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La Purísima volcanic field, Baja California Sur (Mexico): Miocene to Quaternary volcanism related to subduction and opening of an asthenospheric window

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Abstract

Geological mapping and geochemical analyses combined with $^{40}K–^{40}Ar$ ages for lavas from the Late Miocene to Quaternary La Purísima volcanic field (Baja California Sur) provide evidence for five volcanic events. These, in turn, may reflect plate interactions in the region. The oldest event (event 1), prior to 11 Ma, corresponds to the emission of normal to K-rich calc-alkaline lavas, exposed as large mesas in the eastern part of the studied area and as pyroclastic breccias and volcaniclastic sediments to the west. It is associated with the end of the Comondú arc activity resulting from subduction of the Farallon and Guadalupe plates. Between 10.6 and 8.8 Ma (event 2), magnesian andesites and tholeiites were emplaced. At 5.5 Ma (event 3) and 2.5 Ma (event 4) small volumes of magnesian andesites erupted in the central and southern parts of the volcanic field. Finally, between 1.2 Ma and Holocene (event 5), numerous basaltic and magnesian andesitic fissural and central emissions resulted in the formation of strombolian cones and associated lava flows, mainly distributed within a NNW–SSE trending graben located SE of the town of La Purísima.

Magmatic events 2 to 5 occurred well after the supposed end of the subduction event. Their geochemical characteristics are still typical of subduction-modified sources and possibly indicate partial melting of hot slab and formation of an asthenospheric window due to a slab rupture event which followed ridge–trench collision, prior to the continental breakup of the Gulf of California extensional province.

Keywords: Baja California Sur (Mexico); K–Ar ages, Late Miocene to Quaternary volcanism; magnesian andesites, tholeiites; subduction; asthenospheric window

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1. Introduction

Several large volcanic fields, each of them displaying distinct geochemical, petrologic and tectonic characteristics, occur in Baja California (Gastil et al., 1979; Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991). Among them, La Purísima and Comondú areas in Baja California Sur display a wide geochemical and petrologic variability, i.e., calc-alkaline, tholeiitic, and magnesian andesites

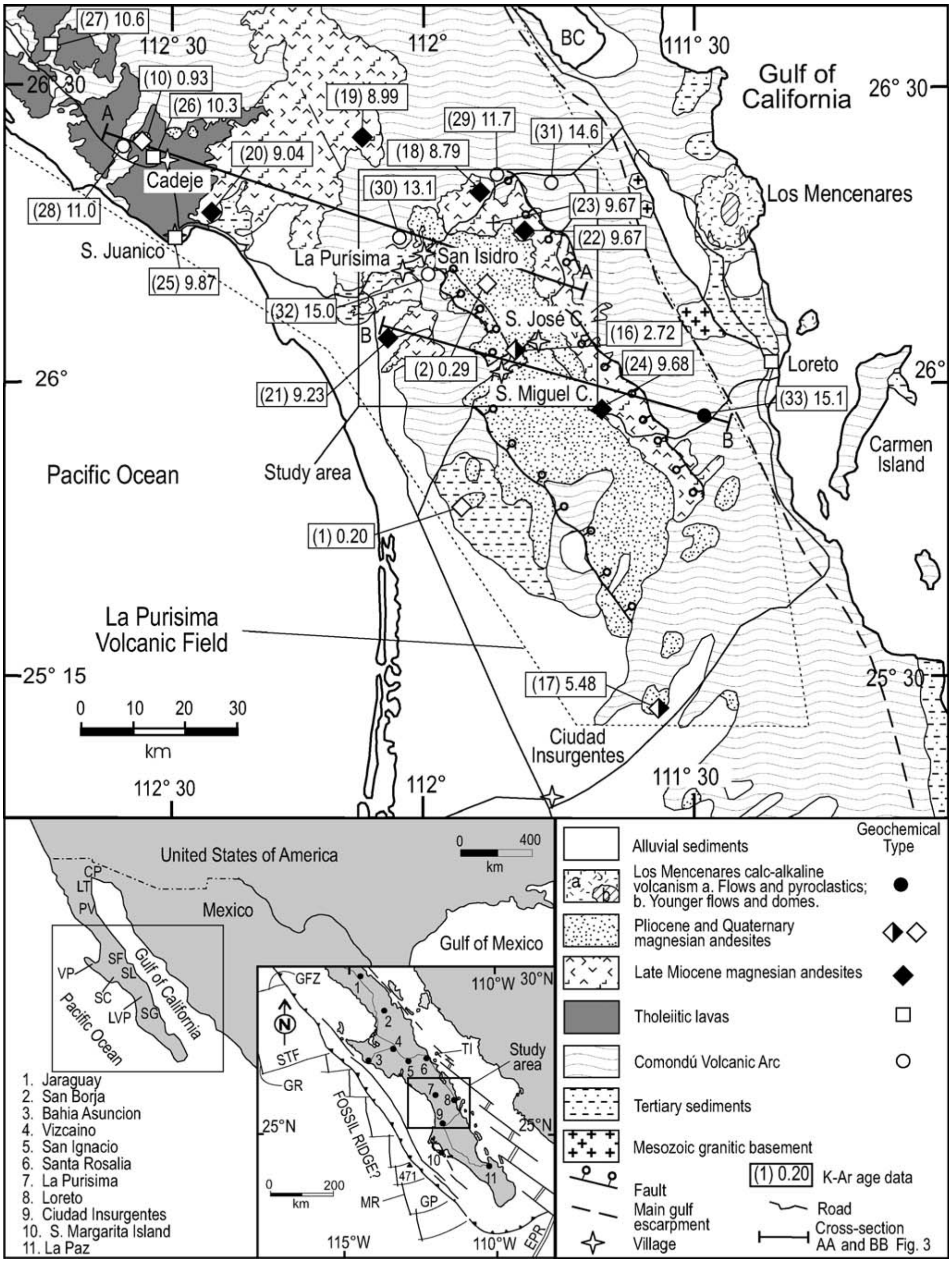

Fig. 1. Geological sketch map of northern Baja California Sur, between 25° 15′–26° 40′N and 111°–113°W. It shows sample localities and isotopic ages (Table 2). The regional geology is modified from Ortega-Gutiérrez et al. (1992). BC, Bahia Concepcion; CP, Cerro Prieto geothermal field; LVP, La Purísima volcanic field; LT, Sierra Las Tinajas; PV, Puertecitos volcanic field; SC, Santa Clara volcanic field; SF, Sierra San Francisco; SG, Sierra La Giganta; SL, Sierra Santa Lucia; TI, Tortuga island. Identical symbols are used for representing the main geochemical types of lavas in all the figures. Note the cross symbol used for the transitional lava at site 23.

among the Middle Miocene to Quaternary volcanic rocks.

La Purísima volcanic field extends over an area of almost 9000 km^2 (Fig. 1) between latitudes 25°20′N and 26°40′N. It is limited to the east by the Main Gulf Escarpment, and to the west by the Pacific shoreline. Volcanism in the region was coeval with complex tectonic changes that occurred in Baja California Sur during the past 15 Ma. This evolution involved successively the subduction of the Farallon plate below the North America plate, the apparent cessation of volcanic arc building at 12.5 Ma coinciding with the proposed age for the death of the entire segment of the Pacific–Guadalupe spreading center (Mammerickx and Klitgord, 1982; Atwater, 1989; Lonsdale, 1991; Stock and Lee, 1994; Atwater and Stock, 1998), and finally the opening of the Gulf of California.

This paper is based on a extensive sampling of lavas from the previously poorly studied large La Purísima volcanic field (Fig. 1), and documents the ages and geochemical characteristics of a succession of magmatic events in this restricted area where Late Miocene basalts and magnesian andesites were erupted contemporaneously with tholeiitic lavas, and post-date calc-alkaline andesites. Volcanic activity resumed during the Plio-Quaternary, when three predominantly magnesian andesitic events occurred. We also point out the peculiar timing of emplacement of magnesian andesites, which followed the end of typical arc magmatism. Likewise we discuss their relationship with geodynamic processes either connected with subduction or marking the post-subduction history.

2. A general overview of Baja California magmatism

2.1. A large geochemical diversity among the Neogene to Quaternary magmatism

During its Cenozoic tectonic evolution, Baja California has been the locus of numerous volcanic events involving the eruption of calc-alkaline volcanic rocks, tholeiites, adakites and magnesian andesites. Calc-alkaline magmatism has been classically associated with the subduction of the Farallon plate beneath the North American plate (Hausback, 1984; Sawlan and Smith, 1984; Dorsey and Burns, 1994), whereas both tholeiitic and alkaline volcanism were related to the opening of the Gulf of California (e.g., Hausback, 1984). Adakites associated with Nb-enriched basalts in the Vizcaino Peninsula (Aguillón-Robles et al., 2001; Benoit et al., 2002), indicate that the sources of post-calc-alkaline Late Miocene to Quaternary volcanism of southern Baja California were also subduction-related, as also argued for magnesian andesites of northern Baja California (Rogers et al., 1985).

Between 38 and 23 Ma, the Sierra Madre Occidental was built east of the Peninsula of Baja California, mainly by huge ignimbritic emissions along the western margin of continental Mexico (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979; Cameron et al., 1980; Cochemé, 1985; Albrecht, 1990). At the end of Oligocene and beginning of Miocene time, magmatism shifted westward to the region now located at the eastern part of the Baja California Peninsula, along the modern western coast of the Gulf of California (Gastil et al., 1979; Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991; Martín-Barajas et al., 1995; Martín-Barajas et al., 2000), forming the Comondú volcanic arc. Calc-alkaline volcanism was active until 16 Ma in northern Baja California, and 11 Ma in Baja California Sur (Sawlan, 1991). Between 15 and 10.5 Ma, medium to high-K calc-alkaline andesites were erupted mainly along the eastern coast of the peninsula and the western flank of Sierra San Pedro (McLean et al. 1987; Sawlan, 1991).

