

## Isotope geochemistry and petrogenesis of peralkaline Middle Miocene ignimbrites from central Sonora: relationship with continental break-up and the birth of the Gulf of California

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**Key-words.** – Peralkaline ignimbrites, Middle Miocene, Isotope geochemistry, Gulf of California.

**Abstract.** – Middle Miocene peralkaline ignimbrites constitute a specific geodynamic marker of the early stage of opening of the Gulf of California, preserved either in central Sonora or the Puertecitos area, in Baja California. Very uniform ages (12-12.5 Ma) obtained on these rocks show that this volcanic episode corresponds to a specific stage in the tectonic evolution of the proto-gulf area. Field observations and slightly different Sr and Nd isotopic signatures support eruptions from several small volume magma batches rather than from a large-volume caldera forming event. Isotopic ratios help to constrain the petrogenesis of the peralkaline liquids by fractional crystallization of transitional basalts in a shallow reservoir, with slight contamination by Precambrian upper crustal material. Less differentiated glomeroporphyritic icelandites erupted at about 11 Ma, mark an increase in the magma production rate and highlight an easier access to the surface, illustrating an advanced stage in the weakening of the continental crust. The tilting of the Middle Tertiary sequences results from a major change in the tectonic regime, from E-W extension giving rise to N-S grabens, to NNW-SSE strike-slip motion that can be related to the transfer of Baja California from North America to the Pacific plate. The location of peralkaline volcanism coincides with the southern edge of the Precambrian crust and the southernmost extension of the California slab window at 12.5 Ma.

## Géochimie isotopique et pétrogenèse des ignimbrites hyperalkalines du Miocène moyen du Sonora central : relations avec la déchirure continentale et la naissance du golfe de Californie

**Mots-clés.** – Ignimbrites hyperalkalines, Miocène moyen, Géochimie isotopique, Golfe de Californie.

**Résumé.** – Les ignimbrites hyperalkalines du Miocène moyen constituent un excellent marqueur du stade initial de l'ouverture du golfe de Californie. Elles sont préservées aussi bien en Sonora central que sur la marge orientale de la péninsule de Basse Californie, dans la région de Puertecitos. Les âges uniformes obtenus sur ces roches (12.5-12 Ma) montrent que cet épisode volcanique correspond à un stade spécifique de l'évolution du golfe de Californie. Les données de terrain, ainsi que les données isotopiques, indiquent que les ignimbrites correspondent à plusieurs venues de faibles volumes, plutôt qu'à une éruption majeure se terminant par un effondrement en caldera. Les données isotopiques permettent en outre de préciser que les ignimbrites sont le résultat de processus de cristallisation fractionnée à partir de basaltes transitionnels, avec une faible contamination par la croûte supérieure précambrienne. Les laves vitreuses glomeroporphyriques de 11 Ma (islandites) témoignent d'une production magmatique plus importante et d'un accès plus aisé vers la surface, en relation sans doute avec une croûte continentale plus amincie. Le basculement des séquences du Miocène moyen et supérieur témoigne d'un changement majeur du champ de contrainte, depuis une extension E-W à l'origine de grabens N-S, à un système transtensif NNW-SSE qui résulte du transfert de la péninsule de Basse Californie, de la plaque Amérique du Nord à la plaque Pacifique. Le volcanisme hyperalkalin s'est manifesté sur la bordure méridionale du craton nord-américain, à l'aplomb de la terminaison du *slab-window* de Californie, à 12.5 Ma.

## INTRODUCTION

The generation of peralkaline silicic volcanic rocks is a long-standing debated problem in igneous petrology [e.g. Scaillet and Macdonald, 2001; Peccerillo *et al.*, 2003 and

references therein]. An origin through fractional crystallization of mildly alkalic to transitional basalts, as exposed in the pioneer works on the Afar rift, Ethiopia [Barberi *et al.*, 1974, 1975; Bizouard *et al.*, 1976, 1980], is a popular model that seems to apply in many cases, either in continental

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[e.g. Gasparon *et al.*, 1993; Civetta *et al.*, 1998] or oceanic environments [e.g. Mungall and Martin, 1995]. However, such an origin is difficult to invoke when the volume of felsic rocks is much greater than that of the basalts. In that case, other petrogenetic models such as partial melting of the crust [e.g. Davies and Macdonald, 1987; Macdonald *et al.*, 1987; Lighfoot *et al.*, 1987; Black *et al.*, 1997] or partial melting of mafic precursors followed by fractionation and crustal contamination [e.g. Mahood and Baker, 1986; Mahood *et al.*, 1990; Lowenstern and Mahood, 1991] have been proposed. Furthermore, specific conditions control the generation of oversaturated peralkaline magmas [Bohrson and Reid, 1997; Caricchi *et al.*, 2006]; (1) they are the result of low pressure crystallization in shallow crustal magma reservoirs, as shown by the predominance of alkali feldspar phenocrysts, and (2) these magmas are restricted to extensional tectonic settings in regions characterized by moderate rates of extension [Macdonald, 1974b; Mahood, 1984].

In central Sonora (NW México), a peculiar volcanic episode represented by peralkaline ignimbrites and rhyolites has been defined and dated at about 12.5–12 Ma [Vidal Solano, 2005; Vidal Solano *et al.*, 2005]. The chronology and petrochemical characteristics of the Middle Miocene volcanic sequences have been presented elsewhere [Vidal Solano *et al.*, 2007]. In this paper, we report on the first Sr, Nd and Pb isotope data of peralkaline ignimbrites from central Sonora. These results are discussed with the aim of placing constraints on: (1) the genesis of these peralkaline oversaturated volcanics and (2), the timing and conditions of continental break-up and opening of the Gulf of California rift system.

## GEOLOGICAL AND PETROLOGICAL BACKGROUND

Middle Miocene ignimbrites have long been recognized in central Sonora [Morales-Montaña *et al.*, 1990; Paz-Moreno, 1992; Bartolini *et al.*, 1992, 1994; McDowell *et al.*, 1997; Mora-Álvarez and McDowell, 2000] but never considered, until recently [Vidal Solano *et al.*, 2005], as a specific geodynamic marker. Their peralkaline character [Vidal Solano *et al.*, 2005] is defined (1) by a peculiar mineralogical association (fayalite + Fe-rich augite + alkali feldspar phenocrysts and zircon as a common trace mineral) and (2) their major element geochemistry (Al-poor and alkali-rich) that classify them as comendites [Sutherland, 1974; Macdonald, 1974a; Le Maitre, 1989]. Peralkaline ignimbrites are preserved as scattered tilted mesas in a vast area from coastal Sonora to the foot of the Sierra Madre Occidental (fig. 1) and from San Miguel de Horcasitas (29°30'N) to Guaymas (28°N).

The stratigraphic columns presented in figure 2, constrained by  $^{40}\text{Ar}/^{39}\text{Ar}$  age determinations [Vidal Solano *et al.*, 2005, 2007], summarize the volcanic successions observed in central Sonora. Ignimbrites rest mostly on top of poorly-sorted detrital sediments that accumulated in elongated fault-bounded half-graben basins related to Tertiary crustal extension [Gans, 1997; McDowell *et al.*, 1997; Gans *et al.*, 2003]. They correspond to a single cooling unit (up to 50 m thick), with a black to dark brown vitrophyre commonly

present in the lower part, near the contact with gravels and conglomerates that represent the beds of palaeovalleys flooded by the pyroclastic unit. In the surroundings of the small mining town of La Colorada two ignimbritic sheets are present (e.g. Cerro Chapala); yet the absence of any unconformity between them shows that the two pyroclastic units were emplaced in a short time interval. Indeed, all the geochronological data [e.g. Bartolini *et al.*, 1994; McDowell *et al.*, 1997; Oskin, 2002; Oskin and Stock, 2003a; Vidal Solano *et al.*, 2005, 2007] converge to show that peralkaline ignimbrites in coastal and central Sonora were erupted at 12.5–12 Ma. Rhyolitic domes with similar peralkaline characteristics are exposed in the southern part of the study area. The 12.1 Ma age obtained on a peralkaline rhyolite lava from Cerro Sarpullido (fig. 2) manifests that rhyolite and ignimbrite are part of the same volcanic episode. Moreover, granophyric fragments that can be considered as the solidified intrusive equivalent of the lavas [Lowenstern *et al.*, 1997], observed in the rhyolites attest for the presence of subvolcanic bodies. In this southern area, volcanic products exhibit fragmentation and yellow quenched margins that evidence contact with water [Stroncik and Schmincke, 2002; Vidal Solano, 2005]. This shows that extension was clearly underway in central Sonora during the Middle Miocene and that lakes could have flooded parts of the grabens.

