The lower Mesozoic record of detrital zircon U-Pb geochronology of Sonora, México, and its paleogeographic implications

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ABSTRACT

Detrital zircon U-Pb geochronology from each of the formations of the Triassic-Lower Jurassic Barranca and El Antimonio groups of central and northwestern Sonora and from the Lower Jurassic Basomari and Middle Jurassic Lily formations of northern Sonora indicate they contain distinctive zircon populations. A Proterozoic population has peak ages near 1.8, 1.7, 1.6, 1.4, and 1.1 Ga. A population of Permo-Triassic grains with important peak ages near 269, 254, 245, 234 and 227 Ma. A third population of Early Jurassic age (~190 Ma) is only present in the middle member of the Lower Jurassic Sierra de Santa Rosa Formation and in the Basomari Formation. The fourth population of Middle Jurassic zircons with age peaks near 168 and 162 Ma is only present in the Lily Formation. A fifth population of Neoproterozoic and Paleozoic zircons, present only in the Basomari and Lily Formations, has Silurian and Devonian grains (~430 – 380 Ma) and Neoproterozoic grains (590 – 547 Ma). Possible source areas for these populations are Proterozoic igneous and metamorphic basement and/or Neoproterozoic and Paleozoic sandstones of southwestern USA and Sonora, the mostly Triassic magmatic arc of the Mojave Desert in California and the Permo-Triassic arc of northern Mexico, the Jurassic continental magmatic arc of southwestern North America, and the Jurassic eolian sand seas in Arizona.

Regional lithofacies, fossils, and paleocurrents indicate that the Barranca Group records a large fluvio-deltaic system on the margin of the El Antimonio marine basin, and Proterozoic and Permo-Triassic zircon populations common to the Barranca and El Antimonio Groups indicate that detritus was derived from the same source areas to the north. Lithofacies, age, and detrital zircon populations of the Basomari and Lily Formations indicate that they were deposited within the Jurassic magmatic arc of North America. The Basomari and Lilly Formations contain abundant Early Jurassic zircon grains, as does the middle member of the Sierra de Santa Rosa Formation; however, the Sierra de Santa Rosa Formation lacks a Neoproterozoic and Paleozoic grain population present in the Basomari and Lily Formations. The Basomari Formation, which is located north of the proposed trace of the Mojave-Sonora megashear, contains Proterozoic granitic clasts derived from Caborcan basement, which suggests that the Caborca block must have been located close to the Basomari basin by Early Jurassic time, a relation that contradicts the existence of the Mojave-Sonora megashear. The new data also indicate a maximum Early Triassic

depositional age for the previously undated Arrayanes Formation and correlation with the Antimonio Formation on the basis of a shared young detrital zircon peak age at ~254 Ma. A Coyotes Formation sample fails to confirm its supposed Early Jurassic age as it only yielded Proterozoic grains. Young zircon grain ages in the Lily Formation indicate a maximum Middle Jurassic age for that formation.

Key words: detrital zircon, Barranca Group, El Antimonio Group, Triassic-Jurassic, Sonora, Mexico.

RESUMEN

Nuevas edades obtenidas del fechamiento U-Pb de circones detríticos de cada una de las formaciones de los grupos El Antimonio y Barranca (Triásico-Jurásico), así como de las formaciones jurásicas Basomari y Lily, de Sonora, permiten distinguir las siguientes poblaciones de circones detríticos. Una población proterozoica que da grupos de edad cercanos a 1.8, 1.7, 1.6, 1.4 y 1.1 Ga. Una población permo-triásica que da grupos de edades cercanas a 269, 254, 245, 234 y 227 Ma. Una tercera población de edad jurásica temprana (~190 Ma) que sólo se presenta en el miembro medio de la Formación Sierra de Santa Rosa y en la Formación Basomari. La cuarta población sólo se encuentra en la Formación Lily y consiste en grupos de circones que dan edades de 168 y 162 Ma. La quinta población es de circones neoproterozoicos (edades entre 590 y 547 Ma) y paleozoicos (silúricos y devónicos; edades entre 430 y 380 Ma) y está presente en las formaciones Basomari y Lily. Las posibles áreas fuente para estas poblaciones de circones detríticos son los basamentos proterozoicos y/o las secuencias sedimentarias neoproterozoicas y paleozoicas del suroeste de los Estados Unidos y Sonora; el arco magmático de edad principalmente triásica del Desierto Mojave en California y el arco permo-triásico del norte de México; el arco magmático continental jurásico del suroeste de los Estados Unidos y el norte de México, y los campos eólicos jurásicos del centro-norte de Arizona. Las litofacies, fósiles y datos de paleocorrientes conocidos del Grupo Barranca indican que su deposito se debió a un importante sistema fluvio-deltáico que desembocaba en las áreas marginales de la cuenca marina donde se depositó el Grupo El Antimonio y sus poblaciones de circones proterozoicos y permo-triásicos indican que sus detritos fueron derivados de áreas localizadas hacia el norte de Sonora.

Las litofacies, edad y poblaciones de circones detríticos de las Formaciones Basomari y Lily muestran que estas unidades fueron depositadas dentro del arco magmático jurásico y comparten su población de circones de ~190 Ma con el miembro medio de la Formación Sierra de Santa Rosa, la cual, sin embargo, no contiene los circones neoproterozoicos que sí tienen esas dos unidades. A pesar de estas diferencias, la Formación Basomari que se localiza al norte de la traza propuesta de la megacizalla Mojave-Sonora contiene clastos ígneos del basamento del bloque Caborca, lo cual sugiere que ambas entidades deben haber estado localizadas en posición cercana durante el Jurásico Temprano, no apoyando de esa manera la idea de la existencia de la mencionada falla. Los nuevos datos proveen además una edad máxima del Triásico Temprano para la Formación Arrayanes, ya que la edad más joven de un grupo de sus circones detríticos es de 254 Ma, el cual también está presente en la Formación Antimonio. Los circones datados de la Formación Coyotes no probaron su supuesta edad jurásica temprana ya que sólo proporcionaron edades proterozoicas, mientras que los grupos más jóvenes de circones detríticos de la Formación Lily proporcionaron una edad máxima de Jurásico Medio para esa unidad.

Palabras clave: circones detríticos, Grupo Barranca, Grupo El Antimonio, Triásico-Jurásico, Sonora, México.

INTRODUCTION

Recent advances in laser ablation inductively coupled mass spectrometry permit analysis of large numbers of detrital zircon ages in sedimentary units. Determination of zircon ages, combined with knowledge of stratigraphy, sedimentology and biostratigraphy, provides useful information that contributes to the understanding of different tectonic problems, including evolution of basins, provenance and paleogeography. For instance, a detrital zircon reference frame has been advanced in the recent years for the Neoproterozoic to Triassic strata of western North America with the objective of constraining the terrane evolution of that region (Gehrels, 2000); the resulting data set provides a basis of comparison for data from a wide area.