From 11 to 8 Ma, tholeiitic volcanism was developed mostly in a large area (2500 km^2) extending from near the Gulf of California to the Pacific Ocean, in northern Baja California Sur, between Tres Vírgenes, San Ignacio, and San Juanico (Gastil et al., 1979; Sawlan and Smith, 1984; Hausback, 1984; McLean et al., 1987; Sawlan, 1991; Rojas-Beltrán, 1999). These tholeiitic magmas were interpreted as associated with the initial stages of continental breakup (Sawlan, 1991), during the formation of a proto-Gulf (Karig and Jensky, 1972). Sawlan and Smith (1984) gave the name “Esperanza basalt” to these tholeiitic rocks, and reported the presence of some tholeiitic basaltic flows in the Vizcaino Peninsula, north of Bahía Asunción. Studies by Aguillón-Robles et al., (2001) show that these basalts, dated at 7 Ma by the K–Ar method, are of Nb-enriched “orogenic” type, and are better related to subduction processes rather than to the opening of the Gulf. A same conclusion was reached by these authors for similar basalts closely associated in space and time with the adakites of the Santa Clara volcanic field.

Magmatic activity in the Santa Rosalía region, 100 km north of la Purísima volcanic field, has registered the transition from arc volcanism, active from 24 to 10 Ma, to rift-related magmas erupted from 11 to 7.7 Ma (Conly et al., 2005).

Magnesian andesites represent the third widespread volcanic group in the entire peninsula, and range in age from Late Miocene to Holocene. They can occur as small isolated edifices, but most of them are grouped into four main volcanic fields, which are from north to south: Jaraguay and San Borja in northern Baja California, and San Ignacio, La Purísima and San José Comondú in Baja California Sur (Inset, Fig. 1). This volcanic association was referred to as "the alkalic suite" by Sawlan and Smith (1984), and was also considered by these authors to be of syn-rift origin. Rogers et al. (1985) and Saunders et al. (1987) considered such rocks in the Jaraguay and San Borja fields as magnesian andesites and named them "bajaites". They interpreted their unusual geochemistry as reflecting the melting of mantle peridotites metasomatised by slab melts, the latter derived either from young downgoing oceanic crust or from a subducting active spreading center. New geochemical data (Benoit et al., 2002) and the study of adakites in Baja California Sur (Aguillón-Robles et al., 2001) confirm that these magnesian andesites are products of partial melting of the Baja California mantle wedge metasomatised by adakitic liquids. Lastly, Pliocene to Recent magnesian basaltic andesites and andesites with high K_2O contents erupted along small grabens and hemi-grabens trending NNW–SSE (Sawlan and Smith, 1984; Sawlan, 1991). The last volcanic events also emplaced calc-alkaline lavas, which locally occur along the Gulf coast and form the Tres Vírgenes, La Reforma, and Mencenares volcanic centers (Sawlan and Smith, 1984; Demant, 1984; Sawlan, 1991; Bigioggero et al., 1995). Furthermore tholeiitic volcanism associated with this continental breakup and rifting is documented in the Gulf Province as the Isla Tortuga (Batiza, 1978), the Guaymas basin (Saunders et al., 1987), the Isla San Luis (Paz-Moreno and Demant, 1999), and the Cerro Prieto geothermal field in northern Baja California (Herzig, 1990).

2.2. Special interest for "bajaites" and magnesian andesites

Rogers et al. (1985) used the term "bajaites" to describe magnesian lavas from Baja California ranging in composition from basalts to basaltic andesites. These are almost primitive rocks, with Mg# varying from 0.75 to 0.53 (Rogers and Saunders, 1989), up to 8 wt.% MgO, 57 wt.% SiO_2, and low Fe/Mg and high Na/K ratios. The trace-element characteristics of bajaites include high Sr (>3000 ppm) and Ba (>1000 ppm) contents, low Rb concentrations, negative anomalies in high field strength elements (HFSE), and very low Y and heavy rare earth elements (HREE) contents (Calmus et al., 2003). Although the term "bajaite" is not widely used anymore, rocks of this composition can be related to convergent plate margins and particularly to active ridge-subduction processes and slab-window formation, resulting in an increase of thermal input and/or chemical input from the slab, as suggested by Rogers et al. (1985), Saunders et al. (1987), and recently by Yogodzinski et al. (2001). These rocks also show high Cr and Ni contents, in accord with their high Mg numbers. In Santa Margarita island (Inset Fig. 1), Bonini and Baldwin (1998) recognized adakitic dacites with chemical characteristics similar to those of bajaites, i.e., very high positive Sr anomalies and HFSE depletion. Desonie (1992) interpreted the 3 Ma old unusual calc-alkaline siliceous rocks of San Esteban island as possibly originated by the subduction of a spreading center.

Other occurrences of magnesian andesites are now well-documented in the western Aleutian islands (Yogodzinski et al., 1994, 1995, 2001). They include Adak-type magnesian andesites, with characteristically high La/Yb ratios and Sr contents. These may also be very rich in compatible elements such as Mg, Cr, and Ni (Yogodzinski et al., 2001), a feature that reflects interaction of slab melts with the mantle wedge. The Piip-type magnesian andesites display lower La/Yb ratio, which denote a greater interaction of slab melts with peridotites, possibly by direct melting of a mantle wedge metasomatised by slab melts (Defant and Kepezhinskas, 2001). However, generation of magnesian andesites may also possibly be linked to the melting of subducted sediments and subsequent interaction of these magmas with the mantle, as proposed for the Setouchi volcanic belt in Japan (Tatsumi, 2001).

3. Field work in La Purísima area: geological and petrologic data on magmatism

Geological mapping and sampling of the area was done during three field investigations conducted in 1996, 1997 and 1999. The study area (frame in Fig. 1) lies between latitudes 26°N and 26°22′N, and longitudes 111°43′W and 112°07′W. We used published 1:50,000 topographic maps (INEGI), satellite-eye views (Miller and Baxter, 1975), the 1:250,000 Landsat images published by INEGI (1995a,b), and 1:25,000 aerial photographs. La Purísima volcanic field itself extends over 100 km in length, and it partly overlies a Mesozoic basement and/or Tertiary sedimentary rocks, the oldest lava flows being interfingered with the units at the top of the Tertiary sedimentary sequence (Fig. 2).

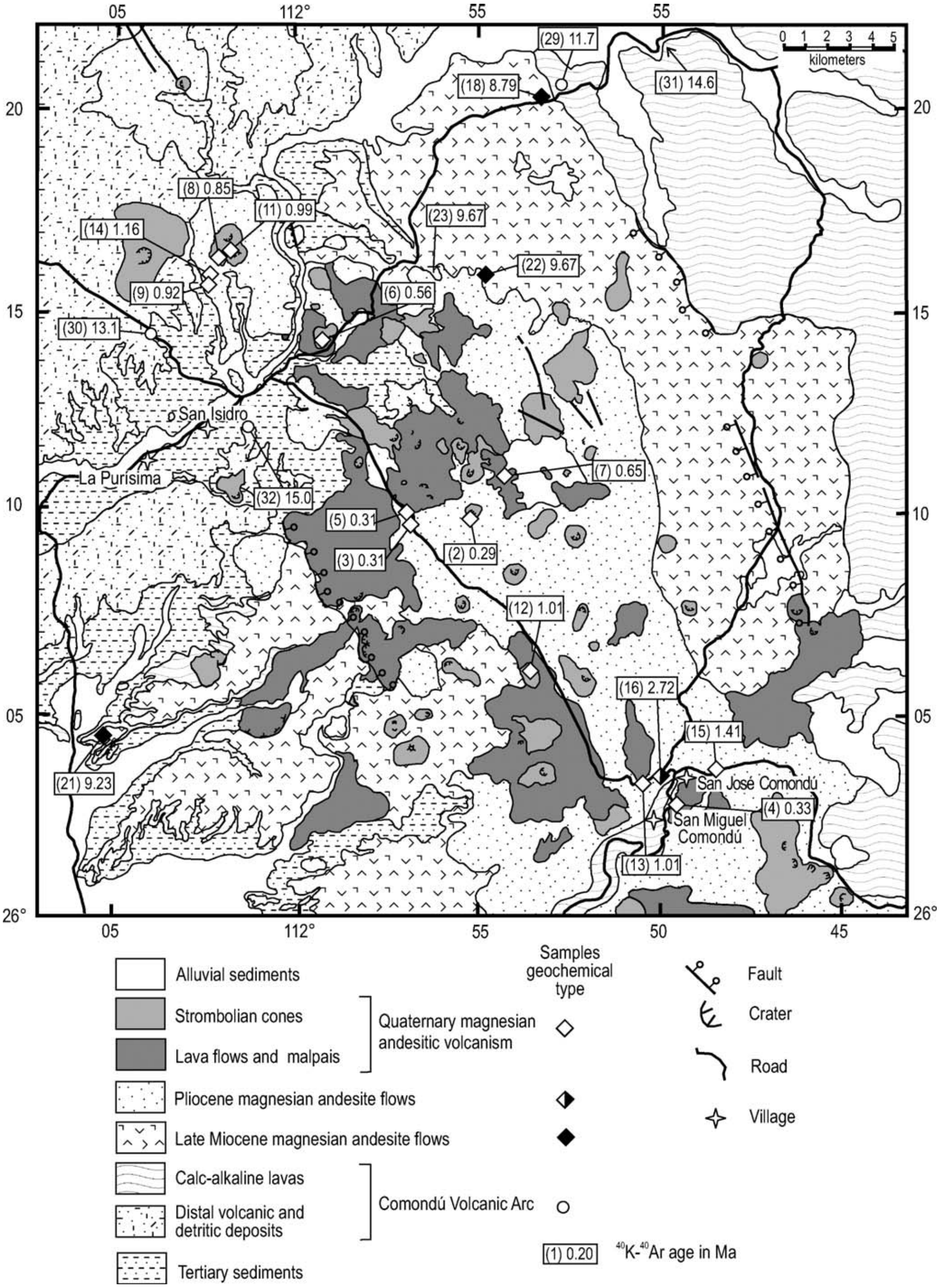

Fig. 2. Geological map from the central portion of La Purísima Volcanic field, between 26°–26° 22′N and 111° 44′–112° 06′W. Sample localities and corresponding isotopic ages are taken from Table 1. Symbols as in Fig. 1.

