Detrital zircon U-Pb ages of sandstones in continental red beds at Valle de Huizachal, Tamaulipas, NE Mexico: Record of Early-Middle Jurassic arc volcanism and transition to crustal extension

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ABSTRACT

Continental strata and volcanic rocks of the type Huizachal Group in Valle de Huizachal record magmatism and subsequent crustal extension prior to seafloor spreading in the Gulf of Mexico. The older La Boca Formation consists of two informal members, a lower unit of siliciclastic and volcanic rocks discordantly overlain by a predominantly siliciclastic upper member. The younger La Joya Formation is an upward-thinning, alluvial-braided fluvial succession with a basal conglomerate.

U-Pb detrital-zircon ages (n = 576) from six Huizachal Group sandstones (five from La Boca and one from La Joya) consist of four groups indicating a mixed provenance: (1) Grenville grains (~1.3–1.0 Ga) derived from Gondwana (Novillo Gneiss); (2) early-middle Paleozoic grains (430–300 Ma) derived from peri-Gondwanan accreted rocks (Granjeno Schist); (3) Permoo-Triassic grains (296–222 Ma) derived from volcanic and plutonic rocks (West Pangaeam arc) and/or turbidites (Guacamaya Formation); and (4) Early-Middle Jurassic grains (199–164 Ma), locally derived from the Nazas arc. Groups 1–3 increase in abundance upsection as a result of unroofing of Jurassic volcanic and sedimentary carapace from uplifted basement.

The Huizachal Group records three stages in the pre-breakup history of Gondwana: (1) The lower member of La Boca Formation (maximum depositional age 184–183 Ma; Pleinsbachian) indicates Nazas arc activity; (2) the upper member (maximum depositional age 167–163 Ma; Bathonian–Callovian) indicates continued arc magmatism as early Jurassic age 167–163 Ma; Bathonian–Callovian) indicates Nazas arc activity; (3) the La Joya Formation represents late rift basin development and widespread exposure of flanking basement rocks. Although our La Joya sample lacks a coherent age group of young grains, its single youngest grain age (164 ± 3 Ma; Callovian) is consistent with its stratigraphic position beneath inferred Oxfordian strata.

RESUMEN

Depósitos continentales y rocas volcánicas del Grupo Huizachal en el Valle de Huizachal registran magmatismo de arco y subsecuente extensión corticial previa a la generación de piso océanico en el Golfo de México. La formación La Boca consiste en dos miembros informales, una unidad inferior de rocas siliciclásticas y volcánicas discordantemente sobrecayadas por un miembro superior siliciclástico. La formación La Joya es una sucesión aluvial-fluvial trenzada grano decreciente con un conglomerado basal.

Edades U-Pb en circones detríticos (n = 576) de seis muestras de areniscas del Grupo Huizachal (cinco de la La Boca y una de La Joya) consisten en cuatro grupos que indican una procedencia de mezcla: (1) granos Grenvillianos (~1.3–1.0 Ga) derivados de Gondwana (Gneis Novillo); (2) granos de la fase Paleozoica temprano-medio (430–300 Ma) derivados de rocas peri-Gondwanicas acercindadas (Esquisto Granjeno); (3) Permoo-Triácticos (296–222 Ma) derivados de rocas volcánicas y plutónicas (arco oeste de Pan-gea) y/o turbiditas (formación Guacamaya); y (4) granos del Jurásico Temprano-Medio (199–164 Ma), localmente derivados del arco Nazas. Los grupos 1–3 incrementan en abundancia hacia la cima de la sección como resultado de la exhumación de la cubierta de rocas volcánicas y sedimentarias del Jurásico de bloques levantados.

El Grupo Huizachal registra tres etapas en la historia previa al rompimiento de Gondwana: (1) El miembro inferior de la Formación La Boca (edad máxima de depósito 184–183 Ma, Pleinsbachiano) indica la actividad del arco de Nazas; (2) el miembro superior (edad máxima de depósito 168–163 Ma; Bathoniano–Calloviano) indica el continuo magmatismo de arco mientras la temprana extensión corticial formaba horst que aportaron granos a una cuenca de rift incipiente; y (3) la Formación La Joya representa el desarrollo tardío de la cuenca de rift y la extensa exposición de flancos de rocas de basamento. A pesar de que nuestra muestra de La Joya carezca de un grupo de edades coherentes de granos jóvenes, la edad de su único grano mas joven (164 ± 3 Ma; Calloviano) es consistente con la posición estratigráfica por debajo de depósitos inferidos del Oxfordiano.