A provenance data set for the Neoproterozoic and Paleozoic marine sandstones of Sonora, based on U-Pb geochronology of detrital zircons, has recently emerged as the result of a number of separate studies. Quartzarenites from the Neoproterozoic Las Viboras, El Aguila and Cerro Las Bolas groups (Stewart *et al.*, 2002; Izaguirre and Iriondo, 2007) that extend from northwestern to south-central Sonora

have yielded distinctive Proterozoic populations with peaks on relative probability distribution diagrams (Ludwig, 2003) near 1.7, 1.4 and 1.1–1.0 Ga, whereas the Neoproterozoic to early Paleozoic Cordilleran miogeoclinal succession of northwestern Sonora yielded detrital zircon population peaks with ages around 1.1 and 0.68 Ga (Stewart *et al.*, 2001). The Cambrian Proveedora and Bolsa Quartzites have a dominant population with a peak around 1.1 Ga and minor peaks at 1.7, 1.4 and 1.2 Ga (Gehrels and Stewart, 1998; Gross *et al.*, 2000; Stewart *et al.*, 2001). Other Paleozoic sandstones from the eugeoclinal and miogeoclinal successions of Sonora also yielded distinctive zircon populations. Ordovician miogeoclinal and eugeoclinal strata yielded zircons with ages that cluster at ~1.8 Ga, ~1.1 Ga and an Archean peak at ~2.7 Ga (Gehrels and Stewart, 1998); the Devonian and Permian miogeoclinal and eugeoclinal strata yielded main age groups at ~1.9, ~1.7-1.6, ~1.4 and 1.1–1.0 Ga (Gehrels and Stewart, 1998; Poole *et al.*, 2008). This reference data set indicates that source areas for most of the detrital sediments of the Neoproterozoic and Paleozoic strata

of Sonora may be the Proterozoic basement of southwestern USA and Sonora (*e.g.*, Karlstrom *et al.*, 1990, 2004; Gehrels and Stewart, 1998; Stewart *et al.*, 2001; Iriondo *et al.*, 2004; Anderson and Silver, 2005; Farmer *et al.*, 2005; Nourse *et al.*, 2005; Amato *et al.*, 2008a, Poole *et al.*, 2008), although Poole *et al.* (2008) have suggested that some detritus in the Permian foredeep sequence may be derived from an evolving accretionary wedge to the south.

Previously published detrital zircon geochronology for lower Mesozoic strata of Sonora is restricted to a few sandstone samples of the Triassic and Lower Jurassic Barranca and El Antimonio groups (Figure 1). Results of detrital zircon analysis from three sandstone samples of the El Antimonio Group were reported by González-León *et al.* (2005) and the results of one sample from the Santa Clara Formation of the Barranca Group were previously reported by Gehrels and Stewart (1998). In this paper, we report new data on detrital zircon geochronology from each of the six representative formations that compose the Triassic-Lower Jurassic Barranca and El Antimonio groups of central and
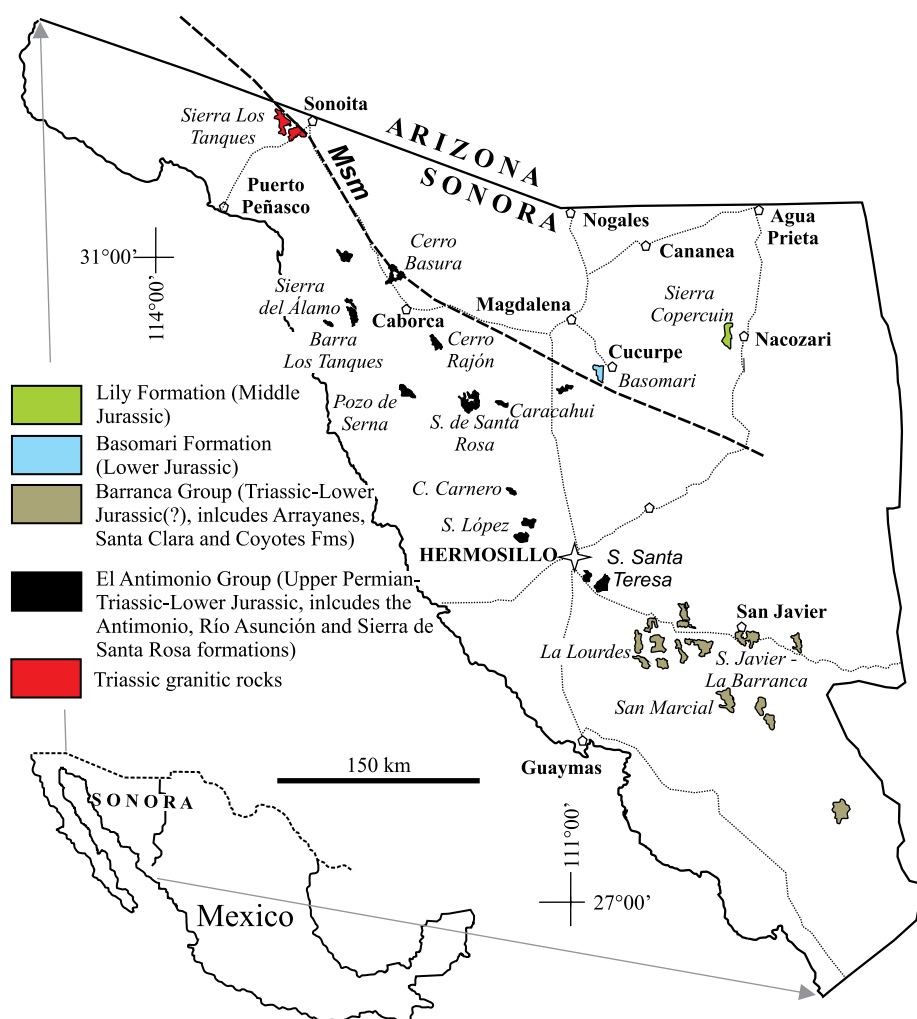

Figure 1. Map of Sonora showing localities mentioned and main outcrops of rock units described in this work. Msm: proposed trace of the Mojave-Sonora megashear (from Anderson and Silver, 1981).

northwestern Sonora, respectively. We also report new data obtained from one sample collected from the Lower Jurassic Basomari Formation and from two samples of the Middle Jurassic Lily Formation. These new analyses contribute to a more complete data set on detrital zircon geochronology for the Mesozoic stratigraphy of Sonora, which in turn sheds light on the interpretation of detrital provenance of these units. Our results provide a better understanding of the Triassic and Jurassic paleogeography of Sonora and have implications for the existence of major Mesozoic strike-slip faulting in Sonora, especially in view of the fact that the Barranca and El Antimonio groups are located south, and the Basomari and Lily formations are located north of the hypothetical trace of the Mojave-Sonora megashear (Silver and Anderson, 1974).

