Stratigraphy and age of Upper Jurassic strata in
north-central Sonora, Mexico: Southwestern Laurentian
record of crustal extension and tectonic transition

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ABSTRACT

Stratigraphy, sedimentology, and geochronology of the Upper Jurassic Cucurpe Formation in north-central Sonora, Mexico, provide new insights into Late Jurassic rifting along the southwestern margin of Laur- entia. The Cucurpe Formation is the fill of the Altar-Cucurpe Basin. This basin developed upon attenuated crust of the Triassic-Middle Jurassic continental arc and was part of the Arivechi-Cucurpe seaway; a narrow marine embayment oriented parallel to and located west of the Chihuahua trough. The Cucurpe Formation unconformably overlies Middle Jurassic arc assemblages and represents upward-coarsening marine prodeltaic deposits. New U-Pb zircon geochronology and a Kimmeridgian ammonite (Idioceras cf. I. densicostatum) constrain its age to between ca. 158 and 149 Ma. Detrital zircon ages from the unconformably overlying Lower Cretaceous Bisbee Group indicate a maximum depositional age of 139 ± 2 Ma (2σ error), demonstrating a hiatus of at least 10 m.y. between Jurassic and Cretaceous strata. Detrital zircon ages and petrographic data indicate the provenance of Cucurpe Formation and lowermost Bisbee strata. The lower part of the Cucurpe was derived dominantly from Middle Jurassic volcanic and exhumed Caborcan basement, Paleozoic-Lower Jurassic sedimentary cover, and Lower Cretaceous intermediate volcanic rocks. Revised stratigraphy of the Cucurpe-Tuape region indicates that several conglomeratic units, formerly interpreted as Late Jurassic pull-apart basin deposits, are not of Late Jurassic age.

INTRODUCTION

The Late Jurassic marked changing interplate dynamics in the Cordillera of the southwestern U.S. and northwestern Mexico. Incipient opening of the Gulf of Mexico during the breakup of Pangaea was coincident with Late Jurassic continental rifting and marine incursion in north-central Sonora. Opinions vary as to the dominant tectonic mechanisms that initiated this rifting. Some workers infer that extension resulted from rollback of the subducting oceanic slab (e.g., Lawton and McMillan, 1999; Dickinson and Lawton, 2001b), whereas others infer transensional extension associated with the Mojave-Sonora megashear (MSM; e.g., Anderson and Nourse, 2005; Busby et al., 2005). Mesozoic sedimentary successions exposed in the Cucurpe-Tuape region of north-central Sonora (Fig. 1, Plates 1–2) provide details concerning volcanic activity, basin subsidence, and basement uplift during this critical period of transition.

We present new data on the stratigraphy, sedimentology, and age of Upper Jurassic strata of the Cucurpe Formation and review stratigraphically adjacent units of Middle Jurassic and Early Cretaceous age. Upper Jurassic strata are significant because they record onset of major extension and marine incursion into northern Sonora. Our data improve the lithostratigraphy of the region, refine temporal limits of Upper Jurassic strata and the unconformities bounding them, and shed light on the stratigraphic relationships of the Glance Conglomerate, a synorogenic unit inferred to establish the locations and timing of extensional basins in the region. This study was carried out within a main study area and within a broader general study area (Fig. 1) where comparative reconnaissance geology was completed. The main study area is located ~13 km northwest of the village of Cucurpe along the eastern flank of Sierra de Cucurpe, where an extensive Lower Jurassic to Lower Cretaceous section is exposed. Although structurally disturbed, this section is intact and contains a complete section of the Cucurpe Formation.

METHODS

Research in the main study area included geologic mapping at a scale of 1:25,000, stratigraphic measurement, U-Pb zircon geochronology, and petrography of the Cucurpe Formation and basal strata of the overlying Bisbee Group. In the general study area, local mapping and comparative stratigraphy were accompanied by compilation of previous mapping (Plate 2) to unify the stratigraphic nomenclature and identify problem areas.

Sandstone thin sections for point counts were selected on the basis of quality, minimal alteration, and grain size. Each thin section was stained with sodium cobaltinitrate. The Gazzi-Dickinson method was utilized for point count analysis (Ingersoll et al., 1984; Zuffa, 1980). A single operator performed all point counts with a node spacing of 0.66 mm for medium-grained sandstones and a node spacing of 0.99 mm for coarse-grained sandstones. Point count parameters, raw count data, and normalized modal percentages of framework grains are presented in Supplemental Table 1.

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Geosphere; April 2011; v. 7; no. 2; p. 390–414; doi: 10.1130/GES00600.1; 13 figures; 2 tables; 2 plates; 2 supplemental tables.
U-Pb geochronology was performed for detrital zircons using the laser ablation multicollector induced-coupled-plasma mass spectrometer (LA-MC-ICPMS) at the University of Arizona. Geochronology on tuffs was completed at the Stanford/U.S. Geological Survey (USGS) facility using the sensitive high-resolution ion microprobe (SHRIMP). Sample preparation used standard mineral crushing and separation techniques. Analytical errors associated with the LA-MC-ICPMS facility at the University of Arizona are detailed elsewhere (Gehrels et al., 2008). Errors on ages of individual detrital zircon grains are reported at the 1σ level, and errors on igneous crystallization ages are reported at the 2σ level. Analytical results, age data, and global positioning system (GPS) coordinates for each sample are included in Supplemental Table 2. GPS coordinates use the 1927 North American Datum for Mexico.

Only detrital zircons in coherent age groups of three or more were considered representative for obtaining maximum depositional ages due to problems that can arise from discordance (e.g., Dickinson and Gehrels, 2009b). The youngest coherent age groups from detrital zircon analysis were determined using the Detrital Age Pick program of Gehrels (2006). Weighted means of these groups were calculated using Isoplot 3.0 (Ludwig, 2003). We employ the time scale of Walker and Geissman (2009).

**GEOLOGIC SETTING AND TECTONIC MODELS**

Mesozoic tectonic events proposed for the southwestern margin of Laurentia include large-scale sinistral truncation and translation (MSM), continental arc magmatism, arc extension and rifting, exotic arc or fringing arc accretion, post-rift thermal subsidence, and Late Cretaceous metamorphism and magmatism. The evidence for and existence of several of these events remain controversial (Molina-Garza and Iriondo, 2005). The following summarizes some of the hypotheses concerning the Mesozoic tectonic evolution of southwestern Laurentia.
Plate 1. Paleoproterozoic basement provinces and Jurassic granitoid and supracrustal rocks in southeastern California, southern Arizona, and northernmost Sonora (from Mauel, 2008). Mapped areas locally include minor older or younger rocks; smaller exposures may be slightly exaggerated in size. Modified from Stewart et al. (1986); Reynolds et al. (1986); Chepega (1987); Stephens (1988); Tosdal et al. (1989); Rodríguez-Castañeda (1988, 1991, 1994, 1996, 1999); Gastil et al. (1991); Nourse et al. (1994); Nourse (1995); Iriondo et al. (2004); Karlstrom et al. (2004); Anderson et al. (2005); Haxel et al. (2005); Haxel et al. (2008); and González-León et al. (2009). For the full-sized PDF file of Plate 1, please visit http://dx.doi.org/10.1130/GES00600.S3 or the full-text article on www.gsapubs.org to view Plate 1.
Plate 2. Geologic map of the Magdalena-Tuape region (the general study area), Sonora, Mexico. For the full-sized PDF file of Plate 2, please visit http://dx.doi.org/10.1130/GES00600.S4 or the full-text article on www.gsapubs.org to view Plate 2.
Mojave-Sonora Megashear and Basement Ages

The MSM was originally proposed to explain the apparent distribution of Proterozoic basement provinces in northern Sonora (Plate 1; Silver and Anderson, 1974; Anderson and Silver, 2005). Two Precambrian basement age provinces were recognized in northwestern Sonora, a northeastern group with ages of 1.7–1.6 Ga, and a southwestern group with ages of 1.8–1.7 Ga (i.e., the Caborca Block; Plate 1; Anderson and Silver, 1979). This basement age distribution led Silver and Anderson (1974) to propose that 1.8–1.7 Ga rocks in Sonora were displaced sinistrally along the MSM from rocks of similar age in the Mojave Desert region (Plate 1). Correlation of the overlying Neo-proterozoic-Paleozoic strata from both regions supports this assertion (e.g., Stewart, 2005). These relationships led Anderson and Silver (1979) to propose that the Caborca block translated 700–800 km along the MSM during the Late Jurassic to reach its present location. Evidence in support of Late Jurassic translation includes (1) deformation of fossiliferous Oxfordian strata along the fault in central Sonora, (2) 158 Ma hypabyssal rocks displaced along the fault, (3) emplacement of the undeformed 148 Ma Independence dike swarm near the fault, and (4) crosscutting relationships among deformed and undeformed plutons in the central Mojave Desert that indicate deformation between 164 and 149 Ma (Anderson and Silver, 2005). Other workers have proposed similar truncation and translation of the Caborca block in late Paleozoic to Triassic time (Stevens et al., 2005; Dickinson and Lawton, 2001b). This alternate Early Permian to Middle Triassic (c.a. 281–241 Ma) sinistral strike-slip fault has been termed the California-Coahuila transform (Dickinson, 2000; Dickinson and Lawton, 2001b).