INTRODUCTION

In this study, we investigate the detrital zircon age populations of continental Mesozoic strata in the Valle de Huizachal, located ~15 km southwest of Ciudad Victoria in the northeastern Mexican state of Tamaulipas (Fig. 1) in order to determine sandstone provenance and place age constraints on the stratigraphic succession. The Valle de Huizachal (Fig. 2) contains a well-exposed stratigraphic succession of continental red beds and volcaniclastic strata included in the Huizachal Group, which consists of the La Boca and La Joya formations, exposed beneath the widespread carbonate rocks of the Sierra Madre Oriental. This succession contains an important Jurassic vertebrate fossil assemblage (Clark et al., 1991, 1994; Fastovsky et al., 1995, 2005), but the age range of the strata has continued to be...
debated due to a lack of unambiguous biostratigraphic information. Our U-Pb detrital zircon analysis contributes critical information on pre-Late Jurassic strata of the Huizachal Group and indicates that the La Boca Formation, consisting of an older succession of volcanic and epiclastic rocks and a younger succession of dominantly epiclastic strata (Fastovsky et al., 1995, 2005), is entirely of Early to Middle Jurassic age. The detrital zircon data also indicate a striking upsection change in provenance as volcanic and sedimentary rocks were increasingly eroded and dissected on blocks uplifted during crustal extension.

U-Pb detrital zircon analysis is a valuable tool for sediment provenance studies, especially in light of technological developments that permit precise single-grain radiometric dating (e.g., Gehrels et al., 2008). Radiometric data provide a critical means for understanding the geological history of deposits and their potential sediment source regions. Radiometric provenance techniques supplement mineralogical information acquired by more traditional petrographic methods, such as light and heavy mineral analysis or whole-rock geochemistry, providing a more complete and accurate characterization of sediment provenance (e.g., Dickinson and Gehrels, 2008a, 2008b, 2009a; Lawton et al., 2009). Young detrital zircon grain ages have the added potential of indicating maximum depositional ages of a stratigraphic unit (e.g., Dickinson and Gehrels, 2009b), which can indicate true depositional age, if syndepositional volcanism took place in the drainage network providing sediment to a basin or if zircons derived from eruptive ash fell into the basin.

Characteristics of zircon that favor its use in provenance studies include physical and chemical stability, which makes it resistant during sedimentary recycling, and its high temperature of formation, which reduces its susceptibility to subsequent thermal resetting by burial in sedimentary and low-grade metamorphic conditions. Zircon forms predominantly in felsic-intermediate igneous rocks and high-grade (granulite facies) metamorphic rocks (Hoskin and Schaltegger, 2003).
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Figure 2. Generalized modified geologic map of Valle de Huizachal (García-Obregón, 2007). Lowercase letters a, b, and c indicate locations of measured sections (Fig. 3). Map symbols: Jlbi—lower member of La Boca Formation; Jlbs—upper member of La Boca Formation; Ji—rhyolite domes; Jlj—La Joya Formation; Jn—Novillo Formation; Jo—Olvido Formation; Jc—La Casita Formation; Ku—undifferentiated Cretaceous strata.
GEOLOGIC SETTING

The Valle de Huizachal occupies a structural dome on the southeastern extension of the NW-SE–trending Huizachal-Peregrina anticlinorium in the Sierra Madre Oriental (Fig. 1). Proterozoic metamorphic and igneous rocks and Paleozoic strata of the Oaxaquia terrane (Ortega-Gutiérrez et al., 1995; Keppie et al., 2004) are widely exposed in the Huizachal-Peregrina anticlinorium. Outcrops of the Novillo Gneiss, a granulite facies metamorphic and igneous complex (Orozco, 1991), represent the northernmost exposures of ~1 Ga basement of Oaxaquia in northeastern Mexico. The gneiss consists of metasedimentary rocks intruded by two gabbro-anorthosite suites (~1010–1035 Ma and ~1115–1235 Ma; Cameron et al., 2004) that experienced polyphase deformation and granulite facies metamorphism at 990 ± 5 Ma (Cameron et al., 2004), and post-tectonic anorhotic pegmatite emplacement at 978 ± 13 Ma (U-Pb zircon, Cameron et al., 2004). The complex is intruded by two sets of mafic dikes (550 Ma, Keppie et al., 2006). In structural juxtaposition with the gneiss is the Silurian to Carboniferous Granjeno Schist, which consists of polydeformed, low-grade pelitic metasedimentary and metavolcaniclastic rocks that enclose lenses of serpentinite metagabbro (~430–300 Ma; Dow et al., 2005; Nance et al., 2007). An unmetamorphosed succession of Paleozoic marine clastic strata nonconformably overlies the Novillo Gneiss. The base of the Paleozoic succession consists of Middle Silurian clastic shallow-marine strata with a Gondwanan fauna (Stewart et al., 1999). This succession is unconformably overlain by Lower Mississippian sandstone and shale containing a shallow-marine fauna of Laurentian affinity (Stewart et al., 1999). These rocks are depositionally overlain by a flow-handed rhyolite dated at 334 ± 34 Ma (lower intercept U-Pb zircon age; Stewart et al., 1999), which is in turn unconformably overlain by Permo-Carboniferous turbidites and volcaniclastic flysch (Gursky and Michalzik, 1989). All Proterozoic and Paleozoic rocks contain NNW-trending folds and associated northeast-vergent thrusts and dextral transcurrent faults (Carrillo-Bravo, 1961; Gursky, 1996; Stewart et al., 1999; Dow et al., 2005).