TRIASSIC AND JURASSIC STRATA

Triassic and Lower Jurassic strata present in northwestern and central Sonora include the Barranca (Alencáster, 1961a) and El Antimonio (González-León *et al.*, 2005) groups (Figure 1). The Barranca Group is divided into the Arrayanes, Santa Clara and Coyotes formations (Alencáster, 1961a) and the El Antimonio Group consists of the Antimonio, Río Asunción and Sierra de Santa Rosa formations (Hardy, 1981; Lucas and Estep, 1999; González-León *et al.*, 2005) (Figure 2). Strata of the Barranca Group are estimated to be ~3.5 km thick and represent mostly alluvial, fluvial, and transitional deltaic to shallow-marine deposits. The lowermost Arrayanes Formation records fluvial deposition; Marzolf and Anderson (2005) assigned it a
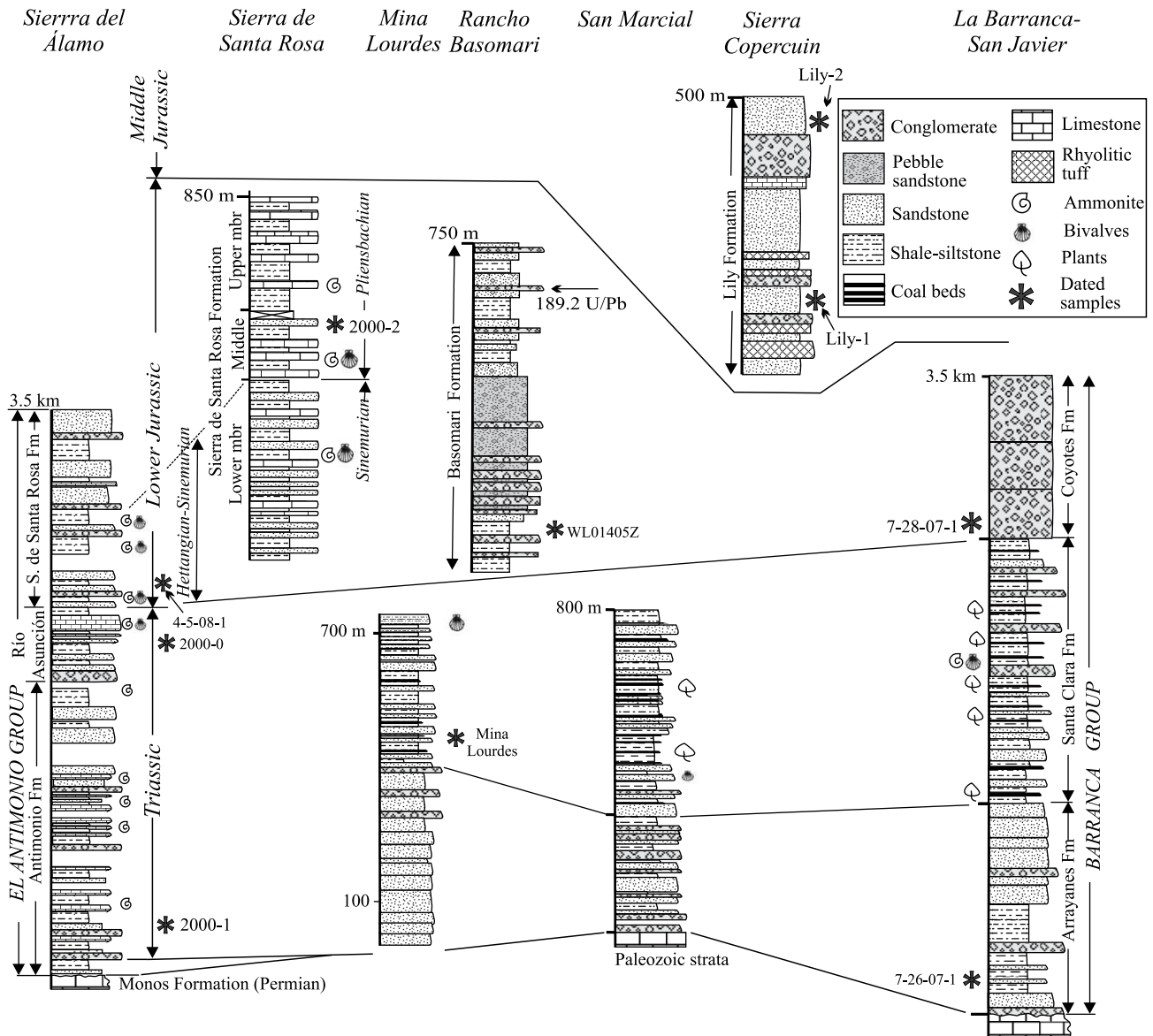

Figure 2. Stratigraphic columns and correlation of the El Antimonio and Barranca groups, and the Rancho Basomari and Lily formations. Stars and numbers indicate stratigraphic position of dated samples.

Middle to Late Triassic age based on tectono-sequence correlations. The Santa Clara Formation is the only fossiliferous unit of the group and includes fluvial, deltaic, and shallow-marine terrigenous strata that have an abundant Late Triassic (Carnian-Norian?) paleoflora (Weber, 1997, and references therein) and uncommon marine fossils (Alencáster, 1961b). Alluvial conglomerate of the Coyotes Formation unconformably overlie the Santa Clara Formation and its age is inferred to be Early Jurassic (Alencáster, 1961a; Stewart and Roldán-Quintana, 1991).

The El Antimonio Group (3.5 km thick) is divided into 14 marine sequences in the Sierra del Álamo (Figures 1 and 2), the lowermost of which is Late Permian in age (González-León, 1997). The Triassic Antimonio Formation comprises sequences II to VI and spans the Dienerian(?), Spathian, Anisian, Ladinian(?) and Carnian stages according to paleontologic and paleomagnetic data (summarized in González-León *et al.*, 2005; Steiner *et al.*, 2005). The Río Asunción Formation includes sequences VII to IX (Norian to Rhaetian). An erosional disconformity that overlies sequence IX separates the Lower Jurassic Sierra de Santa Rosa Formation (sequences X to XIV) from the Triassic strata. Partial outcrops of the Sierra de Santa Rosa Formation occur at several other localities in northwestern Sonora, including the hills south of Sierra Caracahui, Sierra López (Gameño Formation of Poole *et al.*, 2000) and Pozo de Serna (Figure 1), although the most complete section, besides Sierra del Álamo, is at Sierra de Santa Rosa (Figures 1 and 2), where the formation was defined and divided into lower, middle, and upper members (Hardy, 1981).

Other Jurassic units in Sonora that pertain to this study are the Basomari and Lily formations, which crop out near Rancho Basomari, southwest of Cucurpe, and at Sierra Copercuin, west of Nacozari, respectively (Figures 1 and 2). The Basomari Formation is ~750 m thick; its lowermost 140 m comprises dark purple massive siltstone with interbedded matrix-supported, poorly sorted, subrounded to subangular, granule- to pebble-conglomerate with local large olistolithic blocks of Paleozoic(?) limestone. Upsection, a 340 m thick interval consists of granule sandstone with interbedded, lenticular, poorly sorted, subangular, massive, matrix- to clast-supported pebble to cobble conglomerate in beds up to 10 m thick. The upper part of this formation consists of thick massive sandstone (up to 50 m thick) with lenses of granule conglomerate, intervals (up to 30 m thick) of massive siltstone and rhyolitic tuffs in the uppermost part of this unit. Clasts in the conglomerate are quartzite, porphyry granite, metamorphic rocks, andesite, sandstone, basalt and chert. Its Early Jurassic age is indicated by a rhyolite tuff in its upper part that was dated at 189.2 ± 1.1 Ma (U/Pb; Leggett *et al.*, 2007). This formation, which underlies the Rancho San Martin Formation (Leggett *et al.*, 2005), is here interpreted as a fluvial and alluvial continental deposit based on lithology and absence of fossils.

The Lily Formation (McAnulty, 1970) is a 500 m thick succession composed in its lower part of interbedded rhyolitic tuff and welded tuff, quartz-rich and arkosic fluvial sandstone and polymictic pebble conglomerate. Its upper part consists of quartzarenite, conglomerate (with clasts of quartzarenite, andesite, rhyolite and granitic rocks) and subordinate, lacustrine limestone beds. This unit crops out in the western flanks of Sierras Copercuin and Cobriza in northeastern Sonora (about 10 km west of Nacozari, Figures 1 and 2) where it is in fault contact with the Cambrian Bolsa Quarzite and intruded by Laramide plutons. The age of this unit is Middle Jurassic according to a U/Pb age of 174 Ma obtained by Anderson *et al.* (2005) from a tuff collected at Sierra Copercuin. This unit is considered correlative with the Rancho San Martin Formation where Leggett *et al.* (2007) reported a U/Pb age of 168.4 ± 1.6 Ma from a rhyolitic ash flow tuff.

DETRITAL ZIRCON GEOCHRONOLOGY

Mineral separations, and U-Pb geochronology on individual detrital zircon grains of the samples was conducted by laser-ablation-multicollector inductively coupled plasma-mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center in the Department of Geosciences, University of Arizona using the procedures described by Gehrels *et al.* (2006). Analytical data of the studied samples are reported in the Table A1 (electronic supplement) and their age probability curves are presented in relative probability distribution diagrams (Ludwig, 2003) in Figure 3. The Pb/U concordia plots are presented in Figure 4. All age errors are quoted at 1σ (Ma) level, and errors for isotopic ratios are quoted at 1σ (%). All reported UTM sample locations utilize the World Geodetic System 1984 .

