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Slab-tearing following ridge-trench collision: Evidence from Miocene volcanism in Baja California, México

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Abstract

Neogene magmatic activity in Central Baja California underwent a major change at ca. 12.5 Ma, when the Pacific–Farallon active oceanic ridge collided with the trench east of Vizcaíno Peninsula. The calc-alkaline magmatism which built the Comondú volcanic arc vanished and was replaced by unusual volcanic associations, which were erupted within six Late Miocene to Quaternary volcanic fields (Jaraguay, San Borja, San Ignacio, Santa Rosalía, Santa Clara, La Purísima), delineating a 600 km array along the Baja California Peninsula.

New fieldwork, K–Ar datings and geochemical analyses on Jaraguay and San Borja lavas, combined with previous data, allow us to show that these associations include: (1) adakites emplaced between 12.5 and 8.2 Ma in the Santa Clara, Santa Rosalía and Jaraguay volcanic fields; (2) niobium-enriched basalts (NEB) in Santa Clara and Santa Rosalía (11.2 to 7.4 Ma); (3) tholeiitic basalts and basaltic andesites (11.3 to 7.2 Ma) displaying a very weak subduction imprint in La Purísima and San Ignacio; (4) alkali trachybasalts in Mesas San Carlos and Santa Catarina, northwest of Jaraguay (9.3 to 7.5 Ma), and finally (5) basalts and associated magnesian basaltic andesites and andesites. Locally referred to as "bajaites", the latter lavas display very specific geochemical characteristics, including very high Sr and Ba contents. They were emplaced in all the above-mentioned volcanic fields between 14.6 and 5.3 Ma.

The origin of these Late Miocene volcanics has been considered linked either to the opening of an asthenospheric window through which they ascended (tholeiites and alkali trachybasalts), or to the melting of its edges due to thermal erosion (adakites) and the subsequent reaction between adakitic melts and the supraslab mantle (NEB and "bajaites"). However, the identification of the remnants of the Pacific–Farallon fossil ridge south of Vizcaíno Peninsula indicates that active ridge subduction was not responsible for the opening of the asthenospheric window. We propose that the emplacement of slab window-related volcanic rocks between 13 and 7 Ma from ca. 25°N to 30°N, was due to a process of slab-tearing, which started when the active ridge collided with the trench east of Vizcaíno Peninsula. The oldest part of the downgoing plate sunk into the mantle, leading to the opening of a

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tear-in-the-slab, which likely started from the southern limit of the already existing Southern California slab window. It propagated parallel to the trench over about 600 km and developed into an asthenospheric window.
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1. Introduction

The Cenozoic magmatic history of the western margin of North America has been largely controlled by the subduction of the Farallon oceanic lithosphere, generating abundant calc-alkaline volcanism. However, it was also characterized by the eruption of magmatic types uncommon in a subduction context, e.g. alkali basalts and related rocks displaying Ocean Island Basalt (OIB) geochemical signatures in California (Dickinson, 1997) and México (Ferrari, 2004), and magnesian andesites of adakitic affinity ("bajaites") in Baja California (Rogers et al., 1985; Calmus et al., 2003). The emplacement of these unusual volcanic rocks has been ascribed to the opening of asthenospheric windows in the subducting Farallon plate (Rogers et al., 1985; Saunders et al., 1987; Hole et al., 1991; Cole and Basu, 1995; Dickinson, 1997; Ferrari, 2004).

The tectonic evolution of the North American margin has been marked by the approach of several oceanic spreading ridges, which have either collided with it or been subducted beneath it (Atwater, 1970; Dickinson and Snyder, 1979). These interactions lead to the opening of asthenospheric windows following either ridge subduction (Thorkelson, 1996) or slab-tearing due to the detachment of the deep part of the subducted plate after ridge-trench collision (van den Beukel, 1990; Yoshioka and Wortel, 1995). More specifically, during the Tertiary subduction of the Farallon plate beneath the North American margin, the active Pacific–Farallon ridge approached the trench and the corresponding triple junction migrated towards the south during the Miocene (Atwater, 1970; Mammerickx and Klitgord, 1982; Atwater, 1989). Therefore, the subduction of this active ridge below Southern California and northernmost Baja California at ca. 20 Ma caused the formation of a ridge-related asthenospheric window (Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989; Dickinson, 1997; Atwater and Stock, 1998), the size of which increased progressively through thermal erosion of its edges (Dickinson and Snyder, 1979; Severinghaus and Atwater, 1990). The spatial distribution and ages of magmatic rocks unrelated to "regular" calc-alkaline series have been used to constrain the geometry of the subducting slabs, and especially to locate slab tears or slab windows within which magma genesis was triggered by decompression melting of upwelling mantle (Dickinson and Snyder, 1979; Dickinson, 1997; Wilson et al., 2005). For instance, the evolution of the edges of the Southern California slab window has been reconstructed at 18.9, 17.5, 16.0 and 14.5 Ma (Wilson et al., 2005).

Late Oligocene to Miocene calc-alkaline magmatism in Baja California led to the emplacement of the Comondú arc all along the Peninsula from ca. 25 to 16–11 Ma (Gastil et al., 1979; Martín et al., 2000). Although calc-alkaline volcanism continued sporadically until the Quaternary, it was largely replaced during the Upper Miocene by the emplacement of a complex magmatic association including adakites and associated niobium-enriched basalts (NEB: Aguillón-Robles et al., 2001), magnesian andesites, and tholeiitic basaltic andesites showing only a weak subduction imprint (Benoit et al., 2002). The emplacement of this association has been ascribed to the opening of an asthenospheric window due to the subduction of a spreading ridge (Benoit et al., 2002; Bourgois and Michaud, 2002). However, this hypothesis seems inconsistent with the occurrence, east of the Vizcaíno Peninsula and Baja California Sur, of abandoned spreading centers along the Magdalena Rise (Michaud et al., 2004, 2005, 2006) as originally hypothesized by Mammerickx and Klitgord (1982) and Lonsdale (1991). Thus, another hypothesis than ridge subduction has to be found to explain the unusual composition of Late Miocene volcanics from Baja California.

In this paper, we present new field, petrologic and geochronometric (^{40}K–^{40}Ar) evidence for the occurrence in the Jaraguay and San Borja volcanic fields (Baja California State) of Late Miocene adakites, alkali trachybasalts and magnesian andesites, emplaced since 11 Ma. Combining our results with previously published data on similar rocks and tholeiites from Baja California Sur (Aguillón-Robles et al., 2001; Benoit et al., 2002; Calmus et al., 2003; Conly et al., 2005; Bellon et al., 2006), we are able to trace the location and extent of an asthenospheric window which developed below the Peninsula between ca. 13 and 7 Ma. Then we discuss the origin of this window taking into account recent data on the structure and ages of the fossil ridges abandoned west of the Peninsula, and their incidence on the Late

Miocene history of the Guadalupe and Magdalena plates (Michaud et al., 2006). We will show that a model of slab-tearing followed by the detachment of the deep part of the subducted oceanic plate accounts for the magmatic successions on land (Calmus et al., 2003; Bellon et al., 2006) as well as for the kinematic history of the Pacific–Farallon plate.

2. Geological setting and magma types

2.1. Tectonic evolution of Baja California during the Neogene

The western active margin of North America has experienced a complex Cenozoic history involving the subduction of the Mesozoic Kula and Farallon oceanic plates. During the Paleogene, subduction-related magmatism built the Sierra Madre Occidental belt in México. Then, during Lower Miocene, the volcanic front migrated towards the west, building the Comondú magmatic arc (Fig. 1) which developed all along the Baja California Peninsula (Atwater, 1989; Lonsdale, 1991; Stock and Lee, 1994).

The active Pacific–Farallon ridge progressively subducted below California and northernmost Baja California, causing the formation of asthenospheric windows (Dickinson and Snyder, 1979; Dickinson, 1997; Atwater and Stock, 1998). However, its southern segments, Magdalena, Guadalupe and Soledad (Fig. 2) were abandoned off southern and central Baja California when subduction stopped at ca. 12.5 Ma (Mammerickx and Klitgord, 1982; Stock and Hodges, 1989; Lonsdale, 1991), leading to the extinction of the Comondú arc and to the breakup of Guadalupe plate into the remnant Guadalupe plate and the Magdalena plate, separated by the Shirley FZ (Fig. 2). The remnant Guadalupe plate off Vizcaíno Peninsula is documented by bathymetric and magnetic anomaly data showing the well-preserved axial trough of its fossil ridge (Batiza and Chase, 1981; Lonsdale, 1991), as well as by the 15 to 14.5 Ma ages of sediments drilled at Deep Sea Drilling Site 471 (Yeats and Haq, 1981). South of the Shirley FZ, the seafloor fabric was poorly known and the age of the oceanic crust not well constrained, casting some doubts about the presence of a Pacific–Magdalena fossil ridge (Lonsdale, 1991; Muller et al., 1997). Thus, the occurrence of Late Miocene adakites, magnesian andesites and tholeiites in Baja California Sur was first interpreted as indicative of the opening of an asthenospheric window which followed the subduction of the Pacific–Magdalena Ridge (Aguillón-Robles et al., 2001; Benoit et al., 2002; Bourgois and Michaud, 2002).

Swath bathymetry magnetic and seismic profiles collected off Baja California Sur during the Famex cruise (R/V *L'Atalante*, April 2002) clearly evidence several abandoned spreading centers along the Pacific–Magdalena Ridge (Michaud et al., 2004, 2005, 2006). Prior to their extinction, which may have occurred as late as 8–7 Ma, these spreading segments accommodated part of the transcurrent motion between the Pacific and North American plates. Then, this motion was progressively transferred to the Tosco–Abreojos dextral strike-slip fault (Spencer and Normark, 1989), which propagated southwards (Michaud et al., 2006). The rapid slowdown of spreading and demise of the Guadalupe and Magdalena ridges are best explained by the removal of slab pull. The clockwise rotation and break-up of the Pacific–Magdalena Ridge into a series of short segments is attributed to an increasing coupling between the Magdalena and North American plates, which ended when the Tosco–Abreojos fault and the Gulf of California took up all the Pacific–North America dextral shear motion (Michaud et al., 2006). This observation thus indicates that subduction along Baja California stopped at ca. 12 Ma, when the Farallon slab detached from the Guadalupe and Magdalena plates.

2.2. Distribution of Neogene volcanism

The prominent feature of Neogene volcanism in Baja California is the Comondú Late Oligocene to Middle Miocene calc-alkaline arc (Hausback, 1984; Umhoefer et al., 2001). It extends all along the eastern part of the Peninsula from 32°N to 24°N (Fig. 1), mostly as coalescent stratovolcanoes, which form its main ridge. Medium-K to high-K andesites are prominent, with subordinate dacites, basaltic andesites and basalts. This volcanic belt was active between 21 and 15 Ma in northern Baja California peninsula (Martín et al., 2000), and from 24 to 11 Ma in Baja California Sur state (Sawlan and Smith, 1984; Sawlan, 1991) where it is more developed. Its extinction is generally considered as a consequence of the end of the subduction at ca. 12.5 Ma (Stock and Hodges, 1989; Martín et al., 2000). However, limited calc-alkaline activity persisted during the Plio-Quaternary (Fig. 1), e.g. in Cerro Mencenares (Bigioggero et al., 1995), Tres Virgenes volcano (Capra et al., 1998), La Reforma caldera (Demant, 1984) and Isla San Esteban (Desonie, 1992).

