuff ring.
3 Enmedio dome.
4 Pyroxene andesite in upper part of Los Frailes caldera.
5 Black, glassy, dacite dome on south margin of Los Frailes caldera.
6 Dacite dome from the center of the Frailes caldera.

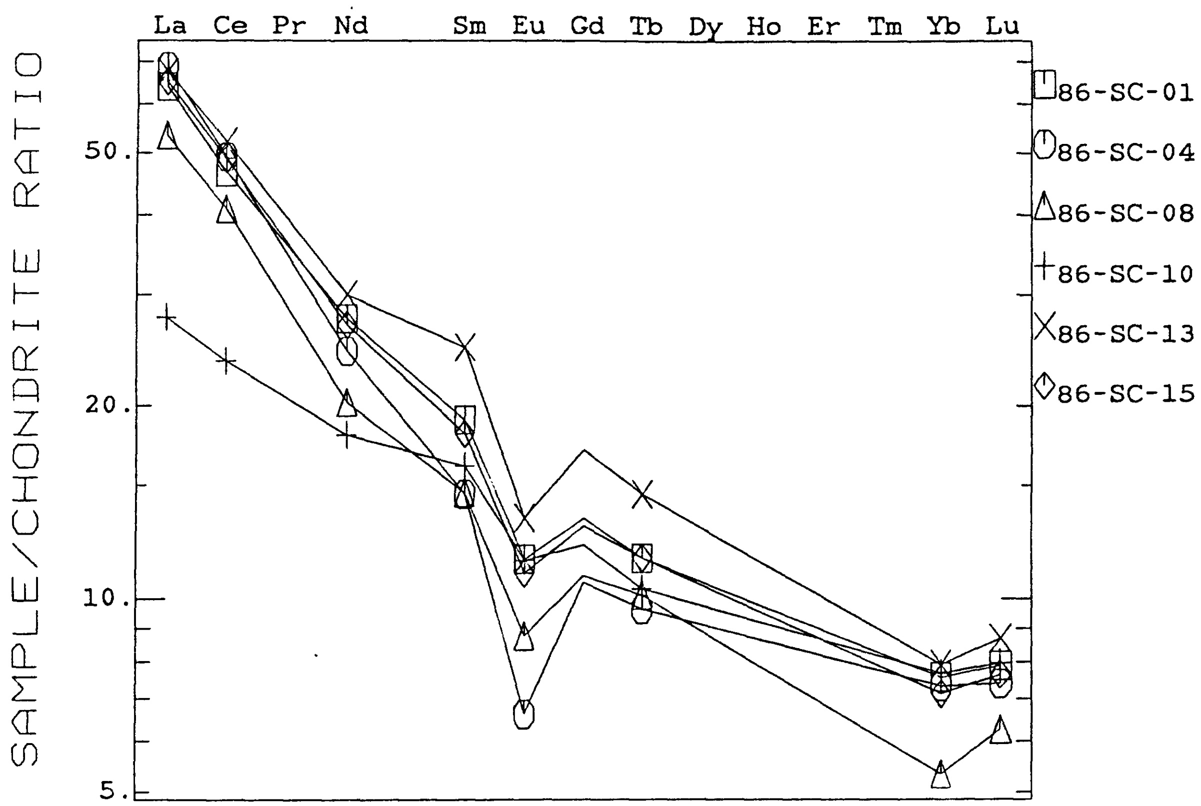

Figure 10.--Chondrite normalized rare earth-element abundances in rocks associated with the Los Frailes caldera.

near-surface magmatic plumbing system as the earlier dacites. A similar abrupt transition from intermediate/rhyolitic composition rocks to pyroxene andesites in the vicinity of the Rodalquilar caldera suggests that magmatic evolution was similar at both locations. Magmatic activity evidently was controlled by regional extensional tectonic features along the western margin of the Mediterranean Sea (Larouziere et al., 1988; Martin Escorza and Lopez Ruiz, 1988); Doblas and Dyarzun, 1989). Tectonic activity guided the movement of pyroxene andesite magma that erupted to form stratovolcanoes and caused melting of crustal rocks to form magmas of dacite/rhyolite composition. These magmas were erupted as domes, flows, and ash-flow tuffs, the latter resulting in the formation of calderas. Later, perhaps in response to renewed extensional tectonic activity, voluminous pyroxene andesites intruded these younger volcanic rocks over a wide area, but especially within calderas.

In contrast to the Rodalquilar caldera, Cabo de Gata center, and Enmedio dome, the Los Frailes caldera rocks are virtually unaltered and contain no known metal deposits. The Rodalquilar system, which is slightly younger than the Los Frailes, evolved magmatically to the extent that quartz-bearing rhyolites were erupted at Rodalquilar, in contrast to the dacites associated with Los Frailes (Rytuba et al., 1989). The timing of episodic tectonic activity along the northern margin of the Mediterranean Sea may also have been a critical factor in determining the style of mineralization in this region. Much of the gold at Rodalquilar is localized in north-south structures and structures related to caldera margins. The structural control suggests that tectonic activity about 11 Ma, which initiated another pulse of magmatic activity, facilitated development of high-level magma chambers with protracted magmatic evolution to form rhyolites and evolved hydrothermal systems, triggered pyroclastic eruptions, and opened structures to localize the flow of hydrothermal fluids to form ore deposits. This tectonic activity may have opened the magmatic system to seawater, as suggested by Arribas et al. (1989), which would have facilitated formation of alunite and deposition of gold.

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