Samples 2000-1, 2000-0 and 2000-2 from the El Antimonio Group (Figure 1) were first analyzed using isotope dilution and thermal ionization mass spectrometry (Gehrels, 2000) and results from 20 grains per sample were reported in González-León *et al.* (2005). For the present study we reanalyzed *ca.* 100 grains from samples 2000-1 and 2000-0 of Triassic age and collected and analyzed a new sample (4-5-08-1) from the Lower Jurassic sequence XI in the Sierra del Álamo.

Sample 2000-1(UTM 12R: 347580E, 3402960N) is from a medium-grained sandstone in the lower part of Spathian sequence 3 of the Antimonio Formation. Eighty percent of the total zircon grains are Proterozoic with ages near 1.7, 1.4 and 1.1 Ga and a peak age at 1.7 Ga. Eight grains yielded Permo-Triassic ages between 267 and 240 Ma with a peak at ~254 Ma, five grains have ages between 640 and 420 Ma, and three grains yielded, although discordant, ages between 2.7 and 2.6 Ga (Figures 3a and 4). Sample 2000-0, collected from a medium-grained, shallow marine sandstone of the Norian sequence VII of the Río Asunción Formation (UTM 12R: 351461E, 3399957N), yielded mostly grains with Proterozoic ages (~90%) with a major
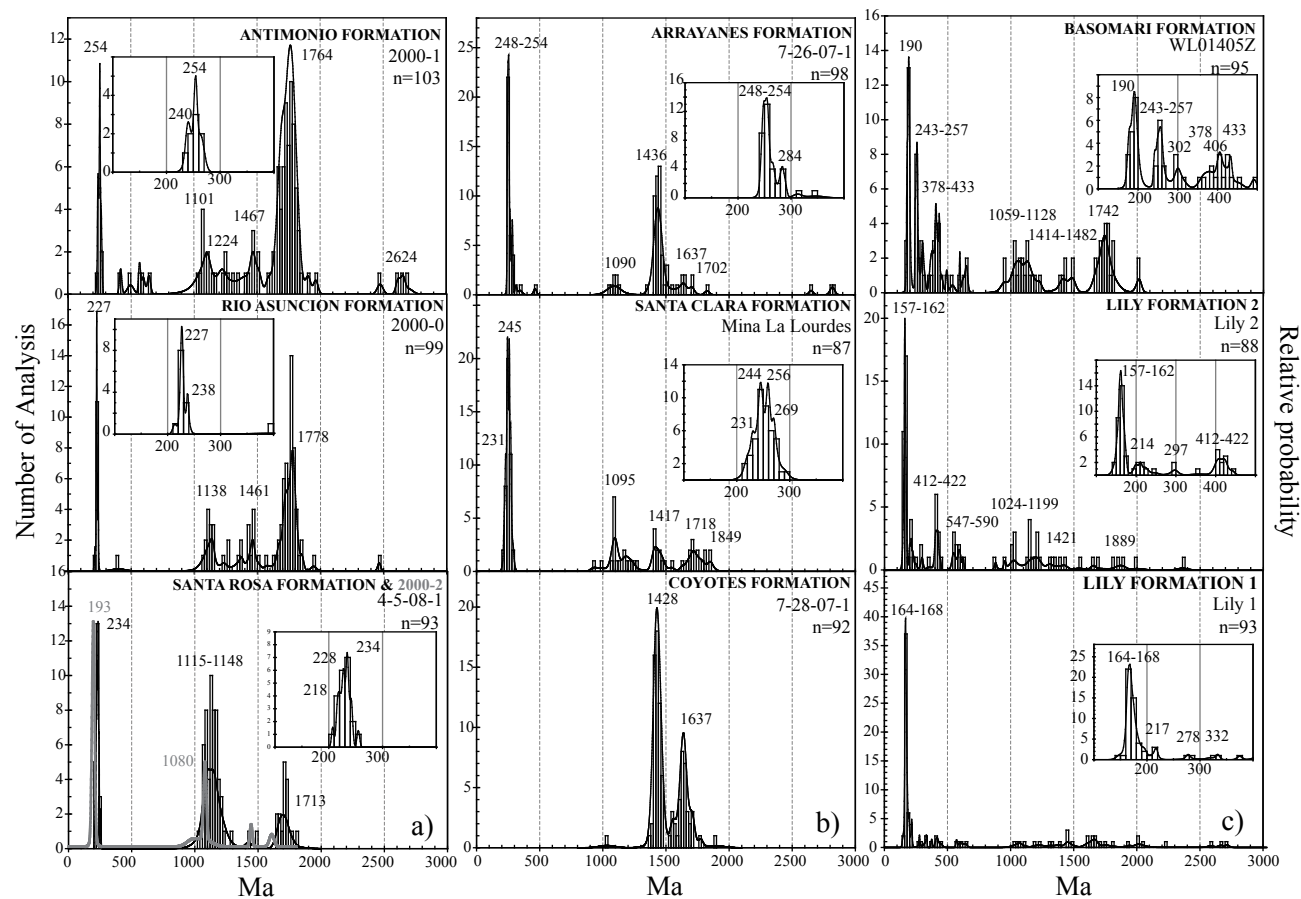
Figure 3. Age probability diagrams for Triassic and Jurassic samples. a: samples from the Antimonio, Río Asunción and Sierra de Santa Rosa formations of the El Antimonio Group, including sample 2000-2 (thick, gray line) from the middle member of the Sierra de Santa Rosa Formation reported in González-León *et al.* (2005). b: Samples from the Arrayanes, Santa Clara and Coyotes Formations of the Barranca Group. c) Samples from the Basomari and Lily Formations.

peak at 1.7 Ga, and a small population of Triassic grains (~10%) with a peak at 227 Ma (Figure 3a). Sample 4-5-08-1 was collected (UTM 12R: 351169E, 3399907N) from a bed of medium-grained, fluvial sandstone that overlies a 20-m-thick clast supported conglomerate (lower part of unit 17 in González-León, 1997) located at the base of sequence XI of late Sinemurian age (Pálfy and González-León, 2000; Taylor *et al.*, 2001). This sample yielded a zircon population of Proterozoic grains (78% of the grains) with peaks at 1.7 and 1.1 Ga and a Triassic population (22% of the grains) with a peak at 234 Ma (Figure 3a). Sample 2000-2 from the younger (lower Pliensbachian, Pálfy and González-León, 2000) middle member of the Sierra de Santa Rosa Formation at Sierra de Santa Rosa (Figure 2) was reported by González-León *et al.* (2005) to contain Lower Jurassic grains with a peak at 193 Ma (~55% of the grains) and Proterozoic grains with a peak at ~1.1 Ga (Figure 3a).