Magmatic types other than calc-alkaline ones are generally younger and occur in front-arc position with respect to the Comondú arc (Fig. 1). A summary of their petrographic and geochemical features has been presented by Benoit et al. (2002). Five types can be

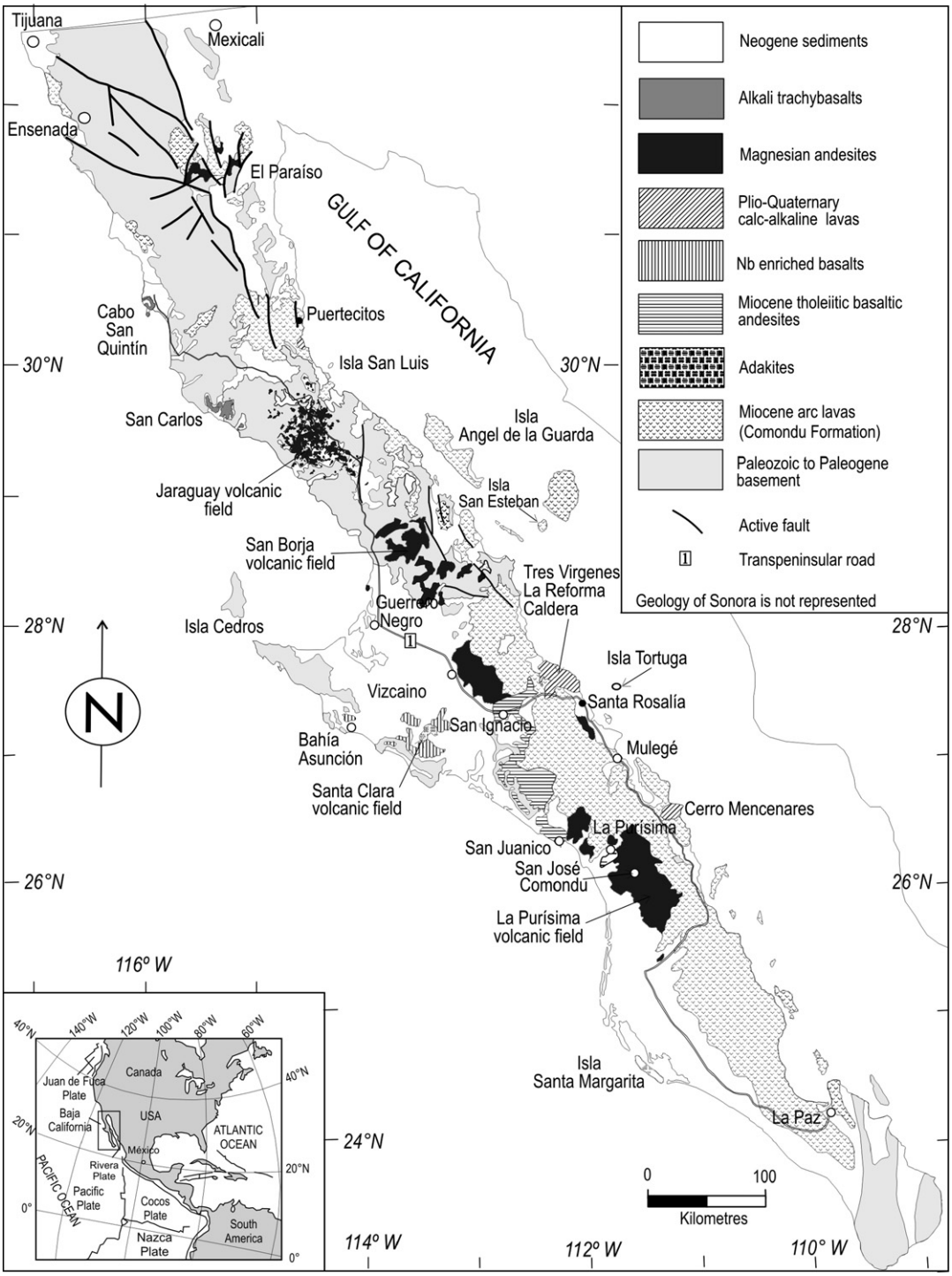


Fig. 1. Geological sketch map of Baja California, showing the major Neogene volcanic fields and the distribution of the main lava types. The regional geology is modified from Ortega-Gutiérrez et al. (1992) and Calmus et al. (2003).

distinguished: adakites; niobium-enriched basalts (NEB) spatially and temporally associated to adakites; magnesian basaltic andesites, andesites and basalts displaying very specific geochemical features, and termed "bajaites" by Rogers et al. (1985); tholeiitic basaltic andesites displaying only a weak subduction imprint;

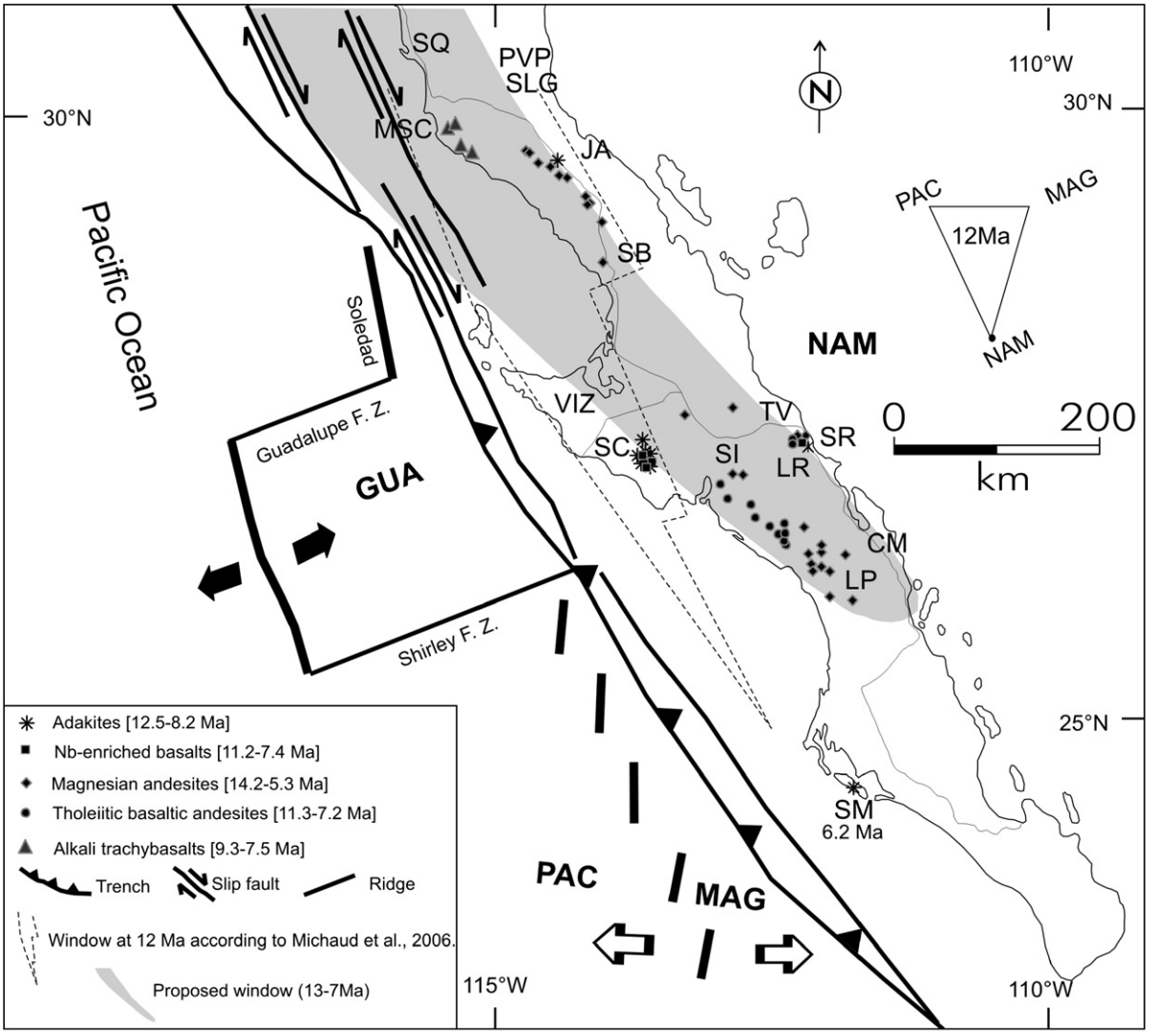


Fig. 2. Sketch of Baja California showing the locations and types of Miocene lavas together with Late Miocene structural elements of the adjacent Pacific Ocean and the Baja margin (slightly modified from Michaud et al., 2006). GUA: Guadalupe plate; NAM: North America plate; MAG: Magdalena plate; PAC: Pacific plate. Abbreviations for volcanic fields/localities discussed in the text are as follows: JA: Jaraguay; CM: Cerro Mencenares; LP: La Purísima; LR: La Reforma; MSC: Mesas San Carlos and Santa Catarina; PVP: Puertecitos Volcan Prieto; SB: San Borja; SC: Santa Clara; SI: San Ignacio; SLG: San Luis Gonzaga; SQ: San Quintín; SR: Santa Rosalía; TV: Tres Virgenes; VIZ: Vizcaíno. Locations of Late Miocene non-calc-alkaline lavas are shown; their ages are reported in Fig. 5 with the exception of those of a tholeiite from El Paraiso (6 Ma; Aguillón-Robles, 2002) and of an adakite from Santa Margarita Island (6.2 Ma; Bonini and Baldwin, 1998).

and finally OIB-type alkali basalt-related trachybasalts (hawaiites).

These lavas range in age from Late Miocene to Quaternary and are found in several volcanic fields, which include from south to north (Fig. 1): La Purísima–San José Comondú (Bellon et al., 2006); Santa Clara (Aguillón-Robles et al., 2001) located in the Vizcaíno Peninsula; San Ignacio (Benoit et al., 2002); Santa Rosalía (Conly et al., 2005); San Borja; Jaraguay; the revisited San Carlos volcanic field; and San Quintín area (Luhr et al., 1995). We present in this paper new petrologic and age data for Miocene lavas from San Borja, Jaraguay and San Carlos volcanic fields which had not been investigated in detail, except in the framework of a comparative study of magnesian andesites (Calmus et al., 2003). Corresponding data for the other areas are mostly taken from the above-mentioned papers, in which the major and trace element analyses and ^{40}K–^{40}Ar datings were done in the same laboratory and using the same analytical methods that those presented in this paper.