3.1. Mesozoic basement and Tertiary sedimentary formations

In this area the Mesozoic basement is only represented by granitoids exposed northwest of Loreto (Fig. 1). One of them yielded a K–Ar whole-rock age of 94 ± 2 Ma (McLean, 1988), but on the western side of the Bahía Concepción peninsula (Fig. 1), a granodiorite is exposed, that was dated by the same method on biotite concentrates at 78.4 ± 2.8 Ma (McFall, 1968).

The oldest Tertiary sedimentary unit, the Eocene Bateque Formation (Mina-Uhink, 1957), consists mainly of marine sandstone and siltstone. It is overlain by the sedimentary San Gregorio Formation, first described by Beal (1948), which consists of laminated white diatomite, porcellaneous shale with fish scales, and dark gray phosphatic shale interbedded with pelletoidal phosphatic sandstones and white vitric tuff (McLean et al., 1987). K–Ar ages for glassy rhyolitic tuffs within the San Gregorio layers range from 28 to 25.5 Ma (Hausback, 1984). The San Isidro Formation (Heim, 1922), also named "Yellow beds" by Darton (1921), includes calcareous sandstone and siltstone, light-grayish-green porcellaneous shale with continental molluscs, and yellowish pebble conglomerate. North of La Purísima, this formation interfingers with distal continental deposits of the Comondú Formation, mainly north of La Purísima town (Sawlan and Smith, 1984; Hausback, 1984; McLean et al., 1987). In that area, large andesitic mesas of the Comondú Formation overlie the sedimentary formations. The Bateque, San Gregorio, and San Isidro Formations have been grouped as a single map unit in Figs. 1 and 2.

3.2. *The calc-alkaline series of the Comondú volcanic arc*

The Comondú volcanic arc is composed mainly of rhyolitic ash-flow tuffs plus andesitic lahars and lava flows in the proximal areas of the arc, with associated volcanic sandstone, interbedded conglomerate, and volcaniclastic strata in the westernmost distal areas (McLean et al., 1987). Actually, Heim (1922) assigned the name of Comondú Formation to sedimentary rocks exposed near San José Comondú, and Beal (1948) and Mina-Uhink (1957) extended the use of this term to Cenozoic volcanic rocks from Sierra La Giganta, which is part of the long volcanic belt extending along the Gulf coast from Sierra Las Tinajas to the La Paz area (Inset Fig. 1), and is truncated to the east by the Main Gulf Escarpment.

Deposits of the Comondú volcanic arc are at least 1800 m thick at the crest of the Sierra La Giganta, (McLean et al., 1987). Between Bahía Concepción and Loreto, the Comondú volcanic rocks are intruded by andesitic porphyry stocks dated at 19.7 ± 0.9 Ma on

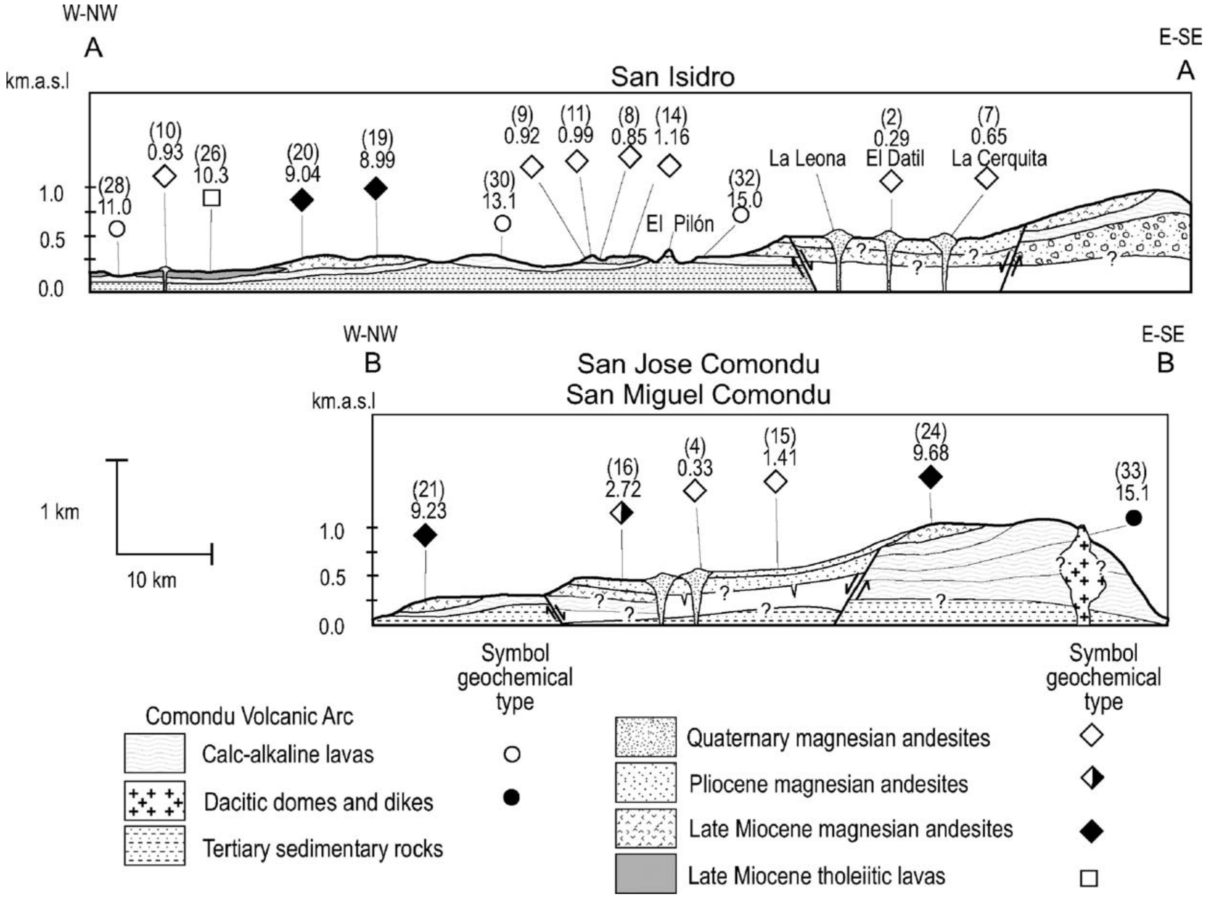

Fig. 3. WNW–ESE cross-sections, A–A′ and B–B′ (Fig. 1), showing the spatial and temporal relationships between the different volcanic units. Vertical exaggeration 10×. Thickness of volcanic units is not shown to scale. Symbols as in Fig. 1.

separated hornblendes by the K–Ar method (Hausback, 1984). The upper part of the Comondú volcanic arc in the study area consists of large calc-alkaline mesas in the northern and eastern parts of the quadrangle (Figs. 1 and 2). The volcanic rocks resting over the sedimentary units yield ages ranging from 24 to 11 Ma in various places (Sawlan, 1991).

3.3. The tholeiitic lavas

In the northwestern part of the study area exist large mesas made of tholeiitic basalts, which overlie tilted Tertiary sedimentary rocks (Figs. 1 and 3). They correspond to the southernmost outcrops of the Esperanza Basalt, which extends from the Tres Vírgenes volcanic center towards San Juanico, and were interpreted as erupted from the Gulf of California area before breakup and subsidence (Sawlan and Smith, 1984; Sawlan, 1991). Rojas-Beltrán (1999) has shown that these flows were issued from volcanoes scattered over the Peninsula, some clearly outside of the Gulf Extensional Province. The ages of these lava flows range between 12.5 and 9 Ma. The average chemical characteristics reported for Esperanza Basalt (Gastil et al., 1979; Sawlan and Smith, 1984; Sawlan, 1991; Rojas-Beltrán, 1999) are: 54 wt.% SiO_2; 14 wt.% Al_2O_3; 9 wt.% CaO; 11 wt.% FeO; 6 wt.% MgO; 3 wt.% Na_2O; and finally 0.1 to 0.4 wt.% K_2O.

3.4. The magnesian andesitic series

In La Purísima area (Figs. 1–3), the Late Miocene to Quaternary volcanism described by Sawlan and Smith (1984) and Hausback (1984) corresponds to the magnesian andesitic series (Calmus et al., 2003), and is represented by 8 Ma old lava flows capping mesas (McLean, 1988), and Late Pliocene to Quaternary cinder cones and canyon-filling flows. The Quaternary volcanic rocks erupted from cinder and spatter cones are roughly aligned along faults that define a northwest–southeast trending succession of small grabens and half-grabens (Fig. 1). The common phenocryst paragenesis of the magnesian andesites includes plagioclase, clinopyroxene, olivine (often iddingsitized), and oxides, plus occasional phlogopite and oxyhornblende (McLean et al., 1987). Their main geochemical characteristics are SiO_2 contents ranging from 51.5 to 55.5 wt.%, high values of MgO and K_2O, together with high contents of incompatible elements such as Ba (more than 900 ppm) and Sr (higher than 1700 ppm). In addition, these lavas are LREE-enriched and HREE-depleted (Sawlan and Smith, 1984; Sawlan, 1991).

4. Field relationships and K–Ar ages

K–Ar dating were performed on whole-rock samples. After crushing and sieving, the size fraction of 0.3 to 0.15 mm was cleaned with distilled water and then saved for analytical purposes: (i) one aliquot was powdered in an agate grinder for K analysis by atomic absorption after hydrofluoric acid chemical attack, and (ii) 0.3 to 0.15 mm grains were used for argon isotopic analysis. Argon extraction from grains (0.6 to 1 g of whole-rock sample or separated minerals) was performed under high vacuum by induction heating of a molybdenum crucible. Extracted gases were cleaned on two titanium sponge furnaces and finally purified by using two Al–Zr SAES getters. Isotopic composition of argon and concentration of radiogenic ^{40}Ar were measured using a 180°-geometry stainless steel mass spectrometer equipped with a 642 Keithley amplifier. The isotopic dilution method was applied using a ^{38}Ar spike buried as ions in aluminum targets, following the original procedure described by Bellon et al. (1981). Mean isotopic ages were calculated using the constants recommended by Steiger and Jäger (1977).