Zircons were separated from sandstone samples of the Arrayanes, Santa Clara and Coyotes formations of the Barranca Group, yielding the next results (Figure 3b). An arkosic, medium-grained sandstone from the Lower Member of the Arrayanes Formation (sample 7-

26-07-1) collected in the San Javier - La Barranca region (Figures 1 and 2) (UTM 12R: 634347E, 3167294N) yielded Proterozoic grains (~60%) with age peaks near 1.7, 1.6, 1.4 and 1.1 Ga, the largest peak at 1.4 Ga. 33% of the grains are Triassic and Permian with ages between 288 and 239 Ma and a peak at 250-254 Ma. Three grains (although two of them are discordant) have ages between ~465 and ~300 Ma and two others with ages between 2.8 and 2.6 Ga (Figure 3b). One quartzarenitic, coarse-grained sandstone from the Santa Clara Formation collected in the locality of mina La Lourdes area (UTM 12R: 549022E, 3163600N; Montijo Contreras, 2007) yielded zircon grains with ages between 297 and 205 Ma (50% of the grains) with peak ages at 269, 245 and 231 Ma, and Proterozoic grains with a peak at 1.1 Ga and subordinate peak ages at 1.7 and 1.4 Ga (Figure 3b). One pebble-sandstone sample from the Coyotes Formation (sample 7-28-07-1) collected about 2.5 km south of the town of San Javier (Figure 1), along the main road (UTM 12R: 622512E, 3162331N), yielded only Proterozoic grains in two populations with peak ages near 1.4 Ga (~60% of the grains) and 1.6 Ga (~30% of the grains) (Figure 3b).

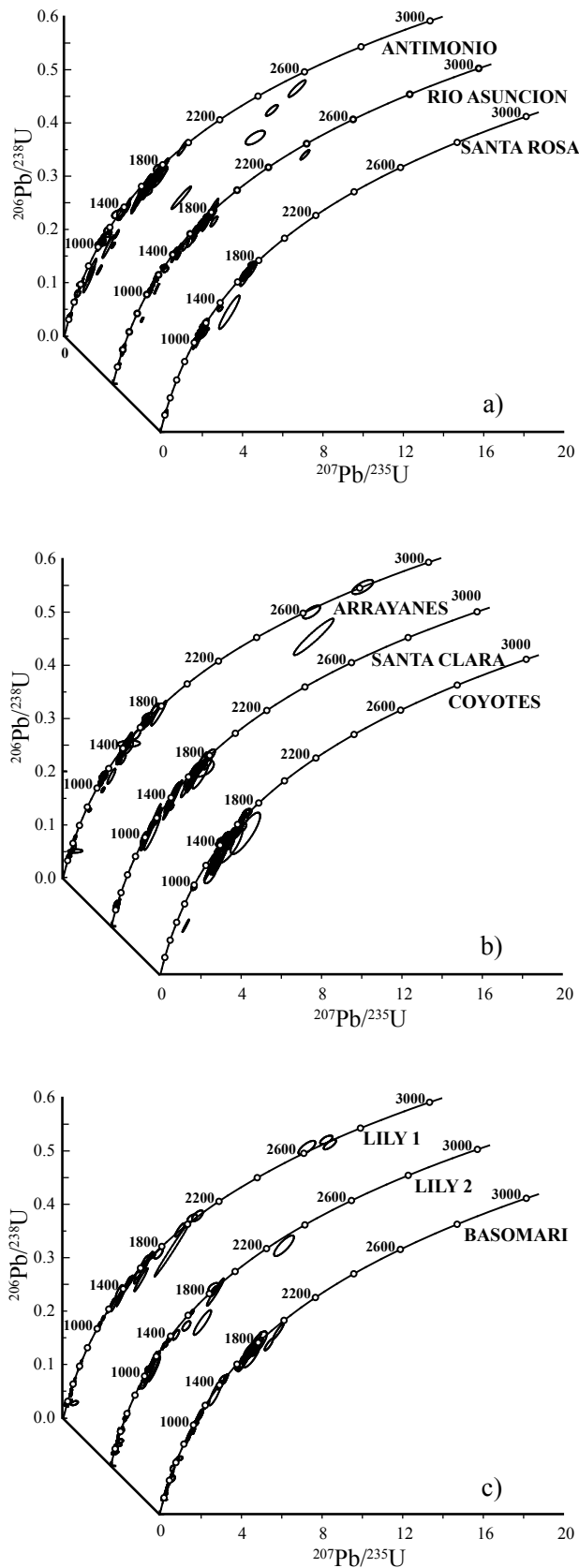A sandstone sample (WL01405Z) collected from the

Figure 4. U-Pb concordia plots for detrital zircons from (a) El Antimonio Group, (b) Barranca Group, and (c) Basomari and Lily formations. Errors are shown at the 2-sigma level.

lower part of the Basomari Formation (Figure 2) yielded Early Jurassic grains (17%) with a major peak age near 190 Ma, Triassic and Permian grains (13%) with peaks near 243–257 Ma, Paleozoic and Neoproterozoic grains (20%) with ages between 645 to 310 Ma, and Proterozoic grains (~50%) with peaks near 1.7, 1.4, 1.1 and 1.0 Ga (Figure 3c). Zircons from two different sandstone samples of the Lily Formation collected from the southwestern flank of Sierra Copercuin (sample Lily 1 located at UTM 12R 622131E, 3361530N; and sample Lily 2 at 621809E; 3362217N) yielded a maximum late Middle Jurassic age for this unit. Both samples yielded Jurassic zircons (25–43% of the total grains) with ages between 195 and 160 Ma and peak ages ~164 and 160 Ma, respectively, Triassic and Permian grains with ages between 300 and 200 Ma (<10% of the grains) that show subordinate concentration of ages at 214 and 217 Ma, Paleozoic and Neoproterozoic grains (11–22% of the grains) with ages between 954 and 385 Ma and concentrations at 590–547 and 412–422 Ma, and Proterozoic grains (27% of the grains) with concentration of ages near 1.8, 1.4 and 1.0-1.2 Ga (Figure 3c).

DISCUSSION AND CONCLUSIONS

Zircon populations

The new detrital zircon geochronology data reported herein from nine samples of Triassic and Lower and Middle Jurassic strata permit new inferences regarding the early Mesozoic provenance and paleogeography of Sonora. These data also provide a maximum Early Triassic (IUGS-ICS chart, 2007) depositional age for the previously undated Arrayanes Formation, which according to its younger zircon peak age it must be younger than about 250 Ma. This data also indicate that the Arrayanes may be about the same age as the Antimonio Formation, as both units share a common detrital zircon peak age at ~254 Ma. On the other hand, all of the zircons analyzed from the Coyotes Formation are Proterozoic, and thus inconclusive with regard to its inferred Early Jurassic age. The zircon population of this sample may be biased to older age because it contains abundant quartzarenite pebbles recycled from older strata.

The following distinctive zircon populations identified in the analyzed samples are described and discussed according to their decreasing abundance. The first population (Figure 3d) belongs to Proterozoic zircons whose abundance varies between 30 and 100% in the analyzed samples, and has peak ages around 1.8, 1.7, 1.6, 1.4, and 1.1 Ga. Proterozoic zircons are more abundant in the Triassic samples where they compose 50–90% of the analyzed grains but decrease in the Jurassic samples where they compose 30–50 % of the analyzed grains. The exception to this trend is the Coyotes Formation which, as noted, may be biased by the abundance of quarzarenite clasts that are recycled from Proterozoic and/or Paleozoic sedimentary units in

Sonora, which have similar detrital-zircon age populations (Gehrels and Stewart, 1998; Stewart *et al.*, 2002) to this unit. Proterozoic grains in the El Antimonio Group samples have dominant peak ages near 1.7, 1.4 and 1.1 Ga, whereas those of the Barranca Group have a dominant peak age near 1.4 Ga and subordinate peaks at ~1.7 and 1.1 Ga. The Jurassic Basomari and Lily formations have dispersed Proterozoic peaks near 1.8, 1.7, 1.2, and 1.0 Ga.