Table 1
Chemical analyses of Miocene lavas from Baja California (San Borja, Jaraguay and San Ignacio volcanic fields and San Carlos–Santa Catarina Mesas)

Sample	BC05-01	BC05-03	BC05-42	BC05-40	BC05-30	BC05-18	BC05-101	BC05-103	BC05-17	BC05-102
Rock type	CA	CA	CA	CA	CA	ATB	ATB	ATB	ATB	ATB
Age (Ma)	20.30±0.52	20.06±0.51	14.64±0.46	10.93±0.32	7.30±0.40	9.38±0.31	8.68±0.36	7.63±0.19	7.53±0.22	
Major elements (wt.%)										
SiO_2	57.80	50.00	54.50	50.50	55.75	48.60	48.20	49.10	48.50	48.2
TiO_2	0.66	1.01	0.84	1.53	0.42	3.86	2.80	2.74	2.53	2.8
Al_2O_3	17.05	16.60	15.20	14.90	15.80	14.40	14.70	14.90	14.65	14.5
$Fe_2O_3^*$	6.47	8.50	7.22	9.65	5.86	11.65	10.40	10.35	10.75	10.3
MnO	0.12	0.14	0.12	0.15	0.10	0.13	0.14	0.14	0.15	0.14
MgO	4.60	6.55	6.64	7.76	8.57	5.62	7.52	6.92	6.93	7.09
CaO	7.20	11.00	8.62	9.75	7.70	8.45	7.00	7.75	7.55	8.2
Na_2O	4.06	3.00	3.37	3.28	3.82	3.80	3.78	4.17	3.64	4.05
K_2O	0.94	1.20	1.38	1.21	0.84	1.33	2.00	2.01	1.58	1.96
P_2O_5	0.18	0.24	0.26	0.44	0.13	0.82	1.02	1.03	0.77	1.03
LOI	1.06	2.19	1.40	0.71	0.34	0.84	1.93	0.25	2.40	1.36
Total	100.14	99.61	99.55	99.88	99.33	99.50	99.49	99.36	99.45	99.63
CIPW minerals										
Q	9.30	0	3.87	0	2.43	1.20	0	0	0	0
ne	0	0	0	0	0	0	0	0.65	0	1.55
hy	11.61	5.10	14.67	8.80	20.83	7.56	5.33	0	9.72	0
mg#	70.03	70.07	68.18	65.20	77.31	52.92	62.75	60.91	60.03	61.60
Trace elements (ppm)										
Rb	12.2	14.5	21.3	14.5	9.0	18.8	29.0	28.5	22.8	26.0
Ba	324	690	770	688	555	325	380	480	281	390
Th	1.40	2.25	2.75	4.85	1.20	2.90	3.70	3.80	2.95	3.75
Nb	3.0	5.0	7.0	9.7	1.4	48.0	57.0	56.0	45.0	56.0
La	9	16.2	19.5	26.0	9.0	36.0	44.0	43.0	34.5	43.0
Ce	19.5	35.0	41.0	58.0	18.5	83.0	102.0	100.0	77.0	100.0
Sr	467	780	570	670	690	694	850	865	620	850
Nd	12.3	22.0	20.5	32.0	8.9	55.0	62.0	61.0	46.0	59.0
Sm	2.90	4.60	4.20	6.40	1.80	12.20	13.00	12.70	10.30	13.00
Zr	109	130	160	181	69	403	450	460	375	460
Eu	0.93	1.40	1.25	1.80	0.55	3.75	4.00	3.90	3.10	4.00
Gd	3.00	4.50	4.10	5.70	1.80	10.70	10.60	10.40	8.80	11.20
Dy	2.80	4.00	3.45	4.85	1.65	7.35	7.10	6.95	6.40	7.10
Y	17.5	24.0	21.0	28.0	10.2	34.8	34.0	32.5	31.0	33.0
Er	1.75	2.30	2.00	2.60	1.05	2.80	2.70	2.60	2.65	2.70
Yb	1.69	2.18	1.93	2.52	1.04	2.06	2.08	2.06	2.06	2.08
Sc	18.0	28.5	20.0	27.0	19.5	16.5	17.5	17.5	19.0	17.0
V	137	235	138	238	143	240	195	195	202	195
Cr	155	170	160	274	295	120	215	230	210	210
Co	22.5	31.5	33	40	30	41	40	39	41	40
Ni	70	50	162	154	235	135	200	210	184	200

ICP-AES analyses according to the procedures described by Cotten et al. (1995). Fe_2O_3*: total iron as Fe_2O_3; LOI: Loss on Ignition; Q: normative quartz; ne: normative nepheline; hy: normative hypersthene; mg#=Mg/(Mg+Fe^{2+}). CIPW norm and mg# calculated with 15 at.% of total iron as Fe^{3+} and 85% as Fe^{2+}. CA: calc-alkaline lavas; ATB: alkali trachybasalts; AD: adakite; MA: magnesian andesites.

Therefore, in addition to the 21 new samples analyzed in Table 1, among which 19 were dated (Table 2), we collected data on 53 other Miocene samples. They include: 5 magnesian andesites, 1 tholeiite and 1 calc-alkaline lava from La Purísima–San José Comondú (Bellon et al., 2006); 5 adakites and 4 NEB from Santa Clara (Aguillón-Robles et al., 2001); 2 adakites and 2 NEB from Santa Clara, and 8 tholeiites, 3 magnesian andesites and 8 calc-alkaline lavas from San Ignacio and La Purísima (Benoit et al., 2002); 1 adakite, 2 tholeiites, 1 NEB and 1 calc-alkaline lava from Santa Rosalía (Conly et al., 2005); and finally 6 magnesian andesites

BC05104	BC05-29A	BC05-38	BC05-46	BC05-02	BC05-47	BC05-50	BC05-19	BC05-28	BC05-31	BC05-20
ATB	AD	MA	MA	MA	MA	MA	MA	MA	MA	MA
	9.40±0.33	10.80±0.29	10.78±0.26	9.43±0.22	8.12±0.22	6.79±0.22	6.30±0.30	5.77±0.28	5.54±0.22	5.32±0.24
49.85	62.80	55.60	53.50	55.50	53.20	54.8	52.00	56.65	53.60	52.60
2.62	0.52	0.95	1.55	1.20	1.62	1.52	0.67	0.58	1.99	0.68
15.00	16.00	15.25	14.30	15.65	14.4	15.8	16.85	15.75	15.35	17.25
10.2	3.50	5.90	6.43	7.55	6.92	6.55	6.83	5.62	6.78	6.92
0.14	0.05	0.09	0.09	0.12	0.10	0.08	0.12	0.09	0.09	0.12
7.00	3.48	7.20	6.92	3.36	7.81	5.47	7.80	7.74	5.66	7.08
7.45	5.17	6.90	8.05	6.65	7.45	7.8	9.10	7.04	8.40	9.15
4.25	4.21	4.12	3.93	4.39	4.03	4.56	3.70	3.87	4.20	3.90
2.03	1.68	2.14	2.78	3.51	2.38	1.81	1.03	1.16	2.18	1.04
1.00	0.16	0.42	0.90	0.79	0.69	0.66	0.30	0.18	0.82	0.30
−0.04	1.78	0.47	0.62	0.69	0.37	0.65	1.02	0.38	0.49	0.57
99.5	99.35	99.04	99.07	99.41	98.97	99.7	99.42	99.04	99.56	99.61
0	17.55	1.27	0	0.97	0	1.61	0	4.64	0.97	0
0.02	0	0	0	0	0	0	0	0	0	0
0.00	7.13	15.02	7.68	6.56	8.66	8.44	9.85	18.60	7.07	9.16
61.53	69.85	73.98	71.49	50.91	72.45	66.06	72.69	76.24	66.05	70.45
28.8	22.0	26.5	28.8	67.5	16.0	7.3	7.4	10.6	18.8	7.4
650	770	1450	2150	2625	1800	815	1035	650	1350	705
3.60	4.15	10.70	13.00	13.30	7.50	1.55	1.65	2.15	5.95	1.70
54.0	2.1	7.3	16.0	13.8	10.9	8.0	3.9	2.5	11.0	3.8
43.0	13.8	44.5	77.0	79.5	45.0	27.0	18.0	14.0	49.0	18.0
100.0	29.0	94.0	160.0	157.0	98.0	62.0	37.5	31.0	111.0	36.5
870	982	1500	2200	1670	1930	2140	840	905	2200	872
59.0	15.0	42.0	76.0	85.0	44.0	34.0	19.0	15.0	54.5	19.0
12.50	2.85	6.70	11.40	14.30	6.70	5.65	3.60	2.90	9.05	3.45
470	124	212	310	476	224	145	97	99	272	100
3.80	0.83	1.64	2.62	3.26	1.66	1.58	1.02	0.78	2.32	1.03
10.70	2.40	4.70	6.80	10.00	4.15	3.70	3.05	2.20	5.50	3.20
6.80	1.30	2.70	3.25	5.60	2.30	1.90	2.40	1.55	2.85	2.50
31.0	7.4	15.0	15.8	31.5	11.5	8.8	14.6	9.0	14.2	15.4
2.60	0.70	1.30	1.30	3.00	1.00	0.70	1.45	0.90	1.30	1.50
2.01	0.59	1.21	1.02	2.20	0.84	0.59	1.40	0.82	0.95	1.44
17.0	8.4	13.3	14.0	19.0	14.0	12.7	22.5	17.4	15.5	23.0
190	71	128	162	222	187	180	194	135	187	195
22.5	120.0	250.0	300.0	14.0	300.0	185.0	250.0	230.0	197.0	246.0
38	14	26	25	21	33	26	30	27	23	30
205	98	227	210	27	275	140	162	222	134	152

from Santa Rosalía and 3 from San Borja and Jaraguay (Calmus et al., 2003).