Analytical parameters and results are reported in Table 1 and ages are shown in Figs. 1–3 (maps and cross-sections AA′ and BB′). Before detailing the ages for the different types of lavas, we emphasize the chronodiagram of Fig. 4. There, if we suppose no sampling bias, so that the exposed distribution of ages reflects the characteristics of activity through time in La Purísima area, it clearly appears that: (i) in the study area, the volcanic activity represents only the last 4 of the 13 My (from 24 to 11 Ma) activity of the magmatic arc in the whole Baja California Sur (event 1); (ii) events that emitted magnesian andesites (events 2 and 5) lasted only ca. 1 My. The first one is contemporaneous of adakitic magmatism that occurred in the Santa Clara volcanism field in the Vizcaino Peninsula (Aguillón-Robles et al., 2001). The second one is contemporaneous of calc-alkaline Quaternary volcanism, and finally (iii) the short duration observed for the emission of the magnesian andesite magmatism was possibly connected with a rather abrupt event responsible for their emission.

4.1. Ages of calc-alkaline magmatism

Six whole-rock K–Ar ages ranging from 16.4 ± 0.9 to 11.0 ± 0.3 Ma have been measured on lava flow samples collected along the road from Cadeje to Mulege, west of Cadeje village (Fig. 2). In that area, the 10 to 15 m thick andesite flows overlie the sedimentary rocks and tuffa-

Table 1
Whole-rock isotopic ages for 33 selected lavas from the La Purísima

Site number[a]	Sample number	Coordinates[b]		Magmatic type	Mean age (Ma) ± error 1s[c]	$^{40}Ar_R$[d]	% $^{40}Ar_R$	K_2O (wt.%)	Fraction[e]	Lab. reference[f]
		N	E							
1	CO96-29	2,854,299	405,185	Mg And	0.20 ± 0.11	0.28	5.6	3.46	wr	B4891
						0.15	1.3			B5771
2	99-30	2,894,325	407,944	Mg And	0.29 ± 0.08	3.60	8.3	3.73	wr	B5067
3	99-04	2,893,436	405,347	Mg And	0.31 ± 0.04	0.38	13.6	3.62	wr	B5056
						0.35	18.8			B5075
4	99-08	2,880,699	417,113	Mg And	0.33 ± 0.08	0.19	10.2	1.47	wr	B5092
						0.15	6.6			B5776
5	99-24	2,894,034	405,020	Mg And	0.45 ± 0.07	0.43	6.4	2.96		B5877
6	97-36	2,904,641	403,745	Mg And	0.56 ± 0.17	0.42	4.7	2.20	wr	B5741
						0.37	6.9			B5041
7	99-32	2,895,945	409,268	Mg And	0.65 ± 0.09	0.61	9.6	2.91	wr	B5062
8	99-47	2,906,218	396,336	Mg And	0.85 ± 0.06	0.61	19.6	2.21	wr	B5097
9	99-49	2,905,178	395,644	Mg And	0.92 ± 0.18	0.64	10.4	2.16	wr	B5065
10	97-44	2,920,293	344,835	Mg And	0.93 ± 0.06	0.76	16.0	2.50	wr	B5793
						0.74	17.1			B4902
11	99-43	2,906,585	396,455	Mg And	0.99 ± 0.12	0.80	11.3	2.48	wr	B5063
12	99-16	2,886,701	410,470	Mg And	1.01 ± 0.09	0.52	14.8	1.60	wr	B5117
13	99-11	2,881,840	415,900	Mg And	1.01 ± 0.19	0.90	12.9	2.63	wr	B5095
						0.81	06.6			B5705
14	99-48	2,905,927	396,063	Mg And	1.16 ± 0.12	0.90	11.5	2.41	wr	B5658
15	99-06	2,882,115	419,098	Mg And	1.41 ± 0.06	01.25	34.9	2.65	wr	B5091
						1.15	29.4			B5829
16	99-10	2,882,198	416,732	Mg And	2.72 ± 0.16	01.70	24.2	2.00	wr	B5094
						01.81	17.0			B5775
17	CO96-28	2,813,120	447,600	Mg And	5.48 ± 0.14	06.58	67.5	3.74	wr	B4850
						6.62	75.0			B4852
18	97-34	2,913,288	412,126	Mg And	8.79 ± 0.26	9.17	64.9	3.24	wr	B4856
						9.01	60.8			B4883
19	99-39	2,922,101	386,930	Mg And	8.99 ± 0.25	7.57	79.1	2.74	wr	B5188
						8.23	62.7			B5301
20	99-34	2,905,402	357,124	Mg And	9.04 ± 0.41	11.63	38.0	4.04	wr	B5300
						11.96	37.8			B5302
21	97-38	2,884,198	390,033	Mg And	9.23 ± 0.21	8.85	84.4	2.97	wr	B5042
22	99-65	2,905,239	408,715	Mg And	9.67 ± 0.25	9.51	59.2	3.04	wr	B5098
23	99-59	2,905,699	406,344	Tr Mg And	9.67 ± 0.26	0.74	64.4	2.38	wr	B5658
24	CO96-27	2,873,244	430,764	Mg And	9.68 ± 0.15	0.78	78.5	3.38	wr	B5759
25	99-35	2,903,351	352,618	Th	9.87 ± 0.64	1.18	23.2	0.39	wr	B5835
						1.23	22.8			B5833
						1.25	23.6			B5765
						1.31	24.5			B5834
	99-36	2,903,351	352,618	Th	9.33 ± 0.32	0.83	46.4	0.28	gl	B5135
26	99-38	2,917,711	348,749	Th	10.3 ± 0.8	0.58	17.0	0.18	wr	B5836
27	99-37	2,939,345	326,970	Th	10.6 ± 0.8	1.01	16.2	0.30	wr	B5761
28	97-43	2,919,159	341,966	And	11.0 ± 0.3	6.15	52.9	1.65	wr	B4889
29	97-33	2,913,564	412,267	And	11.7 ± 0.6	4.97	24.9	1.34	wr	B4854
30	99-42	2,902,956	393,148	Mg And	13.1 ± 0.3	5.15	59.3	1.21	wr	B5081
31	99-68	2,915,863	418,340	Mg And	14.6 ± 0.3	19.99	88.5	4.30	wr	B5769
32	99-60	2,898,591	397,253	And	15.0 ± 0.4	6.01	55.2	1.26	wr	B5114
33	00-01	2,872,174	451,353	Adak	15.1 ± 0.9	4.35	68.8	0.89	gm	B5613
					16.4 ± 0.9	1.70	40.5	0.32	f	B5503

ceous sedimentary rocks of the San Gregorio Formation. The oldest age of 16.4 ± 0.9 Ma has been measured for separated plagioclase feldspars from the dacitic adakite-like lava sampled at site 33, from the dome of Las Parras, which intrudes the lower sequence of the Comondú volcanic arc, west of Loreto.

The huge andesitic mesa that gently dips to the west towards the Pacific Ocean, which crops out at the top of

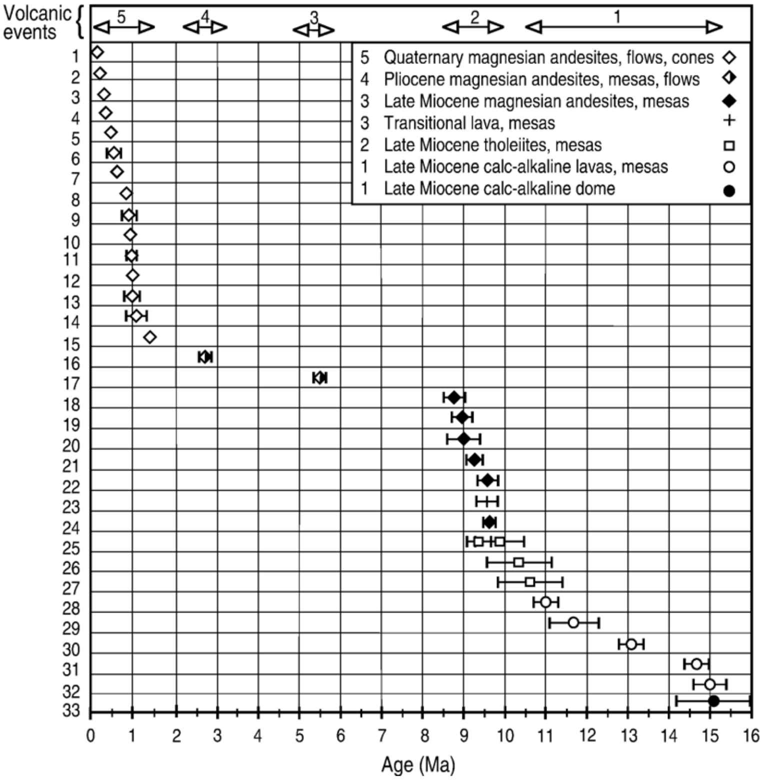

Fig. 4. Chronodiagram showing the five successive magmatic stages recognized in La Purísima area since the Middle Miocene: 1, from 15 to 11 Ma; 2, 9.6 to 8.7 Ma; 3, 5.4 Ma; 4, 2.7 Ma; 5, 1.3 to 0 Ma. First column to the left corresponds to the sampling site numbers shown in Figs. 1–3, and in Table 1. Symbols as in Fig. 1.

the cliffs south of La Purísima and at the top of Cerro El Pilón, has been dated at 15.0 ± 0.4 Ma. A high-K andesite shoshonitic-like lava collected at site 31 from a vent along the Gulf coast in the Sierra La Giganta, has been dated at 14.6 ± 0.3 Ma. The youngest ages are at 11.7 ± 0.6 and 11.0 ± 0.3 Ma.