A second distinctive age population consists of Permian and Triassic zircons that make up between 8% and 50% of the analyzed samples. This population is prominent in the Triassic formations and its abundance decreases in the Jurassic formations. The Permo-Triassic grains are more abundant in the Barranca Group, in which they compose up to 50% of the analyzed grains, than in the El Antimonio Group in which they compose no more than 22% of the analyzed grains. Permian grains dominate over the Triassic grains in the Arrayanes and Santa Clara samples, and are largely absent from the formations of the El Antimonio Group except for uncommon grains in the Antimonio Formation. Triassic grains in the El Antimonio Group increase in abundance upsection from 3% in the Antimonio Formation, 10% in the Río Asunción Formation and 22% in the lower part of the Sierra de Santa Rosa Formation, but are not present in the Middle Member of the Sierra de Santa Rosa Formation (sample 2000-2 in González-León *et al.*, 2005; Figure 3a). The Permo-Triassic grains in the Basomari Formation make up nearly 13% of the analyzed grains, but Triassic grains are scarce. This same population composes about 10% of the total analyzed grains in the Lily Formation.

The Permo-Triassic zircon grains of the Barranca Group have peak ages near 284, 269, 254, ~246 and 231 Ma, peak ages near 254, 239, 234 and 227 Ma in the El Antimonio Group, and peak ages near 257–243 Ma in the Basomari Formation. A minor peak age at ~217 Ma is present in the Lily Formation (Figure 3).

The third zircon population of Early Jurassic age is present in the middle member of the Sierra de Santa Rosa Formation and in the Basomari Formation. The middle member of the Sierra de Santa Rosa Formation has a prominent Jurassic age population (55%) with a peak age near 190 Ma, similar to the Basomari Formation that has a population (17%) with a peak age at 190 Ma (Figure 3). It is also present, but subordinate (<10%), in the Lily Formation and was not identified in the lower part of the Sierra de Santa Rosa Formation (sample 4-5-08-1), where a biostratigraphic late Sinemurian age is the same as the geochronologic age (189.2 ± 1.1 Ma) of a tuff in the upper part of the Basomari Formation (Leggett *et al.*, 2007; Figure 2). The fourth population is only present in the Lily Formation and consists of Middle Jurassic zircons with age peaks at 168 (sample Lily 1, Figure 3) and 162 Ma (sample Lily 2, Figure 3) and has an abundance of ~30% of the total analyzed grains.

A fifth population that consists of Neoproterozoic and Paleozoic zircon grains is present in the Basomari and Lily formations. The Paleozoic grains are Silurian and Devonian in age and compose ~13% of the analyzed grains in the Basomari Formation and ~10% of the grains in the Lily Formation. The Basomari has peak ages at 433–378 Ma and the Lily shows concentrations of ages at 422–412 Ma. The Neoproterozoic zircons compose up to 10% in the Lily Formation, in which they show concentrations at 590–547 Ma and they compose ~6% in the Basomari Formation, in which they show a subordinate peak at 612 Ma (not indicated in Figure 3c). Very scarce grains with scattered ages between ~400 and ~1000 Ma occur in the Arrayanes (*n*=1), Santa Clara (*n*=2), Asunción (*n*=1) and Antimonio formations (n=6). As many as three grains with Archean ages between 2.8 and 2.6 Ga are present in each of the Lily, Arrayanes and the Antimonio formations.

Provenance

The prominent population of detrital zircons with Proterozoic ages with peaks near 1.7, 1.6, 1.4, and 1.1 Ga was probably derived from Proterozoic igneous and metamorphic basement of the southwestern USA and Sonora. This basement includes the Yavapai and Mazatzal provinces and ~1.1 and ~1.4 Ga granitic plutons that intrude them (see references cited above). The grains also may have been recycled from Neoproterozoic and Paleozoic sandstones that contain similar grain-age populations (references cited above). The near absence of 1.8 Ga zircons that could reflect provenance of the Mojave province, however, is noteworthy; uncommon grains of that age occur only in the Santa Clara and Lily formations. This could indicate that the Proterozoic grains were mostly recycled from Neoproterozoic and Paleozoic sedimentary rocks of Sonora and the southwestern USA, in which grains older than ~1.7 Ga are nearly absent (Gehrels and Stewart, 1998; Gross *et al.*, 2000; Stewart *et al.*, 2001).

Possible source areas for the Permo-Triassic zircon population in the Barranca and El Antimonio groups are more controversial and uncertain, but they include the mostly Triassic magmatic arc of the Mojave Desert in California (Barth and Wooden, 2006) and the Permo-Triassic arc of northern Mexico (Torres *et al.*, 1999). The second region was considered by Gehrels and Stewart (1998) to have been the source of Permo-Triassic detrital zircons in the Barranca Group and the first region was considered by González-León *et al.* (2005) as a source area for the El Antimonio strata zircons. Permo-Triassic rocks of the Mojave Desert are granitic plutons that range in age from ~210 Ma to ~260 Ma (Barth *et al.*, 1990, Miller *et al.*, 1995, Barth *et al.*, 1997, Barth *et al.*, 2001; Walker *et al.*, 2002; Barth and Wooden, 2006), whereas the Permo-Triassic magmatic arc of northern Mexico in the nearby states of Chihuahua and Coahuila includes mostly granitic intrusives and rhyolitic rocks with ages between 270 to 220 Ma (the published

data are presented in Table 1, while four other K/Ar ages between ~266 and ~250 Ma of granitic intrusives from that region were reported by Torres *et al.*, 1999, as taken from PEMEX internal reports). In addition, granitic clasts within the San Marcos Formation in north-central Mexico are dated between 225 and 213 Ma and were probably derived from that arc (*in* McKee *et al.*, 1990, McKee *et al.*, 1999). The Permo-Triassic zircon population from the Barranca and El Antimonio groups has peak ages near 269, ~250, ~240, ~234 and 227 Ma, some of which are common to both groups. The Jurassic Basomari and Lily formations show close similar peak ages at 257, 243, and ~217 Ma.

Upper Triassic strata in the western interior USA, for example the Chinle Formation in Arizona and equivalent Osobb Formation in Nevada, and Dockum Group and Santa Rosa Formation in New Mexico and Texas, respectively, yield similar Permo-Triassic populations of detrital zircons (Gehrels and Dickinson; 1995; Riggs *et al.*, 1996; Fox *et al.*, 2005; Fox *et al.*, 2006). The Chinle and Dockum groups in New Mexico and Texas have age peaks at 280–220 Ma (Fox and Lehman, 2005) and 295–225 Ma (Fox *et al.*, 2006); the sources of detritus in these strata have been interpreted as the magmatic arc of northeastern Mexico and the Cordilleran magmatic arc in southwestern USA. Similarly, Triassic detrital zircon populations in the Late Triassic formations of the Luning and Pine Nut assemblages of southern Nevada yield zircons with ages between 243 and 218 Ma and peak probability ages at 231 Ma and 223 Ma (Manuszak *et al.*, 2000), whose provenance was assigned to arc-type related magmatism of the Sierra-Klamath region in southwestern USA (Manuszak *et al.*, 2000).

The Early Jurassic zircon population (age peak near 190 Ma) is well represented in the Basomari and middle member of the Sierra de Santa Rosa Formation (Figure 3a and 3c). This population is poorly represented in the Lily Formation and is absent from the lowermost part of the Sierra de Santa Rosa Formation (sample 4-5-08-1). This population probably records the inception of the Jurassic continental magmatic arc of southwestern North America, whose oldest, although scarce, igneous record occurs in southern Arizona and in the Mojave Desert regions (Asmerom *et al.*, 1990; Riggs and Busby-Spera, 1990; Riggs *et al.*, 1993; Miller *et al.*, 1995). The Middle Jurassic zircon population is abundant in the Lily Formation and is also considered to be derived from the Jurassic continental magmatic arc, which by Middle Jurassic time was well developed in southwestern USA and northern Sonora (Anderson *et al.*, 2005).