The main locations of these lavas are shown schematically in Fig. 1. The magnesian andesites and related lavas (i.e. the "bajaites"), are by far the most common (Calmus et al., 2003), especially in La Purísima–San José Comondú where they range in age from Late Miocene to Holocene, Santa Rosalía (Late Miocene), San Ignacio (Pliocene), San Borja (Late Miocene, Pliocene and Quaternary) and Jaraguay (Late Miocene and Pliocene). They commonly crop out as viscous lava flows emitted along fissures, which display a very irregular and blocky

Table 2
^{40}K–^{40}Ar datings of Miocene lavas from Baja California (San Borja, Jaraguay and San Ignacio volcanic fields and San Carlos–Santa Catarina Mesas)

Sample	Field	Age in Ma	Mean age	Coordinates		$^{40}Ar_R$	$^{40}Ar_R$ / $^{40}Ar_T$ (%)	K_2O	Fraction	Ref.
		±1σ	in Ma±1σ	Latitude N	Longitude W	(10^{-7} cm^3/g)		(wt.%)		Analysis
Adakites: Jaraguay (JA)										
BC0529A	JA	9.40±0.33		29°31′08.6″	114°29′48.7″	5.104	29.5	1.68	WR	B6906
Magnesian andesites: Jaraguay (JA), San Borja (SB), San Ignacio (SI)										
BC05-20	JA	5.32±0.24		29°15′58.6″	114°14′59.4″	1.769	21.3	1.03	WR	B6896
BC05-31	JA	5.54±0.22		29°30′81.2″	114°30′06.9″	3.899	24.9	2.18	WR	B6898
BC05-28	JA	5.77±0.28		29°28′50.8″	114°27′46.5″	2.159	19.5	1.16	WR	B6905
BC05-19	JA	6.30±0.30		29°15′57.5″	114°15′06.0″	2.095	20.2	1.03	WR	B6948
BC05-50	SI	6.92±0.21	6.79±0.22	27°34′12.3″	113°20′0.07″	4.180	34.8	1.87	WR	B6809
		6.66±0.22				4.023	34.4			B6821
BC05-47	SB	8.12±0.22		28°38′58.2″	114°00′30.0″	5.960	46.1	2.33	WR	B6858
BC05-02	SI	9.37±0.22	9.43±0.22	27°30′29.6″	112°49′46.7″	10.840	66.5	3.58	WR	B6881
		9.50±0.23				11.450	61.9			B6957
BC05-46	SB	10.80±0.26	10.78±0.26	28°40′25.7″	114°01′84.6″	9.918	64.6	2.84	WR	B6853
		10.77±0.26				9.894	60.5			B6953
BC05-38	JA	10.80±0.29		29°14′32.9″	114°09′60.7″	7.650	44.3	2.14	WR	B6841
Alkali basalts: San Carlos (SC), Santa Catarina (ST)										
BC05-17	ST	7.58±0.22	7.53±0.22	29°31′55.6″	115°32′03.3″	4.064	39.8	1.66	WR	B6825
		7.48±0.21				4.012	43.1			B6831
BC05-103	SC	7.63±0.19		29°43′71.3″	115°30′36.7″	4.954	59.2	2.01	WR	B6963
BC05-101	SC	8.92±0.36	8.68±0.36	29°43′71.3″	115°30′36.7″	5.869	23.8	2.06	WR	B6820
		8.54±0.36				5.682	23.0			B6830
BC05-18	ST	9.15±0.31	9.38±0.31	29°31′41.6″	115°16′17.2″	3.903	30.0	1.32	WR	B6826
		9.60±0.31				4.104	33.3			B6827
Calc-alkaline lavas: Jaraguay (JA), San Borja (SB), San Ignacio (SI)										
BC05-30	JA	7.65±0.40	7.30±0.40	29°32′07.0″	114°30′24.2″	2.075	18.0	0.84	WR	B6949
		6.96±0.33				1.887	20.0			B6959
BC05-40	SB	10.71±0.31	10.93±0.32	28°56′32.1″	113°49′11.8″	4.022	38.2	1.16	WR	B6842
		11.15±0.32				4.183	39.5			B6843
BC05-42	SB	14.56±0.46	14.64±0.46	28°57′93.2″	113°34′23.8″	6.597	34.0	1.40	WR	B6846
		14.73±0.45				6.674	36.2			B6850
BC05-03	JA	20.06±0.51		29°43′10.0″	114°35′59.0″	7.869	54.6	1.21	WR	B6882
BC05-01	SI	20.30±0.52		27°30′29.6″	112°49′46.7″	6.385	50.8	0.94	WR	B6880

See text for the analytical procedure.

surface locally referred to as “malpais”. Well-preserved Quaternary strombolian cones are common in La Purísima area.

Late Miocene tholeiitic basaltic andesites crop out between San Juanico and San Ignacio, as very fluid flows overlying tilted Tertiary sedimentary rocks. They cap large sub-horizontal plateaus (mesas) and have probably been emitted from fissures. Despite numerous descriptions (Gastil et al., 1979; Sawlan and Smith, 1984; Hausback, 1984; McLean et al., 1987; Sawlan, 1991; Rojas-Beltrán, 1999; Bellon et al., 2006) their field features have not yet been studied in detail. Similar tholeiitic lavas dated to 6 Ma have been collected in northern Baja California peninsula near 31°22′N (El Paraiso, Aguillón-Robles, 2002).

Late Miocene adakites and associated NEB occur mostly in the Santa Clara volcanic field, Vizcaíno Peninsula (Aguillón-Robles et al., 2001). Adakites crop out either as dacitic domes and dykes or as dacitic pyroclastic flow deposits, the volume of which is estimated to ca. 25 km^3. Niobium-enriched basalts occur as fluid lava flows, which cap large mesas and overlie the adakitic pyroclastic flow deposits. In addition, adakites dated between 6.2 and 4.9 Ma have been reported by Bonini and Baldwin (1998) from Isla Santa Margarita.

Despite its small size, the Santa Rosalía basin seems to have recorded most of the Miocene magmatic events of the Peninsula (Conly et al., 2005). Calc-alkaline arc volcanism, active from 24 to 13 Ma, was

followed by the emplacement of adakitic flows (the Santa Rosalía dacites) between 12.5 and 12.3 Ma, then by those of the Boleo tholeiitic basalts and basaltic andesites, together with NEB, from 11 to 9 Ma, and the Cerro San Lucas magnesian andesite suite from 11 to 7.7 Ma.

3. New petrologic and ^{40}K–^{40}Ar data on San Borja, Jaraguay and San Carlos volcanic fields

3.1. Field results and petrographic notes

In 2005 and 2006, we collected additional samples of magnesian andesites from the San Borja and Jaraguay volcanic fields, complementing the samplings of Calmus et al. (2003). Pliocene "bajaitic" lava flows emplaced between 5 and 3 Ma are very abundant and they cap most of the mesas which represent the prominent morphological feature of these two fields. Late Miocene magnesian andesites are comparatively less common. They usually occur as thick sheeted flows. Close to the eastern coast, they form a tilted lava flow sequence overlying either the Comondú volcanics or widespread felsic pyroclastic flow deposits, the latter representing probable equivalents of the Mesa-Capping Rhyolite Tuff (Dorsey and Burns, 1994), which gave an age of 12.5±0.3 Ma north of Cataviña area. This sequence crops out near the unpaved road connecting San Borja Mission to Bahía de Los Ángeles. In the western part of San Borja and in Jaraguay area, the Late Miocene basaltic andesites frequently overlie either Tertiary sedimentary rocks or directly the Peninsular Range Batholith (Sedlock, 2003). They cap the highest volcanic mesas, which are surrounded by lower Pliocene flows, e.g. north of Rosarito; along a track connecting the main road 20 km south of Chapala to Bahía Blanca; at El Crucero; at Cerro Prieto; and near El Pedregoso granitic hill. Towards southwest, e.g. near Laguna de Chapala and along the Bahía Blanco unpaved road, the Miocene–Pliocene basaltic andesites capping the Las Lagunitas, La Zorra, and El Carrizo mesas overlie either pyroclastic flow deposits or metamorphic rocks (mainly gneiss). These magnesian andesites are moderately porphyritic, with 5 to 20 modal% phenocrysts which include, by order of decreasing abundances, olivine, diopsidic clinopyroxene, orthopyroxene, labradorite, titanomagnetite, and occasional phlogopite and sanidine. Their groundmass contains microcrysts of plagioclase, clinopyroxene, titanomagnetite, hemoilmenite and variable amounts of glass.

Calc-alkaline basalts and basaltic andesites have been occasionally sampled from the base of the magnesian andesite sequence, especially near Bahía de Los Ángeles, along the road connecting this town to San Borja Mission, and near El Pedregoso granitic body. They also occur as thick sheeted mafic lava flows, which can be difficult to distinguish from bajaitic flows in the field because both contain similar phenocrysts, including plagioclase (labradorite), clinopyroxene (augite, diopside) and olivine altered to iddingsite, together with occasional crystals of hornblende, titanomagnetite and orthopyroxene.

A single adakitic occurrence, the first documented in Baja California Norte, has been found along an arroyo located east of Cerro Prieto (29°31′08.6″ N and 114°29′48.7″ W). It consists of a 5 m thick dyke trending N40°E, overlain and surrounded by Pliocene bajaitic flows. It is likely that other adakitic intrusions occur in the area, but are masked by younger flows. The rock is highly porphyritic with ca. 15 modal% hornblende phenocrysts, together with plagioclase and small amounts of olivine and diopside.

During our 2005 and 2006 field trips, we discovered that the two large plateaus (ca. 600 km^2 each) Mesa San Carlos and Mesa Santa Catarina, located along the west coast of northern Baja California Peninsula 100 km south of El Rosario, are capped by Late Miocene alkali basalt-related trachybasaltic (hawaiitic) flows. These lavas overlie Tertiary sediments (sandstones and conglomerates) and granites. They contain 10 to 15 modal% phenocrysts of olivine, augite, plagioclase and titanomagnetite phenocrysts set in a plagioclase-rich groundmass. The only genuine alkali basalts previously documented in Baja California are the Quaternary San Quintín strombolian cones and associated flows which contain peridotitic and granulitic xenoliths (Gastil et al., 1979) and are thought to derive from deep asthenospheric mantle (Rogers et al., 1985; Luhr et al., 1995).

3.2. Major and trace element compositions

Major and trace element data were obtained by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). The samples were finely powdered in an agate grinder. International standards were used for calibration tests (ACE, BEN, JB-2, PM-S and WS-E). Rb was measured by flame emission spectroscopy. Relative standard deviation are ±1% for SiO_2 and ±2% other major elements except P_2O_5 and MnO (±0.01%), and ca. 5% for trace elements. The analytical techniques are described in detail by Cotten et al. (1995). The corresponding chemical analyses are listed in Table 1.

All the samples analyzed (Table 1) are relatively fresh, with Loss on Ignition (LOI) values lower than

2.4 wt.%. They generally lack secondary minerals, with the exception of some carbonates and zeolites as vesicle fillings, which have been removed during sample preparation. Their K_2O and SiO_2 contents have been plotted in the Fig. 3 classification diagram after Peccerillo and Taylor (1976), together with those of the other Late Miocene samples selected from earlier papers. However, this classification grid is not adapted to the San Carlos and Santa Catarina alkali trachybasalts. Indeed, the major and trace element compositions of these lavas do not display any "subduction imprint" as evidenced by their high contents in TiO_2, Nb, Zr and low La/Nb and equivalent ratios compared to the other studied samples (Table 1). Their Na_2O and K_2O contents are quite high, and they plot definitively in the alkalic fields in Middlemost's (1975) and Miyashiro's (1978) diagrams (not shown). In the TAS diagram (Le Bas et al., 1986, not shown) these lavas plot in the trachybasalt field. They are either silica-saturated or slightly undersaturated (normative nepheline less than 2%). With respect to them, niobium-enriched basalts (NEB) are much less rich in K_2O (Table 1) and they plot in the subalkalic fields in Middlemost's (1975) and Miyashiro's (1978) diagrams.

The other lavas display contrasted positions in Fig. 3. As expected, the tholeiites plot consistently in the field of low-K basaltic andesites, and adakites range from low-K to medium-K andesites and dacites. Most of the associated NEB plot in the fields of medium-K basalts and basaltic andesites. The Miocene calc-alkaline lavas from our sample set plot generally within the medium-K series, and they include basalts, basaltic andesites, andesites and dacites. The plots of "bajaitic" lavas are rather scattered because of their chemical variability (Calmus et al., 2003), but these lavas are consistently K-rich (high-K basalts, basaltic andesites and andesites, shoshonitic basalts and shoshonites).