A belt of Permo-Triassic dioritic and granodioritic intrusive rocks cuts all older units along a northwest-southeast trend extending from the Sierra Madre Oriental, through the Coahuila block, and into the North American craton in the northwest. Geochemical and isotopic analyses indicate a continental arc origin for the intrusive rocks, which range in age from 287 to 232 Ma (Bartolini et al., 1999; Torres et al., 1999; Dow et al., 2005). This arc has been termed the East Mexican arc (Dickinson and Lawton, 2001); we refer to it as the West Pangaea arc after its inferred paleogeographic position on the western edge of Pangaea and possible extent into Laurentia in current northwestern Mexico (e.g., Arvizu et al., 2009).

Paleozoic and Triassic rocks are locally unconformably overlain by the Huizachal Group, which includes red beds of the La Boca and La Joya formations (Mixon et al., 1959; Mixon, 1963a, 1963b). The southwest flank of Valle de Huizachal is the type locality of the Huizachal Group, originally termed the Huizachal Formation (Imlay et al., 1948; Humphrey and Diaz, 1956). Outcrops of similar red beds are present in the Sierra Madre Occidental at scattered localities northward from Valle de Huizachal to the vicinity of Galeana, Nuevo León (Barboza-Gudiño et al., 2008a, 2008b; Barboza-Gudiño, 2009). Triassic strata considered as part of the Huizachal Group have recently been recognized beneath the La Joya Formation near Galeana (Barboza-Gudiño, 2009; Barboza-Gudiño et al., 2010).

The stratigraphic section that includes red strata exposed in the core of the dome at Valle de Huizachal is naturally divisible into three stratigraphic successions (Mixon et al., 1959; Fastovsky et al., 1995, 2005; García-Obregón, 2007; Barboza-Gudiño et al., 2008; Rubio-Cisneros et al., 2010). The lower interval contains a succession of volcanic and volcanoclastic strata that include lapilli tuffs, crystal tuffs, lava flows, volcanoclastic breccias, ignimbrites, shale, siltstone, sandstone, and conglomerate (Fastovsky et al., 1995, 2005; García-Obregón, 2007; Barboza-Gudiño et al., 2008; Rubio-Cisneros et al., 2010). Siliciclastic strata are well indurated and contain a pronounced steep cleavage. Interbedded basaltic flows are massive or locally have flow breccias and brecciated vesicular flow tops. Peperites consisting of red clastic dikes and mixtures of red siltstone and brecciated basalt are common in the basalt flows (Fig. 3). The unit dips generally moderately to steeply (20°–40°) with local subvertical dips in the vicinity of rhyolite intrusions. Most of the rocks have undergone extensive late-stage or post-depositional silicification.

The nomenclature of the pre-Upper Jurassic strata in Valle de Huizachal has varied significantly since their initial description, and age interpretations are likewise debated due to a paucity of biostratigraphic and geochronologic data. The lower interval has been interpreted as part of an unnamed Permo-Triassic volcanic succession (Bartolini et al., 1999), as a Late Triassic and/or Early Jurassic volcanic succession included in the La Boca Formation (Mixon et al., 1959), or...
termed the Volcanic and Epiclastic Suite of pre-Early Jurassic age (VES, Fastovsky et al., 2005), which consists of feldspathic to lithic arenites (Rubio-Cisneros et al., 2010).

The middle interval unconformably overlies the lower volcanic interval and consists of conglomerate and overlying siliciclastic and subordinate volcaniclastic strata (Fastovsky et al., 1995, 2005; García-Obregón, 2007). The sandstones consist of compositional lithic arenites (Rubio-Cisneros et al., 2010). The middle interval displays gentle radial dips in the vicinity of the Valle de Huizachal, where it forms an open domal structure (García-Obregón, 2007). Red, vertebrate-bearing silty mudstone and pebbly mudstone in the lower part of the interval are interpreted as debris-flow deposits, possibly syn-eruptive (Fastovsky et al., 1995; Rubio-Cisneros et al., 2010). The matrix-supported rocks grade upsection to interbedded clast-supported conglomerate, sandstone, and siltstone lacking fossil material (Fastovsky et al., 2005). Angular discordance between the lower and middle intervals ranges from slight, only a few degrees, to as much as 70° where strata in the lower interval are steep (Fastovsky et al., 2005; García-Obregón, 2007; Rubio-Cisneros et al., 2010). This interval was termed the superjacent red bed suite (SS) by Fastovsky et al. (2005).

Rhyolite bodies that have been interpreted as domes intrude the lower and middle intervals (García-Obregón, 2007; Barboza-Gudiño et al., 2008; Rubio-Cisneros et al., 2010). These rhyolites have steep to vertical flow banding, commonly with spherulites of devitrified glass aligned with the banding (Fig. 4; Barboza-Gudiño et al., 2008). The rhyolite domes were included in unit A of the VES, and the aligned spherulites were interpreted as layers of accretionary lapilli, which led to the interpretation of a widespread, strongly angular unconformity between the lower and middle intervals (Fastovsky et al., 2005), which is only locally the case. Elsewhere, the typical angularity between the lower and middle intervals is 10°–20° (Fastovsky et al., 2005; García-Obregón, 2007). We infer that locally steep dips of volcanic flows in the lower interval resulted from folding during rhyolite intrusion; therefore, the strongly angular unconformity developed locally as a result of dome emplacement and does not indicate the representative degree of regional tectonic tilting between deposition of the lower and middle intervals.

