Detrital zircon U-Pb geochronology of the Sierra de Santa Rosa Formation, Sonora, Mexico, and implications for an Early Jurassic retroarc basin

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ABSTRACT

A succession of Triassic to Jurassic strata occurs in the vicinity of Caborca, Mexico, where the Antimonio, Río Asunción, and Sierra de Santa Rosa Formations contain a nearly continuous marine section deposited in previously reported shallow basin environments. The Sierra de Santa Rosa Formation is known to be Early Jurassic, but with an 18 m.y. uncertainty in age. Here we establish the ages of the three members of the Sierra de Santa Rosa Formation as early Sinemurian to middle Toarcian. Detrital zircon U-Pb geochronology from a set of 2334 grains along with ammonite zonation is used to establish depositional ages and to support the interpretation of the formation as being deposited in a retroarc basin. We find 2 zircon populations of 199 Ma and 192 Ma that mark the onset of Early Jurassic magmatic activity in the formation. Older Neoproterozoic and Early Devonian populations not attributable to local sources imply a robust Early Jurassic exchange with southwestern Laurentian eolianites. Here we also establish the ages of three fossiliferous units containing solitary and colonial corals in the Sierra de Santa Rosa Formation. The end-Triassic mass extinction decimated coral reefs worldwide and reports of Early Jurassic corals have been particularly rare in North America. The ages indicate an earlier regional recovery for North American corals than previously proposed; this has implications for understanding postextinction reef recovery.

INTRODUCTION

For more than 700 m.y., through the Neoproterozoic to the Carboniferous, the miogeoclinal western margin of Laurentia was without significant magmatic activity. This passive margin was in contrast to an active eastern Laurentia with the succession of the Grenville, Taconic, Acadian, and Alleghanian orogenies (Park et al., 2010). The onset of the orogenic quiescence in eastern Laurentia gave way to a convergent process on the western margin during the late Paleozoic and early Mesozoic. A magmatic arc developed across western Laurentia, recorded in the Permian to Jurassic plutons of the North American Cordilleran and its less frequent sedimentary records (Riggs et al., 2016). In northern Mexico this magmatic arc became particularly active during the Early to Middle Jurassic, but much of the geologic record is now covered by Cenozoic volcanic rocks. The Mesozoic magmatic activity in northwestern Mexico had a gap between the Late Triassic and the earliest Jurassic (Arvizu and Iriondo, 2015). The onset of the earliest Jurassic magmatism is relevant to understanding the magmatic episodes of southern Laurentia. The upper Permian–Triassic and lower Jurassic sedimentary succession of the El Antimonio Group in Sonora, Mexico, is rare, perhaps one of the most complete early Mesozoic stratigraphic records of the North American Cordilleran (González-León et al., 2005).

The El Antimonio Group consists of the Antimonio, Río Asunción, and Sierra de Santa Rosa Formations, which are located south of the proposed Mojave-Sonora megashear (González-León et al., 2005; Silver and Anderson, 1974). The El Antimonio Group is highly fossiliferous, representing 4.5-km-thick, fluvial to shallow to open marine sedimentary strata. It was previously proposed to have been deposited in an evolving shallow shelf to forearc basin on the southern margin of Laurentia that migrated southeast to its present position by left-lateral displacement on the Caborca terrane during the Late Jurassic.

The Sierra de Santa Rosa Formation is the upper component of the group with a previously reported Jurassic age range from the Hettangian to the Pliensbachian, as determined primarily from relative dating techniques, most specifically with marine bivalves and ammonites (Damborenea and González-León, 1997; González-León et al., 2005). Two detrital zircon U-Pb ages have also been reported (González-León et al., 2009), but did not narrow the extensive uncertainty in the age of the formation. Here we describe the absolute dating techniques used to determine the depositional ages of each member of the Sierra de Santa Rosa Formation. The detrital zircon U-Pb geochronology also displays a time of ongoing magmatic deposition suggesting a retroarc basin. Youngest zircons represent ongoing magmatic activity and older zircon populations indicate that significant sediments derived from cratonic Laurentia were deposited as the Sierra de Santa Rosa Formation, consistent with the exchange allowed in a retroarc basin.