Compatible transition elements Ni, Co and Cr display positive correlations with MgO contents (Table 1). Their high contents in "bajaites" (Ni up to 275 ppm, Cr to 300 ppm) are typical of magnesian andesitic suites (Yogodzinski et al., 1994). The uppermost values nearly match those of primitive basaltic liquids in equilibrium with a lherzolitic mantle source (Allègre et al., 1977; Villemant et al., 1981). The lowermost ones are similar to those found in adakitic magmas (Sen and Dunn, 1994a,b; Drummond et al., 1996). Although they are not primitive (MgO <7.5 wt.%), some trachybasalts from Mesas San Carlos and Santa Catarina display rather high Ni contents (up to 210 ppm).

Incompatible multi-element plots show very characteristic patterns, which match closely those previously described for such lavas (Fig. 4). The trachybasalts from San Carlos and Santa Catarina display smooth fractionated patterns, with considerable enrichments in the most incompatible elements (30 to 100 times the primitive

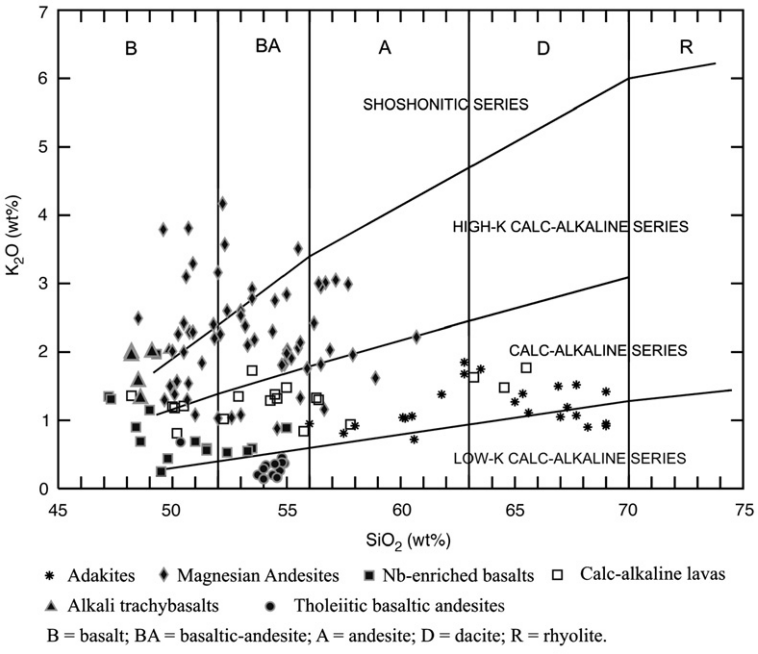


Fig. 3. Miocene lavas from the Baja California Peninsula plotted in a K_2O–SiO_2, plot according to Peccerillo and Taylor (1976). Symbols as in Fig. 2.

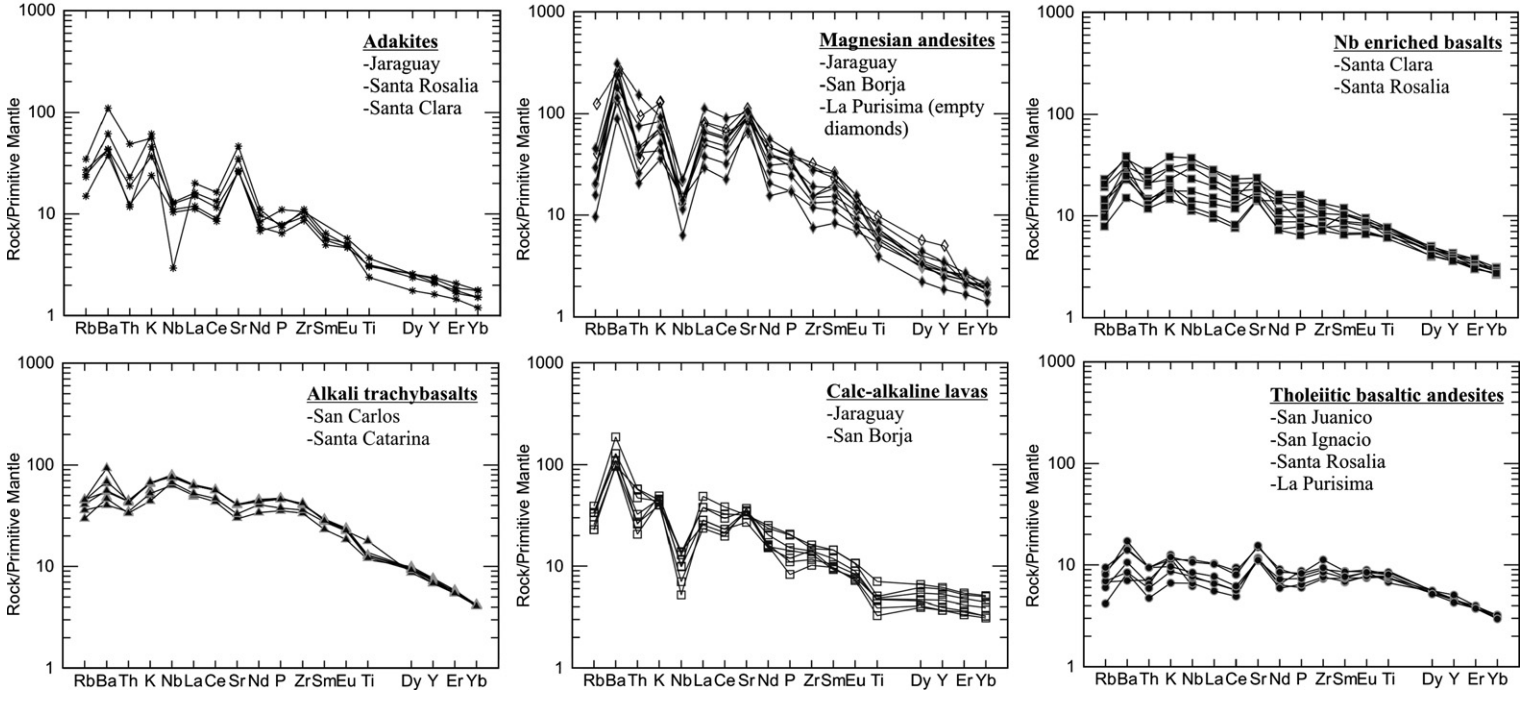


Fig. 4. Incompatible multi-element patterns of selected Miocene lavas normalized to the Primitive Mantle of Sun and McDonough (1989). Symbols as in Figs. 2 and 3.

mantle) and maximum enrichment in Nb (mantle-normalised Th/Nb, K/Nb and La/Nb lower than unity), consistent with an OIB-type geochemical signature. Niobium-enriched basalts from Santa Clara and Santa Rosalía display relatively similar patterns, but they are clearly less enriched in the most incompatible elements (10 to 40 times the primitive mantle). In addition, they display positive Sr spikes, a common feature among adakite-related magmas (Defant and Drummond, 1990), while alkali trachybasalt patterns show negative Sr anomalies (Fig. 4).

The adakite from Jaraguay and its equivalents from Santa Rosalía and Santa Clara display highly fractionated patterns, with characteristically low Y and heavy rare earth element (HREE) normalized values (less than 2.5 times the primitive mantle). Their patterns also show obvious positive anomalies in Sr and negative anomalies in Nb (the latter being especially strong for the Jaraguay sample). They plot within the adakite field in the diagnostic diagrams (not shown) Sr/Y versus Y (Defant and Drummond, 1990) and La/Yb versus Yb (Martin, 1999). Magnesian andesite patterns share with those of adakites their highly fractionated character with very low Y and HREE values, as well as their strong positive Sr anomalies and negative Nb anomalies. However, they are as a whole richer in several highly incompatible elements, e.g. in light REE (LREE), K, Th, and especially in Sr (up to 2200 ppm) and Ba (up to 2625 ppm, Table 1).

Calc-alkaline samples from San Borja and Jaraguay do not differ appreciably from those from other volcanic fields. They display moderate to strong enrichments in the most incompatible elements, strong negative anomalies in Nb and slight ones in Ti. They also display a clear positive spike in Ba, which seems to be characteristic of Baja California magmas. Indeed it appears, although with variable intensity, in all the patterns shown in Fig. 4, whatever the rock type. For instance, the tholeiitic basaltic andesites from the San Juanico–San Ignacio–Santa Rosalía field display nearly flat patterns from Rb to Eu and Ti, except for their slight positive anomalies in Sr and Ba. The positive Ba spikes are not due to an analytical bias or sample contamination, because lavas from other regions powdered and analyzed at the same time and using the same apparatus and techniques do not display such anomalies. These also appear when plotting compositions of Baja California lavas taken from the literature.

3.3. K–Ar geochronometry

K–Ar isotopic datings were performed on whole-rock lavas. After crushing and sieving, the rock fraction of 0.3 to 0.15 mm in size was cleaned with distilled water and then retained for analytical purposes: (i) one aliquot was powdered in an agate grinder for K analysis by atomic absorption after HF chemical attack, and (ii) 0.3 to 0.15 mm grains were used for argon isotopic analysis. Argon extraction 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 procedure described by Bellon et al. (1981). Ages listed with their respective characteristic parameters in Table 2, are calculated using the constants recommended by Steiger and Jäger (1977) and $\pm 1\sigma$ errors are calculated following the equation of Cox and Dalrymple (1967); for ages less than 1 Ma, the $\pm 1\sigma$ are calculated using the equation of Mahood and Drake (1982).

Data presented in Table 2 concern only Miocene samples (>5.3 Ma), but we have also dated a number of Pliocene (5 to 2.5 Ma) magnesian andesite flows from San Borja and Jaraguay, which form the largest part of these fields. The occurrence of the other lava types seems restricted to the Miocene volcanic events. We did not sample specifically the Comondú Formation, but two of its andesitic flows gave ages of 20.3±0.5 Ma (from Sierra San Francisco) and 20.1±0.5 Ma (near Cataviña), respectively. In addition, calc-alkaline flows from the base of the magnesian andesite pile have been dated to 14.6±0.4 and 10.9±0.3 Ma, respectively. The occurrence of a 7.3±0.4 Ma old basaltic andesite flow with "malpais" blocky surface near El Pedregoso shows that sporadic calc-alkaline activity still occurred during the Late Miocene in northern Baja California Peninsula. Although additional datings are in progress, available results already suggest that the alkali trachybasaltic event that built Mesas San Carlos and Santa Catarina was relatively long (9.4±0.3 to 7.5±0.2 Ma). The age of 9.40±0.33 Ma obtained for the adakite dyke sampled near Cerro Prieto falls within the range previously found for Santa Clara adakites (11 to 8.7 Ma, Aguillón-Robles et al., 2001).