In many places southeast of Hermosillo (e.g. Sierra Lista Blanca (fig. 3a) or Sierra San Antonio) ignimbrites or rhyolites are capped by black glomeroporphyritic lava flows (fig. 3b), with dominant phenocrysts of plagioclase (An<sub>42-30</sub>), augite (Wo<sub>38</sub>En<sub>35</sub>Fs<sub>27</sub>), pigeonite (Wo<sub>8.5</sub>En<sub>45.5</sub>Fs<sub>46</sub>) and Fe-Ti oxides. These crystals are set in a glassy groundmass with perlitic fractures [Vidal Solano, 2005]. At Cerro Chivato (fig. 2), one of these lava flows was dated at  $10.9 \pm 0.4$  Ma [Vidal Solano *et al.*, 2007]. This Ar/Ar age is concordant with previously published K/Ar dates at Sierra Lista Blanca [Morales-Montaña *et al.*, 1990; McDowell *et al.*, 1997], indicating that the emplacement of the intermediate lavas was contemporaneous. A major extensional event occurred after this volcanic episode because the whole Middle to Upper Miocene Sierra Lista Blanca sequence is tilted toward the west (fig. 3b). This tectonic episode was furthermore responsible for erosion and massive deposition of detrital alluvial fan material during the latest Miocene and Pliocene.

Middle Miocene basalts are scarce in central Sonora. A small outcrop of mafic rocks is observed at the base of Cerro Las Cuevitas, near Hermosillo [Vidal Solano *et al.*, 2005]. The  $12.54 \pm 0.84$  Ma Ar/Ar age obtained on this basalt confirms it is penecontemporaneous with the peralkaline acidic sequence [Vidal Solano *et al.*, 2005]. Flat lying basaltic mesas overlie the peralkaline ignimbrites west of Santa Rosalía (fig. 1). These basalts include olivine, clinopyroxene and plagioclase megacrysts, a discriminant feature for Plio-Quaternary alkali volcanism in central Sonora [Paz-Moreno, 1992; Paz-Moreno *et al.*, 2003]. In short, as a result of its mode of emplacement, the Middle Miocene peralkaline ignimbrite event is a good stratigraphic marker for the tectonic evolution of the region. Moreover, the eruption of large volumes of intermediate transitional magmas after the ignimbrite outburst, helps to constrain the petrogenetic and tectonic processes that precede the Gulf of California opening.

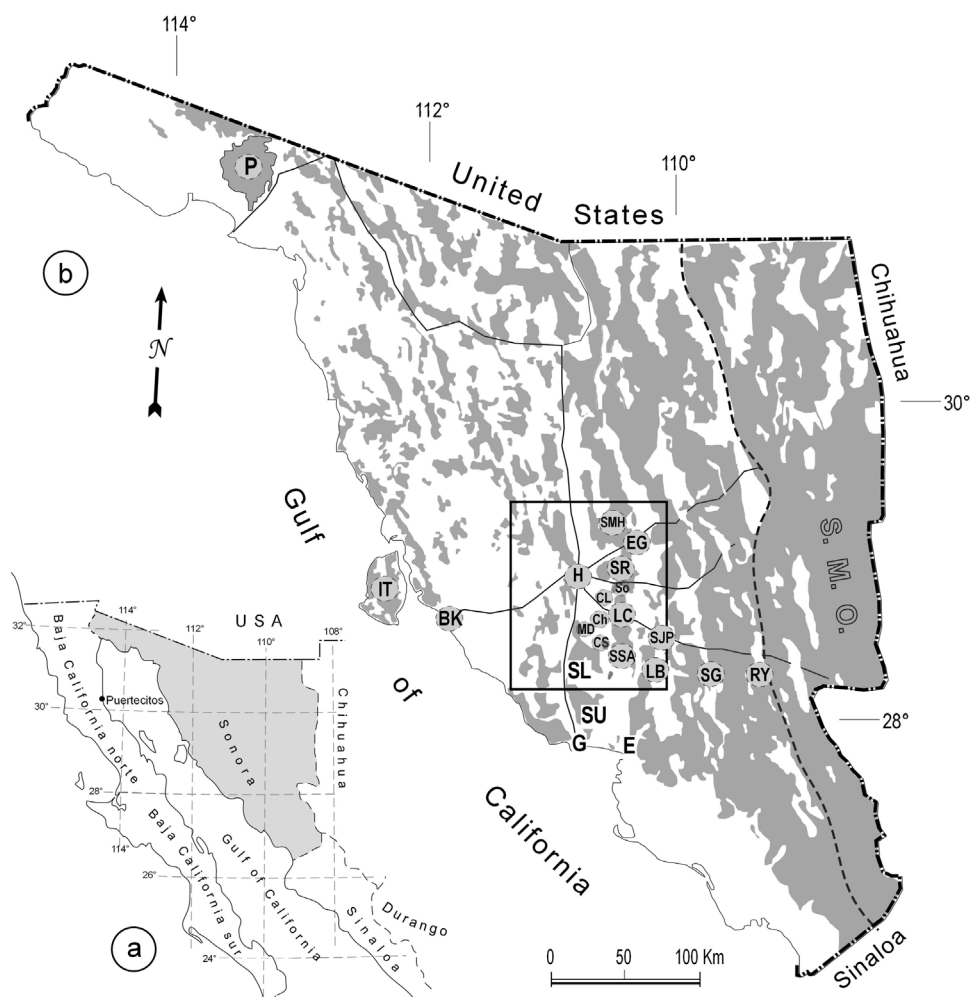


FIG. 1. – (a) Geographic framework of the Sonora State. (b) Basin and range morphology in the State of Sonora, and location of the study area. Basins are in white, ranges in grey. Main outcrops of peralkaline ignimbrites : BK, Bahía de Kino; Ch, Cerro Chapala; CL, Cerro La Legua; CS, Cerro Sarpullido; EG, El Gavilán; IT, Isla Tiburón; LB, Sierra Lista Blanca; MD, Mina Divisadero; P, Pinacate; RY, Río Yaqui; SG, Suaqui Grande; SJP, San José de Pima; SL, Sierra Libre; SMH, San Miguel de Horcasitas; So, Cerro La Sonora; SR, Santa Rosalía; SSA, Sierra San Antonio; SU, Sierra Santa Ursula. Populated places : E, Empalme; G, Guaymas; H, Hermosillo; LC, La Colorada. For a more precise location of the studied samples refer to the maps in Vidal Solano [2005]. The stippled line marks the western limit of the Sierra Madre Occidental (S.M.O.) ignimbrite plateau.

FIG. 1. – (a) Cadre géographique de l'Etat du Sonora. (b) Morphologie en « Basin and range » de l'Etat du Sonora et localisation du secteur d'étude. Les bassins sont en blanc et les reliefs en gris. Principaux affleurements d'ignimbrites hyperalkalines. Pour une localisation plus précise des échantillons étudiés voir les cartes figurant dans Vidal Solano [2005]. La ligne en pointillés, marque la limite occidentale du plateau de la Sierra Madre Occidental (S.M.O.).