The ages of the formation are defined with extensive detrital zircon U-Pb geochronology from the Early Jurassic marine sedimentary rocks.
in the Sierra de Santa Rosa locality (Fig. 1). Eight samples of sandstone and sandy siltstone spanning the lower to upper sections of the formation (Fig. 2) were processed to extract 2334 detrital zircons. The zircons were analyzed for U-Pb ages utilizing the high efficiency of laser ablation−multicollector−inductively coupled plasma−mass spectrometry. The large zircon data set yielded distinctive Precambrian, Paleozoic, and Mesozoic populations (Fig. 3) that are compared to the previously published detrital zircon populations and then correlated with ammonite zones established for the Sierra de Santa Rosa Formation.

By establishing absolute ages for the Sierra de Santa Rosa Formation and its members we produce a record within a major gap that was previously considered to be a time lacking regional magmatic activity in southwestern North America. The signatures of magmatic arc activity within the prior gaps of the Early Jurassic have implications regarding paleoecology. Furthermore, the geochronology results have implications for understanding the fauna within the fossiliferous sequences. Early Jurassic corals are rare in North America (Beauvais, 1989). Here we establish absolute ages of Early Jurassic North American corals during the time of recovery after the end-Triassic mass extinction, and this supports a recovery for corals of eastern Panthalassa earlier than previously thought (Hodges and Stanley, 2015).

**GEOLOGIC SETTING**

The Sierra de Santa Rosa Formation is the uppermost formation of the El Antimonio Group, an upper Permian to lower Jurassic fossiliferous marine succession unit located in northwestern Sonora, Mexico. The El Antimonio Group is well exposed in the foothills of the Sierra del Álamo at the old El Antimonio mine, 40 km west of Caborca, Mexico. At this location the group is represented by 14 upward-fining unconformity-bounded sequences of the Late Permian to Late Triassic Antimonio Formation, the Late Triassic Río Asunción Formation, and the lower portion of the Early Jurassic Sierra de Santa Rosa Formation (González-León et al., 2005). The upper part of the Sierra de Santa Rosa Formation is located in the mountains of the same name 85 km southeast of Caborca, where it conformally underlies the conglomerate and volcanic Cerro San Luis Formation (Hardy, 1981).

The El Antimonio Group represents one of the more complete early Mesozoic stratigraphic records of the North American Cordillera. It has been proposed that an early Mesozoic magmatic arc in the Mojave Desert and along the California-Nevada (USA) border separated a shallow shelf to the north from the extensive El Antimonio marine basin to the south (González-León et al., 2009). The El Antimonio Group is considered part of the allochthonous Antimonio terrane (González-León, 1997), which some suggest may have undergone considerable southeastern displacement as part of the Caborca block (González-León et al., 2005). A more recent interpretation of the earliest development of the magmatic arc concluded that it first started in Sonora with an offshore subaerial topography in the Late Permian and developed a land bridge between the arc and the continent ca. 230 Ma (Riggs et al., 2016). The onshore migration of the arc that followed is proposed to have remained topographically low in the Early and Middle Jurassic between much of the region and the Colorado Plateau (Riggs et al., 1993), allowing incursions of eolian sands from the ergs (sand seas) of the Colorado Plateau (Dickinson and Gehrels, 2009).