4.2. Ages of tholeiitic lavas

The tholeiitic lava flows are located in the NW portion of the study area (Fig. 1). They erupted from fissures or central vents and have wide distributions. In the Cadeje area they display columnar jointing, as visible at site 26. Some flows reached the paleo-sea level as exemplified at San Juanico where they occur as a pile of very well-preserved pillows. Whole-rock isotopic ages range between 10.6 ± 0.8 Ma (Site 27), northwest of Cadeje, and 10.3 ± 0.8 Ma (Site 26), north of Cadeje, to 9.87 ± 0.66 Ma (Site 25) and 9.33 ± 0.32 Ma obtained for the well-crystallized cores of pillow lavas and their glassy margins, respectively, sampled at San Juanico beach.

Notes to Table 1:

See text for analytical methods and constants used for age calculations.

Samples are stored in the Geochronology laboratory's collections at the Université de Bretagne Occidentale.

Magmatic types are abbreviated as follows: Th, tholeiite; And, andesite; Adak, adakite; Mg And, magnesian andesite with a special regard to sample 99-59, which has transitional characteristics.

Ages of samples collected at sites 20, 21, 25, 26, 27, 28, 29, 30 and 31 have been previously reported in Benoit et al. (2002), and age of sample collected at site 11 has been reported in Calmus et al. (2003).

[a] Site number is used for Figs. 1–3 and Table 1.

[b] Coordinates are expressed in UTM, unit in m.

[c] Error at one σ level is quoted using the equation given by Mahood and Drake (1982).

[d] $^{40}Ar_R$; radiogenic argon in sample is expressed in 10^{-7} cm^3/g.

[e] Dated material: wr, whole rock; gl, glass; gm, groundmass; f, feldspar.

[f] Experimental reference for each sample analysis performed in the Geochronology laboratory.

The field relationship of the tholeiitic flows at site 26 with the calc-alkaline lavas at site 28, west of Cadeje (cross-section AA′, Figs. 1 and 3), clearly shows that the calc-alkaline mesas underlie the tholeiitic flows. This observation is supported by K–Ar ages, according to which tholeiitic lavas, dated at 10.3 Ma, are 0.7 My younger than the calc-alkaline mesas. In the same area of Cadeje, the magnesian andesite mesas at sites 20 and 19, dated at 9.04 and 8.99 Ma, respectively, are ca. 1 My younger than the tholeiitic flows.

4.3. Magnesian basalts and andesites

Four relatively short magnesian andesites events occurred from Late Miocene to Quaternary times, as evidenced in Table 1 and Fig. 4.

The oldest magnesian andesites (event 2), which have very high potassium contents between 3 and 4.2 wt.%, are dated between 9.7 and 8.8 Ma (Table 1). This first group includes the mesa sampled at site 22, north-east of La Purísima dated at 9.67 Ma, the mesa south-east of San José Comondú at 9.68 Ma sampled at site 24 (cross-section BB′, Fig. 3), and two mesas (Sites 18 and 19; cross-section AA′, Fig. 3) at ca. 9 Ma.

The second magnesian andesitic event (event 3) is less well-defined because two samples only yield Early Pliocene ages. One from the area northeast of Ciudad Insurgentes (Site 17, Fig. 1) is dated at 5.48 Ma, a result in very good agreement with that formerly given for the same locality by Hausback (1984).

A large magnesian andesite mesa at site 16, extending from La Purísima to the area south of San José Comondú is dated at 2.72 Ma (event 4). Although this result is not supported by similar data elsewhere in La Purísima volcanic field, we consider that this activity is significantly separated from events 3 and 5.

Younger mesas (for instance at site 15 dated at 1.4 Ma), as well as rather small flows associated with spatter and strombolian cones were then emplaced inside a N–NW trending graben (Figs. 1 and 2) until very recent times (event 5). The highly vesicular viscous lavas erupted as blocky flows of aa type, the irregular surfaces of which are locally referred to as “malpaís”. These vesicular lava flows are very difficult to date using the K–Ar method, since their atmospheric argon contents are anomalously high. Isotopic ages obtained for massive lava flows range from 1.41 ± 0.06 Ma (Site 15) to 0.20 ± 0.11 Ma (Site 1) for those emitted from the morphologically youngest cinder cones. The ages of 14 dated samples (Site 14 to site 1, Fig. 4 and Table 1) are bracketed by these two values. They seem to cluster together between 1.16 and 0.2 Ma. Their distribution may suggest that Quaternary volcanic activity was discontinuous. Additional very precise ages determined by the K–Ar Cassignol Technique for neighboring and similar lavas range from 209 ± 14 to 48 ± 0.3 Ka (Nauret, 2000) and document the youth of the event 5, in agreement with the well-preserved shapes of source strombolian-type volcanoes.

5. Petrologic and chemical results: major and trace elements

Nearly 80 samples were analyzed using inductively coupled plasma atomic-emission spectrometry (ICP-AES), except Rb which was measured by flame-emission spectroscopy. Samples were powdered in an agate grinder. Major and trace elements were analyzed without chemical separation (Cotten et al., 1995). International standards (ACE, BEN, JB-2, PMS, and WSE) were used for calibration tests. Relative standard deviations were ca. 1% for SiO_2 and 2% for other major elements, except for P_2O_5 and MnO concentrations at ± 0.01%, and ca. 5% for trace elements. Eleven representative chemical analyses are reported in Table 2, but we also used in the plots 22 additional analyses reported in Benoit et al. (2002) and Calmus et al. (2003).

Mineral compositions were determined using an automated CAMECA SX 50 electron microprobe (Microsonde Ouest, Brest, France). Analytical conditions were 15 kV, 10–12 nA, and a counting time of 6 s (for additional information on analytical methods, see Defant et al., 1991).

Fifty-four whole-rock K–Ar ages were measured in the Université de Bretagne Occidentale on samples selected (Aguillón-Robles, 2002) from an initial set of 85 volcanic rocks. Table 1 lists data for 33 of these samples, among which a few have been published in Benoit et al. (2002) and Calmus et al. (2003).

5.1. Petrographic and mineralogical notes

Calc-alkaline lavas from the Comondú volcanic sequence contain phenocrysts of clinopyroxene ($En_{44}Wo_{44}Fs_{12}$), euhedral olivine ($Fo_{85}Fa_{15}$) that is sometimes fractured and iddingsitized, oxidized hornblende, zoned plagioclase, magnetite, and ilmenite; their groundmass is mainly composed of clinopyroxene, olivine, and plagioclase microcrysts showing a fluidal texture.

A lava collected at site 23 (Table 2), having a composition transitional between calc-alkaline and

Table 2
Major and trace element analyses of eleven selected lavas from La Purísima area

Site number[a]	2	5	9	15	16	17	19	20	24	33	25
Sample	99-30	99-24	99-49	99-06	99-10	CO96-28	99-39	99-34	CO96-27	00-01	99-35
Age[b]	0.29	0.45	0.92	1.46	2.61	5.48	8.99	9.04	9.68	15.10	9.33
SiO_2	49.60	57.00	54.00	55.70	53.00	49.60	54.50	52.20	52.30	61.85	54.80
TiO_2	2.86	1.42	1.93	1.39	2.62	2.05	1.46	2.35	1.87	0.45	1.66
Al_2O_3	13.80	16.20	15.55	15.39	15.00	13.30	14.80	13.82	15.38	18.00	14.50
Fe_2O_3T	9.30	5.65	7.33	5.85	8.44	7.39	6.70	8.22	7.68	4.13	10.35
MnO	0.10	0.07	0.09	0.07	0.11	0.09	0.09	0.08	0.10	0.15	0.15
MgO	5.08	4.25	5.09	4.74	4.87	5.78	6.18	4.75	4.40	1.17	5.94
CaO	9.70	6.10	7.55	7.00	8.01	9.05	7.00	8.15	8.10	8.43	8.90
Na_2O	3.50	4.90	4.58	4.98	3.96	3.68	4.04	3.43	3.90	3.96	2.80
K_2O	3.77	2.87	2.14	2.71	1.94	3.79	2.75	4.17	3.57	1.24	0.38
P_2O_5	1.10	0.63	0.72	0.63	0.95	1.17	0.65	0.96	0.78	0.18	0.13
LOI	0.69	0.73	0.97	0.81	0.44	2.73	0.71	1.52	1.60	2.08	0.15
Total	99.50	99.82	99.95	99.78	99.34	98.63	98.88	99.65	99.60	99.84	99.76
Mg#[c]	53.40	44.01	59.30	63.00	54.80	62.10	66.00	54.80	54.60	22.90	37.60
Normative minerals (CIPW)											
Q	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.17	8.08
ne	9.13	0.00	0.00	1.11	0.00	9.52	0.00	3.72	4.25	0.00	0.00
hy	0.00	7.06	0.26	0.00	9.71	0.00	5.87	0.00	0.00	6.19	18.95
ol	4.22	1.79	7.81	6.22	0.78	5.25	6.26	5.21	5.85	0.00	0.00
Trace elements (ppm)											
Rb	21.00	7.80	8.00	8.50	7.40	16.60	20.00	25.50	24.00	14.30	3.80
Ba	2300.00	1480.00	1155.00	1380.00	970.00	1930.00	1350.00	1820.00	1565.00	790.00	74.00
Th	1.30	1.40	1.35	1.35	0.90	2.70	3.60	3.00	4.10	0.65	0.55
Nb	17.70	8.20	11.40	8.10	14.00	20.70	10.50	15.00	15.30	8.60	5.30
La	54.00	34.00	33.00	38.00	36.00	75.00	47.00	55.00	62.00	21.00	4.60
Ce	125.00	72.00	77.00	79.00	86.00	157.00	100.00	122.00	128.00	42.00	10.00
Sr	2970.00	2600.00	2520.00	2600.00	2560.00	3800.00	2080.00	2400.00	2860.00	672.00	245.00
Nd	68.00	38.00	42.00	40.00	51.00	80.00	51.00	63.00	57.00	21.50	8.60
Sm	10.40	5.60	7.10	6.70	9.10	11.90	8.20	10.60	9.25	4.00	3.30
Zr	230.00	133.00	147.00	145.00	161.00	216.00	260.00	300.00	223.00	22.00	82.00
Eu	2.24	1.53	1.92	1.70	2.52	2.83	2.05	2.65	2.18	1.22	1.25
Gd	5.50	3.25	4.25	3.65	5.85	6.30	5.20	6.00	5.40	2.30	4.10
Dy	2.65	1.60	2.20	1.85	3.40	3.00	2.85	3.15	2.45	2.80	4.10
Y	11.70	7.80	10.00	8.90	15.30	14.30	14.50	15.00	13.20	16.50	21.00
Er	1.00	0.70	0.80	0.80	1.25	1.30	1.30	1.40	1.20	1.65	1.80
Yb	0.77	0.51	0.65	0.61	1.00	0.90	1.10	0.95	0.94	1.57	1.50
Sc	19.00	10.5	14.00	8.80	16.60	12.80	12.80	16.20	15.20	3.80	22.00
V	345.00	150.00	196.00	99.00	232.00	182.00	182.00	255.00	230.00	52.00	155.00
Cr	128.00	140.00	139.00	124.00	144.00	235.00	235.00	180.00	133.00	3.00	236.00
Co	30.00	22.00	25.00	21.00	24.00	31.00	31.00	29.00	28.00	4.00	30.00
Ni	41.00	102.00	90.00	115.00	80.00	154.00	154.00	84.00	71.00	3.00	114.00
Nb/La	0.32	0.24	0.35	0.21	0.39	0.28	0.22	0.27	0.25	0.41	1.15
La/Yb	70.17	66.67	50.76	62.30	36.00	83.33	42.73	57.89	65.96	13.37	2.87
Sr/Y	253.84	333.33	253.84	292.13	167.32	265.73	143.45	160.00	216.66	40.72	11.67