## GEOCHEMISTRY

### Analytical procedures

Rock samples were first ground in a steel jaw crusher and then finely powdered in an agate grinder. Major and trace elements were obtained by inductively coupled plasma-atomic emission spectrometry (ICP-AES) at CEREGE (Université Paul Cézanne, Aix-Marseille 3), except for Na, K and Rb, which were determined by flame atomic absorption spectrophotometry, and Fe<sup>2+</sup> by titration. Rare earth elements (REE) and additional trace elements were analysed by inductively coupled plasma-mass spectrometry (ICP-MS) in LGCA at the Université Joseph Fourier Grenoble 1, following the procedure of Barrat *et al.* [1996] or the Centre de Recherches Pétrographiques et Géochimiques (CRPG) at Nancy. Analytical errors are 1-3% for major elements and less than 3% for trace elements.

Sr (static acquisition) and Nd (dynamic acquisition) isotopic ratios were measured on nine samples at the Université Paul Sabatier (Toulouse) on a Finnigan MAT261 multicollector mass spectrometer using the analytical procedures of Lapierre *et al.* [1997]. Results on La Jolla Nd standard yielded  $^{143}\text{Nd}/^{144}\text{Nd} = 0.511850 \pm 8$  (mean on 39 runs), corresponding to an external reproducibility of 0.00001. Results on NBS 987 Sr standard yielded  $^{87}\text{Sr}/^{86}\text{Sr} = 0.710250$  (mean on 200 runs). The within-run precision ( $2\sigma$  absolute) for  $^{87}\text{Sr}/^{86}\text{Sr}$  was 0.000008-0.000015 and 0.000007-0.000011 for  $^{143}\text{Nd}/^{144}\text{Nd}$ .

For lead separation, six powdered samples were weighed to obtain approximately 100 to 200 ng of lead. The chemical separation of Pb was carried out following the procedure modified from Manhès *et al.* [1980]. Total Pb blanks are less than 65 pg for a 100 mg sample. Lead isotopes were analysed on a VG Plasma 54 multicollector inductively coupled plasma-mass spectrometer (MC-ICP-MS) at



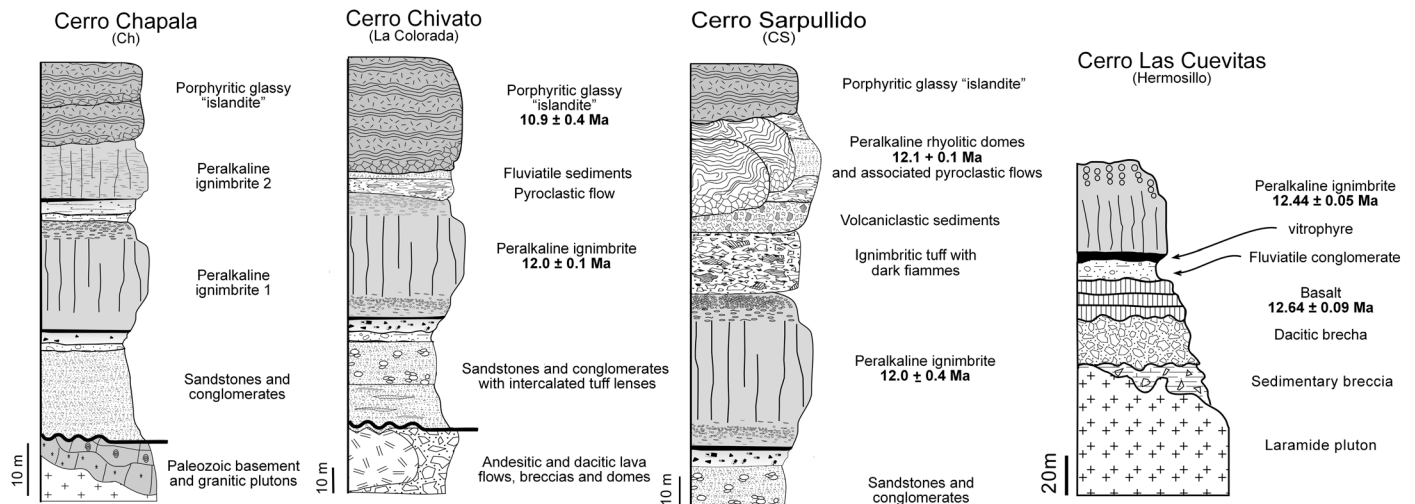


FIG. 2. – Representative stratigraphic columns showing the age and relationship of Middle Miocene volcanic sequences in central Sonora. Cerro Chapala and Cerro Chivato are located just southwest of La Colorada (fig. 1).

FIG. 2. – Colonnes stratigraphiques et âge des principales séquences volcaniques du Miocène moyen du Sonora central. Les Cerros Chapala et Chivato sont situés immédiatement au sud-ouest de La Colorada (fig. 1).

the Ecole Normale Supérieure de Lyon. Lead isotope compositions were measured using the Tl normalization method described by White *et al.* [2000]. For Pb isotope analysis, samples were bracketed between NIST 981 standards and calculated with respect to the value reported for this standard by Todt *et al.* [1996]. This technique yields internal precision of ca. 50 ppm (2 $\sigma$ ) and an external reproducibility of ca. 150 ppm (2 $\sigma$ ) for  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios determined on 20 NIST standards. Because corrections for recent volcanic rocks are negligible, initial ratios of the isotopic data have not been calculated.

### Sample classification and trace element geochemistry

Twenty five samples of the Middle Miocene volcanic sequences from central Sonora have been analysed for major and trace elements. Thirteen representative analyses are reported in table I. Previously published data from the Hermosillo region [Vidal Solano *et al.*, 2005] are also used for the discussion of the geochemical signature.

Basalts crop out mostly at Cerro Las Cuevitas near Hermosillo. They have a transitional character: high  $\text{TiO}_2$  (> 2.5 wt%), low  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , and little nepheline in the norm, are characteristic of alkaline lavas, while high total iron (> 13 wt%) is more akin to tholeiitic series.

The porphyritic glassy lavas (JR03-1, JR 04-49 & JR 04-59b, tabl. I) that rest on the peralkaline ignimbrites have intermediate silica content (60-65 wt%) and low alumina (13-14 wt%). Based on the total alkalis silica (TAS) classification diagram [Le Bas *et al.*, 1986], one of these samples is a high-silica andesite, whereas the others plot in the trachyte field (fig. 4). Nonetheless, high FeOt (5-13 wt%) and FeOt/MgO ratios characterize intermediate lavas of the tholeiitic series (icelandites) [Vidal Solano *et al.*, 2006].

Middle Miocene ignimbrites and rhyolites have high silica contents (~ 72-74 wt%), low alumina (~ 12 wt%) and highly variable total alkalis (tabl. I, fig. 4). The mobility of the alkalis, particularly Na, has a critical effect on the

absence of acmite in the norm of the majority of the ignimbrite samples. Low contents in alumina and iron contribute furthermore to the classification of these oversaturated rocks as comendites [Sutherland, 1974; Macdonald, 1974a; Le Maitre, 1989].

Major and trace element compositions of the Middle Miocene lavas from central Sonora have been discussed in a companion paper [Vidal Solano *et al.*, 2007]. We will therefore only briefly summarize here their main characteristics. The rare-earth element (REE) patterns (fig. 5) are very similar for all the peralkaline ignimbrites (fifteen samples). They are enriched in light REE ( $[\text{La}/\text{Yb}]_N = 6.8$  to 8.3), present relatively flat but irregular heavy REE (HREE) patterns, and a strong depletion in Eu. Evidence for extensive feldspar fractionation involved in the generation of these liquids also comes from low Sr abundances (tabl. I). REE patterns of icelandites are slightly less enriched ( $[\text{La}/\text{Yb}]_N \sim 6.5$ ), and they display a smaller negative anomaly in Eu. On the MORB-normalized spidergram [Pearce, 1983], the Hermosillo basalt is slightly enriched in the less incompatible trace elements compare to N-MORB, and presents a positive anomaly in Ba (fig. 6). Patterns of icelandite and peralkaline ignimbrites are subparallel to that of the basalt, from Nb to Yb, but strongly enriched in K, Rb, Th, and depleted in Sr. Increasing negative anomalies in Ti, P, and Ba are clearly related to differentiation involving Fe-Ti oxides, apatite and feldspar. The behaviour of the trace elements suggests therefore some kind of genetic link between the transitional basalt, the porphyritic glassy lavas (icelandites), and the peralkaline oversaturated ignimbrites.