The section of the lower part of Sierra de Santa Rosa Formation in the Sierra del Álamo is composed of five unconformity bounded sequences that generally start with a basal fluvial or marginal marine conglomerate and are succeeded upward by shallow-marine fine-grained sandstone, siltstone, and limestone (González-León et al., 2005). This section does not correlate lithologically with the stratotype of the Sierra de Santa Rosa Formation in mountains of the same name, where the formation is a mostly terrigenous marine succession with more abundant shallow-marine fossils (Damborenea and González-León, 1997). It was here in the Sierra de Santa Rosa that the formation was originally defined by Hardy (1981), who divided the formation into lower, middle, and upper members. The lowermost portion of the lower member, which is disconformable with the underlying Río Asunción Formation at the assumed Triassic-Jurassic boundary, is only present at Sierra del Álamo. Conversely, the upper portion of the middle member and the upper member only crop out in the Sierra de Santa Rosa.

**STRATIGRAPHY**

The Sierra de Santa Rosa Formation was named and divided into lower, middle, and upper members by Hardy (1981) at the locality of the same
Figure 2. Stratigraphic section of the Sierra de Santa Rosa Formation (Fm.; mbr—member).
The formation has also been identified in the Sierra del Álamo. This unit consists of 1460 m of alternating andesitic lithic wacke, calcareous arkose, sandy biomicrite, and argillite. Depositional environments interpreted for this unit are shallow to nearshore marine environments (Damborenea and González-León, 1997; González-León et al., 2005). Biochronology at the Sierra del Álamo allowed relative dating of correlations with the Sierra de Santa Rosa Formation Hettangian to Sinemurian beds (González-León et al., 2005) in five unconformity-bounded sequences. Each sequence begins with a pebble conglomerate or pebble sandstone that is then succeeded by shallow-marine fine-grained sandstone, siltstone, and limestone. Compared to the strata in the Sierra de Santa Rosa, the outcrops of the formation in Sierra del Álamo have greater lateral continuity and locally contain abundant, better preserved ammonites and occasional bivalves (Taylor et al., 2001). At the Sierra del Álamo, the formation is underlain by the Late Triassic Río Asunción Formation (Fig. 2), consisting of carbonate and siliciclastic marine strata (González-León et al., 2005). Prior geochronology of the Río Asunción Formation includes Triassic detrital zircons dated from sample 2000–0 (González-León et al., 2005), whereas samples 4–5-08–1 from sequence XI and 2000–2 from the middle member were dated from the Sierra de Santa Rosa Formation. Sample 4–5-08–1 did not contain any Jurassic zircons and sample 2000–2 was dated as 193 Ma (González-León et al., 2009).

In the Sierra de Santa Rosa the upper part of the upper member is a source of abundant Early Jurassic zircons, which are rare in the middle and lower members. The lower member consists of interbedded lithic wacke, calcareous siltstone and mudstone, occasional volcanic pebble conglomerate, and sandy limestone with scarce ammonites, bivalves, and solitary corals. The lithic wacke contains aphanitic volcanic rock fragments (Hardy, 1981) indicating an episode of volcanic activity. The middle member consists of silty biomicrite, sandy shale, and arkose. There are thin beds of tuffaceous mudstones and one bed of devitrified volcanic ash indicative of some volcanic activity occurring within the otherwise fairly quiet middle member. The upper member consists of interbedded mudstone with ammonites, calcareous sandstone, limestone with bivalve assemblages, volcanic conglomerate beds, and carbonate buildups with reef-building corals. In the Sierra del Álamo there is evidence of volcanic activity with well-separated tuff beds in the middle part of the Sierra de Santa Rosa Formation. Because rock lithology varies between the Sierra de Santa Rosa and the Sierra del Álamo regions, and ammonites have not been reported in detail from the first locality, it is difficult to establish accurate relative time-stratigraphic correlations. This necessitates the use of geochronology to correlate beds between the two outcrops.

In this study we collected the following sandstone samples for geochronology of the Sierra de Santa Rosa Formation from the locality of same name. Samples SR-13, SR-1, and SR-16 were collected from the lower member (Fig. 2). Sample SR-4 was collected in the lower stratigraphy of the middle member, which is composed of calcareous mudstone, volcanic lithic wacke, limestone with ammonites, bivalves, crinoids, and solitary corals. Prior work also dated the upper part of the middle member with sample 2000–2 (Gonzalez-Leon et al., 2005). Samples SR-17, SR-6, SR-11, and SR-12 were collected from the upper member.