The middle interval is overlain by an upper red siliciclastic section with a basal conglomerate of crudely bedded, clast-supported conglomerate with angular clasts (Rubio-Cisneros et al., 2010). The conglomerate grades upsection into brick-red sandstone and shale significantly less indurated and blocky than those of the lower and middle intervals. Previous workers have generally referred to this upper interval as the La Joya Formation (Mixon et al., 1959; Fastovsky et al., 1995, 2005). The La Joya Formation consists of continental to marginal-marine siliciclastic strata with subordinate freshwater limestones (Michalzik, 1988, 1991). The La Joya consists of shale, siltstone, volcanic to feldspathic arenite and dominant lithic arenite, and conglomerate that record infilling of areally restricted rift basins (Salvador, 1987; Rubio-Cisneros et al., 2010). The La Joya pinches out onto basement highs and is overlain by Oxfordian evaporite strata (Salvador, 1987). The uppermost La Joya Formation marks the onset of prolonged Late Jurassic marine transgression (Rueda-Gaxiola et al., 1991; Goldhammer, 1999).

In this paper, we designate the lower and middle intervals as informal lower and upper members of the La Boca Formation. The lower member generally corresponds to the northern part of the VES as mapped by Fastovsky et al. (2005; Petrofacies I of Rubio-Cisneros et al., 2010). The lower member was termed the Huizachal Formation by García-Obregón (2007), a name originally used for the entire red bed succession (Inlay et al., 1948) and subsequently superseded by the term Huizachal Group, including the La Boca and La Joya formations (Mixon et al., 1959). Our upper member (Rubio-Cisneros et al., 2010) corresponds to the SS of Fastovsky et al. (2005), except that those authors included the rhyolite intrusions in the southern and western exposures of their VES. The rhyolite intrusions appear to cut both the lower and upper members of the La Boca Formation as defined here (Fig. 2), but do not intrude the La Joya Formation, which contains clasts of the rhyolite in its basal conglomerate.

The age of the La Boca and La Joya formations has long been debated. The Huizachal Formation was considered Upper Jurassic by Inlay et al. (1948) on the basis of comparison with a red bed–evaporite succession of that age in southern Mexico. It was nevertheless considered Lower-Middle Jurassic by Humphrey and Diaz (1956) on the basis of its stratigraphic position beneath inferred Upper Jurassic carbonate and evaporite strata. Upon subsequent division of the Huizachal Group into the La Boca and overlying La Joya formations, the La Boca Formation was considered Late Triassic–Early Jurassic on the basis of plant fossils (Mixon et al., 1959; Mixon, 1963a, 1963b). Vertebrate fossils near the base of the La Boca Formation suggested a Middle Jurassic age (Clark and Hopson, 1985; Fastovsky et al., 1995). An inferred tuff at the base of the upper member of the La Boca Formation, unconformably overlying the lower La Boca member or VES, yielded a U-Pb zircon age of 189.0 ± 0.2 Ma (early Pleinsbachian; time scale of Walker and Geissman, 2009) on the basis of a concordia intercept age calculated from eleven age groups, each consisting of 8–20 zircon grains, which range from 194 to 186 Ma (Fastovsky et al., 2005). Accordingly, the age of the VES was interpreted as older than 189 Ma, and possibly an exposure of upper Paleozoic volcanic rocks (Fastovsky et al., 2005). The
lower interval was similarly interpreted as part of an unnamed Permo-Triassic volcanic succession (Bartolini et al., 1999). Recent discovery of more extensive exposures of the lower La Boca unit (García-Obregón, 2007; Rubio-Cisneros et al., 2010) permitted a widespread sampling of sandstone beds for detrital zircon geochronology presented here.

METHODS

Zircons were extracted from selected fine- to medium-grained sandstones by traditional crushing and grinding methods, followed by separation on a Wilfley table, a Franz magnetic separator, and in heavy liquids. Zircon grains were embedded in a 1-inch-diameter epoxy mount together with fragments of Sri Lanka zircon, which served as the standard for isotopic analyses. The faces of the mounts were then sanded to a depth of ~20 µm, polished, imaged, and cleaned prior to further isotopic analysis. Age determinations of ~100 individual grains per sample were conducted by laser ablation–multicollector–inductively coupled plasma mass spectrometry (LA-ICP–MS) at the Arizona LaserChron Center. Analytical methods and uncertainties of the LA-ICP–MS are described elsewhere (Gehrels et al., 2008).