Petrochemical similarities exist between the Middle Miocene volcanic sequences from central Sonora and the Quaternary comenditic rhyolites from Sierra La Primavera, Jalisco (figs. 4 and 5). By contrast, petrology and isotopic signatures of felsic rocks (fig. 7) clearly differ from those of the Miocene sequences from Sierra Santa Ursula [Mora-Álvarez and McDowell, 2000], located at the western edge of the Empalme graben (fig. 1).

TABLE I. – Representative chemical analyses of Middle Miocene volcanic rocks from central Sonora. Major elements are in weight %, trace elements in ppm. Rock types: B = basalt; I = icelandite; Ign = ignimbrite; R = rhyolite. Localities: Hilo = Hermosillo; CCha = Cerro Chapala; SSA = Sierra San Antonio; MD = Mina Divisadero; CS = Cerro Sarpullido; CL = Cerro La Legua; CLS = Cerro La Sonora; SMH = San Miguel de Horcasitas; SJP = San José de Pimas. For the ignimbrites, vitrophyric facies have been sampled. A.I. = Agpaic Index [molar Al/(Na+K)].

TABL. I. – Analyses chimiques représentatives (majeurs et traces) de roches volcaniques du Miocène moyen du Sonora central. Éléments majeurs en poids %, éléments traces en ppm. Les échantillons d'ignimbrites ont été prélevés dans les niveaux vitrophyriques. A.I. = indice d'agpaicité [Al/(Na+K)].

Sample N°	H96-2**	JR03-1*	JR04-49	JR04-59B	JR03-9*	JR04-40	JR04-30A	JR04-35A	JR02-19*	JR03-7	JR02-21A	JR02-71c	JR04-12B
Rock-type	B	I	I	I	Ign	Ign	Ign	R	Ign	Ign	Ign	Ign	Ign
Locality	Hilo	CCha	SSA	SSA	MD	MD	CS	CS	CCha	CL	CLS	SMH	SJP
SiO <sub>2</sub> (wt%)	47.69	61.41	65.96	64.70	73.60	72.63	72.65	74.18	74.31	73.57	72.67	71.91	72.96
TiO <sub>2</sub>	2.51	0.85	0.86	0.86	0.17	0.13	0.13	0.14	0.24	0.12	0.12	0.11	0.13
Al <sub>2</sub> O <sub>3</sub>	15.37	13.34	13.99	13.97	11.89	12.72	12.22	11.75	12.89	12.24	12.42	12.18	12.42
Fe <sub>2</sub> O <sub>3</sub>	7.36	9.97	4.91	5.03	0.80	1.77	1.85	1.80	2.09	1.75	1.75	1.74	1.82
FeO	5.90	2.90	—	—	0.85	0.23	0.47	0.63	0.39	—	—	—	0.37
MnO	0.21	0.11	0.09	0.09	0.04	0.03	0.04	0.03	0.07	0.02	0.04	0.03	0.03
MgO	5.94	1.00	1.01	1.07	0.09	< L.D.	< L.D.	< L.D.	0.15	0.13	0.08	0.10	< L.D.
CaO	8.60	2.22	2.77	2.78	0.55	0.50	0.76	0.58	0.51	0.67	0.65	0.48	0.57
Na <sub>2</sub> O	3.34	3.12	3.80	3.76	3.81	3.49	4.09	3.12	3.85	3.87	4.06	3.25	3.07
K <sub>2</sub> O	0.70	3.48	4.12	3.78	3.83	5.19	3.93	5.08	5.00	4.97	4.50	5.22	5.78
P <sub>2</sub> O <sub>5</sub>	0.49	0.22	0.24	0.24	0.03	< L.D.	< L.D.	< L.D.	0.08	0.17	< L.D.	< L.D.	< L.D.
H <sub>2</sub> O+	0.41	1.85	—	—	3.35	—	—	—	0.15	—	—	—	—
H <sub>2</sub> O-	0.27	0.12	—	—	0.04	—	—	—	0.32	—	—	—	—
LOI	—	—	2.10	3.00	—	3.52	4.15	3.42	—	1.08	3.79	3.67	3.19
Total	98.79	100.59	99.86	99.27	99.05	100.21	100.28	100.72	100.05	98.58	100.07	98.68	100.35
A.I.	—	—	—	—	0.88	0.89	0.90	0.91	0.91	0.96	0.93	0.90	0.91
Rb (ppm)	14.0	136.3	134.0	129.4	178.0	171.0	203.0	188.0	148.0	176.9	190.5	180.3	166.0
Sr	482.0	187.4	195.0	211.2	13.8	11.4	42.2	10.0	31.1	23.5	13.0	11.2	10.2
Ba	356.0	1116.5	1059.7	1033.0	48.1	36.0	44.6	170.0	451.6	60.3	36.0	40.1	61.5
Zr	248.0	428.6	445.0	430.7	317.0	314.0	321.0	272.0	499.2	297.5	347.3	294.7	348.0
Y	40.0	50.6	55.9	46.7	53.1	54.5	52.9	58.4	50.9	49.1	52.2	49.0	54.5
Nb	21.0	19.43	19.71	15.35	23.70	23.20	23.30	22.40	22.17	20.26	21.59	20.70	23.80
Cs	0.2	3.99	3.66	3.88	6.58	6.81	8.74	6.76	2.86	3.01	5.80	5.05	5.95
Th	1.00	13.45	13.46	12.53	18.90	19.30	18.10	20.80	16.72	18.99	18.56	18.87	19.50
Ta	0.50	1.38	1.34	1.38	1.80	1.81	1.75	1.85	1.66	1.93	1.95	1.91	1.83
U	0.50	4.16	4.22	3.99	5.74	5.69	5.48	7.33	4.62	5.33	5.81	5.79	5.68
Pb	5.00	17.79	17.25	17.00	26.80	26.80	24.10	25.90	54.33	25.26	30.07	33.41	25.00
Hf	7.00	9.64	10.43	9.59	9.52	9.47	9.63	8.51	11.28	9.34	10.09	9.17	10.40
La	24.5	42.86	42.49	41.75	56.90	58.40	55.20	55.30	47.57	57.87	58.80	57.06	57.70
Ce	55.5	96.01	92.47	88.15	118.00	122.00	117.00	119.00	105.06	116.60	121.60	117.90	126.00
Pr	7.4	11.42	11.34	10.88	13.70	14.40	14.00	14.40	12.15	14.04	14.24	13.70	14.20
Nd	31.5	44.82	45.03	42.15	50.20	51.90	51.10	54.00	46.06	51.51	52.36	49.97	52.20
Sm	7.5	9.54	10.00	9.01	9.74	10.50	9.73	10.90	9.17	10.25	10.34	9.94	10.50
Eu	2.3	1.83	1.91	1.78	0.12	0.13	0.14	0.55	0.54	0.13	0.12	0.10	0.12
Gd	7.9	8.28	8.73	8.21	8.47	9.22	8.62	9.32	8.53	8.73	8.99	8.50	8.74
Tb	1.4	1.37	1.49	1.31	1.43	1.54	1.45	1.63	1.40	1.44	1.47	1.40	1.51
Dy	6.6	8.57	8.86	7.99	8.68	9.17	8.42	9.93	8.16	8.63	8.87	8.42	9.04
Ho	1.4	1.78	1.83	1.56	1.83	1.91	1.84	2.03	1.73	1.71	1.74	1.67	1.91
Er	3.8	5.10	5.21	4.56	5.41	5.47	5.20	5.89	5.08	4.96	5.04	4.89	5.55
Yb	3.9	4.73	5.03	4.64	5.12	5.24	5.03	5.70	4.99	5.08	5.39	5.06	5.27
Lu	0.6	0.78	0.80	0.72	0.78	0.80	0.77	0.87	0.71	0.79	0.80	0.77	0.82

< L.D. = Lower than detection limit. Trace elements : \* Chemex ; \* Grenoble ; others CRPG

## Sr, Nd and Pb isotopic data

Sr, Nd and Pb radiogenic isotope data for samples from central Sonora are listed in table II. Middle Miocene rocks display a large degree of isotopic heterogeneity on the  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$  plot (fig. 7). Other data included in this plot will be discussed subsequently. Hermosillo basalt has the lowest Sr (0.7045) and the highest Nd ratio (0.51279). The porphyritic glassy icelandite from Sierra Lista Blanca has slightly higher Sr (0.7054) and lower Nd (0.51265). The five peralkaline ignimbrite samples display a large range of  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.7067 to 0.7187), but a relatively limited variation in  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51265-0.51270). Isotopic ratios for Sarpullido rhyolite are in the same range as those of the ignimbrites (tabl. II). A biotite ignimbrite sample from Mina Divisadero, lying below a peralkaline ignimbritic unit [see Vidal Solano, 2005], has low Nd and high Sr ratios (tabl. II); it plots in the field of the Sierra Madre Occidental (SMO) ignimbrites.