Late Jurassic basin geometry and subsidence have been attributed to transtension along releasing bends of the MSM. Anderson and Nourse (2005) described upward-fining Upper Jurassic conglomerate gradationally overlain by finer-grained Bisbee Group strata and interpreted dominant fault orientations as representing pull-apart geometries. A Jurassic history for these faults, which typically exhibit Late Cretaceous displacement, is inferred on the basis of an unconformity between Upper Jurassic (?)–Lower Cretaceous strata. Rifting and subsidence in the pull-apart model occurred between 162 and 148 Ma.

Late Triassic to Middle Jurassic Magmatic Arc

By the Late Triassic, arc magmatism had developed along the southwestern margin of Laurentia. Rocks of the Late Triassic to Middle Jurassic magmatic arc consist dominantly of calc-alkaline to alkaline granitoids and rhyolitic to dacitic ash flow tuffs and flows locally interbedded with quartz arenite and sedimentary strata with abundant volcanic clasts (Plate 1; May and Haxel, 1980; Hardy, 1981; Haxel et al., 1985; Segerstrom, 1987; Tosdal et al., 1989; Palafox et al., 1992; Nourse et al., 1994; Nourse, 1995; Rodríguez-Torres et al., 2003; González-León et al., 2005; Haxel et al., 2005; Leggett, 2009). Intersтратified eolian and shallow-marine quartz arenite indicate that the Middle Jurassic arc was low standing and occupied a graben depression which acted as a trap for quartz-rich sand transported southwest from the Late Triassic–Middle Jurassic arc complex of the Colorado Plateau (Bilodeau and Keith, 1986; Busby-Spera, 1988). The arc trend from northern Sonora to a southeastern segment extending to Guatemala, termed the Nazas arc, has alternately been interpreted as continuous (Bartolini et al., 2003) or as offset by the MSM (Jones et al., 1995).

Upper Jurassic Igneous and Supracrustal Rocks of Southern Arizona and Sonora

Upper Jurassic rocks of the U.S.-Mexico border region are less studied and correlations are more tenuous than those of the Upper Triassic to Middle Jurassic magmatic arc rocks. The Upper Jurassic includes the Ko Vaya Suite, the Cucurpe Formation, the Glance Conglomerate, and various correlative units (Fig. 1 and Plate 1). Late Jurassic age assignment until recently has been based solely on stratigraphic position due to a lack of geochronological data.

The Ko Vaya Suite consists of granitic rocks, characterized in part by textural and compositional heterogeneity and alkaline tendencies, and associated sedimentary and volcanic rocks (Haxel et al., 2008). The supracrustal rocks of the Ko Vaya Suite have also been termed the “Artesa sequence” (Tosdal et al., 1989), which contains a number of lithologies with common lateral facies changes and local unconformities. The most widespread and indicative lithology interbedded within volcanic tuffs and flows is laminated or well-bedded immature volcanic litharenite (Tosdal et al., 1989).

The Cucurpe Formation and related marine shales and turbidites in north-central Sonora contain Oxfordian–Tithonian ammonites (Rangin, 1977; Imlay, 1980; Almazán-Vázquez and Palafox-Reyes, 2000; Villaseñor et al., 2005). These and correlative strata to the south (Lyons, 2008) represent a northwest-trending arm of the Mar Mexicanos termed the Arivechi-Cucurpe seaway, which lay roughly parallel to, but west of, the Chihuahua trough in central Chihuahua (Haenggi and Muehluberger, 2005; McKeel et al., 2005). A Late Jurassic to Early Cretaceous bathymetric high known as the Aldama platform (Haenggi, 2002) separated these Late Jurassic marine depocenters and was likely contiguous with the Cananea high along the Sonora-Arizona boundary (McKee and Anderson, 1998).

The basal conglomerate member of the Bisbee Group, the Glance Conglomerate (Ransom, 1904), is widely exposed in ranges of southeastern Arizona and north-central Sonora (Plate 1), where its dominantly alluvial deposits vary greatly in thickness, clast composition, texture, contact relations, and age (Bilodeau et al., 1987; Tosdal et al., 1989; Nourse, 1995). The stratigraphic relation of the Glance Conglomerate to the marine Upper Jurassic strata of northern Sonora remains in question; the Glance is commonly identified on the basis of coarse texture, stratigraphic position, and/or unconformable relation with older rocks (Tosdal et al., 1989). In southern Arizona, stratigraphic variation of clast composition records unroofing of adjacent uplifted fault blocks (Bilodeau et al., 1987). The lower parts of the Glance Conglomerate locally contain silicic tuffs with ages of 147 ± 6 Ma (K-Ar, biotite), 149 ± 11 Ma (Rb-Sr, whole-rock), and 151 ± 2 Ma (Rb-Sr, whole rock) (Marvin et al., 1978; Kluth et al., 1982). These ages, if correct, indicate that the Glance is generally younger than or correlative with the upper parts of the Upper Jurassic strata we describe here. Some workers interpret Glance Conglomerate deposition as the result of rifting and back-arc extension related to the opening of the Gulf of Mexico (Bilodeau, 1982) rather than transtension.

Changes in Inter-plate Kinematics during Late Jurassic Time

Most workers agree that the Late Jurassic was a time of transition from the tectonic regime of the Late Triassic to Middle Jurassic. Potentially interrelated tectonic events proposed for the Late Jurassic include: (1) Initiation of continental rifting along the southwestern margin of Laurentia following an episode of extensive caldera development and emplacement of silicic tuffs (“quartz porphries”) by 168 Ma (Riggs et al., 1993); (2) trenchward migration of the Jurassic arc from ca. 157 to 148 Ma; and (3) rapid increase in absolute northward motion of western North American from ca. 160 to 125 Ma.

A mechanism proposed for initiation of Late Jurassic rifting is westward rollback of the Farallon slab or a pre-Farallon slab by steepening of the slab-subduction angle (Lawton and McMillan, 1999; Dickinson and Lawton,
2001b), which resulted in passive intra- and back-arc extension within the upper plate, asthenospheric upwelling, and resultant partial decompression melting of the elevated asthenospheric mantle. Attendant lithospheric melting produced mafic and effusive silicic volcanic rocks interbedded with Upper Jurassic conglomerates during slab retreat; and continued upwell- ing, resulting from return mantle flow following slab retreat, caused decompression partial melting of the asthenosphere and produced basaltic with ocean-island chemical affinities.

The apparent polar wander path of the North American plate reveals an abrupt change in the rate and direction of plate movement during Late Jurassic time (Beck and Housen, 2003). Earlier in the Jurassic (ca. 200–160 Ma), North America slowly rotated clockwise and moved north with respect to the paleomeron. This was followed by rapid northwestward absolute motion of western North America from Late Jurassic to Early Cretaceous time (ca. 160–125 Ma; Beck and Housen, 2003). The beginning of rapid Late Jurassic North American plate movement coincided with the onset of marine deposition in the Altar-Cucurpe Basin.