The maximum and minimum depositional ages are described elsewhere (Gehrels et al., 2008). The young age group consists of from 3 to 20 grains in each sample is determined by the 1σ error of the weighted mean of the coherent group of youngest grain ages that overlap at one-sigma (1σ) analytical error. This young age group consists of from 3 to 20 grains in the sample suite. The number of grains used in each sample is determined by the 1σ error of the weighted mean of the grains with a ratio of observed to expected deviation (mean square of weighted deviates [MSWD]) above a best-fit line that is nearest to unity, indicating that assigned analytical errors, rather than nonanalytical scatter or under- or overestimated errors, are the primary cause of the scatter (Ludwig, 2005; Table 1). Application of the weighted mean to the grain-age group results in a conservative estimate of the maximum depositional age for the sample (e.g., Dickinson and Gehrels, 2009b); in other words, the sample cannot be older than the calculated mean age of the young grains. An alternative estimate of maximum depositional age from the youngest single concordant grain in the sample is sometimes valid, but is a less reliable estimate of maximum depositional age (Dickinson and Gehrels, 2009b).

RESULTS

Six detrital-zircon samples were collected from three measured sections of the Huizachal Group in Valle de Huizachal (Fig. 5). In total, the six samples yielded 576 individual grain ages. We were unsuccessful in obtaining detrital zircons from the lowermost part of the exposed lower member of the La Boca Formation, but the remainder of the stratigraphic section is represented by productive samples. Four distinct detrital zircon age populations are recognized in the sample set: (1) Grenville grains (~1.3–1.0 Ga); (2) early Paleozoic grains (430–300 Ma); (3) Permo-Triassic grains (296–222 Ma); and (4) Early-Middle Jurassic grains (199–164 Ma).

The characteristics of the individual detrital zircon samples are described here in stratigraphic order from base to top. Individual detrital zircon analyses are listed in Supplemental Table 1.

Two samples (VH31-03 and -02) were collected from steeply dipping beds of the lower member of the La Boca Formation along measured section A (Fig. 6). Three samples (VH31-06, -08, and -09) were collected from the upper member along measured section B. The stratigraphically lowest of these Upper La Boca samples, VH31-06, was collected 22 m above the angular unconformity. The uppermost sample (VH31-10), was collected from the base of the La Joya Formation within a coarse-grained pebbly sandstone bed on measured section C (Fig. 6). The stratigraphic level, youngest grain age and the maximum depositional age for each sample are summarized in Table 1.

Zircon grains in all samples are dominantly rounded to subrounded but with subordinate subangular shapes, and subsequent to elongate crystal form. They also display varied colors. There is no systematic correlation among shape, color, rounding, and age. From their general characteristics, we conclude that the grains represent heterogeneous sources, an inference corroborated by the ages of the zircon grains. Most of the zircon grain ages lie along and near the concordia (Fig. 7).

The two lower La Boca samples (VH31-03 and -02) have similar age spectra (Fig. 8). In sample VH31-03, the youngest concordant grain age is 179 ± 2 Ma. A weighted mean age on 20 young grains is 183.4 ± 0.9 Ma (Table 1; 2σ error; systematic error = 1.0%; MSWD = 1.0). In sample VH31-02, the youngest grain age is 179 ± 1 Ma, and a weighted mean age on 12 young grains is 184.2 ± 1.2 Ma (2σ error; systematic error = 1.1%; MSWD = 1.1). This maximum depositional age is indistinguishable from that of VH31-03 and indicates a likely Early Jurassic (Pleinsbachian) age for the lower member. The two lower La Boca samples are dominated by Jurassic grains (201–164 Ma; 53%), fewer Grenville grains (1.3–1.1 Ga; 21%), and subordinate Early Paleozoic (Cambrian–Devonian; 10%) and Permo-Triassic grains (292–243 Ma; 7%). Neoproterozoic grains (900–550 Ma) are uncommon (2%).

The three upper La Boca samples (VH31-06, -08, and -09) have similar age spectra, but their spectra are different from the lower La Boca samples. Older grains are more abundant in these samples (Fig. 8). In sample VH31-06, the weighted mean age on five young grains is 167.0 ± 1.5 Ma (Table 1; 2σ error; systematic error = 1.1%; MSWD = 0.8). The youngest concordant grain is 162 ± 5 Ma. Because sample VH31-08 lacks a coherent group of young grains from which to calculate a maximum depositional age, the resultant calculation is