Lead isotopic compositions were determined on five samples. Ignimbrite, rhyolite and icelandite samples display very little variations in  $^{208}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{206}\text{Pb}/^{204}\text{Pb}$  (tabl. II), forming a tight cluster on lead isotope plots (fig. 8). Hermosillo basalt has the least radiogenic concentrations in Pb. All these data plot above the northern hemisphere reference line (NHRL) of Zindler and Hart [1986] on a  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  plot, but very close to the NHRL on a  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  plot.

TABLE II. – Isotopic compositions of Middle Miocene volcanic rocks from central Sonora. Same abbreviations as in table I. T Biot = biotite tuff.

TABL. II. – Compositions isotopiques de roches volcaniques du Miocène moyen du Sonora central. Mêmes abréviations que pour la table I. T Biot = tuf à biotite.

Sample	Rock-type	Locality	$^{143}\text{Nd} / ^{144}\text{Nd}$	$\pm$	$^{87}\text{Sr} / ^{86}\text{Sr}$	$\pm$	$^{206}\text{Pb} / ^{204}\text{Pb}$	$^{207}\text{Pb} / ^{204}\text{Pb}$	$^{208}\text{Pb} / ^{204}\text{Pb}$
JR03-1	I	CCha	0.512654	14	0.705414	8	19.016	15.630	38.714
JR04-30A	Ign	CS	0.512651	14	0.709598	16	19.041	15.634	38.747
JR04-35A	R	CS	0.512592	6	0.714584	26	19.063	15.631	38.743
JR04-39	T Biot	MD	0.512520	6	0.707885	11	—	—	—
H3-94	Ign	Hilo	0.512671	6	0.714229	8	19.026	15.620	38.702
H96-1	B	Hilo	0.512798	6	0.704499	2	18.808	15.584	38.419
JR02-71C	Ign	SMH	0.512703	5	0.718700	12	—	—	—
JR02-21A	Ign	CLS	0.512696	5	0.716566	11	—	—	—
JR02-19	Ign	CCha	0.512681	8	0.706767	12	—	—	—

## DISCUSSION

### Petrogenetic processes and mantle source

Nearly constant Nd isotope values but highly variable Sr isotopic ratios in the ignimbrites indicate that the opening of the Rb-Sr system occurred in an upper crustal reservoir. Moreover, as seen with other Miocene peralkaline outcrops in North America [Scott *et al.*, 1995; Edwards and Russell, 2000; Miller *et al.*, 2000], isotopic ratios give also information on the nature of the mantle source. Peralkaline ignimbrites from central Sonora have, as a whole, relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios; they define on the  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$

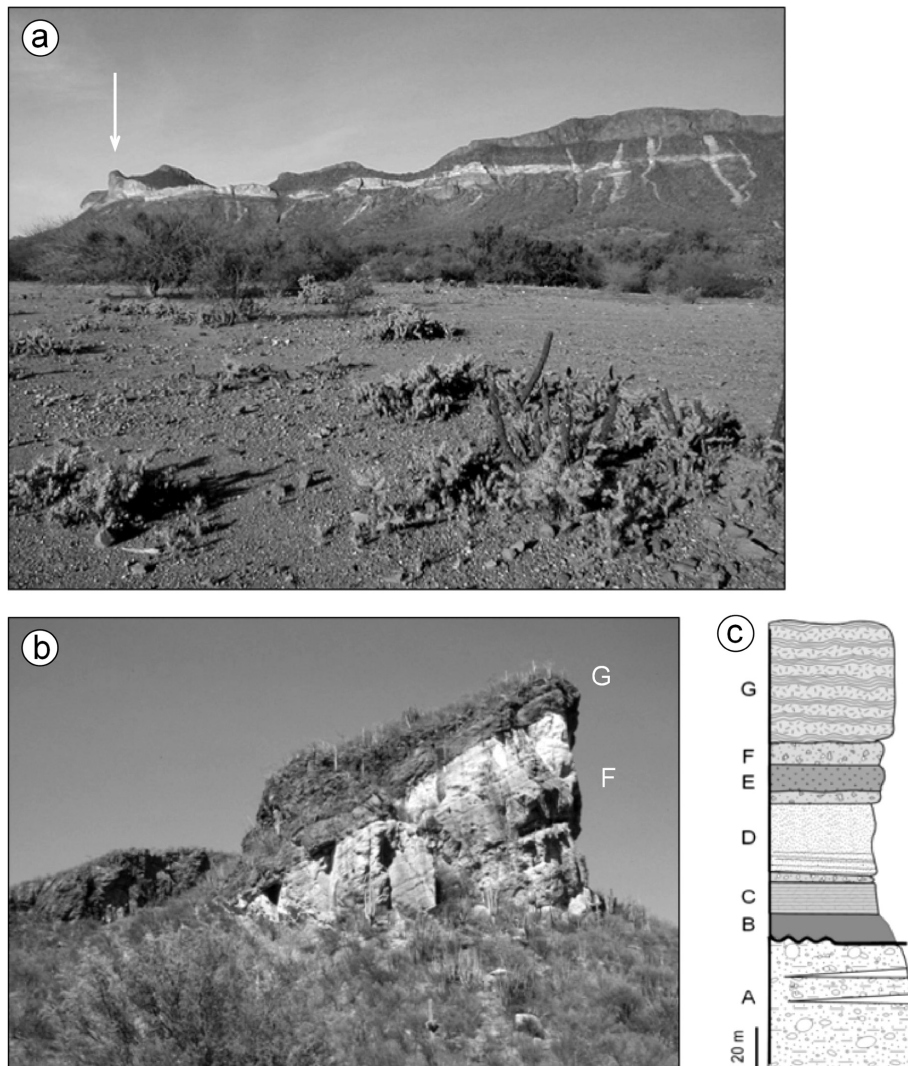


FIG. 3. – Volcanic and sedimentary succession observed at Sierra Lista Blanca (SLB). (a) Overview of the eastern flank of SLB; the arrow indicates the southern part of SLB shown in (b). (b) Photograph of the southern end of SLB showing the icelandite flows (G) and volcano-sedimentary deposits (F), tilted toward the west. In the southern part of SLB, basalts (E) are not represented. (c) Composite stratigraphic column at SLB; A, sandstones and conglomerates (Báucarit Formation); B, welded peralkaline ignimbrite; C, less welded peralkaline unit; D, biotite tuff and volcano-sedimentary deposits forming the whitish stripe on (a); E, basaltic flows intercalated with breccias and conglomerates (F); G, porphyritic glassy lava flows (icelandites).