**Early Cretaceous Extension and Subsidence within the Bisbee Basin**

The post-Glance Bisbee Group of southwestern Arizona was originally divided, in ascending order, into the Morita Formation, the Mural Limestone, and the Cintura Formation (Ransome, 1904). Subsequent studies have documented the presence of correlative strata in southwesternmost New Mexico (Mack et al., 1986; Lawton and Happian, 1998; Lucas and Lawton, 2000; Lawton, 2004), southeastern Arizona (Bilodeau 1978, 1982; Dickinson et al., 1986, 1989; Lawton and Olmstead, 1995), and north-central Sonora (Jacques-Ayala, 1989, 1995; González-León, 1994; González-León and Lucas, 1995; Lawton et al., 2004; Peryam, 2006). The Bisbee Basin of northern Sonora has been defined as the “Bisbee fl ank basin” on the basis of its thinner (<100 m) intervals of Glance Conglomerate than in Arizona, which was occupied by the “Bisbee core basin” (Dickinson and Lawton, 2001a). These thinner, more fl uvial, Glance intervals and the Ko Vaya Suite lie within the Papago domain (Fig. 1), a region characterized by its general lack of exposed autochthonous Proterozoic–Paleozoic rocks (Anderson et al., 2005). Post-GLance Early Cretaceous deposition in the Bisbee Basin records post-extensional thermotectonic subsidence (Dickinson et al., 1989; McKee et al., 2005).

**STRATIGRAPHY AND CORRELATION OF JURASSIC–LOWER CRETACEOUS STRATA, NORTH-CENTRAL SONORA**

Lower Jurassic–Lower Cretaceous stratigraphic units of the general study area include, in ascending order, the Basomari, Rancho San Martin, Cucurpe, Rancho La Colgada, Morita, Mural, and Cintura and La Juana formations (Plate 2 and Fig. 2). Nowhere in the general study area is this succession continuously exposed; rather, unit contacts are commonly faults, and stratigraphic sections are themselves faulted (Plate 2). Therefore the stratigraphic column is a composite section based on relations observed at various locations in the general study area. Conglomerate identified as Glance directly underlies the Morita Formation in the northern part of the general study area at a locality where strata of known Late Jurassic age do not crop out; we discuss the Glance with the Cucurpe Formation below. Our revised stratigraphic column is correlated with strata of adjacent regions on the basis of published and new biostratigraphic and geo-chronologic data (Fig. 3).

We refer to the sedimentary basin in which Upper Jurassic marine and continental syn-rift strata accumulated as the Altar-Cucurpe Basin, which lay south of the Cananea high. The geographic extent of the Altar-Cucurpe Basin is more narrow and elongate than that of the “Bisbee fl ank basin” of Dickinson and Lawton (2001a) and extends farther to the southeast beneath Cenozoic cover of the Sierra Madre Occidental. Definition of the Altar-Cucurpe Basin distinguishes Jurassic syn-rift from Lower Cretaceous post-rift deposits, which are separated by an angular unconformity. It also takes into account new data presented in this paper and Mauel (2008) indicating that a thick Upper Jurassic marine section, commonly tightly folded and partly correlative with the Glance Conglomerate, underlies Lower Cretaceous strata along a trend that passes generally southeast from just west of the community of Altar, past Cucurpe, and on to the southeast to embrace outcrops of black shale described by Rodríguez-Castañeda (1994), which we include in the Cucurpe Formation. The Bisbee fl ank basin was defined to include only thin Glance Conglomerate sections (Dickinson and Lawton, 2001a) and so lacks the structural distinction of a deeply subsided Late Jurassic depocenter to which we ascribe the basin here.

**Lower and Middle Jurassic Strata**

**Basomari Formation**

The Basomari Formation is exposed in the main study area north of Rancho Basomari (Figs. 4 and 5), where it consists of ~750 m of thickly bedded granule to boulder muddy matrix-supported conglomerate with intercalated maroon to dark-gray volcanic litharenite and siltstone beds (González-León et al., 2009). Conglomerate beds contain clasts of intermediate volcanic rocks, gneiss, granite, diorite, and uncommon quartzite. The Basomari Formation is interpreted as a fl uvial and alluvial continental deposit based on lithology and absence
Figure 3. Correlation of stratigraphic units in north-central Sonora with those of other regions in the southwestern United States and timing of inferred tectonic events and basin-forming mechanisms, Early Jurassic–Early Cretaceous time. Sources of data: (1) Barth et al. (2004), Spencer et al. (2005); (2) Jacques-Ayala (1995), García y Barragán et al. (1998), González-León et al. (2009); (3) Peryam (2006), Leggett et al. (2007), Leggett (2009); (4) adapted from Riggs et al. (1993), Lawton and Olmstead (1995), Haxel et al. (2005); (5) Lawton and Harrigan (1998); (6) Kowallis et al. (2001); (7) Haenggi (2002); (8) Peryam (2006); (9) Anderson et al. (2005); (10) Barth et al. (2008); (11) Dickinson and Lawton (2001b); (12) Dickinson et al. (1989), Lawton and McMillan (1999); and (13) González-León et al. (2009).
of fossils (González-León et al., 2009). Paleo-
zoic(?) micritic limestone olistoliths(?) tens to
hundreds of meters in length along strike crop
out in southwestern exposures. The Basomari
Formation was formerly considered Late Jur-
sassic (Stephens, 1988); however, a dacitic tuff
~130 m from its top yielded an age of 189.2 ±
1.1 Ma (U-Pb zircon SHRIMP; Leggett et al.,
2007; Leggett, 2009), indicating that this unit is
at least partly correlative with the Lower Jur-
sassic Sierra de Santa Rosa Formation (Fig. 3). The
Basomari is in fault contact with the Rancho
San Martin Formation in the main study area
(Leggett, 2009).

Rancho San Martin Formation

The Rancho San Martin Formation is best
exposed in the main study area southeast of
Rancho San Martin (Fig. 5) and along Arroyo
El Cajón west of Rancho La Tesota (Fig. 6).
In the main study area it consists of ~700 m
of volcanioclastic conglomerate, eolian quartz
arenite, lacustrine limestone, and interbedded
basaltic andesitic and dacitic flows (Leggett,
2009). The lowest 250 m consists of well-sorted
fine-grained quartz arenite intercalated with
moderately sorted, fine- to medium-grained,
volcanic and feldspathic litharenite, overlain by
an ~50-m-thick interval of dacitic ash flow
tuff with an age of 168.4 ± 1.2 Ma (U-Pb zir-
con SHRIMP; Leggett et al., 2007; Leggett,
2009). Overlying the tuff is ~250 m of pebble to
cobble volcanioclastic conglomerate with inter-
bedded andesitic flow breccia above which an
~40 m interval of laminated algal boundstone
grades upward into oolitic-cobble wackestone
(Leggett, 2009). The uppermost 110 m
consists of pebble to cobble volcanioclastic
conglomerate interbedded with discontinuous beds of fine-grained quartz arenite (Leggett,
2009). The Rancho San Martin Formation represents eolian, alluvial fan, and lacustrine deposits in an
extensional basin within or adjacent to the active
Middle Jurassic Nazca arc (Leggett, 2009). In
the main study area, the Cucurpe Formation unconformably overlies the Rancho San Martin Forma-
tion.

Upper Jurassic Strata

Cucurpe Formation

The Upper Jurassic Cucurpe Formation is
widespread in the general study area (Plate 2),
where it is typically isoclinally folded and
faulted. The strata were first described by Rangin (1977) near Rancho La Colgada (Fig. 1), who
assigned them a late Oxfordian age on the
basis of ammonites in the section. Araujo-
Mendieta and Estavillo-González (1987) later
assigned strata near El Venado (Fig. 1) to the
Cucurpe Formation and designated the locality
as the type section. This section is structurally
complex, incomplete, and consists of ~161 m of
ammonite-bearing upper Oxfordian tuffaceous
sandstone, shale, and siltstone. Subsequently,
Rodríguez-Castañeda (1991) assigned Upper
Jurassic ammonite-bearing strata of the area to
the La Colgada Formation. Following the rule
of priority in the North American Stratigraphic
Code (NACSN, 1983), we refer to Upper Jurassic
strata of the Cucurpe-Tuape region as the
Cucurpe Formation.

The Cucurpe Formation consists of more
than 1000 m of thinly bedded shale, mudstone,
tuffaceous siltstone and sandstone, and subor-
dinate granule-pebble conglomerate beds. Its
lower part contains intercalated thin beds of
black, gray, and reddish gray shale, tuffaceous
siltstone and mudstone, less common volcanic
litharenite, and rare andesitic flows. Locally,
the Cucurpe Formation coarsens up-section into
to meter to decimeter scale intervals of amal-
gamated medium-to coarse-grained volcanic
litharenite and volcanioclastic granule to pebble
conglomerate beds which commonly exhibit
inverse to normal grading, cross stratification,
horizontal laminae, scour surfaces, black to
gray subrounded “floating” shale intraclasts,
and rare flute and load casts at bed bases.
Conglomerates are typically matrix supported, with
dominant rhyolite clasts. Fine- grained intervals
locally contain uncommon belemnites, bivalves,
silicified wood, rare dinosaur bone fragments,
and locally abundant ammonites. The Cucurpe
Formation is unconformably overlain by the
La Colgada Formation in the southern part of
the general study area and by the Morita
Formation in the central part (Plate 2).