The Neoproteozoic and Paleozoic zircon population represented in the Basomari and Lily formations is nearly absent in formations of the El Antimonio and Barranca groups. Zircons of these ages were probably transported by wind into the Jurassic magmatic arc (Riggs *et al.*, 1993) of Sonora from Jurassic eolian sand fields in Arizona (Wingate, Navajo and Entrada sandstones), where grains of population B of Dickinson and Gehrels (2003), with an age range between 747 and 309 Ma, are well represented. The Lily Formation records fluvial, alluvial and lacustrine deposition concomitant with rhyolitic volcanism of the Cordilleran volcanic arc, but the fluvial quartz-rich beds likely record reworking of eolian deposits. Jurassic eolianite deposits within this arc are present in northern Sonora within the Rancho San Martin Formation (whose youngest detrital zircons have ages near 169 ± 6 Ma; Leggett *et al.*, 2005), in the Elenita Formation (Valentine, 1936) near Cananea and in other localities like Sierra San Antonio, east of Nogales (C.G-L. unpublished data), and at Planchas de Plata, west of Nogales (Riggs and Busby-Spera, 1991).

Table 1. Permian and Triassic igneous rocks reported from northern Mexico.

Locality	Rock	Age (Ma)	Reference
San Marcos(Ch)	Gneiss clast in SMF	230±3 (Rb/Sr)	McKee *et al.* (1990)
Aldama (Ch)	Granite	250±20 (K/Ar)	*in* Torres *et al.* (1999)
Carrizalillo (Ch)	Granite	267±21 (K/Ar)	*in* Torres *et al.* (1999)
Plomosas (Ch)	Rhyolite	270±30 (Pb-α)	deCserna *et al.* (1970)
Sierra Mojada (Co)	Qmd clast in SMF	213±14 (Rb/Sr)	McKee *et al.* (1990)
Sierra Mojada(Co)	Qmd clast in SMF	215±2 (U/Pb)	*in* McKee *et al.* (1999)
S. Los Remedios(Co)	Tonalite	216 (Ar/Ar)	Molina Garza (2005)
		ca. 220 (U/Pb)	Jones *et al.*, 1995 (*in* Molina Garza, 2005)
El Coyote(Co)	Granodiorite	220±4 (U/Pb)	*in* McKee *et al.* (1999)
Pozo Mayran1(Co)	Rhyolite	222±2 (Rb/Sr)	*in* Grajales-Nishimura *et al.* (1992)
Sierra Mojada(Co)	Qmd clast in SMF	225±4 (Rb/Sr)	McKee *et al.* (1990)
Pozo Paila1 (Co)	Ignimbrite	236±39 (Rb/Sr)	*in* Grajales-Nishimura *et al.* (1992)
Potrero Mula(Co)	Granite	238±2 (U/Pb)	*in* McKee *et al.* (1999)
Las Delicias(Co)	Granodiorite	256±20 (K/Ar)	*in* Torres *et al.* (1999)
Las Delicias(Co)	Dacite clast in LDF	268±6 (U/Pb)	*in* McKee *et al.* (1999)
Pozo Tarahumara(Co)	Andesite	272±22 (?)	Moreno *et al.* (2000)

Ch: Chihuahua, Co: Coahuila, Za: Zacatecas, Ta: Tamaulipas, SMF: San Marcos Formation (Lower Cretaceous), Qmd: Quartz monzodiorite, LDF: Las Delicias Formation (Upper Permian *in* Molina-Garza, 2005).

Detrital zircon ages and paleogeography

Alencáster (1961a) first proposed that the Barranca Group in central Sonora was deposited in the San Marcial basin that connected to the northwest with the El Antimonio paleo-bay ("paleobahía del Antimonio"), where the El Antimonio Group was deposited (Figure 5). Stewart and Roldán-Quintana (1991) proposed that deposition of the Barranca Group occurred by large fluvial systems in a rift basin adjacent to high-relief uplifts in central Sonora. Stewart *et al.* (1997) also proposed that the embayment connection between the San Marcial basin and El Antimonio paleo-bay was recorded by the Upper Triassic–Lower Jurassic(?) succession of the Sierra Santa Teresa (Figures 1 and 5) that lithologically resembles strata of the Barranca Group and contains strata and fossils of sequence VII of the Río Asunción Formation (Goodwin, 1999). Based on newly described sections of the Barranca Group in central Sonora and on correlation with the El Antimonio strata, Montijo-Contreras (2007) proposed that strata of the Barranca Group were deposited in a large fluvio-deltaic and shallow marine setting that graded southward and westward into open marine environments (Figure 5). Previously, Stanley and González-León (1995) considered that the El Antimonio succession was deposited adjacent to southern California, in the USA, later thrusted over its Cordilleran miogeoclinal basement of the Caborca block, and subse-

quently translated southeastward to its present position by the Mojave-Sonora megashear in Middle Jurassic time (Silver and Anderson, 1974; Anderson and Silver, 2005). Stanley and González-León (1995) also suggested that the El Antimonio strata were deposited close to, and correlated with Triassic strata of, southwestern USA, like the Luning Formation of Nevada, based on paleontologic similarities. Other authors, based on paleontologic and lithologic criteria also correlated the Triassic strata between these two regions (Lucas *et al.*, 1997; Blodgett and Frýda, 2001; González-León *et al.*, 2005; Marzolf and Anderson, 2005; Blodgett and Stanley, 2006; Scholz *et al.*, 2008).

Following the Mojave-Sonora megashear hypothesis, the El Antimonio and Barranca groups are located south of the trace of this fault, while the Lower and Middle Jurassic Basomari and Lily formations [along with other units in northern Sonora like the Rancho San Martin (Leggett *et al.*, 2005) and the Elenita formations (Valentine, 1936)] that record fluvial and eolian deposition associated with silicic magmatism of the North America Jurassic volcanic arc are located north of the fault (Figure 5). Alternatively, if the Mojave-Sonora megashear did not exist, the Barranca and El Antimonio groups record marginal marine to distal marine facies of a basin that developed close to its present position, south of where the Jurassic arc developed (Lucas *et al.*, 1999), although tectonic accretion of the El Antimonio strata during Middle to Late Jurassic time is suggested by
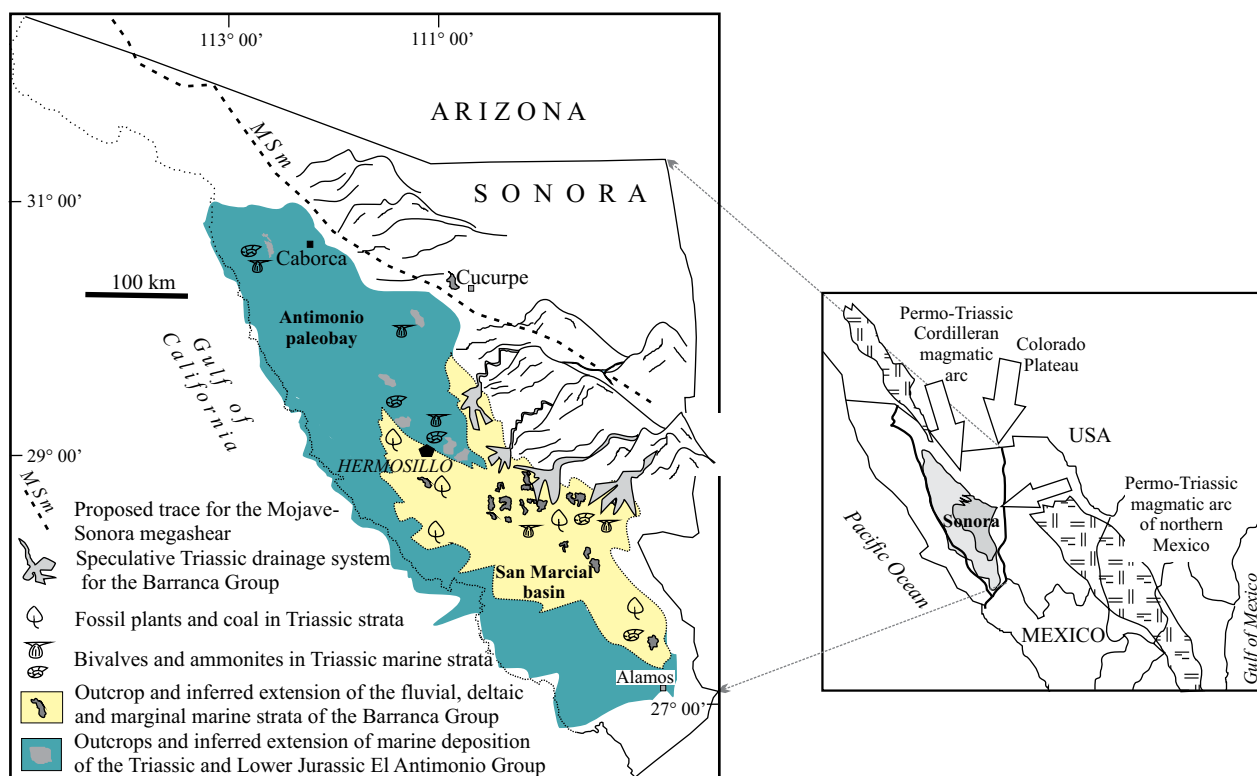