FIG. 3. – Séquence stratigraphique de la Sierra Lista Blanca (SLB). (a) Vue d'ensemble du flanc est de la SLB ; la flèche marque la partie méridionale de la SLB représentée sur la photographie (b). (b) Photographie de l'extrémité sud de la SLB montrant les coulées d'icelandite (G) et les dépôts volcano-sédimentaires sous-jacents (F) basculés vers l'ouest. Dans cette partie méridionale de la SLB, les basaltes (E) ne sont pas présents. (c) Colonne stratigraphique de la SLB ; A, grès et conglomérats (formation Báucarit) ; B, ignimbrite hyperalkaline soudée ; C, unité ignimbritique hyperalkaline moins soudée ; D, tuf à biotite et dépôts volcano-sédimentaires formant le liseré blanc sur la photo (c) ; E, coulées basaltiques intercalées dans des brèches et conglomérats (F) ; G, coulées vitreuses porphyriques (icelandites).

plot (fig. 7) a trend that does not overlap the field of the SMO ignimbrites [McDowell *et al.*, 1999; Albrecht and Goldstein, 2000; Housh and McDowell, 2005] nor that of the Sierra Santa Ursula (SSU) Miocene sequences [Mora-Klepeis and McDowell, 2004]. Simple assimilation-fractional crystallization (AFC) calculations, based on the correlations between Nd and Sr isotope ratios, were used to estimate crustal contamination. For AFC calculations we used the equations of De Paolo [1981], assumed a constant ratio for the rate of mass assimilation to the rate of crystal fractionation, and considered the Hermosillo basalt as the mantle end-member. The range of Sr isotopic compositions of the Middle Miocene ignimbrites can be reproduced by 70-90% fractional crystallization of this transitional basalt with relatively limited ( $r = 0.03-0.1$ ) assimilation of a

highly radiogenic contaminant, which certainly consisted of the Precambrian upper crust represented in northwestern Sonora [Iriondo *et al.*, 2004]. Such a small crustal contribution is not really surprising: given the very low Sr content of the felsic magma, even a weak assimilation of a highly radiogenic contaminant can rapidly raise the Sr isotopic ratios. The involvement of an upper crustal contaminant is in agreement with the final stage of differentiation of the peralkaline liquids in a shallow magma chamber. These data, like the isotopic results obtained on the granitoids [Valencia-Moreno *et al.*, 2001], confirm the presence of a Precambrian basement in central and coastal Sonora. On another hand, variations observed in the Sr and Nd isotope ratios indicate that Sonoran Middle Miocene peralkaline ignimbrites studied here are not all from a single large-scale volcanic



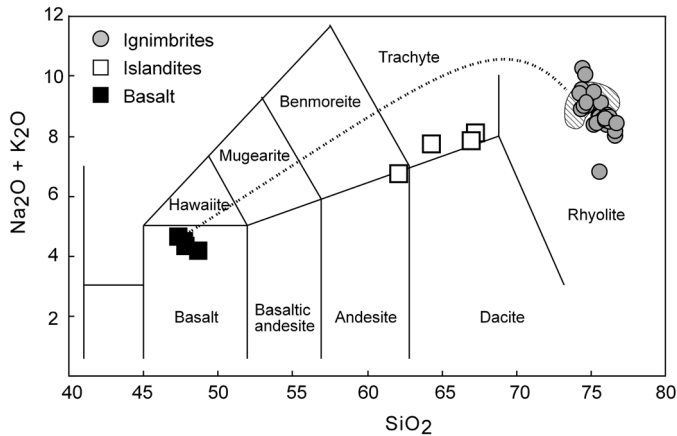


FIG. 4. – Total alkalis silica (TAS) classification diagram [Le Bas *et al.*, 1986; Le Maitre, 1989] for the Middle Miocene Sonoran volcanic rocks. Analyses recalculated to 100% on a water-free basis. The dashed curve reproduces compositional variations of rocks from the Boina centre, Afar [Barberi *et al.*, 1975]. The hatched field corresponds to comendites from the Primavera caldera, Jalisco [Mahood, 1981].

FIG. 4. – Diagramme alcalins-silice (TAS) [Le Bas *et al.*, 1986; Le Maitre, 1989] pour la classification des roches volcaniques de la séquence du Miocène moyen. Analyses recalculées en base anhydre. La courbe en pointillés correspond à l'évolution de la composition chimique des roches du volcan Boina, en Afar [Barberi *et al.*, 1975]. La zone hachurée correspond aux analyses de comendites de la caldera de La Primavera, Jalisco [Mahood, 1981].

event such as that hypothesized to have occurred farther to the west [Oskin, 2002]; rather, they may be related to several moderate-volume pyroclastic pulses. The absence of caldera structure is consistent with such independent magma batches rising separately and erupting from distension fractures related to rift evolution. In the Afar depression, a good analogue for illustrating the volcano-tectonic activity linked to rift propagation, silicic lavas erupted prior to the main extensional phase associated with fissural basaltic activity [Lahitte *et al.*, 2003]. In such a context, the time required

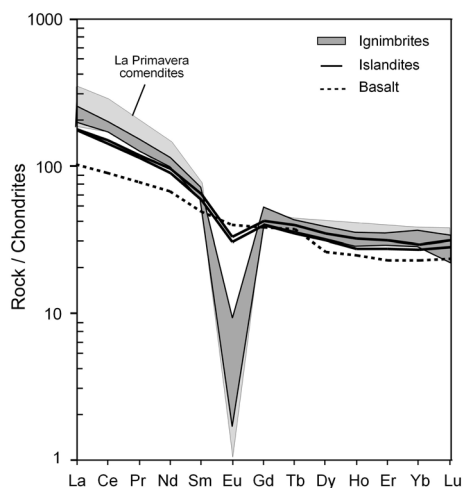


FIG. 5. – Chondrite-normalized REE abundances for the Middle Miocene volcanic rocks from central Sonora. Normalizing values from Sun and McDonough [1989]. REE patterns of La Primavera comendites from Mahood [1981].

FIG. 5. – Diagramme de terres rares normalisé aux chondrites des roches volcaniques de la séquence du Miocène moyen. Valeurs de normalisation de Sun et McDonough [1989]. Spectres de terres rares des comendites de La Primavera d'après Mahood [1981].

for the generation of small-volume rhyolitic melts is relatively short; it has been estimated as less than 50,000 years [Lowenstern *et al.*, 2006].

For the icelandites, AFC calculations [following the method of De Paolo, 1981] show that they could have been derived from 50% fractional crystallization of a tholeiitic basalt – similar to the Trincheras basalts that crop out south of Sierra Santa Ursula [Paz-Moreno, 1992; Mora-Álvarez and McDowell, 2000] – with limited ( $r = 0.05$ ) assimilation of upper crustal Precambrian material [Vidal-Solano *et al.*, 2006]. The glomeroporphyritic texture and glassy matrix of these rocks require that a basaltic magma trapped in the crust suffers crystal fractionation in a periodically refilled reservoir [Couch *et al.*, 2001] with minor assimilation of Precambrian material, and rises rapidly to the surface [Vidal-Solano, 2005]. These characteristics illustrate an increase in magma supply rate and an easier access to the surface along fractures related to rifting. The absence of Plio-Quaternary basaltic activity demonstrates that the whole region extending north of Guaymas-Empalme [Paz-Moreno, 1992; Roldán-Quintana *et al.*, 2004; Vargas-Navarro, 2005; Vidal-Solano, 2005] is an aborted rift system.

In brief, Sr, Nd and Pb isotopic data support an origin of the peralkaline ignimbrites by fractional crystallization of transitional basaltic magma, with slight contamination by an old crustal component, which has the characteristics of the Precambrian upper crust. The same mechanisms have been invoked for the SMO or SSU ignimbrites. The isotopic ratios reflect therefore (1) a clear difference in the nature of the basaltic precursor and (2) the peculiar chemistry of the peralkaline liquids *i.e.* their low Sr contents.