Oxfordian–early Tithonian ammonites indi-
cate the general age range of the Cucurpe For-
mation (Rangin, 1977; Villaseñor et al., 2005).
One ammonite and U-Pb ages of three reworked
silicic ash fall tuffs provide new age constraints
for the Cucurpe Formation and corroborate its
Late Jurassic age. Two of these siliceous tuffs
(3–03-LL-21 and 5–21-CM02) were collected
~150 m and ~20 m, respectively, from the top of
the formation in the main study area, where it is
unconformably overlain by the Morita Forma-
tion (Fig. 5). Sample 3–03-LL-21 produced 12
concordant grains with a weighted mean age of
152 ± 3 Ma and sample 5–21-CM02 yielded 21
concordant grains with a weighted mean age of
150 ± 1 Ma (U-Pb zircon SHRIMP; Fig. 7). A
third tuff (sample 5–22-CU-01), collected north-
west of Rancho La Colgada (Fig. 8), near the
type locality of the Cucurpe Formation, yielded
15 concordant grains with a weighted mean age of
152 ± 2 Ma (U-Pb zircon SHRIMP; Fig. 7). All
three tuff samples have Late Jurassic ages that fall
on the Kimeridgian–Tithonian boundary.
An ammonite discovered in a micritic limestone clast of a belemnite-bearing, micrite-and volcanic-clast conglomerate bed in the main study area was identified as *Idoceras cf. I. densicostatum*, of early Kimmeridgian age (Villaseñor et al., 2005). This clast-supported bed lies ~760 m above the base of the Cucurpe Formation. Approximately 10–20 m upsection, uncommon, lithologically similar, meter-scale micritic limestone blocks contain soft-sediment folds (Mauel, 2008). Soft-sediment deformation indicates that the ammonite-bearing micrite clast is intrabasinal and penecontemporaneous with the coarse-grained deposits that contain it. Geochronology of tuffs that bracket these beds supports this assertion.

**Glance Conglomerate**

The primary exposures of the Glance Conglomerate in the general study area are northeast of Magdalena near Cerro Azul (Plate 2), where its extent remains uncertain. The onlapping and lithologically similar Upper Cretaceous Cocospera Formation is also widely exposed in the area and disagreement exists as to the identity of these two units (e.g., Nourse, 1995; Terán-Ortega and Castro-Escárcega, 1999). The Glance Conglomerate near Cerro Azul contains more than 1000 m of interbedded volcanic pebble to cobble conglomerate, volcanic litharenite, mudstone, quartz feldspar tuff and agglomerate, and feldspar porphyry (McKee and Anderson, 1998) with a general upward-fining trend (Nourse, 1995). The clast population of the Glance is dominated by quartzite, rhyolite, and quartz arenite (Nourse, 1995). The Glance Conglomerate near Cerro Azul is overlain by the Morita Formation on a contact variously interpreted as depositional (Nourse, 1995; Peryam, 2006) or structural (McKee and Anderson, 1998). In the main study area, the Cucurpe Formation contains a basal conglomerate, ~2 m thick, composed of rounded pebbles, cobbles, and boulders of volcanic litharenite and quartz arenite derived from the underlying Rancho San Martin Formation. The conglomerate concordantly overlies andesite flow breccias of the Rancho San Martin Formation. Our new age constraints indicate that this thin conglomerate is the probable Glance correlative there. Previous workers have correlated a nearby basement clast-bearing conglomerate to the Glance (Nourse, 1995; Anderson and Nourse, 2005); however, recent geochronology has shown that unit to be Early Jurassic (i.e., the Basomari Formation; Leggett, 2009). Similar depositional contacts, although not well exposed, and lacking a conspicuous basal conglomerate, are present in the southern part of the general study area. Near Rancho La Tesota, along Arroyo El Cajón,

![Figure 5. Geologic map of eastern flank of Sierra de Cucurpe near Rancho San Martin, ~13 km north-northwest of the village of Cucurpe (main study area). Adapted from Stephens (1988). Explanation of symbols in Figure 4.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/7/2/390/3714949/390.pdf)
Suprajacent Lower Cretaceous Strata

Strata younger than Upper Jurassic strata described here include the Rancho La Colgada, Morita, Mural, Cintura, and La Juana formations. The Rancho La Colgada Formation unconformably overlies the Cucurpe Formation in the southern part of the general field area, near Rancho La Colgada (Plate 2 and Fig. 8), whereas the Morita Formation overlies the Cucurpe Formation in the central part of the study area near Rancho San Martin (Fig. 5) and the Glance Conglomerate in the northern part of the general study area (Plate 2).

Rancho La Colgada Formation

The Rancho La Colgada Formation consists of less than 150 m of fine- to coarse-grained, locally conglomeratic sandstone, siltstone, and sandy bivalve-bearing limestone beds (González-León et al., 2001). It is the lowest stratigraphic unit of the Bisbee Group in the general study area and is present only in southern exposures, where it exhibits both faulted and unconformable contacts with the Cucurpe Formation (Plate 2). Sandstone beds of the Rancho La Colgada Formation commonly contain horizontal laminae and planar cross-beds (facies association E; Tables 1 and 2) and were deposited in foreshore and shoreface environments (Peryam, 2006). The Rancho La Colgada Formation is gradationally overlain by the Morita Formation but warrants formal identification due to its different bedding styles, color, and inferred depositional setting. The Rancho La Colgada Formation has been assigned to the upper Barremian–lower Aptian on the basis of detrital zircon young grain ages (Peryam, 2006).

Morita Formation

The Morita Formation is composed of 300–1100 m of cyclic fluvial sequences containing pebble conglomerate, volcanic litharenite, and siltstone. Maroon to greenish-gray siltstone with common ~1–2 cm calcareous pedogenic nodules and uncommon asymmetrical ripples of facies association F (Table 2) dominates the succession. Volcanic litharenite beds commonly have trough cross-bedding, horizontal laminae, and maroon siltstone intraclasts. Sandstone and lenticular channel conglomerate beds of fluvial-deltaic origin are abundant in the lowermost Morita Formation. Clast populations include rhyolite, andesite, quartzite, and uncommon limestone. The Morita Formation fines upward and is conformably overlain by the Mural Limestone. A tuff in the uppermost Morita Formation along Arroyo San Joaquin southwest of Rancho La Tesota (Fig. 6) has been dated at 115.5 ± 0.7 Ma (U-Pb LA-MC-ICPMS; Peryam, 2006).

Mural Limestone

The Mural Limestone consists of ~800–900 m of shallow-marine limestone and shale. Carbonate lithologies include oyster-bearing wackestone-packstone and rudistid boundstone which represent discontinuous moundlike biherms. Siliciclastic intervals are dominated by gray to black shale containing ammonoids and trigonids. Six formal members of the Mural have been identified in the Cucurpe-Tuape region. In ascending order these members are (1) Cerro La Ceja, (2) Tuape Shale, (3) Los

and at a locality ~14 km southeast of Cucurpe, Upper Jurassic shale concordantly overlies interbedded andesitic flows and volcanic-clast conglomerates of the Rancho San Martin Formation, but the contact intervals are not exposed (Figs. 1 and 5 and Plate 2).

Figure 6. Geologic map of area near Rancho La Tesota in southern part of general study area. Adapted from Chepega (1987) and Palafox et al. (1992). Explanation of symbols in Figure 4. See Mauel (2008) for geochronologic sample details.
Figure 7. U-Pb zircon geochronology of three tuff beds in the Cucurpe Formation. Sample 3-03-LL-21 is from the upper part of the formation and sample 5-21-CM-02 is from the uppermost part of the formation, both near Rancho San Martin. Sample 5-22-CU-01 is from Arroyo el Potrero, northwest of Rancho La Colgada.
Coyotes, (4) Cerro La Puerta, (5) La Espina, and (6) Mesa Quemada (Lawton et al., 2004). Fossils indicate a latest Aptian to mid-late Albian age for the Mural Limestone, which is conformably overlain by the Cintura Formation.