See text for analytical methods.

Chemical analyses of selected lavas from La Purísima volcanic field.

Note: The chemical analyses were performed by ICP-AES method at the Université de Bretagne Occidentale; the detection limits for trace elements are (in ppm): Ce, 1.5; Ba, Zr, Gd, V, Cr, Co, Ni, 1; Nd, Sm, Er, 0.6; Sr, Nb, La, 0.5; Th, Y, Dy, 0.3; Eu, Yb, Sc, 0.1.

[a] Site number refers to Figs. 1–3 and Table 2.

[b] Ages are given in Ma (see Table 2).

[c] Mg# [magnesium number $=100 \times Mg/(Mg+Fe^{2+})$]; $FeO=Fe_2O_3T \times 0.85$.

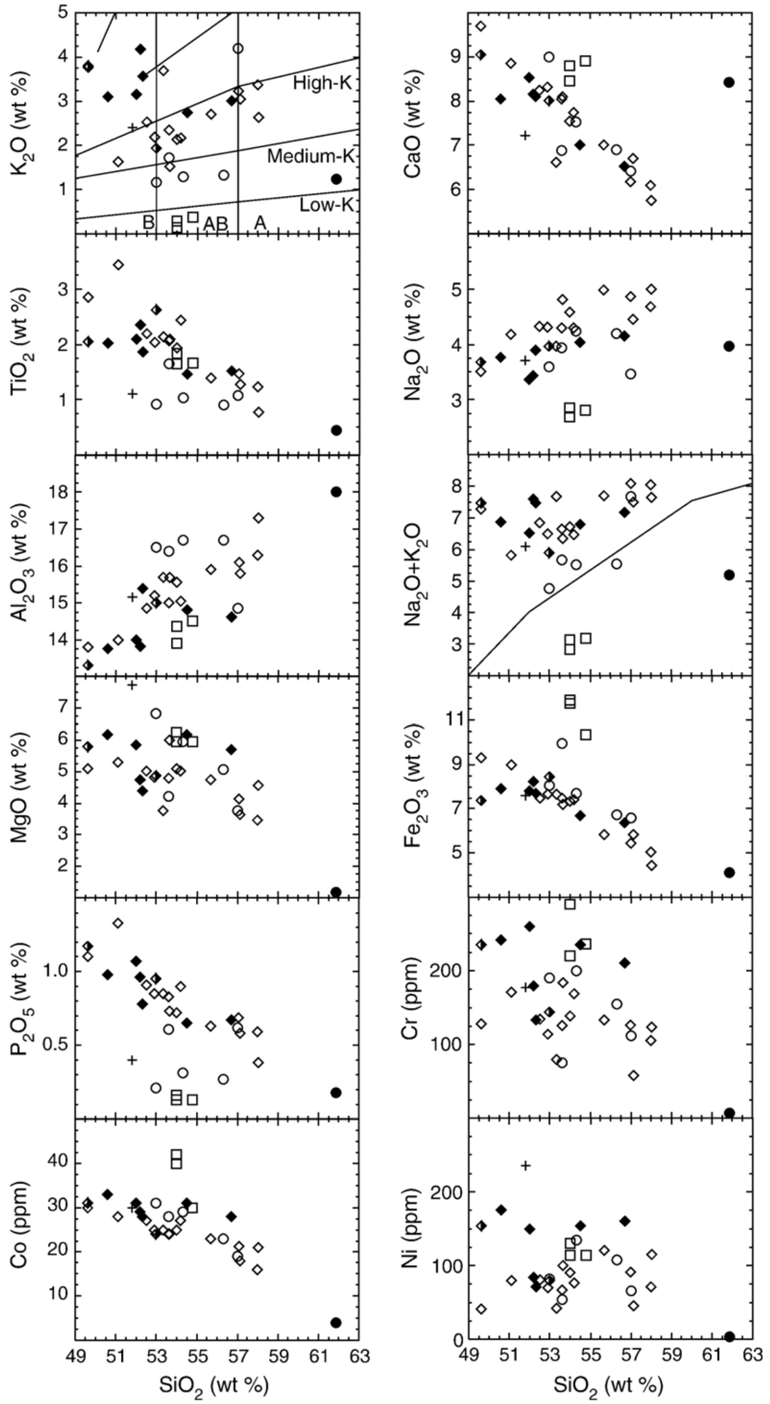

Fig. 5. Major element oxides (wt.%) and Cr, Ni and Co trace element contents (ppm) versus SiO_2 (wt.%) for 33 lavas from la Purísima, allowing the recognition of five distinct magmatic types. Circles: calc-alkaline lavas; filled circles, porphyry body in the Comondu fm., near Loreto; squares, tholeiitic lavas; diamonds, magnesian andesites, cross: sample transitional between calc-alkaline and magnesian andesites. Emplacement ages of magnesian andesites are indicated as follows: filled diamonds, Late Miocene; half empty diamonds, Pliocene; empty diamonds, Quaternary. Fields and limits defined by Maury (1993) for the K_2O versus SiO_2 diagram. The limit between sub-alkalic and alkalic fields in the alkalis versus SiO_2 plot is from Miyashiro (1978). Symbols as in Fig. 1.

magnesian andesitic suites, contains phenocrysts of clinopyroxene ($En_{46}Wo_{44}Fs_{10}$), olivine ($Fo_{80}Fa_{20}$), plagioclase ($Ab_{52}An_{44}Or_4$), ilmenite, and magnetite.

Late Miocene tholeiitic lavas contain either orthopyroxene ($En_{71}Wo_5Fs_{24}$) and clinopyroxene ($En_{49}Wo_{28}Fs_{23}$) phenocrysts (sample from site 25, Table 1) or clinopyroxene only (site 26) in a microlitic texture with dominant plagioclase ($Ab_{36}An_{64}$) and clusters of pyroxene and olivine ($Fo_{63}Fa_{37}$).

Late Miocene magnesian andesites (e.g., at site 22) are usually vesicular and contain phenocrysts of clinopyroxene ($En_{49}Wo_{43}Fs_8$), euhedral olivine ($Fo_{83}Fa_{17}$) that display a nearly constant iddingsitization at their rims or within the fractures, and plagioclase ($Ab_{55}An_{40}$). Their groundmass contains plagioclase microlites, pyroxene, and olivine microcrysts set into interstitial glass.

Pliocene magnesian andesites (e.g., at site 17, Table 1) are generally more massive than the older ones and have a fine crystallized groundmass made of plagioclase and pyroxene. Phenocrysts of apatite, magnetite and ilmenite are present together with clinopyroxene ($En_{44}Wo_{46}Fs_{10}$) and potassic oligoclase ranging in composition from $Ab_{62}An_{17}Or_{20}$ to $Ab_{75}An_{15}Or_8$. Olivine has not been found in these rocks.

Recent magnesian andesites are either massive, for instance those collected from sites 4 and 2 or highly vesicular at site 13 (Table 1) and frequently show late zeolites and/or calcite as vesicle fillings. Their groundmass is fine-grained with a fluidal orientation of plagioclase microlites, clinopyroxene ($En_{45}Wo_{44}Fs_{11}$), olivine, plagioclase ($Ab_{55}An_{40}Or_5$), and scarce apatite phenocrysts.

5.2. Calc-alkaline lavas

The Comondú volcanic arc units from La Purísima volcanic field consist of calc-alkaline basaltic andesite lavas with 53–57 wt.% SiO_2, 15 to 16.5 wt.% Al_2O_3, 4 to 5 wt.% MgO, and highly variable K_2O ranging from 1 to 4 wt.% (Fig. 5).

CIPW normative compositions are different along the lava locations: the northernmost lava flows are silica-oversaturated (Q + hy normative) and most of the others are silica-saturated (hy = 10–14% and ol = 3–11%, Table 2). Their multielement patterns, when normalized to primitive mantle (Sun and McDonough, 1989), display positive anomalies in Ba, K, Sr, and Zr compared to neighboring elements, and a clear Nb negative anomaly (Fig. 6 d).