**METHODS**

Rock samples of ~13 kg each were collected in the Sierra de Santa Rosa from sandstones and sandy siltstones generally situated in close proximity to previously reported fossiliferous beds (González-León et al., 2005; Damborenea and González-León, 1997). Zircon crystals were extracted from eight samples at the Arizona LaserChron Center (ALC; Tucson, Arizona, USA) using a Wilfley table, Frantz magnetic separator, and heavy liquids. Final heavy minerals along with crystals from three known zircon standards were epoxy mounted and polished to a depth of ~20 µm. A mapped scanning electron microscope image of the mounted sample was used to identify and target the known and unknown zircon crystals.

U-Pb geochronology was conducted using LA-MC-ICP-MS following current ALC protocols (Gehrels et al., 2011). An LA spot diameter of 20 µm was used for both the unknowns and the known standards. Standards

![Figure 3. Zircon grain best ages for the combined eight sites in the Sierra de Santa Rosa Formation. N—number of samples; n—total number of grains.](image-url)
were sampled at approximately every fifth analysis. A Photon Machines Analyte G2 excimer laser was used to ablate the zircons to a depth of ~15 µm. The data were reduced using the ALC in-house AgeCalc program. Standard filters were utilized. Analyses were excluded from the data if the ratio of 206Pb/204Pb < 200; 206Pb/238U age error > 10%; 206Pb/207Pb age error > 10% for ages > 400 Ma; for ages > 400 Ma discordance > 20%; or reverse discordance > 5%; for ages < 400 Ma if discordance of 238U/206Pb age and 235U/207Pb age > 30%. An overdispersion factor of 0.60 was applied to 238U/206Pb age errors, which brought the dispersion of the youngest standard to its known range. Concordia plots of the reduced data from each site are shown in Figures 4–11.

The youngest robust cluster of zircon ages is the best measure of the maximum depositional age of the sample and the depositional age is of particular importance to the faunal study. In the case where there was ongoing magmatic activity with a relatively rapid transport of a sufficient number of detrital zircons, then the age of the youngest zircons is the depositional age of the strata to within measurement errors. Isoplot fitting routines were used to determine the weighted mean age and MSWD (mean square of weighted deviates) statistic of the youngest cluster of zircon ages (Ludwig, 2012). A youngest cluster is taken as the three or more zircons with overlapping ages. Consideration must be given to the possibility of unknown lead loss affecting the youngest zircons or the older zircons having an older crystallization age. The Isoplot Unmix (Ludwig, 2012) routine was utilized to check for obvious bimodal populations. If the number of zircons in the youngest cluster was >20 and the older zircons could also form a cluster with n > 20, then the older zircons were excluded until the MSWD statistic was <~1.1. Thus the error from the multiple crystallization ages was less than systematic errors. The weighted mean ages from the identified youngest clusters including internal and systematic errors at 2σ are reported for each site.

A Monte Carlo study suggested if n > ~20, a better measure of the age of the youngest crystallization age is achieved by limiting the cluster to the younger set with MSWD <~1.1. The Monte Carlo study was performed using a large zircon population suspected of having a narrow crystallization age range collected from a tuffaceous sandstone from Seldovia, Alaska (mean age = 199 Ma, MSWD = 0.96, n = 313), and analyzed during the same ALC run. An overdispersion factor of 0.6 was used to reduce the reported 206Pb/238U age errors so the youngest known standard zircons had an MSWD = ~1. The zircons were ordered by age and divided into two sets by selecting alternate grains. One set was offset in age by as much as 7 m.y., then the two sets were recombined and again age ordered. Isoplot Unmix and weighted mean age routines were applied to the bimodal zircon population. Unmix was able to identify 2 offset populations of relatively equal size when the offset was as little as 3 m.y. A slightly more sensitive test for the presence of the bimodal populations was given by the MSWD statistic, which increased from a 0.96 with no age offset to 2.1 with a 7 m.y. offset (Fig. 12). The weighted mean age of the combined set was, as expected, older than the younger set age by one-half the offset. When MSWD = 1.2 the inverse-variance weighted mean age of the combined sets was older than the younger set age by ~1 m.y.