Although the Mural Limestone is interpreted here as autochthonous and stratigraphically coherent, other workers have interpreted Mural exposures near Cerro Azul and adjacent areas (Plate 2) as mass-gravity deposits shed from the Cananea high (Fig. 1) (e.g., McKee and Anderson, 1998; McKee et al., 2005; Rodríguez-Castañeda, 1997, 2002). The allochthonous interpretation regards black shale facies of the Mural as deep-marine deposits that form a matrix encasing biostromal blocks shed from the Cananea high and small-scale folds within the Lower Cretaceous section as likewise indicative of mass-wasting processes. McKee and Anderson (1998) also concluded that interbedded shallow-water oyster-bearing facies must be allochthonous on the basis of stratigraphic proximity to deep-marine facies. Alternatively, Lawton et al. (2004) considered folds in the Lower Cretaceous section to be of tectonic origin. Moreover, more recent stratigraphic and sedimentologic studies indicate that the black shale intervals of the Mural Limestone occupy consistent stratigraphic positions with respect to biostromal carbonate facies throughout north-central Sonora and that the shales are marine shelf deposits, rather than deep-marine facies (Lawton et al., 2004; González-León et al., 2008). The revised interpretations of fold origin, stratigraphic consistency, and depositional setting obviate the need for deep-water emplacement of shallow-water facies by mass wasting.

Cintura Formation

The Cintura Formation ranges from greater than 400 m thick in the northern part of the general study area (Bennett, 1993) to more than 2000 m near Tuape (Plate 2), where it was previously termed simply unit E (Chepega, 1987). The Cintura Formation is dominated by maroon to gray siltstone, mudstone, and shale with common calcareous nodules of pedogenic origin, asymmetrical ripples, and horizontal laminae as well as subordinate discontinuous interbedded cross-bedded sandstone and pebbly conglomerate beds interpreted as marine tidal flat and fan-delta deposits, respectively. Calcareous nodules eroded from the thick fine-grained intervals dominate conglomeratic lags at the bases of sandstone beds. Fossil wood and logs as long as 25 m have been reported within intercalated sandstone-conglomerate intervals southeast of Cerro Azul (Bennett, 1993).

La Juana Formation

The La Juana Formation provisionally refers to a >270 m unit which conformably overlies and interfingers with the upper part of the Cintura Formation just west of Rancho Santa Margarita (Plate 2). The La Juana Formation consists of thin- to medium-bedded sandy gray to pinkish gray locally silicified limestone, siltstone, gray fissile shale, gray to brownish gray fine- to medium-grained sandstone, and conglomerate lenses (>20 m in length). Clasts within the conglomerate are dominantly limestone and subordinate quartz arenite. Similar strata overlying the Cintura Formation in the eastern part of

Figure 8. Geologic map of Rancho La Colgada and vicinity. Adapted from Chepega (1987) and Villaseñor et al. (2005). *RLC*—Rancho La Colgada. Explanation of symbols in Figure 4.
the general study area (Plate 2), although lacking conglomerate, contain the upper Albian oyster *Ceratostreon walkeri* (R.W. Scott, 2001, written commun.).

**SEDIMENTOLOGY AND STRATIGRAPHY OF THE CUCURPE FORMATION**

Stratigraphy of the Cucurpe Formation and lower part of the Morita Formation in the main study area and near Rancho La Colgada (Fig. 9) indicates that Late Jurassic marine prodeltaic deposition was succeeded after a hiatus by Early Cretaceous fluvial to marginal marine deposition (Villaseñor et al., 2005; Peryam, 2006; Mauel, 2008).

Both upper and lower contacts of the Cucurpe Formation are unconformities. The basal contact is overlain by a thin conglomerate layer. A sample (DM1–6-54; Figs. 9 and 10), consistent with tuff U-Pb ages in the formation indicating ages of 150–152 Ma (Fig. 7). The concordant detrital zircon age group (n = 13; Fig. 10). This age suggests a hiatus of at least 10 Ma between the Rancho San Martin and Cucurpe formations. The maximum depositional age of the upper part of the formation is 149 ± 1 Ma (sample DM1–6–54; Figs. 9 and 10), consistent with tuff U-Pb ages in the formation indicating ages of 150–152 Ma (Fig. 7). The concordant upper contact with the Morita Formation north of Rancho San Martin is marked by an abrupt shift from marine prodeltaic deposits to fluvial channel and overbank deposits. A detrital zircon...
Figure 9. Measured stratigraphic sections and lithofacies associations of the Cucurpe Formation in Arroyo La Cumarosa near Rancho San Martín and near Rancho La Colgada.
Stratigraphy and age of Upper Jurassic strata in north-central Sonora, Mexico

Sample (DM9–4–3) collected from a basal conglomeratic sandstone in the Morita Formation (Figs. 5 and 9) yielded a young coherent age group \( (n = 9; \text{Fig. 10}) \) with a weighted mean age of \( 139 \pm 2 \text{ Ma} \) (2\( \sigma \) error; Neocomian), indicating a hiatus of ca. 10 Ma at the contact. Near Rancho La Colgada, the Cucurpe and overlying Rancho La Colgada formations are separated by a low-angle angular unconformity (Villasenor et al., 2005). There, the Cucurpe Formation also displays greater deformation than the overlying Bisbee Group strata. Strata of the Cucurpe Formation and lowermost Bisbee Group in the main study area and near Rancho La Colgada were divided into lithofacies adapted from the fluvial lithofacies of Miall (1996) modified to better suit prodeltaic deposits and lithofacies associations modified from Ricci-Lucchi (1975) and Shanmugam (1997) based on bedding characteristics, sedimentary structures, lithology, and stacking patterns (Table 1; Mauel, 2008). Lithofacies were grouped into associations inferred to represent (1) pelagic and distal prodeltaic deposits, (2) interchannel prodeltaic overbank levee deposits, (3) prodelta channel deposits, (4) mass wasting slump/slide deposits, (5) shallow-marine deposits, (6) fluvial channel and overbank deposits, and (7) alluvial deposits (Table 2).

**SANDSTONE PETROLOGY**

Point counts were performed on samples of the Cucurpe, Rancho La Colgada, and Morita formations within the main study area and near Ranchos La Colgada, San Martin, and La Tesota to determine sandstone compositions and identify stratigraphic petrographic variation, or petrofacies.

**Monocrystalline Grain Types**

Monocrystalline framework grains are dominated by quartz and feldspar. Monocrystalline quartz grains (Qm) include grains with undulose and straight extinction. Quartz grains with undulose extinction commonly contain vacuole trains and Boehm lamellae indicative of plutonic quartz (Folk, 1974). Monocrystalline quartz grains with straight extinction and rare embayments indicate a volcanic quartz component of varying abundance. Common fractured Qm grains likely indicate deep burial. Syntaxial quartz overgrowths are common in the Rancho La Colgada, La Colgada, and Morita formations but are uncommon in the Cucurpe Formation. Monocrystalline feldspar grains are dominated by unzoned plagioclase exhibiting albite and Carlsbad twinning. These grains commonly show partial to complete replacement by calcite and finely crystalline white mica. Feldspars are typically blocky with local authigenic overgrowths. The presence of potassium feldspar grains is evident from both staining and visible tafoni plaid twinning indicative of microcline.

**Polycrystalline Grain Types**

Polycrystalline framework components include volcanic, sedimentary, and metamorphic lithic grains. Of these, volcanic grains are by far the most abundant. Volcanic lithic grains (Lv) are typically partially altered to zeolite(?), white mica, and calcite and commonly exist as a pseudo-matrix around more competent grain types such as quartz and feldspar. This alteration and grain deformation commonly make volcanic grain type and grain boundaries difficult to distinguish. Volcanic lithic fragments are assigned to five groups: (1) felsic (Lvf); (2) lathwork (LvL); (3) vitric (LvV); (4) microcrystalline (Lvm); and (5) hypabyssal and plutonic (Lvp). Felsitic grains are the most common of the volcanic lithic grain types. Felsitic grains generally exhibit a tuffaceous, uncommonly eutaxitic, character altered to a microcrystalline feldspar groundmass that accepts sodium cobaltinitrate stain. Lathwork grains are the second most common felsic volcanic grain type. Plagioclase laths within these are both parallel and randomly oriented and typically set within a cryptocrystalline groundmass. Microlitic grains contain subhedral to euhedral, commonly blocky feldspar microlites in a felted, trachytic, or hyalopilitic texture. Vitric volcanic grains consist of glass or altered glass and locally contain feldspar microlites. Hypabyssal and plutonic igneous rock fragments include microgranular subhedral to anhedral intergrowths of feldspar crystals plus or minus quartz and granitic grains with myrmekitic or graphic textures. Sedimentary lithic grains (Ls) and metamorphic lithic grains (Lm) are less abundant than volcanic lithic grains. Sedimentary lithic grains include siltstone, very fine-grained sandstone, and shale clasts. Chert (Qp) was counted in a separate category and was distinguished from finely crystalline volcanic lithic grains on the basis of a clear appearance in plane polarized light. Metamorphic lithic grains (Lm) constitute the least common polycrystalline grain type and include grains with a tectonic fabric and metaquartzite grains of polycrystalline quartz exhibiting strongly sutured boundaries.