Previous ^{40}K–^{40}Ar datings on San Borja and Jaraguay magnesian andesites (Calmus et al., 2003) suggested a gap between the emplacement of Late Miocene flows (ca. 10 to 9 Ma) and that of Pliocene ones. This apparent gap is partly filled up with Table 2 new data, although a smaller one remains between a first event (10.8±0.3 to 8.1±0.2 Ma) and a second one, starting at 6.8 Ma and extending into the Pliocene during which "bajaitic" activity reached its peak.

4. Discussion

4.1. Temporal patterns of magmatic activity

The age results presented above allow, together with previously published data, to discuss the spatial and temporal patterns of Middle to Late Miocene volcanic activity in Baja California Peninsula, and their possible correlation with the major tectonic changes when the subduction stopped at 12.5 Ma and the spreading centers became extinct at ca. 8–7 Ma (Michaud et al., 2006). These data are plotted in an age *versus* latitude diagram (Fig. 5) and the locations of the corresponding samples are also shown in Fig. 2 (where those of calc-alkaline samples have been omitted for more clarity).

Prior to 12.5 Ma, calc-alkaline magmatism was active all along the Peninsula, and other types were not represented with the exception of two magnesian andesite flows (14.6 and 13.1 Ma) in La Purísima (Bellon et al., 2006). A major change occurred at this time, when calc-alkaline activity became quite sporadic (although it persisted until 7.3 Ma in Jaraguay, see Table 1) and was replaced by other types. Between 12.5 and 10 Ma, magnesian andesites, tholeiitic basaltic andesites, adakites and NEB were emplaced more or less simultaneously in the southern volcanic fields (La Purísima, San Ignacio, Santa Clara, Santa Rosalía) while magnesian andesites only erupted in San Borja and Jaraguay. A peak of volcanic activity seems to have occurred between 10 and 8 Ma, leading to the eruption of all types of non-calc-alkaline magmas along the Peninsula, and especially of adakites in Jaraguay and OIB-type trachybasalts in San Carlos area in addition to magnesian andesites. The last eruptions emplacing tholeiites, NEB and trachybasalts occurred between 7.5 and 7 Ma. They were followed by a period of relative paucity during which, according to our data, only a few magnesian andesites were emplaced before the next peak of "bajaitic" activity during the Pliocene in San Ignacio, San Borja and Jaraguay (Calmus et al., 2003).

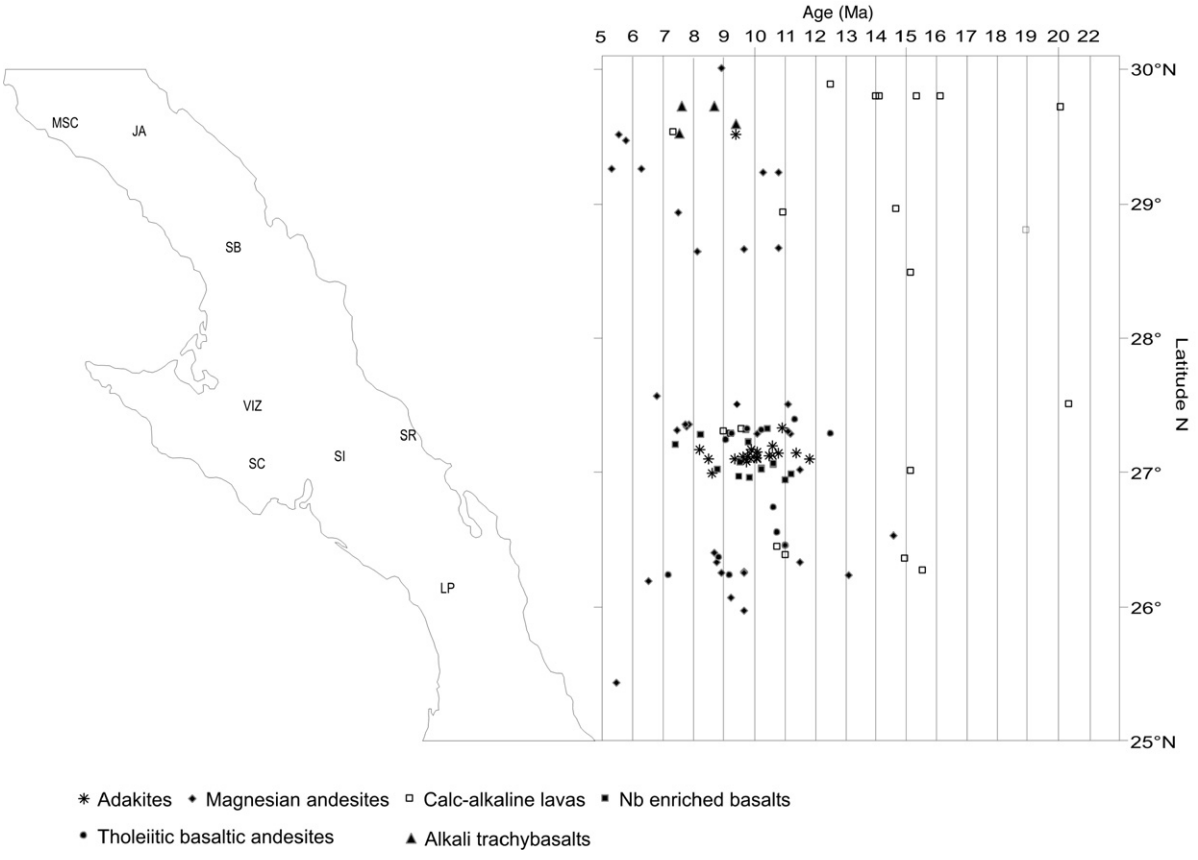


Fig. 5. Age versus latitude plot for Baja California Miocene lavas. Abbreviations and symbols as in Figs. 2 and 3. Ages and chemical data not provided in Tables 1 and 2 are from Aguillón-Robles et al. (2001), Benoit et al. (2002), Calmus et al. (2003), Conly et al. (2005), Bellon et al. (2006).

4.2. Origin of chemical variations: contributions from various magma sources

The geochemical diversity of magmas emplaced between 13 and 7 Ma along a ca. 600 km long zone trending parallel to the trench can only be explained admitting a contribution of multiple sources (Benoit et al., 2002). Adakites are generally considered as derived either (i) from the partial melting of subducted oceanic crust metamorphosed into the garnet amphibolite or eclogite facies (Defant and Drummond, 1990; Sen and Dunn, 1994a; Martin, 1999; Defant and Kepezhinskas, 2001; Martin et al., 2005), or (ii) from the partial melting of the base of thickened Andean-type crust (Atherton and Petford, 1993; Petford and Atherton, 1996; Arculus et al., 1999), although an alternative origin through (iii) high-pressure fractionation in mantle conditions (involving separation of garnet) has been recently proposed (Prouteau and Scaillet, 2003; Macpherson et al., 2006). The average thickness (25 km) of Baja California crust is not consistent with an origin of the local adakites by melting of lower crustal materials. They also display relatively high Mg0, Ni and Cr contents which are often explained postulating their interaction with the supraslab mantle during ascent (Rapp et al., 1999; Sen and Dunn, 1994b; Prouteau et al., 2001). Niobium-enriched basalts (NEB) which are spatially and temporally associated with adakites, e.g. in Santa Clara, are thought to derive from the melting at relatively low pressures, i.e. in the spinel stability field, of amphibole-rich supraslab mantle having interacted with adakitic melts (Defant et al., 1992; Kepezhinskas et al., 1996; Sajona et al., 1996). In addition, the sporadic emplacement of "regular" calc-alkaline lavas during Upper Miocene and Plio-Quaternary means that their usual source, i.e. subslab mantle metasomatized by hydrous fluid transfers from the downgoing plate (Arculus, 1994), was (and is still) present beneath the Peninsula.

The origin of magnesian andesites, which obviously present a number of similarities with adakites except for their less silicic character (Defant and Drummond, 1990; Martin et al., 2005), is still debated. A majority of authors claim that a slab melt component is involved in their petrogenesis (Kay, 1978; Saunders et al., 1987; Yogodzinski et al., 1994, 1995; Hochstaedter et al., 1996; Kepezhinskas et al., 1996; Furukawa and Tatsumi, 1999). Calmus et al. (2003) proposed for the Baja California occurrences a petrogenetic model involving melting of supraslab mantle having interacted with slab melts, as already envisioned in earlier papers on "bajaites" (Rogers et al., 1985; Saunders et al., 1987; Rogers and Saunders, 1989). In this model, reactions between adakitic melts and the deep supraslab mantle led to metasomatized pargasite-rich peridotites. Then, incongruent melting of this amphibole, at depths of 70–110 km, triggered the genesis of bajaitic melts, and left a garnet-rich residue. A major difference with the petrogenetic history of NEB is that, in the latter, interactions between slab melts and the supraslab mantle, as well as the partial melting of this metasomatized mantle, occurred at lower depths (40–60 km), consistent with the usual front-arc position of adakites and NEB with respect to calc-alkaline lavas and magnesian andesites (see Figs. 1 and 2 for the Santa Clara case).

The two other Late Miocene lava types, i.e. tholeiitic basaltic andesites and alkali trachybasalts, do not display any subduction imprint from the point of view of trace elements. However, a small sediment contribution, presumably inherited from interactions with subduction-modified supraslab mantle during their ascent (Benoit et al., 2002), is required to explain the enriched Pb isotopic signature of the tholeiites. Melting of depleted subslab mantle accounts satisfactorily for their rather flat incompatible element patterns and depleted Sr and Nd isotopic signatures (Benoit et al., 2002). No isotopic data are currently available for Mesa San Carlos trachybasalts. However, their typical OIB-type incompatible element patterns suggests an origin through melting of enriched subslab mantle, as proposed for their Quaternary equivalents from San Quintín (Hole et al., 1991; Luhr et al., 1995).

4.3. Ridge subduction or slab-tearing?

The almost simultaneous partial melting, between 13 and 7 Ma, of all these sources (subducted oceanic crust, shallow and deep supraslab mantle having interacted either with hydrous fluids or with slab melts, depleted and enriched subslab mantle) requires (i) a high thermal regime and (ii) a tectonic setting allowing both the presence at depth of these sources, and the possibility for the magmas derived from them to reach the surface along a zone 600 km long parallel to the trench but only ca. 100 km wide (shaded area in Fig. 2).

Complex magmatic associations derived from such sources and including adakites, andesites, MORB-type and OIB-type basalts and their derivatives, are known to occur in modern cases of subduction of active ridges (Thorkelson and Taylor, 1989; Thorkelson, 1996). Their genesis is also consistent with thermal models of ridge subduction (Iwamori, 2000; Thorkelson and Breitsprecher, 2005). One of the most extensively studied examples is that of the subduction of the active Chile ridge beneath the Patagonian margin at the level

of Taitao Peninsula, Chile. There, the very high thermal regime (De Long et al., 1979; Lagabrielle et al., 2000) led to very shallow melting of subducting oceanic crust, resulting in near-trench emplacement of dacites and basaltic andesites (Guivel et al., 1999, 2003), while tholeiitic basalts and adakites were emplaced onland (Forsythe et al., 1986; Lagabrielle et al., 1994; Bourgois et al., 1996). Away from the present-day triple junction, the emplacement of Cerro Pampa adakites has been also related to ridge-trench collision (Kay et al., 1993). In the back-arc Patagonian domain, the emplacement of numerous Neogene OIB-type basaltic plateaus has been attributed to the melting of subslab asthenospheric mantle upwelling through slab windows generated from subducted ridge segments (Ramos and Kay, 1992; Gorring et al., 1997, 2003; D'Orazio et al., 2000, 2001, 2004; Gorring and Kay, 2001).