### TABLE 1. YOUNG GRAIN AGES OF HUIZACHAL GROUP DETRITAL SAMPLES

<table>
<thead>
<tr>
<th>Formation/member</th>
<th>Sample number</th>
<th>Stratigraphic level (meters)</th>
<th>Weighted mean age (Ma)</th>
<th>MSWD</th>
<th>n</th>
<th>Youngest grain age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>La Joya</td>
<td>VH31-10</td>
<td>315</td>
<td>168 ± 17</td>
<td>3.7</td>
<td>3</td>
<td>164 ± 3</td>
</tr>
<tr>
<td>Upper La Boca Member</td>
<td>VH31-09</td>
<td>301.5</td>
<td>163.3 ± 2.6</td>
<td>1.3</td>
<td>4</td>
<td>158 ± 3</td>
</tr>
<tr>
<td>Upper La Boca Member</td>
<td>VH31-08</td>
<td>260</td>
<td>184 ± 14</td>
<td>3.7</td>
<td>3</td>
<td>166 ± 2</td>
</tr>
<tr>
<td>Upper La Boca Member</td>
<td>VH31-06</td>
<td>184</td>
<td>167.0 ± 1.5</td>
<td>1.4</td>
<td>3</td>
<td>162 ± 5</td>
</tr>
<tr>
<td>Lower La Boca Member</td>
<td>VH31-02</td>
<td>117</td>
<td>184.2 ± 1.2</td>
<td>1.1</td>
<td>12</td>
<td>179 ± 1</td>
</tr>
<tr>
<td>Lower La Boca Member</td>
<td>VH31-03</td>
<td>22</td>
<td>183.4 ± 0.9</td>
<td>1.0</td>
<td>20</td>
<td>179 ± 2</td>
</tr>
</tbody>
</table>

Note: Stratigraphic level indicates cumulative meters above base of measured section A. Weighted mean age error is 2σ. n is number of grains used to calculate weighted mean age. Youngest grain age error is 1σ. MSWD for the weighted mean age is mean square of weighted deviates, a measure of ratio between observed deviation or scatter of points (from best-fit line) to expected scatter. MSWD near unity indicates assigned errors are the only cause of scatter (Ludwig, 2005).
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184 ± 14 Ma, and the youngest single grain is discordant at 166 ± 2 Ma. For sample VH31-09, a weighted mean age on a group of six young grains is 163.3 ± 2.6 Ma (Table 1; 2σ error; systematic error = 1.1%; MSWD = 1.3). Its maximum depositional age overlaps within error that of the lowest upper La Boca sample (VH31-06). The single youngest grain is 158 ± 3 Ma, but is reverse discordant and unreliable. The maximum depositional age for the upper member is thus Middle Jurassic (Bathonian–early Callovian). The upper La Boca samples are dominated by Grenville grains (44%), followed in decreasing abundance by Permo-Triassic grains (296–234 Ma; 13%), Jurassic grains (196–166 Ma; 11%), and subordinate Early Paleozoic grains (7%). Neoproterozoic grains are more abundant (8%) than in the lower La Boca.

Sample VH31-10 from the base of the La Joya Formation contains an age spectrum similar to that of the upper La Boca samples. It lacks a coherent group of young grains from which to calculate a maximum depositional age, but its youngest grain is concordant at 163.6 ± 2.6 Ma, statistically indistinguishable from the maximum depositional ages of the upper La Boca samples. The La Joya sample is dominated by Grenville grains (36%), followed in abundance by early Paleozoic grains (17%), Permo-Triassic grains (292–222 Ma; 16%), and uncommon Jurassic grains (188–164 Ma; 4%). Neoproterozoic grains (8%) are similar in abundance to the upper La Boca samples.

**DISCUSSION**

The detrital zircon grain age groups of the Huizachal Group sandstones can be attributed to four different suites of source rocks exposed locally in eastern Mexico. Grenville detrital zircons in the age range of ~1.3 to 1.0 Ga within the La Boca and La Joya formations are inferred to have been derived from the crystalline basement of the Oaxaquia terrane. Rocks of this age are represented by the Novillo Gneiss complex exposed nearby within the Huizachal-Peregrina anticlinorium (Fig. 1). Zircon grains within the range of ~430 to 300 Ma match the ages of the Granjeno Schist, also exposed in the anticlinorium (Fig. 1). Permian–Triassic granitoids (287–232 Ma; Torres et al., 1999; Dowe et al., 2005) that intrude older basement in the Sierra Madre Oriental closely match the range of ages (296 to 222 Ma) in the Permo-Triassic detrital zircon age group. Grains of this age might also have been derived from the Permo-Triassic Guacamaya Formation, which is also exposed in the Huizachal anticlinorium. Early to Middle Jurassic grains (199–164 Ma) appear to have been derived from the Nazas volcanic arc.

Figure 5. Simplified lithostratigraphic column of the La Boca and La Joya formations in Valle de Huizachal (modified by García-Obregón, 2007). Letters correspond to the stratigraphic levels documented in measured sections of Figures 2 and 6. Mu—mudstone; Sil—siltstone; SS—sandstone; P.Clg—polimitic conglomerate; V—volcanic rock (tuff); °—dip of unconformity.
Figure 6. Measured sections and stratigraphic levels of detrital zircon samples, Valle de Huizachal. (A) Lower member of La Boca Formation. (B) Upper member of La Boca Formation. (C) La Joya Formation. Locations of sections in Figure 2. f—fine grained; m—medium grained; c—coarse grained; SS—sandstone; V—volcanic rocks.
There are clear stratigraphic trends in the detrital zircon populations within the Huizachal Group samples. The relative abundance of the different age groups changes markedly upsection. Jurassic grains decrease from 53% to 4% from the base to the top of the Huizachal Group, whereas other grain age groups, specifically Grenville, Neoproterozoic, early Paleozoic, and Permo-Triassic groups, increase in abundance from 38% for the sample at the base to 77%–79% in the samples at the top of the studied succession. The significant decrease in Jurassic grains and enrichment in basement grains suggest a progressive erosional unroofing of uplifted blocks in the source area for the detrital zircons. In addition, the detrital zircon ages of the Huizachal Group in Valle de Huizachal demonstrate that local source rocks could have provided the observed detritus to the La Boca and La Joya formations, an observation consistent with deposition in a rift basin formed during the breakup of Pangaea.