**Diagenesis**

Sandstones examined in this study exhibit characteristics indicative of metasomatism and a discernable cement paragenesis. Cement stratigraphy indicates a typical paragenetic sequence of (1) zeolite interstitial cement and replacement of volcanic lithic grains, (2) calcite cement and partial replacement of feldspars, and (3) iron oxide cement. The extent of each of these diagenetic processes varies between samples but the sequence is consistent. Evidence of albitionization of feldspar grains includes chessboard twinning (e.g., Walker, 1984) and patchy cobaltinitrate staining of relic potassium feldspar. Sodium ions for the albitionization process were likely derived from the breakdown of unstable volcanic lithic grains. Albitionization of grains likely influenced...
relative plagioclase and potassium feldspar abundances and resulting position on QmPK sandstone provenance ternary plots; therefore an interpretive emphasis on plagioclase-potassium feldspar ratios was avoided.

Sandstone Composition

Sandstones range from compositional subarkose through lithic arkose and feldspathic litharenite to sublitharenite. Sandstones of the Rancho San Martin Formation, specifically because of their eolian origin, are atypical of this typically more volcanic lithic-rich unit. Cucurpe Formation sandstones are feldspathic litharenites and volcanic litharenites. Sandstones from lower Bisbee Group strata are compositionally more mature than the Cucurpe Formation and include subarkoses, lithicarkoses, feldspathic litharenites, and volcanic litharenites.

Petrofacies

Three general petrofacies are defined here from point count data. The paleovolcanic and neovolcanic petrofacies, restricted to the Cucurpe Formation, fall dominantly within magmatic arc fields of the QmFLt and QtFLt provenance ternary plots (Fig. 11), but differ in quartz content and general character of volcanic lithic grains. The term neovolcanic refers to material generated by volcanism (subaqueous or subaerial) coeval with sedimentation (Critelli and Ingersoll, 1995). The quartzofeldspatholithic petrofacies, represented by sandstones of the lower Bisbee Group, fall mainly within recycled orogen fields of the QmFLt and QtFLt provenance ternary plots (Fig. 11).

The paleovolcanic petrofacies includes the five lowest sandstone samples from the Cucurpe Formation and two samples from the Morita Formation. These feldspathic volcanic litharenites and volcanic litharenites have total quartz (Qt) contents of 9%–49%. Quartz framework grains of this petrofacies are commonly well rounded and lack quartz overgrowths. This petrofacies...
has a greater variety of volcanic lithic framework grains than the neovolcanic petrofacies with some examples containing a greater proportion of lathwork to felsite framework grains. The stratigraphically lowest sample of the Cucurpe Formation falls in the recycled orogen fields of the QmFt and QtFt provenance ternary plots (Fig. 11) due to its greater abundance of well-rounded quartz grains lacking quartz overgrowths.

The neovolcanic petrofacies is restricted to the upper Cucurpe Formation. This petrofacies includes feldspathic volcanic litharenites and volcanic litharenites which have extremely low quartz abundances ranging from less than 1% to 3%. Felsite volcanic framework grains that typically exhibit greater size and angularity than the subrounded monocrystalline feldspar and quartz grains overwhelmingly dominate these sandstones. Relict bubble wall shards are visible within the matrix of less altered samples. The quartzofeldspatholithic petrofacies is generally restricted to the lower Bisbee Group. These subarkoses, volcanic lithic arkoses, and feldspathic litharenites exhibit greater compositional maturity and more diverse volcanic and sedimentary lithic grains than other petrofacies defined here. Although albitization of framework grains is common in the Cucurpe Formation, the quartzofeldspatholithic petrofacies appears to contain a greater abundance of potassium feldspar grains, some of which exhibit plagioclase alteration. Uncommon graphic granite grains are also present in sandstones of this petrofacies.

DETRITAL ZIRCON ANALYSES

New data constrain the depositional age and reveal the provenance of Jurassic and earliest Cretaceous strata in the general study area. These data include U-Pb SHRIMP ages on tuffs and LA-MC-ICPMS U-Pb detrital zircon ages.

Basal Cucurpe Formation

The stratigraphically lowest geochronologic sample (DM1–6–8) from the Cucurpe Formation in the main study area is a fine-grained subangular tuffaceous subquartzose volcanic lithic sandstone of the quartzofeldspatholithic petrofacies collected ~15 m above the base of the formation. Proterozoic zircon age populations are represented at ca. 2673, ca. 1808–1544, 1332–1024, and 811–574 Ma with a prominent peak at ca. 600 Ma. Phanerozoic age groups are at ca. 441–412 Ma (Silurian–earliest Devonian), 344–256 Ma (Mississippian–Permian), and ca. 187–157 Ma (Early to Late Jurassic) (Fig. 12). The sample’s youngest coherent age peak at 158 ± 1 Ma (2σ error) of 13 zircons (Fig. 10) is interpreted as the maximum depositional age of the sample.

Upper Cucurpe Formation

Sample DM1–6–54 was collected from a succession of amalgamated tuffaceous pebbly sandstone beds of the neovolcanic petrofacies in the upper part of the Cucurpe Formation composed primarily of angular to subangular felsite and lesser plagioclase grains as well as subrounded dark gray shale intraclasts. Uncommon bubble-wall shards are visible in thin section. The sample contains a unimodal coherent age group of 59 zircons with a weighted average age of 149 ± 1 Ma (early Tithonian), statistically indistinguishable from tuff ages higher in the section (Figs. 7, 9, and 10); accordingly, we interpret this as the depositional age of the sample.

Basal Morita Formation

A sandstone (DM9–4–3) from the base of the Morita Formation, collected within 10 m of a well-exposed Morita-Cucurpe contact in the main study area near Rancho San Martin (Fig. 3), is a coarse-grained lithic arkose, rich in volcanic lithic fragments. The sampled bed is intercalated within pebble conglomerate containing pebble lags of fluvial origin. The zircon ages in DM9–4–3 range from latest Archean to Early Cretaceous (Neocomian) with age groups at ca. 1780–1701 Ma, ca. 1184–1167 Ma, ca. 262–231 Ma, ca. 222–207 Ma, and ca. 194–137 Ma (Fig. 12).

DISCUSSION

Petrography, U-Pb zircon geochronology, and revised Jurassic–Early Cretaceous stratigraphy of the Cucurpe-Tuape region provide insights into the Mesozoic tectonic regime of southwestern Laurentia. Petrographic and U-Pb detrital zircon data from the Cucurpe Formation and lower Bisbee Group strata provide a record of nearby arc activity, rift volcanism, and basement uplift. Our stratigraphic revision indicates that many sedimentary units in the region previously assigned to the Late Jurassic are of other ages.