AMMONITE BIOCHRONOLOGY

The fossils identified in the Sierra de Santa Rosa Formation include bivalves, gastropods, ammonites, and corals. Of these, ammonite zonation offers the most specific biochronology and can resolve the relative ages of strata more finely than U-Pb geochronology. Ammonite zones have been established for the Western Cordillera of North America and finely divide the Hettangian, Sinemurian, and Pliensbachian. These North American zones and subzones have been correlated to the northwest European
Figure 7. Concordia plot for Sierra de Santa Rosa Formation sample SR-4.

Figure 8. Concordia plot for Sierra de Santa Rosa Formation sample SR-17.

Figure 9. Concordia plot for Sierra de Santa Rosa Formation sample SR-6.

Figure 10. Concordia plot for Sierra de Santa Rosa Formation sample SR-11.

Figure 11. Concordia plot for Sierra de Santa Rosa Formation sample SR-12.

Figure 12. Monte Carlo simulation of MSWD (mean square of weighted deviates) statistic as a function of separation of mean age of a bimodal zircon population. N — number of samples; n — total number of grains.
A bed within the upper member was assigned to the early Pliensbachian Whiteavesi Zone with corresponding projected age of ca. 189 ± 2 Ma. The MSWD statistic is included with the expectation that after the dispersion normalization to the standards and the results of the Monte Carlo study described here, an abundant cluster of Early Jurassic zircons with a single crystallization age would have an MSWD slightly <1.0. If the MSWD is much >1.0 and the zircon population is larger than n > ~20, we suspect that the youngest cluster age is overstated by an amount that can be estimated from Figure 12.

The individual zircon analyses are listed in Table DR1. For each of the eight sites a youngest zircon cluster was identified. The zircons for each of the youngest age clusters are shown in Figures 13–20. The ages used in our analysis for the base of the Hettangian, Sinemurian, Pliensbachian, and Toarcian stages are 201.3 ± 0.2 Ma, 199.3 ± 0.3 Ma, 190.8 ± 1.0 Ma, and 182.7 ± 0.7 Ma, respectively (Gradstein et al., 2012). At Sierra del Álamo five Hettangian and Sinemurian ammonite subzones have been identified in the lower and middle members of the Sierra de Santa Rosa Formation (Taylor et al., 2001; González-León et al., 2005). The oldest ammonite zone was the Sunrisense with a corresponding upper Hettangian projected age of ca. 200 ± 0.3 Ma. The youngest ammonite zone was the upper Sinemurian Jamesi Zone with a projected age of ca. 194 ± 1 Ma. The Jamesi Zone is the approximate age equivalent to the upper portion of the northwest European Obtusum Zone (Taylor et al., 2001).

Although ammonites have not been studied in detail in the Sierra de Santa Rosa, some ammonite zones have been ascertained but precise stratigraphic positions were not reported (Pálfy and González-León, 2000), and therefore await further study. The oldest ammonite found was correlated with Pálfy and González-León (2000) to the late Sinemurian Harbledowense Assemblage with an age we project as ca. 192 ± 2 Ma. Limestones from within the middle member were assigned to the early Pliensbachian Whiteavesi Zone with corresponding projected age of ca. 189 ± 2 Ma. A bed within the upper member was assigned to the early Pliensbachian Freboldi Zone, which has a corresponding projected age of ca. 188 ± 2 Ma.

