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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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.

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 alkaline 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
GEOLOGICAL AND PETROLOGICAL BACKGROUND

Middle Miocene ignimbrites have long been recognized in central Sonora [Morales-Montaño et al., 1990; Paz-Moreno, 1992; Bartolini et al., 1992, 1994; McDowell et al., 1997; Mora-Alvarez and McDowell, 2000] but never considered, until recently [Vidal Solano et al., 2005], as a specific geochemical and petrographic 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 40Ar/39Ar 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 (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, granophytic 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 glomerophyrritic lava flows (fig. 3b), with dominant phenocrysts of plagioclase (An42-30), augite (Wo38En35Fs27), pigeonite (Wo8.5En45.5Fs46) 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 ± 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-Montaño 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 ± 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 Plin-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 preceded the Gulf of California opening.
GEOCHEMISTRY

Analytical procedures

Rock samples were first ground in a steel jaw crushe 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 Fe2+ 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 143Nd/144Nd = 0.511850 ± 0.000008 (mean on 39 runs), corresponding to an external reproducibility of 0.00001. Results on NBS 987 Sr standard yielded 87Sr/86Sr = 0.710250 (mean on 200 runs). The within-run precision (2σ absolute) for 87Sr/86Sr was 0.0000008-0.000015 and 0.0000007-0.000011 for 143Nd/144Nd.

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
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 (2σ/H268) and an external reproducibility of ca. 150 ppm (2σ/H268) for 206Pb/204Pb 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 TiO2 (> 2.5 wt%), low SiO2 and Al2O3, 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 ([La/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 ([La/Yb]N~ 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 compared 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).
Sr, Nd and Pb isotopic data

Sr, Nd and Pb radiogenic isotopic data for samples from central Sonora are listed in table II. Middle Miocene rocks display a large degree of isotopic heterogeneity on the 208Pb/204Pb vs 206Pb/204Pb 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 87Sr/86Sr ratios (0.7067 to 0.7187), but a relatively limited variation in 143Nd/144Nd (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 lowNd and high Sr ratios (tabl. II); it plots in the field of the Sierra Madre Occidental (SMO) ignimbrites.

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 Rh 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 87Sr/86Sr ratios; they define on the 143Nd/144Nd vs 8Sr/86Sr Bull. Soc. géol. Fr., 2008, n° 5

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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. 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).
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 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...
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
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 locally highlighting the complexity of the lithospheric structure at the edge of the North-American craton [Miller et al., 2007; 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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