The detrital zircon data also provide evidence for the depositional ages of the three intervals of the Huizachal Group. The interpreted maximum depositional ages systematically decrease upsection through the La Boca Formation. Lower La Boca samples have Early Jurassic (ca. 184–183 Ma) maximum depositional ages, and upper La Boca samples have Middle Jurassic (ca. 167–163 Ma) ages. The La Joya sample has a single late Middle Jurassic grain (164 Ma), which is not statistically different from the young grain ages in the upper member of the La Boca Formation. The progressive decrease in maximum depositional age, common interbedded volcanic and pyroclastic rocks, and stratigraphic position beneath Middle-Upper Jurassic evaporate strata suggest that the Early-Middle Jurassic maximum depositional ages of the La Boca Formation approximate the true depositional age of these red beds. On the basis of the systematic stratigraphic decrease in maximum depositional ages, we also infer that magmatism in the age range 184 to 163 Ma was coeval with deposition of the Huizachal Group.

An apparent conflict in the geochronology of the La Boca Formation requires discussion. The 184–183 Ma and 167–163 Ma weighted mean ages in the lower and upper La Boca samples, respectively, are significantly younger than the 189 Ma U-Pb age (Fastovsky et al., 2005) for the tuff at the base of the upper La Boca member. We measured a total of 57 grains with ages younger than 189 Ma in our lower La Boca samples and 29 grains younger than 189 Ma in the upper La Boca samples; therefore, the young ages are based on a large number of grain analyses. Although we are unsure of the reason for the conflict of our detrital grain ages with the apparent tuff age, a plausible explanation is that the intercept age obtained by Fastovsky et al. (2005) was calculated on the basis of grains reworked from older strata of the volcanic-rich lower member. If this is the case, the interpreted tuff age, which was determined from analyses of groups of zircon grains, is a pseudo-concordia intercept age based on a sampling of detrital zircon grains.

Detrital zircon ages in the lower member of the La Boca Formation in Valle de Huizachal corroborate previous inferences of an Early to Middle Jurassic age for the La Boca Formation (Clark et al., 1994; Fastovsky et al., 1995, 2005; Stewart et al., 1999; Barboza-Gudiño et al., 2008). Our data further indicates that the upper member of the La Boca Formation is at least in part Middle Jurassic, consistent with inferences drawn from vertebrate fossils recovered near the base of the member (Clark et al., 1994; Fastovsky et al., 1995), and that the La Joya
Formation was deposited near the end of the Middle Jurassic and is probably Callovian.

The Early-Middle Jurassic age for the two members of the La Boca Formation indicates equivalence with Lower-Middle Jurassic volcanic successions elsewhere in NE Mexico (Barboza-Gudiño et al., 2008). Volcanism recorded by volcanic and volcaniclastic rocks of the Huizachal anticlinorium was likely related to arc magmatism of the correlative Nazas Formation near Torreón, Coahuila (Imlay et al., 1948; Belcher, 1979; Salvador, 1987; Barboza-Gudiño et al., 2008; Rubio-Cisneros et al., 2010), as implied by the existence of roughly coeval Late Triassic–Early to Middle Jurassic magmatic pulses (Bartolini et al., 2003) in northeastern Mexico, and volcanic rocks with a geochemical signature compatible with an arc origin (Fastovsky et al., 2005; García-Obregón, 2007; Barboza-Gudiño et al., 2008). Therefore, we infer that La Boca deposition took place in the Early Jurassic Nazas volcanic arc, consistent with relative age inferences made by Rubio-Cisneros et al. (2010).

Nevertheless, the upsection increase in basement-derived grains is compatible with uplift and progressive exposure of basement as a result of extension-related block faulting. This observation is also compatible with an upsection change in the lithic content of the sandstones (Rubio-Cisneros et al., 2010), and consistent with deposition of the upper member of the La Boca Formation and the La Joya Formation in a tectonic environment increasingly influenced by crustal extension and development of rift basins (e.g., Salvador, 1987).