GEOCHRONOLOGY

Depositional Ages

The rock samples collected at the eight sites each yielded a suite of zircon grains. The combined 2334 zircon population ages are shown in Figure 3 and the individual zircon populations are shown in Figures 13–20. The individual zircon analyses are listed in Table DR1. For each of the eight sites a youngest zircon cluster was identified. The zircons for each of the youngest age clusters are shown (in bold) in Table DR1.

The inverse-variance weighted mean age of the youngest clusters with the corresponding internal analytic uncertainty in the mean age and the estimated external systematic uncertainty are shown in Figures 21–28. The MSWD statistic is included with the expectation that after the dispersion normalization to the standards and the results of the Monte Carlo study described here, an abundant cluster of Early Jurassic zircons with a single crystallization age would have an MSWD slightly <1.0. If the MSWD is much >1.0 and the zircon population is larger than n > ~20, we suspect that the youngest cluster age is overstated by an amount that can be estimated from Figure 12.

The 8 samples span a thickness of about ~800 m and a period of ~20 m.y. The stratigraphically lowest first occurrence of each of the three Early Jurassic magmatic event ages can, to within the approximate 2 m.y. measurement errors (2σ), be assigned as the depositional age of that site. Although there was no sampling inferior to SR-13 a comparison with older strata at Sierra del Álamo and the presence of volcanic clasts at the SR-13 collection site lead us to assign the early Sinemurian depositional age of 199 ± 2 Ma to SR-13 in the lower member. The depositional age of SR-1
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Figure 13. Probability density plot for Sierra de Santa Rosa Formation sample SR-13.

Figure 14. Probability density plot for Sierra de Santa Rosa Formation sample SR-16.

Figure 15. Probability density plot for Sierra de Santa Rosa Formation sample SR-1.

Figure 16. Probability density plot for Sierra de Santa Rosa Formation sample SR-4.

Figure 17. Probability density plot for Sierra de Santa Rosa Formation sample SR-17.

Figure 18. Probability density plot for Sierra de Santa Rosa Formation sample SR-6.
Figure 19. Probability density plot for Sierra de Santa Rosa Formation sample SR-11.

Figure 20. Probability density plot for Sierra de Santa Rosa Formation sample SR-12.

Figure 21. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-13 (pt—point; errs—errors; rej.—rejected).

Figure 22. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-16 (pt—point; errs—errors; rej.—rejected).

Figure 23. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-1 (pt—point; errs—errors; rej.—rejected).
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The Neoarchean to Neoproterozoic zircon populations of the Sierra de Santa Rosa Formation have been recognized in previous contributions and their provenance has been related to inland parts of cratonic North America. For example, subordinate detrital zircons in the range from 3.36 to 2.31 Ga were recognized by Gehrels and Stewart (1998) and Stewart et al. (2001) in some Neoproterozoic and Paleozoic formations of the southwestern USA and from Sonora; the 2.7 Ga zircons in the Sierra de Santa Rosa Formation might be derived from sedimentary recycling of these sedimentary units. The ca. 1.7 and 1.6 Ga zircon population may be derived from the Proterozoic Mojave, Yavapai, and Mazatzal provinces.

Provenance

Detrital zircons from the studied samples of the Sierra de Santa Rosa Formation range in age from Neoarchean to Early Jurassic and they represent the following populations. A subordinate Archean population shows a minor peak at 2.72 Ga (0.6%). One small Paleoproterozoic population has a minor peak at 2.06 Ga (0.8%) and there is a larger Paleoproterozoic population that ranges from 1.73 to 1.65 Ga (3.4%). Two important Mesoproterozoic zircon peak ages are shown at 1.43 Ga (5.4%) and from 1.17 to 1.05 Ga (14.5%), and a minor Neoproterozoic population indicates an age from 620 to 580 Ma (3.6%) with a peak at 604 Ma. A single Paleozoic population is shown by an Early Devonian age peak at 418 Ma (4.5%). One of the largest zircon populations has a Permian–Triassic age and peak ages ca. 250 (4.9%) and 270 Ma (3.9%). As discussed here, the Early Jurassic zircons are abundant and show peak ages at 180 Ma (7.9%), 192 Ma (4.5%), and 199 Ma (1.5%).