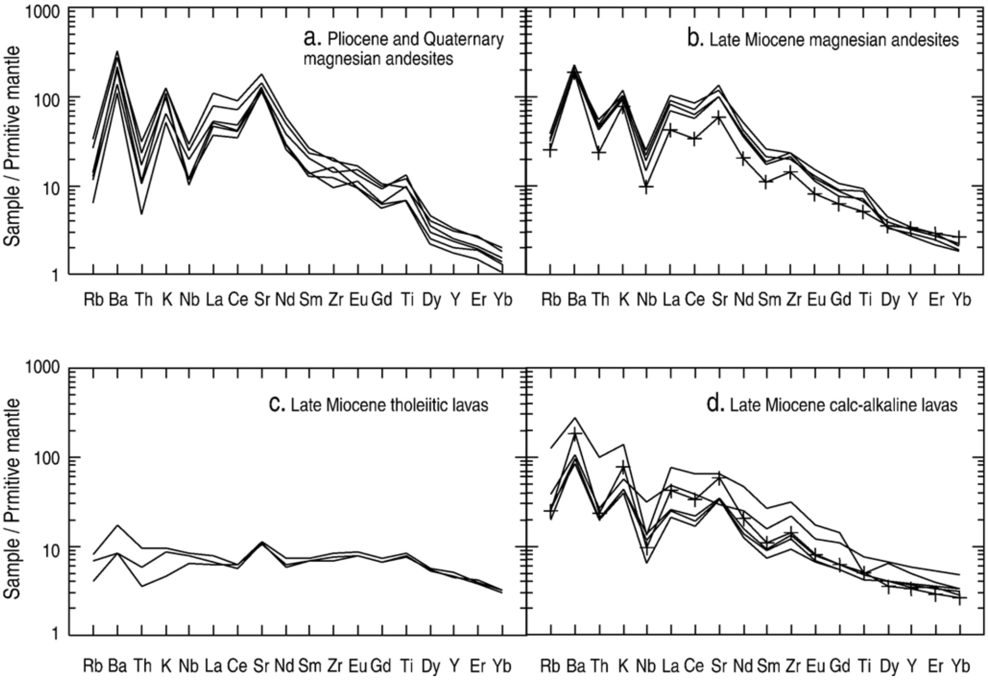

Fig. 6. Primitive mantle-normalized patterns for 19 lavas from La Purísima. Normalization values after Sun and McDonough (1989). a—Pliocene and Quaternary magnesian andesites; b—Late Miocene magnesian andesites; c—Late Miocene tholeiitic lavas; d—Late Miocene calc-alkaline lavas. Sample (cross) transitional between calc-alkaline and magnesian andesites is shown in diagrams d and b for comparison. Symbols as in Fig. 1.

5.3. Tholeiitic lavas

The low-K tholeiitic lavas are silica-oversaturated and display 53.7–54.5 wt.% SiO_2, very low K_2O (0.14–0.22 wt.%), and rather high TiO_2 (1.6–1.8 wt.%) contents (Fig. 5).Their concentrations for the most incompatible elements are low, and the corresponding multielement patterns normalized to primitive mantle (Sun and McDonough, 1989) present rather flat shapes with slight positive Nb anomalies (despite their low Nb absolute contents, 4.5–6 ppm), and stronger positive Ba, Sr, and Ti anomalies (Fig. 6c). These tholeiites are, in addition, depleted in HREE. All these characteristics, which are uncommon in arc-related magmas (Gill, 1981; Arculus, 1994), recall those of MORB-related mafic lavas (Benoit et al., 2002).

5.4. Magnesian andesites

These lavas are basalts, basaltic andesites, and rare andesites (Fig. 5) with SiO_2 contents ranging from 49 to 58 wt.%, K_2O between 2.7 to 4.2 wt.%, and MgO between 4 and 6.2 wt.%. Several Upper Miocene magnesian andesites are richer in MgO compared to their Plio-Quaternary equivalents, and they display systematically higher Na_2O contents and lower K_2O ones. Their TiO_2 contents range from 1.1 to 2.35 wt.% and reach up to 3 wt.% in some Quaternary rocks. As shown in Figs. 5 and 6, several old magnesian andesites differ from the young ones by lower Ti contents. Their primitive mantle-normalized multielement patterns (Fig. 6 a and b) show a marked negative Nb anomaly, very high positive anomalies in Ba, K, and Sr and very low heavy REE contents. HREE, especially Yb, are more depleted in Plio-Quaternary magnesian andesites than in Late Miocene ones. Their Sr/Y ratios range from 165 to 290, and in the Sr/Y vs. Y diagram (not shown) of Defant and Drummond (1990), all the studied magnesian andesites plot within the adakitic field. Negative Th anomalies are more pronounced for the Plio-Quaternary lavas.

6. Discussion

6.1. The chemical signature of magnesian andesites

Magnesian andesites ("bajaites") from La Purísima volcanic field differ from adakites by their less silicic

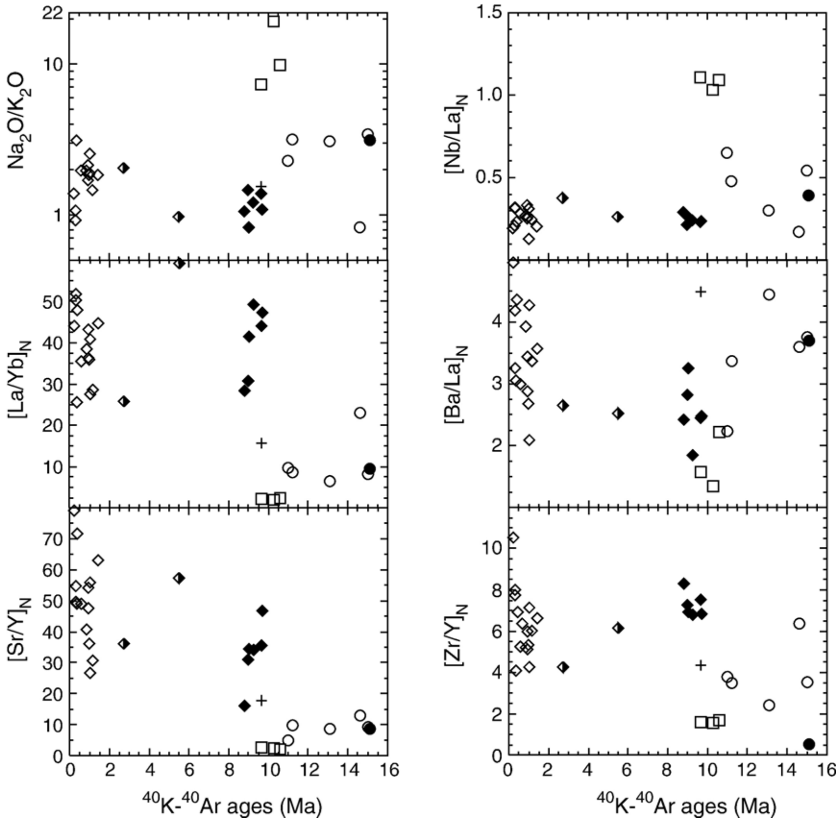

Fig. 7. Diagrams showing selected normalized geochemical ratios versus time for 33 lavas from the La Purísima. Symbols as in Fig. 1.

($SiO_2 < 57$ wt.%) character. They also display higher TiO_2 (>1.2 wt.%) and MgO (>5 wt.%) contents. Typically, adakites from Santa Clara (Aguillón-Robles et al., 2001) have $SiO_2 > 59$ wt.%, $TiO_2 < 1$ wt.%, and MgO less than 4 wt.%. In addition, the studied magnesian andesites show strong positive anomalies in Ba, K, Sr, and a pronounced positive anomaly for Ti (Fig. 6 a–c), probably related to the contribution of rutile to the melt (Prouteau et al., 2000).

$[La/Yb]_N$ ratios (25 to 50) of magnesian andesites are higher than those of the older calc-alkaline magmas (ca. 10). These ratios are almost identical in the Late Miocene and Quaternary magnesian andesites (Fig. 7), and also similar to the ratios of Holocene San Borja magnesian andesites (Saunders et al., 1987). $[Ba/La]_N$ ratios increased from the old magnesian andesites (between 2 and 3.1) to the young ones (2.0 to 4.2). Large variations of $[Ba/La]_N$ ratios among lavas from a single volcanic event may reflect variations in the amount of Ba-rich fluids derived from slab dehydration (Abratis and Wörner, 2001). $[Nb/La]_N$ ratios remain low and almost constant (0.2 to 0.4), suggesting a typical subduction-related signature. $[Sr/Y]_N$ ratios range from 20 to 50 for old magnesian andesites and from 25 to 65 for young ones. High Sr concentrations are typical of adakitic magmas derived from partial melting of a slab with a MORB composition (Defant and Drummond, 1990). $[Zr/Y]_N$ ratios (Fig. 7) are more clustered, from 0.055 to 0.070, for Upper Miocene magnesian andesites and more dispersed (0.035 to 0.070) for young ones.

The high MgO, Cr and Ni contents of the studied magnesian andesites are typical of their derivation from partial melting of mantle peridotites (Calmus et al., 2003). Fig. 8 shows that the oldest magnesian andesites are primitive and Ni-rich (>150 ppm), close to the lower compositional end of niobium-enriched basalts (NEB) from Santa Clara–Vizcaino (Aguillón-Robles et al., 2001), and that the youngest ones are more evolved and poorer in Ni (ca. 50–120 ppm). The latter plot close to the adakitic compositions from Santa Clara (Aguillón-Robles et al., 2001). Similar variations appear for Cr with the highest contents at 270 ppm for the Miocene magnesian andesites, and the lowest ones at 120 ppm for the most recent ones. Pliocene and Early Quaternary magnesian andesites show typically intermediate concentrations for both Ni and Cr. In the Co vs. Mg# diagram, magnesian andesites plot close to the adakites, but still in an intermediate position between NEB and adakitic compositions.