Basement was not extensively exposed during the Early Jurassic, when it was evidently buried by Jurassic volcanic rocks. Subsequent basement uplift and erosion in Middle Jurassic time likely created an angular unconformity of 10°–20° beneath the upper member of the La Boca Formation. Adjacent to intrusive rhyolite bodies, this discordance is greater as a result of local folding and tilting of the intruded strata. An

Figure 8. Age probability plots and histograms of detrital zircon ages from the lower member (VH31-03 and -02) and upper member (VH31-06, -08, and -09) of the La Boca Formation and the La Joya Formation (VH31-10). Each curve sums probability distributions from all of the grains analyzed for that sample. Histogram bin width equals 50 Ma. Vertical axis for each histogram is equal at 60 grain analyses. Some probability peaks that are unlabeled result from a single-grain analysis with low analytical error.
upward increase in zircon grains from Permian-Triassic granitoids, Paleozoic Granjeno Schist, and Grenville Novillo complex reflect the progressive unroofing of the basement complexes. Finally, the La Joya Formation accumulated during a concurring extensional episode, evidenced by recycling of underlying red bed and volcanic strata as clasts in the La Joya Formation (Rubio-Gudiño et al., 2008), extensive exposure of nearby basement rocks indicated by the detrital zircons, and the angular unconformity beneath the La Joya Formation. The exposures at Valle de Huizachal lie on the eastern edge of a band of Jurassic volcanic exposures with an east-west extent of ~170 km (Barboza-Gudiño et al., 2008) and may represent the east flank of the Nazas arc, where crustal extension juxtaposed thin arc volcanics and uplifted basement blocks. Arc rocks of the same age in the southwestern United States and northwestern Mexico have been interpreted as the record of a generic extensional arc system (Busby-Spera, 1988) that continued into what is now eastern and southern Mexico (Grajales-Nishimura et al., 1992; Dickinson and Lawton, 2001).

The new depositional ages and the age range of Jurassic zircon grains in the red beds at Valle de Huizachal suggest that magmatism in the Nazas volcanic arc of northeastern Mexico ceased prior to opening of the Gulf of Mexico. Jurassic grains with concordant ages range 199 to 164 Ma (n = 115 grains; Supplemental Table 1 [see footnote 1]); four younger grains ranging from 162 to 153 Ma have analytical errors of 5 Ma or are discordant. The data thus indicate that no zircon-yielding volcanic rocks younger than Callovian age provided detritus to the Huizachal Group. Moreover, the youngest grains in the data set are present in the upper member of the La Boca Formation, ending the trend of younger grain ages in higher stratigraphic levels and suggesting that magmatism had ceased prior to deposition of the La Joya Formation. Although the age of seafloor spreading in the Gulf of Mexico is not well constrained, it is generally estimated to have begun in the late Oxfordian (~158–157 Ma; Pindell, 1985; Pindell and Kennan, 2007). The existing data thus suggest that Nazas magmatism shut down immediately before the onset of seafloor spreading in the Gulf of Mexico.

CONCLUSIONS

Red beds exposed at Valle de Huizachal consist of the La Boca Formation, divided into a lower volcanic-rich member and an upper member dominated by epispacial sedimentary rocks with an important volcaniclastic component, and the younger La Joya Formation. All units are separated by angular unconformities. Detrital zircon young grain ages indicate that the lower member is Early Jurassic (maximum depositional age 184–183 Ma, Pleinsbachian) and the upper member is Middle Jurassic (maximum depositional age 167–163 Ma, Bathonian–Early Callovian). Continuing detrital input from local volcanic sources indicates that maximum depositional ages are a good approximation of true depositional ages. Detrital zircon ages are inconclusive as to the depositional age of the La Joya Formation, but its position between Bathonian–Callovian red beds and overlying Oxfordian strata is consistent with a Callovian age.

These red bed deposits were derived from Precambrian–Mesozoic rocks exposed nearby in the Huizachal-Peregrina anticlinorium. Four detrital zircon age populations in the Huizachal Group include: (1) Grenville grains (~1.3–1.0 Ga) derived from Gondwanan basement known locally as the Novillo Greense complex; (2) early Paleozoic grains (430–300 Ma) derived from peri-Gondwanan accreted rocks represented locally by the Granjeno Schist; (3) Permio-Triassic grains (296–222 Ma) derived from volcanic and plutonic rocks of the West Pangaea (East Mexican) arc; and (4) Early-Middle Jurassic grains (199–164 Ma) derived from the Nazas volcanic arc.

The La Boca and La Joya formations in Valle de Huizachal record a transition from magmatic arc to rift-basin development during the breakup history of Pangaea. The lower member of the La Boca Formation consists of interbedded volcanic rocks and continental siliciclastic strata with detritus derived primarily from coeval volcanic rocks and represents deposits of the Nazas volcanic arc. The upper member of the La Boca Formation was deposited during continued Nazas volcanism, but basement grain contributions from uplifted flanking blocks increased following tilting of the lower member. Continued Nazas magmatism is indicated by a systematic upsediment decrease in younger grain ages. Continued extension and widespread exposure of basement rocks took place prior to and during deposition of the basal alluvial-fan conglomerate of the La Joya Formation, whose young grain ages are generally older than the inferred late Middle Jurassic depositional age of the strata. The absence of younger grains in the La Joya Formation suggests that Nazas arc magmatism ceased by Callovian time (~166–164 Ma).

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