Figure 24. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-4 (pt—point; errs—errors; rej.—rejected).

Figure 25. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-17 (pt—point; errs—errors; rej.—rejected).

Figure 26. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-6 (pt—point; errs—errors; rej.—rejected).

Figure 27. Weighted (wtd.) mean with MSWD (mean square of weighted deviates) statistic for Sierra de Santa Rosa Formation sample S-11 (pt—point; errs—errors; rej.—rejected).

at the bottom of the middle member is assigned as early Pliensbachian at 192 ± 2 Ma and SR-6 near the top of the upper member is assigned a middle Toarcian depositional age of 180 ± 2 Ma.
that make up the basement of the southwestern North America. Granitoids of ca. 1.4 and 1.1–1.0 Ga age that are common plutons that intrude the Proterozoic basement of this region may be the source of these grains in the Sierra de Santa Rosa Formation. Nevertheless, Neoproterozoic, Paleozoic, and Triassic strata in this region have abundant grains of these ages and may also be the recycled sources.

The Neoproterozoic and Paleozoic zircons are very scarce in Paleozoic strata of Sonora but they are more abundant in quartz-rich sandstones that are intercalated in the lower to middle Jurassic sedimentary and volcanic units of northern Sonora, like the Basomari and Lily Formations (González-León et al., 2009). These formations are considered to be part of the Jurassic continental-margin arc that extended from the southwestern USA into northern Mexico (Busby-Spera, 1988; Busby-Spera et al., 1990; Riggs et al., 1993; Dickinson and Gehrels, 2009). The age peaks at 604 and 418 Ma in the Sierra de Santa Rosa Formation resemble the prominent populations with peaks of 615 and 420 Ma that are present in the Jurassic eolianites (Dickinson and Gehrels, 2009) of the Colorado Plateau. The presence of these populations in the Sierra de Santa Rosa Formation suggests an influx of detritus from the interior continent accumulated in the Sierra de Santa Rosa.

Permian to Triassic zircons (7.5%) in the Sierra de Santa Rosa have an age distribution from ca. 283 to 207 Ma and show an important age peak at 250 Ma. This population may have had a source in the Permian and Triassic Cordilleran magmatism of Sonora and California, where the Sonora suite (Riggs et al., 2016) of northwesternmost Sonora shows a magmatic pulse from ca. 284 to 221 Ma (Arvizu and Iriondo, 2015) and several plutonic suites of the Mojave Desert that range in age from ca. 260 to 207 Ma (Barth and Wooden, 2006). The Jurassic zircons in the Sierra de Santa Rosa Formation show a clear provenance from the Cordilleran Jurassic continental-margin arc (Busby-Spera et al., 1990) that in the nearby region of California and Arizona has ages ranging from ca. 200 to 160 Ma (Riggs et al., 1993; Lawton et al., 2012; Haxel et al., 2005; Tosdal and Wooden, 2015). The early Sinemurian 199–191 Ma age range has a scarcity of local sources with no identifiable plutons. In Sierra del Álamo above the Jamesi ammonite zone (age ca. 194 Ma), a series of tuff beds correspond to the 192 Ma magmatic event. These tuff beds are absent at Sierra de Santa Rosa, indicating that the unidentified magmatic source was closer to Sierra del Álamo, 105 km to the northwest of Sierra de Santa Rosa.