Sediment Provenance

Integration of petrographic and detrital zircon data provides a robust means of revealing sedimentary provenance. Comparison of detrital zircon data from the lowermost Cucurpe Formation and a quartz arenite from the Rancho San Martin Formation (Leggett, 2009) indicates derivation of the paleovolcanic petrofacies from Middle Jurassic arc assemblages. Both samples have zircon age populations of ca. 2750–2650 Ma, ca. 1850–1550 Ma, ca. 1400–1000 Ma, ca. 650–550 Ma, ca. 450–400 Ma, and ca. 190–165 Ma (Fig. 12), indicating that the majority of Paleozoic and Proterozoic zircons in the lower part of the Cucurpe Formation were derived from eolianites interstratified in the Middle Jurassic arc assemblages. Late Oxfordian recycling of these sands probably occurred by erosion of arc rocks exposed along the flanks of the Altar-Cucurpe Basin. The age range of these eroded arc sequences is ca. 190–165 Ma, indicated by the prominent zircon population in the basal Cucurpe Formation (Fig. 12). Paleozoic and Proterozoic zircon populations within Jurassic and Cretaceous deposits of the Colorado Plateau have been interpreted as derived from Appalachian and other distant Laurentian sources and transported westward by transtensional river systems (Dickinson and Gehrels, 2009a). Subsequently, these grains were transported southwest into the Middle Jurassic arc by prevailing winds (Blodewé and Keith, 1986). Local Mesoproterozoic and Paleoproterozoic basement (e.g., Iriondo et al., 2004; Anderson and Silver, 2005) potentially exposed along rift shoulders may have served as an additional source; for example a ca. 1.4 Ga zircon population varies somewhat in abundance between samples (Fig. 12).

Detrital zircon data from the upper member of the Cucurpe Formation, consisting of a single age group of 59 grains near 149 Ma, corroborate the interpretation of syndepositional detritus in the neovolcanic petrofacies (Figs. 10 and 12). Neovolcanic detritus was likely introduced by contemporary volcanism related to emplacement of the Koyo Yava volcanic suite (e.g., Haxel et al., 2008). Massive influx of Kimmeridgian neo-volcanic detritus into the Altar-Cucurpe Basin corresponded temporally with an increased abundance of ash-fall tuffs in correlative upper Kimmeridgian strata of the Morrison Formation (Turner and Peterson, 2004). This coincidence potentially resulted from shifting paleowind patterns as North America drifted northward from the trade winds (late Middle Jurassic–Oxfordian?) into the westerly winds (Peterson, 1988). Northward drift of North America thus appears to have been coeval with a late Kimmeridgian increase in rift-related volcanic activity.

The quartzofeldspatholithic petrofacies of the lowest Bisbee group strata was derived from a mixture of recycled sedimentary, extinct magmatic arc, and basement sources indicated by lower Morita Formation zircon populations (Fig. 12). The lower Morita contrasts with Jurassic samples in lacking Neoproterozoic “pan-African” ages and containing a broader array of Triassic–Early Cretaceous arc-derived...
Figure 12. Detrital zircon probability distribution spectra and histograms of a Rancho San Martin Formation quartz arenite (Leggett, 2009), two samples of the Cucurpe Formation, and a sandstone of the lower Morita Formation. (A) Spectra for Phanerozoic grain ages (<550 Ma). (B) Spectra for grain ages >500 Ma. Number of grains per figure indicated by n.
grains. This is interpreted as a result of dilution by new, increasingly influential sediment sources in the Early Cretaceous indicated by zircon populations at ca. 262–190 Ma and ca. 144–132 Ma (Fig. 12). Proterozoic zircon populations at ca. 1780–1701 Ma, ca. 1450–1400 Ma, and ca. 1296–1015 Ma were likely recycled in part from local sedimentary rocks and basement rocks. The lack of “pan-African” and Paleozoic grains indicates that these zircons were not derived from distant Appalachian sources (e.g., Dickinson and Gehrels, 2009a); furthermore, uncommon micrographic granite grains and microcline suggest a local basement source for some of these grains. Micrographic 1.1 Ga granites have been documented in the main study area and in the Caborca block (Anderson and Silver, 2005; Amato et al., 2009).

Paleozoic–Early Jurassic and Early Cretaceous zircon populations in the basal Morita Formation indicate a change in provenance relative to that of Jurassic depositional systems. Early Mesozoic (ca. 230–190 Ma) zircons are rare to absent in Jurassic samples. These Triassic–Lower Jurassic zircons were derived from magmatic rocks of the early Cordilleran-Nazas arc and/or recycled forearc deposits (e.g., González-León et al., 2005, 2009) exposed on the Caborca block. Early Permian–Triassic (ca. 285–230 Ma) zircon grains were derived from East Mexican arc rocks (Sedlock et al., 1993; Torres et al., 1999), Upper Permian to Lower Triassic plutons in southern California and Nevada (Walker, 1988; Miller and Glazner, 1995; Barth et al., 1997; Stewart et al., 1997), local Permian plutons of the Caborca block (Iriondo and Arvizu, 2009; Arvizu et al., 2009), and/or recycled Triassic–Lower Jurassic forearc deposits exposed on the Caborca block (Gehrels and Stewart, 1998; González-León et al., 2005). No nearby Early Cretaceous (ca. 144–132 Ma) ages have yet been reported for the Cordilleran-Nazas continental arc; however, the offshore Guerrero arc was active during this period (Busby et al., 1998). Air fall tuffs could have been deposited on the continent and subsequently transported into the basin. However, andesite clasts from a fluvial conglomerate bed in the lower Morita Formation have produced an average age of ca. 140 ± 3 Ma (Peryam, 2006). These clasts were derived from either an undocumented Early Cretaceous volcanic suite or a segment of the Guerrero terrane accreted to North America by Aptian time.

Basin Type, Extent, and Significance

Previous studies of Late Jurassic basins and paleogeography in the U.S.-Mexico border region focused on continental alluvial fan deposits of the Glance conglomerate and its correlates. As discussed, some workers propose that marine deposits represent distinct basins into the hypothetical MSM strike-slip system. However, the marine deposits of the Cucurpe Formation and its correlates must also be considered in any paleogeographic and tectonic reconstructions.

Upper Jurassic deposits of Sonora define a marine trough known as the Arivechi-Cucurpe seaway (Haenggi and Muehlberger, 2005), which includes the Altar-Cucurpe Basin. This narrow embayment formed as a result of Late Jurassic rifting along the former trend of the Middle Jurassic continental arc. The basal alluvial conglomerate of the Cucurpe Formation directly overlain by distal slope to prodeltaic deposits that grade in turn to channel and interchannel slope overbank/levee deposits record rapid early rift subsidence and marine transgression followed by local progradation of marine prodelta deposits. The upper part of the Cucurpe Formation (Kimmeridgian–Tithonian) was greatly influenced by coeval volcanism. During its deposition, ash fall tuffs likely blanket the land surface and water-lain tufs were deposited and reworked within the basin. Erosion, rainfall, and prolonged flooding events within the basin catchment likely choked river systems feeding the Altar-Cucurpe basin with eruditive material which resulted in deposition of sediment-laden neovolcanic hydropellic flows.

Distribution of inferred Upper Jurassic marine strata correlative to the Cucurpe Formation approximates the former extent of the Altar-Cucurpe Basin. West of the general study and south of the trace of the MSM near Cerro el Dieziesai, strata lithologically similar to the Cucurpe Formation have been assigned a Late Jurassic age (Plate 1; Gonzalez-Gallegos, 2006). Northwest of this location near Altar, the locally metamorphosed, dominantly fine-grained sediments and uncommon micrite of the Upper Altar Formation (Los Corrales and Bateyera members) are exposed along a northwestern trend from Cerros El Amol to Sierra El Batamote (Plate 1; García y Barragán et al., 1998; Nourse, 2001). Detrital zircon geochronology near Sierra El Batamote has indicated that many conglomeratic intervals previously assigned to the Lower Altar Formation (Nourse, 2001) are more likely Late Cretaceous rather than Late Jurassic in age (Jacques-Ayala et al., 2009). However, along Arroyo El Charrro near Sierra El Batamote, a siliciclastic tuff (?) collected from a sedimentary succession previously mapped as upper Altar Formation has produced an age of 164 ± 1 Ma (U-Pb SHRIMP; Mauel, 2008). This succession lithologically resembles well-bedded and fine-grained marine intervals of the Cucurpe Formation. It either is structurally juxtaposed against or stratigraphically underlies the Morita Formation there. Although Jurassic correlatives remain problematic between the Cucurpe and Altar regions and the Glance Conglomerate has been mapped on the northeastern flank of the Sierra El Chanate (Jacques-Ayala, 1992), we consider these finer-grained strata to represent the former northwestern extension of the Altar-Cucurpe Basin. The northeastern limit of the Altar-Cucurpe Basin in the general study area is located roughly along the present-day San Antonio fault/Imuris lineament (Plate 2), where alluvial deposits of the Glance Conglomerate appear to grade laterally and abruptly into marine turbidite and debris-flow deposits of the Cucurpe Formation. The role of the San Antonio fault/Imuris lineament in Mesozoic tectonics is also evident by its northern projection which also crudely defines the northeastern edge of the Papago domain, the boundary between the Bisbee core and flank basins, which is defined by Glance Conglomerate thickness trends and depositional character, and the apparent northeastern limit of the Ko Vaya Suite (Haxel et al., 2008). The southwestern limit of the Altar-Cucurpe Basin lies somewhere near the El Pimiento and Santa Margarita fault zones (Plate 2), the southern extent of Cucurpe Formation outcrops. Thus the basin appears to overlap the boundary of the Mazatlan and Caborcan basement provinces (Plate 1), which may lie as much as 50 km north of the proposed trace of the Mojave-Sonora megashear (Amato et al., 2009).