### Peralkaline volcanism and the opening of the Gulf of California

The Middle Miocene peralkaline ignimbrites from central Sonora present many petrochemical similarities with a 12.6 Ma volcanic unit defined as the San Felipe tuff in the Puertecitos area of Baja California [Nagy *et al.*, 1999; Stock *et al.*, 1999; Stock, 2000; Oskin, 2002]. This ignimbritic episode, present in regions that initially correspond to

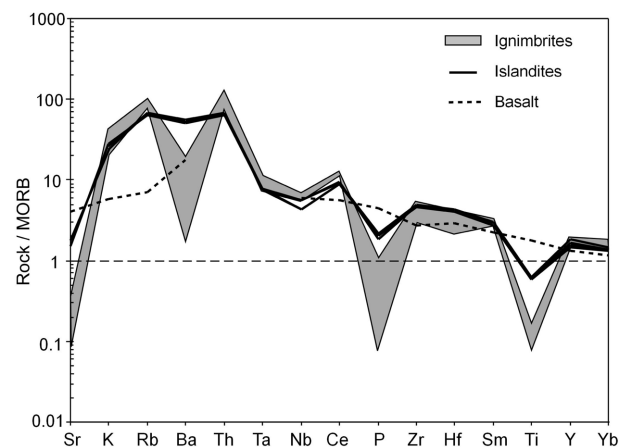


FIG. 6. – MORB-normalized trace element patterns for the Middle Miocene volcanic sequences from central Sonora. Normalizing values from Pearce [1983].

FIG. 6. – Diagramme multi-éléments normalisé aux MORB pour les roches volcaniques de la séquence du Miocène moyen. Valeurs de normalisation de Pearce [1983].

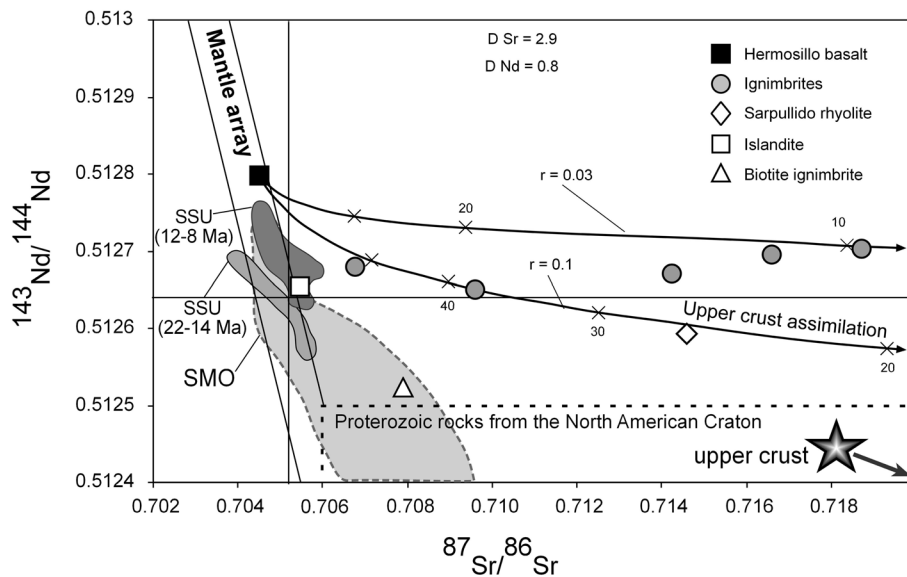


FIG. 7. –  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for Middle Miocene rocks from central Sonora. Additional isotopic ratios from Sierra Santa Ursula (SSU) and the Sierra Madre Occidental (SMO) are used for comparison [Albrecht and Goldstein, 2000; Mora-Klepeis and McDowell, 2004; Housh and McDowell, 2005]. The lines are AFC models [De Paolo, 1981] showing compositional variations of liquids derived from the Hermosillo basalt, assuming the Precambrian upper crust as the contaminant (values of Sr = 16 ppm, Nd = 48.4 ppm, Sri = 0.7390 and eNd = -17.9 are from Miller *et al.* [2000]), and ratios between masses of assimilated and fractionated material  $r = 0.1$  and  $0.03$ . Numbers along the lines represent the amounts of residual liquids.

FIG. 7. – Compositions isotopiques  $^{143}\text{Nd}/^{144}\text{Nd}$  vs  $^{87}\text{Sr}/^{86}\text{Sr}$  de laves du Miocène moyen du Sonora central. Sont également reportées pour comparaison, des données isotopiques de la Sierra Santa Ursula (SSU) et de la Sierra Madre Occidental (SMO) [Albrecht et Goldstein, 2000; Mora-Klepeis et McDowell, 2004; Housh et McDowell, 2005]. Les courbes correspondent aux modélisations d'AFC selon De Paolo [1981], en considérant la croûte précambrienne supérieure comme le contaminant (valeurs du Sr = 216 ppm, Nd = 48.4 ppm, Sri = 0.7390 and eNd = -17.9 d'après Miller *et al.* [2000]), et des rapports entre les masses de matériel assimilé et fractionné compris entre  $r = 0.1$  et  $0.03$ . Les chiffres le long des lignes indiquent les pourcentages de liquide résiduel.

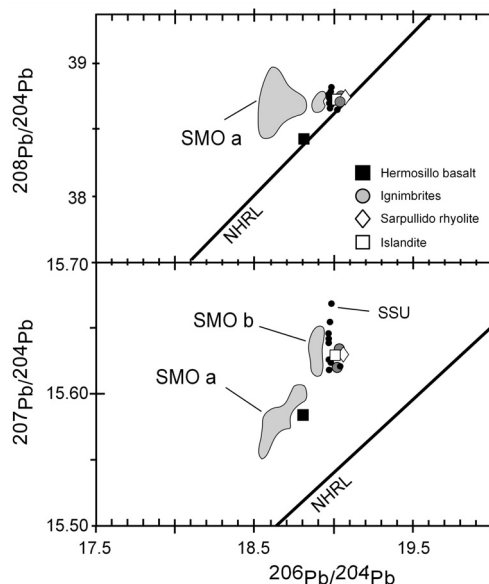


FIG. 8. – Pb isotopic data for Middle Miocene samples from central Sonora. Additional data from Sierra Santa Ursula (SSU, small black dots) [Mora-Klepeis and McDowell, 2004] and the Sierra Madre Occidental (SMO) [Albrecht and Goldstein, 2000; Housh and McDowell, 2005], are used for comparison. SMO a = ignimbrites of the SMO emplaced on the north American basement; SMO b = ignimbrites of the SMO emplaced above accreted terranes.

FIG. 8. – Données isotopiques en plomb de laves du Miocène moyen du Sonora central. Des données de la Sierra Santa Ursula (SSU, points noirs) [Mora-Klepeis et McDowell, 2004] et de la Sierra Madre Occidental (SMO) [Albrecht et Goldstein, 2000; Housh et McDowell, 2005], ont été également reportées pour comparaison. SMO a = ignimbrites de la SMO mises en place sur le craton nord américain; SMO b = ignimbrites de la SMO mises en place au dessus des terrains accretés.

conjugate rifted margins of the Gulf of California [Oskin and Stock, 2003c; Stock *et al.*, 2005], and emplaced during a brief period of time, characterizes the pre-rift stage that precedes continental break-up. It coincides in time with the collision of the Pacific-Farallon ridge with the trench, and the end of subduction [Mammerickx and Klitgord, 1982; Stock and Hodges, 1989; Lonsdale, 1991]. The southern part of the oceanic ridge broke into small ridge segments that were progressively abandoned off Baja California [Michaud *et al.*, 2006; Pallares *et al.*, 2007]. Between 12.5 and 7 Ma, the Tosco-Abreojos fault system developed along Baja California to accommodate the relative motion of the Pacific plate [Spencer and Normark, 1979; Stock and Lee, 1994]. Correlations between the preserved remnants of the peralkaline episode on both side of the gulf enable to support a NW-SE strike slip displacement of Baja California of about 280 km [Oskin *et al.*, 2001; Oskin and Stock, 2003a]. Similarities between the N-S oriented Bahía de los Ángeles and Bahía de las Ánimas grabens in Baja California with the Empalme graben, are also in agreement with this amount of lateral movement (fig. 9).