Figure 5. Inferred paleogeography of Sonora during Triassic and Early Jurassic time if displacement by the Mojave-Sonora megashear is not supported. Arrows in inset map indicate inferred provenance for detrital zircons in the Triassic and Jurassic formations of Sonora, as discussed in the manuscript.

paleomagnetic data (Molina-Garza and Geissman, 1996; 1999).

Detrital zircon data reported here indicate that the Triassic and Lower Jurassic basins of Sonora were fed abundantly with detritus derived from exposed Proterozoic basement and/or from the Neoproterozoic and Paleozoic strata succession of Sonora and southwestern USA. The present geographic distribution of these basement provinces, indicate that the sediment source areas were located to the north of the basins, an inference also supported by predominantly SW-directed paleocurrent directions available only for the Barranca Group (Stewart and Roldán-Quintana, 1991). If a 12 to 50º Jurassic clockwise rotation of the Caborca block (Molina-Garza and Geissman, 1996; 1999; Molina Garza and Iriondo, 2005) is restored, paleocurrents indicate that the large river system that deposited the Barranca Group would have flowed southward into the San Marcial basin. Also, if marginal marine to shallow marine deposition on a passive margin is considered for the Triassic formations of Sonora (González-León *et al.*, 2005), then the San Marcial fluvial system was contemporaneous with a large fluvial system that fed the Potosí submarine fan in central Mexico (Centeno-García, 2005). Both of these fluvial systems drained interior North America. However, the passive margin model is contradicted by evidence for the development of a nearby Triassic continental magmatic arc in southeastern California and southwestern Arizona (Barth and Wooden, 2006) that extended into northwestern Sonora, as indicated by the presence of a ~233 Ma (U/Pb) granite in Sierra Los Tanques in northwestern Sonora (Figure 1; Campbell and Anderson, 2003). Indeed, conglomerate and sandstone of the El Antimonio Group's Triassic formations contain abundant igneous detritus (González-León *et al.*, 2005) that may be derived from the active Triassic arc.

According to differences in sandstone petrography, conglomerate clast composition and Permian zircons of the Barranca and El Antimonio groups, different source areas for sediments of the two successions are possible. Common igneous grains and clasts in fluvial to shallow marine sandstone and conglomerate of the El Antimonio Group formations (González-León *et al.*, 2005) are absent from the Barranca Group, where sandstone composition ranges from subarkosic to quartz-rich and clasts in the conglomerate beds are exclusively quartzarenite, chert and quartz (Stewart and Roldán-Quintana, 1991; Cojan and Potter, 1991). Similarly, Permian detrital zircons that are abundant in the Barranca Group formations (up to 23% of the total grains) are absent in the El Antimonio Group formations, although Triassic grains in both groups occur in similar proportions. The Permian detrital zircons in the Barranca Group more closely resemble ages of the continental magmatic arc of northern Mexico, where Permian ages (Table 1) are older than in the Mojave arc. For this reason, the Permian-Triassic magmatic arc of northern Mexico is considered as the probable source area for the Barranca Permian zircons. The Triassic

zircon population of the El Antimonio and Barranca groups however, could have been derived from either the northern Mexico or the California-Arizona magmatic arcs, whose latest Permian-Triassic ages overlap. Although both arcs are considered separate entities because igneous rocks of Permian and Triassic ages have not been identified in northern Sonora and southern Arizona, it could have been a continuous arc that was obliterated by younger events like the development of the Jurassic magmatic arc, or because it is covered by younger rocks, or simply because its rocks have not yet been dated.

The information provided by the new detrital zircon data, however, do not conclusively support or reject left-lateral displacement of the Triassic-Lower Jurassic formations of the Barranca and El Antimonio groups, either by the Middle Jurassic Mojave-Sonora megashear (Anderson and Silver, 2005) or the Permian-Triassic California-Coahuila transform fault (Dickinson and Lawton, 2001), both models requiring southeastward displacement of the Caborca block by nearly 1,000 km. However, striking differences in zircon populations are present in the Lower Jurassic formations located on opposite sides of the proposed faults. While the Lower Jurassic Basomari Formation located to the north of the Mojave-Sonora megashear contains a significant Paleozoic and Neoproterozoic detrital zircon population that is also present in the Middle Jurassic Lily Formation, that population is not present in the Lower Jurassic Sierra de Santa Rosa Formation located to the south of the inferred strike-slip fault. If the Neoproterozoic and early Paleozoic age population records eolian transport into the Jurassic arc of northern Sonora from sand seas in the Colorado Plateau as herein inferred, these sands did not reach the El Antimonio paleo-bay, possibly because of an intervening geographic barrier or because the marine facies were deposited offshore, far from the influence of those wind systems. In addition, the Early Jurassic zircon population (peak at ~190 Ma) that is present in the lower part of the Basomari Formation and Middle Member (lower Pliensbachian) of the Sierra de Santa Rosa Formation is not present in the lower strata of the Sierra de Santa Rosa Formation (sample 4-5-08-1, late Sinemurian), which could indicate that Jurassic magmatic detritus did not reach the basin by that time, but rather arrived somewhat later during deposition of the middle part of the formation.

Further evidence that may indicate the El Antimonio and Barranca groups were not displaced by the Mojave-Sonora megashear comes from the Basomari Formation. This unit is located 40 km north of the proposed trace of this fault and U-Pb ages and Nd isotopic values obtained form its granitic clasts indicate they share affinity with the basement of the Caborca block (Amato *et al.*, 2009). The age and composition of these Proterozoic clasts suggested to Amato *et al.* (2009) that the Caborca block must have been located close to the Basomari basin in Sonora by Early Jurassic time, a location not predicted by the previous model (Silver and Anderson, 1974; Anderson and Silver,

2005) postulating Middle Jurassic displacement along the Mojave-Sonora megashear.

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APPENDIX A. SUPPLEMENTARY DATA

Table A1 can be found at the journal web site <http://satori.geociencias.unam.mx/>, in the table of contents of this issue (electronic supplement 26-2-01).

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