Near the top of a section interpreted as correlative with basin member 1 of Harding and Coney (1985) of the McCoy Mountains Formation in the New Water Mountains of southwestern Arizona (Plate 1), an andesite flow has yielded an age of 154.4 ± 2.1 Ma (U-Pb zircon; Spencer et al., 2005). It remains unclear how these continential deposits relate to the Altar-Cucurpe marine depocenter, but detailed sedimentology of intercalated strata of the Ko Vaya Suite, also known as the “Artesa sequence,” has the potential to shed light on any interconnectivity between these systems. Common “laminated and well-bedded immature volcanic greywacke” in this unit (Tosdal et al., 1989) may represent further extension of the marine basin or transitional marginal marine facies.

Influence of Revised Correlations on Distribution of Upper Jurassic Conglomerate and Slide Blocks, and Their Relation to the Mojave-Sonora Megashear

Mesozoic conglomerates of several ages are present in north-central Sonora. They tend to be compositionally similar due to the dominance of arc source rocks. Our new geochronology

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and revised regional stratigraphy (Figs. 2 and 3) indicate that several conglomerates, slide blocks, and olistoliths previously interpreted as deposits of Late Jurassic age (Chepega, 1987; Stephens, 1988) are in fact of different ages. These deposits have been used in support of Late Jurassic pull-apart basin models (e.g., Anderson and Nourse, 2005).

In the main study area, near Rancho San Martin, the Basomari and Morita formations were formerly assigned to the La Cumarosa Epi-clastic sequence of inferred Late Jurassic–Early Cretaceous age (Stephens, 1988). The Basomari Formation contains common Proterozoic basement clasts and a possible Paleozoic olistolith measuring over 1000 m in length. However, as discussed, the Basomari Formation is Early Jurassic in age (Leggett, 2009) and therefore was not deposited in a Late Jurassic pull-apart basin. The Morita Formation, which contains a lower fluvial conglomeratic interval, is no older than $139 \pm 2$ Ma (2σ error) based on geochronology presented here. These observations indicate that the ~2-m-thick alluvial conglomerate bed directly underlying the marine shale deposits of the Cucurpe Formation is the only remaining candidate for the Glance Conglomerate at this location on the basis of age, apparent alluvial origin, and stratigraphic position.

In the Tuape quadrangle, near Rancho La Tesota, Chepega (1987) tentatively interpreted each of his units A, B, C, and D as Jurassic–Early Cretaceous in age. Reinterpretation of the stratigraphy in this area indicates that these units represent the Cucurpe, Rancho San Martin, Morita, and Mural formations, respectively (Mauel, 2008). Chepega interpreted unit B as an olistolith that slid into accumulating Cucurpe sediments and was subsequently buried by continuing Cucurpe sedimentation. Although faulted, these strata share common bedding orientations, are generally in correct stratigraphic order, and do not require a slide block interpretation to explain their genesis. The only Upper Jurassic strata at this location are turbiditic marine prodeltaic deposits of the Cucurpe Formation.

These examples illustrate the importance of having proper age constraints on Mesozoic
conglomerates in the region prior to interpreting dominant basin-forming mechanisms. Restriction of Upper Jurassic conglomerate to the more areally restricted exposures of Glance Conglomerate casts doubt on the widespread distribution of pull-apart basins, and thus on a causal link to the MSM.

We infer alternatively that Late Jurassic crustal extension and basin development recorded by the Ko Vaya volcanic suite and Cucurpe Formation were not a result of transtensional tectonics associated with a transient fault system, but rather resulted from changing dynamics of the subduction zone along the southwestern margin of Laurentia (Fig. 13). Although the exotic nature of the offshore Guerrero terrane remains debated, its accretion in the region of NW Mexico in the interval ca. 147–130 Ma is indicated by the unconformity between strongly folded Upper Jurassic strata and less deformed strata of the La Colgada and Morita formations that unconformably overlie the Jurassic. Roll-back of subducted northeast-dipping oceanic lithosphere prior to accretion (e.g., Lawton and McMillan, 1999; Dickinson and Lawton, 2001b) resulted in incipient southwestward migration of continental-margin magmatism in Late Jurassic time (e.g., Barth et al., 2008) prior to reestablishment of a Lower Cretaceous arc in modern Baja California and southern California (Wetmore et al., 2003). Geochemistry and petrology of the Ko Vaya magmatic suite suggest that waning stages of Jurassic igneous activity represent rift-induced, rather than subduction-related, magmatism (Haxel et al., 2008). The coconant development of the marine Altar-Cucurpe Basin and time-equivalent Late Jurassic basins that contain asthenosphere-derived mafic rocks in southern Arizona and southwestern New Mexico (e.g., Lawton and Olmstead, 1995; Lawton and Harrigan, 1998; Lawton and McMillan, 1999) further support the rift interpretation.

CONCLUSIONS

The Cucurpe Formation forms the fill of the Altar-Cucurpe Basin, a narrow rift basin developed on the boundary between the Mazatzal and Caborca basement provinces on the southwestern margin of Laurentia upon attenuated crust of the Triassic–Middle Jurassic continental arc. This basin was part of the Arivechi-Cucurpe seaway, a marine depocenter oriented parallel to and located west of the Chihuahua trough. The Cucurpe Formation represents an upward-coarsening succession of prodeltaic marine slope debris-flow and turbidity-current deposits that contain abundant neovolcanic detritus and interbedded tuffs in its upper part. The formation is divided into informal lower and upper members. The lower member is ~755 m thick and the upper member is ~715 m thick ~13 km north-west of Cucurpe in north-central Sonora.

The Cucurpe Formation unconformably overlies the Middle Jurassic (ca. 170–165 Ma) Rancho San Martin Formation. New U-Pb zircon geochronology on tuffs and sandstones indicate that the Cucurpe Formation was deposited between ca. 158 and 149 Ma (early Oxfordian–early Tithonian). These data corroborate previously reported biostratigraphic ages from Rancho La Colgada, and extend the base of the Cucurpe Formation to early Oxfordian age.

New detrital zircon and sandstone petrography indicate that the Cucurpe Formation contains two petrofacies, termed paleovolcanic and neovolcanic, determined by the relative abundance of syneruptive volcanic detritus in the formation. Sediment sources for the paleovolcanic petrofacies, which dominates the lower member of the Cucurpe Formation, were Middle Jurassic volcanic–sedimentary successions equivalent to the San Martin Formation that were likely exposed along the rift shoulders of the Altar-Cucurpe basin. The neovolcanic petrofacies of the upper member of the Cucurpe Formation is dominated by syneruptive silicic detritus and water-lain reworked tuffs erupted from the Ko Vaya or similar rift-related volcanic centers and potentially derived, in part, from the waning late stages of the continental arc.

The Cucurpe Formation is unconformably overlain by fluvial channel conglomerates and red beds of the Morita Formation near Rancho San Martin. New U-Pb detrital zircon analysis of a sandstone bed from the basal Morita Formation provides a maximum depositional age of 139 ± 2 Ma (2σ error), indicating that the Jurassic–Cretaceous unconformity locally represents a hiatus of at least 10 m.y. We propose that this unconformity records tectonic uplift and deformation resulting from the accretion of offshore volcanic–arc assemblages (the Guerrero terrane) to the southwestern margin of North America at the beginning of the Early Cretaceous.

Reconnaissance geology, map compilation, and new geochronology support revision of the Mesozoic stratigraphy of the Cucurpe-Tuape region. This revised stratigraphy indicates that several conglomeratic units formerly correlated with the Glance Conglomerate and interpreted as deposits of Late Jurassic pull-apart basins are not of Late Jurassic age. In fact, true Glance Conglomerate is absent from much of the basin except near its northeastern margin.

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