A drastic change from pre-rift E-W extension to syn-rift NW-SE transtensional regime occurred at the end of the Miocene. It is documented in central Sonora by (1) the tilting of the 12.5 Ma ignimbrite mesas and their icelandite cover, and (2) the presence of strike-slip duplexes at Cerro Sarpullido [Vidal-Solano, 2005]. In the gulf area, NW-SE striking faults that limit the Yaqui half-graben offshore Sonora, and the Guaymas half-graben, offshore Baja California [Aragón-Arreola *et al.*, 2005], are considered to have accommodated the transtensional strain associated with the



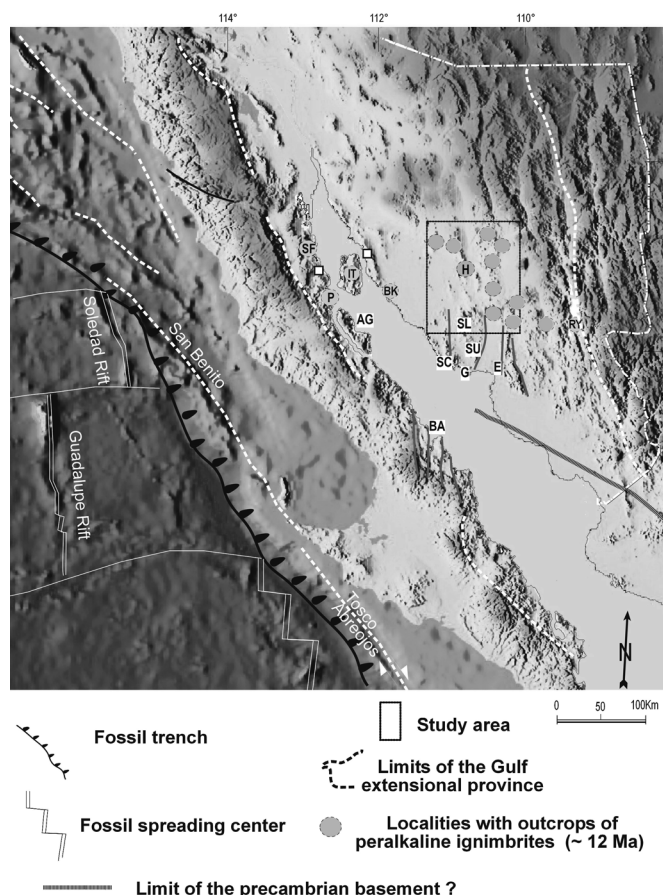


FIG. 9. – Schematic reconstruction of the initial position of Baja California peninsula, and major crustal blocks that became large gulf islands, relative to Sonora in late Miocene time. The relief image used in that figure, generated from the ETOPO2v2 (2006) database, is available on <http://www.ngdc.noaa.gov/mgg/image/2minrelief.html>. The San Felipe and Puertecitos areas in Baja California, Tiburón Island and Bahía Kino in coastal Sonora contains numerous outcrops of a peralkaline ignimbrite, the Tuff of San Felipe, which erupted ca. 12.5 Ma, prior to the opening of the gulf. This ignimbrite, and a series of younger (6 Ma) ignimbrites are used to constrain the reconstructed positions of these blocks [Oskin and Stock, 2003a, 2003c]. G-E = Guaymas-Empalme graben; BA = double graben system of Bahía de Los Angeles (west) and Bahía de las Animas (east); SF = San Felipe; P = Puertecitos (on eastern coast of Baja California); BK = Bahía de Kino; AG = Angel de la Guardia Island; H = Hermosillo; SL = Sierra Libre; RY = Río Yaqui, easternmost outcrop of peralkaline ignimbrite. White squares are additional constraints on this reconstruction and correspond to the locations of pre-Miocene fluvial conglomerates inferred to have been deposited in a westward-draining river system, correlated from Sonora to Baja California by Gastil *et al.* [1973].

FIG. 9. – Reconstitution de la position initiale de la partie nord de la péninsule de Basse Californie, et des blocs crustaux qui forment les îles du golfe, par rapport au Sonora au Miocène moyen. La base topographique utilisée est une image générée par la base de données ETOPO2v2 (2006) disponible sur le site <http://www.ngdc.noaa.gov/mgg/image/2minrelief.html>. La région de San Felipe – Puertecitos en Basse Californie, l'île Tiburón et le secteur de Bahía de Kino sur la côte du Sonora, sont des secteurs où affluent des ignimbrites hyperalkalines datées de 12.5 Ma (Tuff San Felipe), mises en place avant l'ouverture du golfe. Cette ignimbrite, ainsi que les ignimbrites plus récentes (6 Ma), ont servi à reconstituer le déplacement de la Basse Californie [Oskin et Stock, 2003a, 2003c]. RY = Río Yaqui, affleurement d'ignimbrite hyperalkaline le plus oriental. Les carrés blancs correspondent à des conglomérats fluviaux anté-miocènes trouvés de part et d'autre du golfe, considérés par Gastil *et al.* [1973] comme la marque d'un drainage vers l'ouest depuis le Sonora.

progressive transfer of Baja California to the Pacific plate. Marine incursion into the gulf area occurred at about 6.5 Ma, when most of the motion between Pacific and North-American plates was localized within the Gulf of California [Klitgord and Mammerickx, 1982; Stock and Hodges, 1989; Oskin *et al.*, 2001; Castillo *et al.*, 2002; Oskin and Stock, 2003b, 2003c].

At this point a first-order question arises: why did peralkaline magmatism occur only in central Sonora and the Puertecitos area, during the pre-rift Middle Miocene episode? For the genesis of peralkaline silicic melts two conditions are needed: (1) a tectonic regime that enables the liquids to be trapped at an upper crustal level thereby enhancing fractional crystallization under low pressure conditions, and (2) the presence of the Precambrian craton to raise the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of the differentiated liquids. Central Sonora Middle Miocene comendites are located on a major boundary between the Precambrian crust and the Mesozoic accreted terranes [Tardy *et al.*, 1994]. In southwestern United States, Middle Miocene peralkaline volcanism also commonly appears after a long period of subduction-related magmatism [Best *et al.*, 1989]. Its distribution, from Nevada to California [Scott *et al.*, 1995; Perkins and Nash, 2002], and down to the Pinacate area [Vidal-Solano *et al.*, 2008], follows the western edge of the Precambrian basement. Because an old crust has a brittle behaviour, it favours the rapid ascent of parental magmas from the lower crust into shallow magma reservoirs. Geochemistry clearly points to transitional basalts as potential parent magmas for

the comendites; this implies (1) a weakened continental crust and (2) the absence of a subducted slab in that part of the gulf extensional province. However, the calc-alkaline signatures of Middle to Late Miocene volcanic sequences in SSU [Mora-Álvarez and McDowell, 2000] or the Puertecitos area [Martín-Barajas *et al.*, 1995; Nagy *et al.*, 1999], show that subduction-modified supraslab mantle can be preserved locally highlighting the complexity of the lithospheric structure at the edge of the North-American craton [Miller *et al.*, 2000; Vidal-Solano *et al.*, 2008]. Finally, the good fit between the location of peralkaline volcanism and the limit of the southern California slab window at 12.5 Ma [Wilson *et al.*, 2005; Pallares *et al.*, 2007], is obviously not fortuitous.

## CONCLUSION

Peralkaline ignimbrites erupted during Middle Miocene times either in central Sonora or the Puertecitos area, in Baja California, are a good geodynamic marker of the structural evolution of the Gulf of California rift system. This volcanic episode has petrochemical characteristics clearly different from those of the other Miocene volcanic sequences, indicating a change in the mantle source. Isotopic signatures, as well as the lack of caldera collapse post-dating the eruption, show that the 12.5 Ma peralkaline ignimbrites of central Sonora correspond to small independent magma batches evolving in shallow reservoirs rather than to a single large volume erupting system. Moreover, isotopes support

an origin by closed-system fractionation of transitional basalts with slight contamination by the Precambrian upper crust. Less differentiated 11 Ma old icelandites correspond to slightly higher magma supply and slower cooling rates in opened-magma chambers, illustrating an easier access to the surface at that time. The lack of recent voluminous basaltic outpourings shows however that the initial Middle Miocene intra-continental propagating rift has not evolved toward a more mature stage. The early rift system was abandoned in the Late Miocene, when Baja California peninsula became progressively coupled with the Pacific plate. The peralkaline magmatic activity allows us to document the

limit of the Precambrian craton, and the presence of an asthenospheric window below the region at 12.5 Ma.

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