Before the Famex cruise (April 2002) confirmed the presence of remnants of the Pacific–Magdalena ridge off Baja California Sur, the occurrence of Late Miocene adakites and NEB in the Santa Clara volcanic field led Aguillón-Robles et al. (2001) and Bourgois and Michaud (2002) to postulate that the subduction of this active ridge caused the opening of an asthenospheric window. Santa Clara adakites would have resulted from the partial melting of the edges of this window and associated NEB from the subsequent interactions between these slab melts and the shallow supraslab mantle. Benoit et al. (2002) proposed a more complex model taking into account the Late Miocene tholeiites from San Juanico–San Ignacio and the magnesian andesites from La Purísima. In this model (their Fig. 9), depleted tholeiitic melts of subslab origin ascended through the window and interacted with the supraslab subduction-modified mantle, becoming then more radiogenic in Pb. Adakites and NEB derived from the partial melting of the shallow edge of the window and from the interactions between these slab melts and the supraslab mantle, respectively. Finally, magnesian andesites originated from interactions between deep supraslab garnet peridotites and slab melts derived from the partial melting of the lower edge of the window. The latter were consumed by this process, and thus never reached the surface.

Such a model still accounts for the geochemical (major, trace elements and isotopes) compositions of these lavas and is also consistent with available experimental constraints on the petrogenesis of magnesian andesites, as discussed by Calmus et al. (2003). However, it needs obviously to be amended: the origin of the La Purísima/San Ignacio/Santa Clara slab window cannot anymore be ascribed to ridge subduction, given the occurrence, westward of the trench, of remnants from the Pacific–Magdalena and Pacific–Guadalupe ridges (Fig. 2). Our new results lead to extend the occurrence of Late Miocene magnesian andesites and adakites, as well as that of trachybasalts of presumed subslab origin, up to 30°N (Fig. 2). In addition, there is no clear age pattern for the initiation of the non-calc-alkaline activity all along the Baja California volcanic belt (Fig. 5). A model accounting for the opening of an asthenospheric window ca. 600 km long, parallel to the trench but independent from the subduction of the Pacific–Farallon ridge, has thus to be considered.

The opening of a slab window subparallel to the trench can also result from a slab-tearing process following collision or end of subduction (van den Beukel, 1990), leading ultimately to slab detachment (Wortel and Spakman, 2000). Indeed, the slab pull of a subducting plate is related to the density contrast between the asthenospheric mantle and the downgoing oceanic lithosphere, and thus to the age of the latter. An old oceanic lithosphere will sink easily while a plate younger than 10 Ma will be increasingly difficult to subduct when its ridge approaches the trench (Cloos, 1993; Ferrari, 2004). Numerical models (Yoshioka and Wortel, 1995) suggest that slab-tearing would start when strong tectonic coupling in the forearc occurs before the subduction of the ridge axis itself. Then, a tear could propagate laterally, even in the part of the margin where subduction is still active, because of the pull exerted by the still-attached deep part of the slab. Such a situation applies to many parts of the North American margin (Dickinson, 1997; Ferrari, 2004; Wilson et al., 2005) and especially to Baja California Peninsula where several authors have already considered this slab-tearing process as an alternative to active ridge subduction (Calmus et al., 2003; Michaud et al., 2006; Bellon et al., 2006).

Once a tear-in-the-slab opens, the traction exerted by the deep part of the downgoing plate will cause its sinking, and a slab window develops progressively, leading ultimately to slab breakoff (e.g. Davies and von Blanckenburg, 1995; von Blanckenburg and Davies, 1995; Mason et al., 1998). During such a process, unusual magmatic activity can develop in various ways. Partial melting of the oceanic crust from the edges of the tear can occur (Yogodzinski et al., 2001; Lin et al., 2004) leading to the emplacement of adakites or magnesian andesites derived from interactions of slab melts with the supraslab mantle. Such a process is very likely to play a major role when the tear develops in young (and still hot) lithosphere. Indeed, as first suggested by Dickinson and Snyder (1979) and then developed by Severinghaus and Atwater (1990) and Thorkelson and Breitsprecher (2005), a young subducted slab is efficiently re-heated

at the edges of a slab tear or slab window, and thus becomes thermally and rheologically indistinguishable from the surrounding asthenosphere. This process of thermal erosion is very efficient in extending the limits of the slab tear/window with respect to the initial (geometrically defined) ones. Extensive melting of the oceanic crust of the tear edges is therefore expected, generating adakites (Thorkelson and Breitsprecher, 2005), which can then react with the mantle originally in supraslab position, forming magnesian andesites. Tholeiitic or OIB-type magmas might be generated by the partial melting of the subslab asthenospheric mantle uprising through the tear-in-the-slab, possibly near its boundary zone with the overlying lithospheric mantle (Coulon et al., 2002). As the slab window develops (both by sinking of its deep part and by thermal erosion), the deep part of the slab can roll back, inducing asthenosphere to flow laterally in the opening, and thus to experience decompression melting leading to OIB magmas (Ferrari et al., 2001). Alternatively, heat transfer through the tear might induce partial melting of the supraslab mantle (Davies and von Blanckenburg, 1995), eventually resulting in the emplacement of calc-alkaline magmas derived from hydrous fluid-metasomatized peridotites.

The origin of large OIB-type basaltic plateaus in the back-arc Patagonian domain has been recently attributed to a slab-tearing model relatively similar to that we propose here (Guivel et al., 2006). If these plateaus formed above slab windows generated by the successive subduction, from 15–14 Ma to Present and from 52°S to 46°S (Taitao Peninsula), of several Chile ridge segments, one should expect a younging northwards of their emplacement ages. According to Guivel et al. (2006), there is no such age pattern: volcanic activity started between 12 and 8 Ma all along the margin, even in plateaus facing ridge segments which were still active off the trench. Thus, these authors propose that the collision of the southernmost ridge segments with the trench initiated a slab tear which propagated quickly parallel to the trench, allowing subslab-derived magmas to ascend through the corresponding asthenospheric window. However, the Chile case is not exactly similar to that of Baja California: despite the opening of a slab tear, Chile ridge segments were still subducted successively instead of being abandoned off the trench like the Magdalena, Guadalupe and Soledad segments.

4.4. Proposed tectonic model: slab-tearing beneath Baja California

During the Tertiary subduction of the Farallon plate beneath the North American margin, the active Pacific–Farallon ridge approached the trench and then subducted below Southern California and northernmost Baja California, causing the formation of ridge-related asthenospheric windows (Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989; Dickinson, 1997; Atwater and Stock, 1998; Wilson et al., 2005). However, when subduction stopped at ca. 12.5 Ma (Mammerickx and Klitgord, 1982; Stock and Hodges, 1989; Lonsdale, 1991), the southern segments of this ridge (the Magdalena, Guadalupe and Soledad ridges) were abandoned off southern and central Baja California. The geometry and position of these still active segments at 13 Ma is depicted in Fig. 2, after Lonsdale (1991), and modified according to Wilson et al. (2005) and Michaud et al. (2006). At this time, the Pacific–Magdalena ridge had already broken into a series of small ridge segments and the accretion rate had slowed all along the three ridge segments (Michaud et al., 2006).

The Guadalupe and Soledad segments stopped spreading at ca. 12 Ma whilst the Magdalena ridge broke into several short segments that continued spreading perhaps until 8–7 Ma (Michaud et al., 2006). The drastic clockwise rotation after 12 Ma of the Magdalena segments cannot be explained by a rapid change in slab pull direction, but results more likely from an increasing tectonic coupling between the Magdalena and the North American plates (Michaud et al., 2004, 2005, 2006). These events are clearly indicative of slab pull removal, and hence a break or tear in the Farallon slab. The earlier end of accretion along the Soledad and Guadalupe ridge segments, and the clockwise rotation of the remnants of the Magdalena ridge, both suggest that the removal of slab pull (and thus the slab-tearing process which initiated it), started in the north (probably in the prolongation of a ridge-related Southern Californian slab window, as discussed below). There are no evidences that the Pacific–Guadalupe and Pacific–Magdalena spreading ridges subducted and later on jumped westward off the trench, as postulated by Benoit et al. (2002) and Bourgois and Michaud (2002), neither in the few conjugate and symmetric magnetic anomaly pattern identified on the Guadalupe and Magdalena plates, nor in the seafloor tectonic fabric.

The magmatic record in the Peninsula is consistent with this slab-tearing model and provides additional constraints: (i) the nearly concomitant eruption of magnesian andesites, tholeiites, adakites and NEB which started between 11.5 and 10 Ma between 26° and 30°N (Fig. 5) suggests that the tear-in-the-slab occurred at once in a very short period instead of slowly propagating from north to south, and (ii) the extent of