**DISCUSSION**

**Significance of Zircon Ages to Early Jurassic Coral and Reefs**

The great mass extinctions had major impacts on the life on the planet. Reefs and reef-building organisms such as corals are especially sensitive to extinction and appear to have been the hardest hit and slow to recover to their former diversity. Corals are thus important indicators of extinction and recovery. This is especially true for the end-Triassic mass extinction, which had profound effects on life on Earth. During the Triassic Period, corals and reefs reached maximum diversity with the development of extensive carbonate platforms. The end-Triassic breakup of Pangea resulted in rift volcanism, leading to prodigious releases of volcanic gases. Ocean acidification and other global perturbations caused reefs to collapse, and the extinction of most corals and marine biotas. At the end of the Triassic there was a dramatic drop in coral diversity and a nearly complete collapse of reefs. The speed and tempo of the Early Jurassic recovery was slow but unfortunately not well documented in Panthalassa during the earliest stages of the Jurassic. This is due in part to the rarity of good Triassic-Jurassic boundaries, the rarity of shallow-water environments, and lack of precise dating (see following). Compared to Panthalassa, recovery in the Tethys appears to have been faster than expected (Kiessling et al., 2007; Lathuilière and Marchal, 2009; Gretz et al., 2013).

The Jurassic recovery of corals in the Americas, relative to the Tethys, is not well known and there may have been geographic and ecologic differences, especially in the timing and evolutionary dynamics. For example, a slower, two-stage recovery is indicated in the Early Jurassic of Argentina (Echevarría et al., 2017). Low-diversity Early Jurassic corals are reported from Chile and Peru (Prinz, 1991). The precise age of rocks containing corals of Early Jurassic age in North America are rather poorly constrained relative to the Tethyan sites of Eurasia (Hodges and
Stanley, 2015). Considering the general scarcity of Early Jurassic corals in North America, the applications of detrital zircon U-Pb geochronology for Early Jurassic coral-bearing rocks presented here may help clarify these inequities and also provide a more complete picture of this major mass extinction and recovery.

Corals from the earliest stages of the Jurassic are extremely rare in North America. This research illustrates previously uncertain ages for Early Jurassic coral of Sonora. The age of the simple Sinemurian corals was deposited subaerially in meandering streams on a volcanic terrane, northwest of Sierra de Santa Rosa closer to Sierra del Álamo. The Middle to Late Jurassic igneous rocks in northern Sonora can be correlated in age by ammonite zonation to the tuff beds of Sierra del Álamo the Sierra de Santa Rosa Formation terminates in the middle Triassic miogeoclinal and eugeoclinal strata of Sonora, Mexico: Journal of Geophysical Research, v. 103, p. 2471–2487, doi: 10.1029/97JB03251.

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However, the retroarc basin interpretation for the Sierra de Santa Rosa Formation remains speculative in the absence of an identifiable orogen. Measurements of the zircon populations in the tufts and sandstones of Sierra del Álamo and other Early Jurassic or Late Triassic deposits to the west are the necessary next phase of this investigation.

CONCLUSIONS

New detrital zircon data from the Sierra de Santa Rosa Formation of Sonora, Mexico, in combination with published ammonite zonation establish that there were three regional magmatic pulses recorded in this formation at 199, 192 and 180 Ma, all derived from unidentified sources. The geochronology also allows the determination of the depositional ages for the lower, middle, and upper members of the Sierra de Santa Rosa as Early Sinemurian, Pliensbachian, and middle Toarcian, respectively. The determination of these depositional ages also permits the dating of rare Early Jurassic corals in Sonora, Mexico, that bear on their recovery after the end-Triassic mass extinction.

Comparison of the Triassic to Archean detrital zircon population shows a significant influx of continental detritus, perhaps as eolian sands, into the Sierra de Santa Rosa Formation in what is speculated to be the filled stage of a foreland retroarc system. It is proposed that the magmatic events originate in or near the forebulge of the foreland system. The presence of conglomerate and volcanic members for the Cerro San Luis Formation that overlie the Sierra de Santa Rosa Formation are consistent with the final filled stage of the retroarc foreland system contemporaneous with the onshore migration of magmatic activity.


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