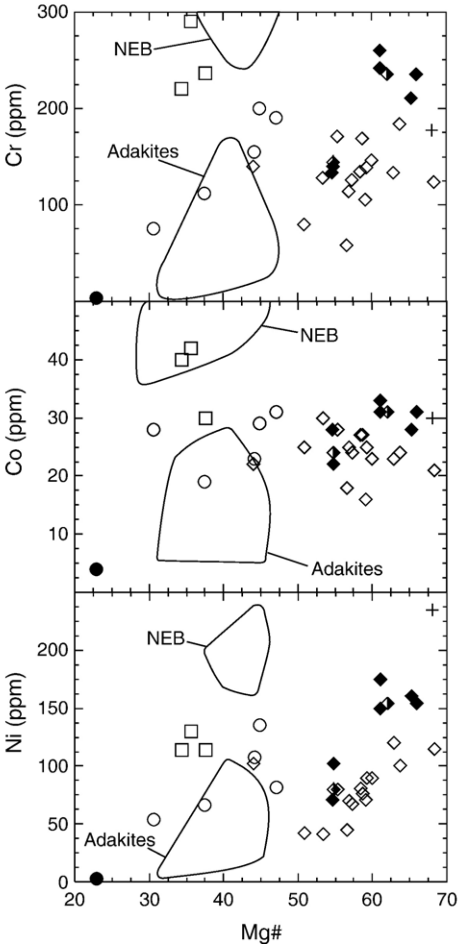

Fig. 8. Compatible element abundances versus Mg number for 33 lavas from the La Purísima. Mg# $[100 \times Mg/(Mg+Fe^{2+})]$ calculated with $FeO = Fe_2O_3\ _{total} \times 0.85$. Outlined areas for adakites and Nb enriched basalts (NEB) refer to the Santa Clara lavas (Vizcaino Peninsula, Baja California), according to Aguillón-Robles et al. (2001).

6.2. Possible origins of magnesian andesites

Some of the geochemical characteristics of magnesian andesites from La Purísima volcanic field suggest a strong relation with slab melting. Aguillón-Robles et al. (2001), Benoit et al. (2002), and Calmus et al. (2003) proposed that the adakitic lavas from Baja California Sur are derived from melting of young subducting oceanic crust, and that the magnesian andesites are derived from the interaction of these adakitic liquids with the mantle wedge, a metasomatic model basically similar to that previously developed by Rogers et al. (1985) and Saunders et al. (1987) for the magnesian andesites of northern Baja California, especially the Jaraguay and San Borja volcanic fields. The source of tholeiitic lavas may be related to deep sub-oceanic mantle associated with an asthenospheric window (Benoit et al., 2002). The occurrence of both volcanic suites may indicate that subduction and related magmatic processes continued well after the end of typical calc-alkaline Miocene volcanism in Baja California Sur. Similar magmatic associations have been previously described in many active subduction zones characterized by a high thermal gradient related to different geodynamical frameworks: subduction of young oceanic crust, as in southwest Japan (Tatsumi, 2001); active ridge subduction as in the present-day example of the Chile triple junction area (Bourgois et al., 1996; Lagabrielle et al., 2000), or the extinct ridge subduction in Costa Rica (Abratis and Wörner, 2001); highly oblique subduction resulting in slab tearing, e.g., in the Aleutians (Yogodzinski et al., 1995; 2001).

6.3. Tectonic framework of magnesian andesite emplacement

The strong slab-melt characteristics of the studied magnesian basalts, basaltic andesites and andesites (Defant and Drummond, 1990) suggest that the origin of these Late Miocene to Quaternary “bajaitic” magmas (less than 10 Ma old) may be linked either to the subduction of a very young part of the Guadalupe plate and/or that of the spreading center between the Guadalupe and Pacific plates, respectively (Calmus et al., 2003). In the latter hypothesis, which is consistent with the occurrence of adakites in Santa Clara volcanic field (Aguillón-Robles et al., 2001), subduction of the still active Pacific–Guadalupe spreading center would have led to the opening of an asthenospheric window below Baja California Sur. This window would represent the southward extension of the slab window proposed below northern Baja California (Rogers et al., 1985; Saunders et al., 1987; Dickinson, 1997; Calmus et al., 2003).

This hypothesis is at odds with previous (and widely accepted) geological models for the evolution of the Baja California Peninsula margin, which propose the end of the subduction event at 12.5 Ma, contemporaneous with the extinction of the Pacific–Guadalupe spreading center (e.g., Mammerickx and Klitgord, 1982; Lonsdale, 1991). The existence of a remnant Guadalupe plate off Baja California Sur is based on ages of 14.5 to 15 Ma sediments (Yeats and Haq, 1981) drilled at the Deep Sea Drilling site 471 (Fig. 1), which are consistent with the ages of the seafloor and with the interpretation of spreading cessation. At 12.5 Ma, the triple junction between Pacific, Farallon and North America plates was located approximately at the latitude of the Vizcaino Peninsula. North of the Guadalupe fault zone, subduction of the spreading ridge produced the formation of an asthenospheric window below California and part of northern Baja California (Dickinson and Snyder, 1979; Dickinson, 1997; Atwater and Stock, 1998). After 12.5 Ma, the subduction regime is assumed to have been replaced by the development of a transform boundary between the Pacific and North America plates along the San Benito–Tosco–Abreojos right-lateral fault, parallel to the Pacific margin of Baja California (Spencer and Normark, 1989), until 5.5 Ma when the transform motion shifted to the Gulf of California.

Recently, data from the FAMEX cruise (Michaud et al., 2004) have confirmed the occurrence of an extinct ridge segment west of Vizcaino Peninsula, and thus are inconsistent with any hypothesis involving subduction of the Pacific–Guadalupe ridge axis and a migration of the triple junction from Vizcaino to the south between 12 and 5–4 Ma (e.g., Bourgois and Michaud, 2002). The occurrence of a slab window beneath La Purísima area at ca. 10 Ma (Benoit et al., 2002) is consistent with the emplacement, from 11.2 to 8.7 Ma, of slab melts (adakites) and associated NEB in the Santa Clara volcanic field located ca. 200 km NW of La Purísima (Aguillón-Robles et al., 2001). Moreover, the occurrence north and northwest of La Purísima volcanic field of “anorogenic” tholeiitic magmas (10.6 and 9.3 Ma old) suggests a contribution of the deep subslab mantle, for which the hypothesis of development of an asthenospheric window provides a likely explanation (Benoit et al., 2002). Van den Beukel (1990) has shown that the collision of an active ridge with the trench can result into the detachment of the deep (and old) part of the downgoing oceanic plate. This process leads to the formation of a tear-in-the-slab inside its young (and still hot) part, which can evolve then into a wide asthenospheric window during slab breakoff (Davies and von Blanckenburg, 1995). Melting of the young oceanic crust from the edges of such a tear may occur (Yogodzinski et al., 2001), leading to the emplacement of adakites and adakite-related lavas such as NEB and magnesian andesites above the upper and lower lips of the developing asthenospheric window (Benoit et al., 2002; Thorkelson and Breitsprecher, 2005).

Presently we cannot propose a timing for the evolution of this asthenospheric window. Its present-day occurrence beneath La Purísima volcanic field seems rather unlikely, as the lack of post-Late Miocene tholeiites suggests that the subslab mantle did not melt anymore after 9.3 Ma. However, magnesian andesitic volcanism remained active until the Quaternary. As these magmas are likely to be derived from slab melt-metasomatised mantle peridotites, as already pointed out by Rogers et al. (1985) and Saunders et al. (1987), melting of such sources may occur in other tectonic contexts. The most likely of them is extension related to the opening of the Gulf of California, as the emplacement of young magnesian andesites from La Purísima volcanic field was largely associated by NW–SE trending normal faults and grabens parallel to the Gulf.

The geochemical diversity of volcanic rocks encountered in La Purísima volcanic field, and more generally in northern Baja California Sur, reflects major progressive tectonic changes, and the synchronism between the end of the subduction of the Guadalupe plate and the beginning of the continental breakup along the nascent Gulf of California during Late Miocene and Early Pliocene. A similar complex relationship between different synchronous magmatic sources is known in the western part of the Trans-Mexican volcanic belt, mainly in the States of Jalisco and Tepic, including basalts with oceanic-island characteristics, or intraplate alkaline basalts coexisting with calc-alkaline basalt (Righter, 2000) The presence of oceanic-island basalt is interpreted in different ways: (i) the extensional regime related with the rifting and the migration of the Jalisco block (e.g., Wallace et al., 1992); (ii) the progressive opening, from west to east along the Trans-Mexican volcanic belt, of a rift associated with a plume activity (Márquez et al., 1999); (iii) a detachment of the slab that began beneath the present southern Gulf of California, just before the subduction of the Farallon plate below North America plates ended, and the inflow of asthenospheric material into the upper plate mantle through a slab window (Ferrari, 2004). Following that model, the volcanism of La Purísima area, together with the peculiar Late Miocene magmatic pulse of the Vizcaino Peninsula (Aguillón-Robles et al., 2001, Benoit et al., 2002) suggests that the opening of the slab window may have initiate beneath the Vizcaino Peninsula rather than the present mouth of the Gulf of California.

7. Conclusions

The Miocene calc-alkaline volcanic activity of La Purísima area was related to the subduction of the Farallon and Guadalupe plates below Baja California. Significant and sudden geochemical changes occurred during the Late Miocene, when magnesian andesites and tholeiites erupted between 10.6 and 8.8 Ma, coevally with both adakites (11 to 8.7 Ma) and Nb-enriched basalts (11.2 to 9.5 Ma) from Santa Clara volcanic field (Aguillón-Robles et al., 2001).

This variety of volcanic rocks reflects the diversity of magmatic sources during this period, associated with melting of hot oceanic lithosphere and opening of a slab window. The presence of a slab window below southern Baja California during the Late Miocene seems to be required to explain the very peculiar magmatic association between adakites and niobium-enriched basalts encountered in Santa Clara, the tholeiites and magnesian andesites of La Purísima and neighboring areas (Benoit et al., 2002), and finally the adakites of Margarita Island (Bonini and Baldwin, 1998). We propose that subduction was blocked by the arrival near the trench of the Pacific–Guadalupe spreading center at ca. 12.5 Ma off Vizcaino Peninsula.

Then, a tear-in-the slab developed within very young crust because of the sinking of the deep part of the down going plate. It evolved towards a slab window, the upper and lower edges of which experienced partial melting. The resulting adakitic magmas were either emplaced at the surface or reacted with the lithospheric mantle, generating NEB and magnesian andesites, while tholeiites mainly derived from the subslab mantle ascended through the asthenospheric window. Finally, magnesian andesites emplaced during events 3, 4 and 5 could have resulted from melting of previously slab melt-metasomatised mantle during extension and heating related to the opening of the Gulf of California.

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