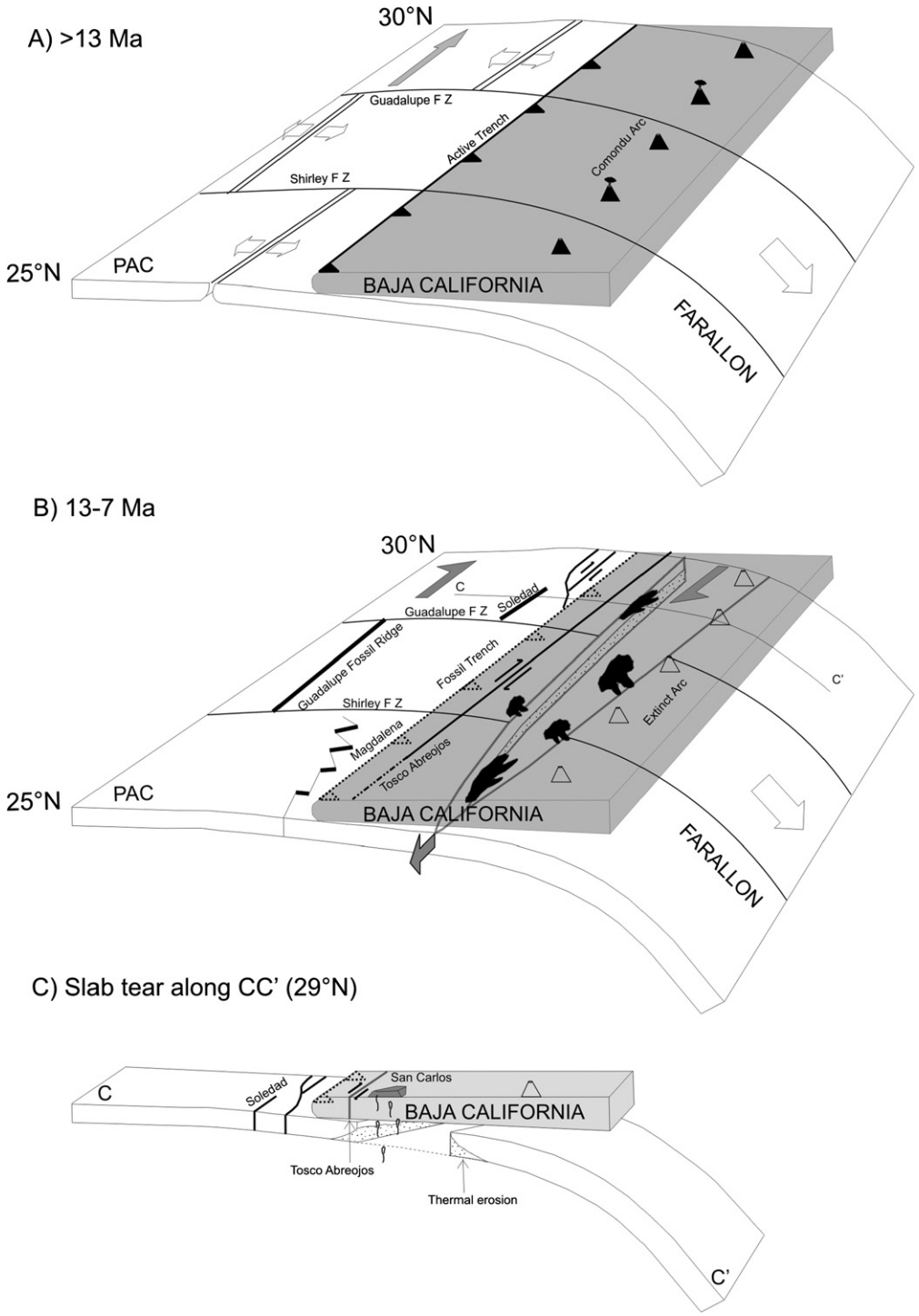


Fig. 6. Proposed schematic model of slab-tearing prior to ridge-trench collision. The upper plate (shaded) is shown with dotted lines, the downgoing plate (white) with plain lines, arc volcanoes (upper cartoon) and basaltic plateau flows (middle cartoon) in black. Scale and main structural elements are as in Fig. 2. Stage A (>13 Ma): active subduction and edification of the Comondú arc. Stage B (13–7 Ma): end of subduction and development of a slab tear which evolves into a slab window, post-subduction magmatism. The trench becomes fossil and the Tosco–Abreojos dextral strike-slip fault propagates southward. The tear is represented at an early stage of development, when thermal erosion (stippled areas) starts to reduce the thickness of its lithospheric edges. C: schematic cross-section along line CC' (in B), at ca. 29°N, depicting the effects of thermal erosion and the ascent of infraslab magmas (San Carlos alkali trachybasalts) through the tear.

the slab window can be derived from the distribution of the non-calc-alkaline lavas (Fig. 2). In fact, slab window-related Late Miocene volcanism seems more abundant and is better documented in the Santa Clara–San Ignacio area (Benoit et al., 2002) than in northern Baja California, despite the evidence provided in this paper for the occurrence of adakites and of trachybasalts of subslab origin in the latter. However, the slab tear may have propagated very quickly along the margin, as also envisioned for the Patagonian example (Guivel et al., 2006); and the occurrence of 6.2 Ma adakites at 24°30'N in Isla Santa Margarita (Bonini and Baldwin, 1998) might be an indication of its further development southward.

The main elements of the proposed tectono-magmatic model, linking Late Miocene volcanism in Baja California Peninsula with a slab-tearing process leading to the opening of a 600 km long slab window parallel to the trench, are schematically depicted in Fig. 6. Until 13 Ma, active subduction led to the melting of hydrous fluid-metasomatized supraslab mantle, and to the emplacement of calc-alkaline lavas along the peninsular Comondú arc (Fig. 6A). Seafloor spreading was still active along the Soledad, Guadalupe and Magdalena ridge segments, although it had slowed; and Comondú arc activity was also decreasing according to age data (Fig. 5). These features suggest that slab-tearing might already have started, releasing the slab pull exerted by the old and deep parts of the Farallon plate.

Between 13 and 7 Ma, the regional tectonic setting became completely different (Fig. 6B). The northward relative motion of the Pacific plate with respect to the Peninsula was transferred to the Tosco–Abreojos Fault. The Soledad and Guadalupe ridges stopped spreading, whereas the Magdalena ridge broke up into a series of small segments, which rotated clockwise. Calc-alkaline volcanism became extinct, except for the sporadic emplacement of andesites resulting from the melting of remnant parts of subduction-modified supraslab mantle. The initial slab tear evolved, through thermal erosion of its edges and sinking of the deep part of the Farallon slab, into a ca. 600 km long and 100 km large slab window which opened in the young (less than 15 Ma) and thus still hot parts of the downgoing Guadalupe and Magdalena plates. In such a hot regime enhanced by thermal erosion processes (Fig. 6C), partial melting of the basaltic crust from the edges of the window produced adakitic magmas, which either (i) reached the surface (Santa Clara, Santa Rosalía, Jaraguay), (ii) reacted at moderate depth with the supraslab mantle, producing the source of the NEB, or finally (iii) interacted with garnet peridotites from the deeper supraslab mantle, generating that of the magnesian andesite ("bajaite") suite. The heterogeneous subslab mantle ascended through the slab window, possibly triggered by the rollback or the detachment of the deep part of the slab. Then, its decompression melting resulted in the emplacement either of (iv) tholeiitic basaltic andesites derived from depleted subslab mantle and interacting with subduction-modified supraslab peridotites during their ascent, or of (v) alkali–basalt-related lavas originating from the melting of the deep enriched subslab mantle, i.e. the San Carlos and Santa Catarina trachybasalts (Fig. 6C).

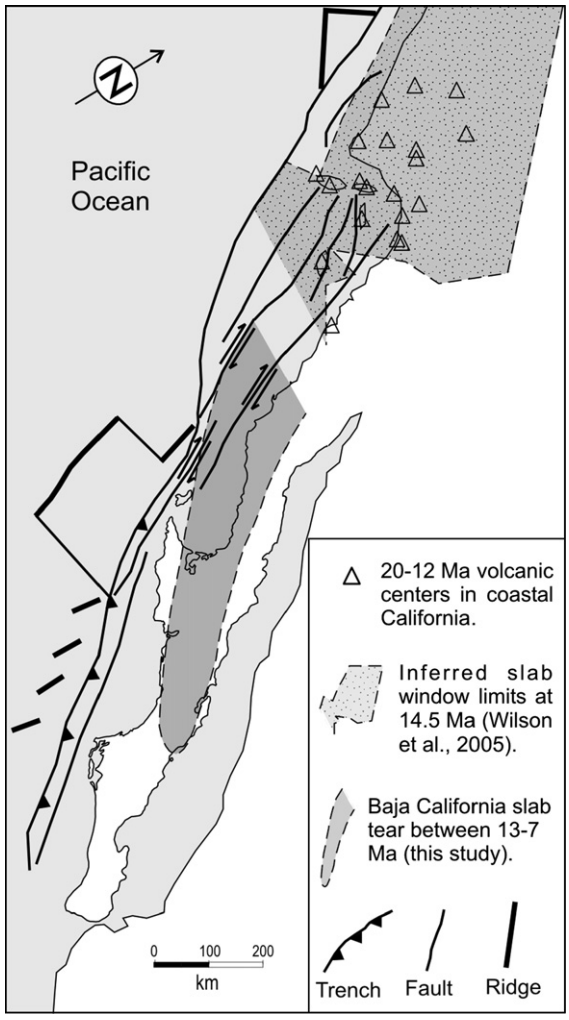


Fig. 7. Relationships between the proposed Baja California slab tear and the Southern California slab window. The relative positions of Baja California and continental America and the main structural elements are from the reconstruction of the margin at 12.5 Ma by Wilson et al. (2005, their Fig. 11). The location of 20–12 Ma volcanic centers and the shape of the Southern California slab window at 14.5 Ma are also taken from Wilson et al. (2005, their Figs. 1 and 8).

Wilson et al. (2005) provided a detailed reconstruction of the evolution of the Pacific margin at the level of California and Baja California during the last 30 Ma. They also used the location of non-calc-alkaline volcanic centers (previously studied by Dickinson, 1997) to delineate the successive positions of the edges of the ridge-related Southern California slab window, the size of which increased considerably from 18.9 to 14.5 Ma. The limits of this window at 14.5 Ma are shown in Fig. 7 together with the locations of 20–12 Ma old Southern California volcanic centers, the position of Baja California at 12.5 Ma and the limits of the 13–7 Ma Baja slab tear inferred from this study. The remarkable fit between the locations of the southern limit of the older Californian window and the northern boundary of the Baja tear suggests that the latter can be considered a southern (and younger) extension of the Californian window. Given the probable southward trend of development of the Baja slab tear, we propose that it started from the already existing window and propagated beneath the Baja California Peninsula between 13 and 7 Ma.

5. Conclusions

New ^{40}K–^{40}Ar datings and petrologic data on the San Borja, Jaraguay and San Carlos lavas in northern Baja California, together with published data from the southern volcanic fields, allow to study the spatial and temporal distribution of Late Miocene volcanism along the Peninsula, from 25° to 30°N.

Especially, this study documents the occurrence in San Borja and Jaraguay of a number of Late Miocene magnesian andesite flows, the emplacement of which started at 11.1 Ma; of an adakitic dyke in Jaraguay, dated at 9.4 Ma; and of OIB-related trachybasalts, 9.3 to 7.5 Ma old, which cap the large Mesas San Carlos and Santa Catarina located near 29°N.

We show that, after the extinction of the Comondú calc-alkaline arc at ca. 12.5 Ma, magmatic activity continued, emplacing magnesian andesites, adakites and associated NEB, tholeiitic basaltic andesites and trachybasalts in a 600 km long and 100 km wide area parallel to the trench, mostly between 11.5 and 7.5 Ma.

The origin of these magmas, unusual in regular subduction settings, is ascribed to the formation of an asthenospheric window through which subslab mantle ascended (tholeiites and trachybasalts), and to the melting of the oceanic crust from the thermally eroded edges of this window (adakites) followed by the interaction of these slab melts with the supraslab mantle (sources of the NEB and magnesian andesites).

This slab window did not result from ridge subduction, but from a slab-tearing event involving the detachment of the deep part of the subducted plate prior to the ridge-trench collision. This process occurred when the Pacific–Magdalena active ridge approached the trench east of Vizcaíno Peninsula at ca. 12.5 Ma. The tear-in-the-slab opened parallel to the trench between 30°N and 25°N, starting from the already existing Southern California slab window. It evolved into an asthenospheric window when the oldest part of the downgoing plate sank into the mantle and the thermal erosion of its edges widened the gap between them.

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