Reconstructing the tectono-sedimentary evolution of the Early–Middle Jurassic Tlaxiaco Basin in southern Mexico: New insights into the crustal attenuation history of southern North America during Pangea breakup

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ABSTRACT

During Pangea breakup, several Jurassic extensional to transtensional basins were developed all around the world. The boundaries of these basins are major structures that accommodated continental extension during Jurassic time. Therefore, reconstructing the geometry of Jurassic basins is a key factor in identifying the major faults that produced continental attenuation during Pangea breakup. We reconstruct the tectono-sedimentary evolution of the Jurassic Tlaxiaco Basin in southern Mexico using sedimentologic, petrographic, and U-Pb geochronologic data. We show that the northern boundary of the Tlaxiaco Basin was an area of high relief composed of the Paleozoic Acatlán Complex, which was drained to the south by a set of alluvial fans. The WNW-trending Salado River–Axutla fault is exposed directly to the north of the northernmost fan exposures, and it is interpreted as the Jurassic structure that controlled the tectono-sedimentary evolution of the Tlaxiaco Basin at its northern boundary. The eastern boundary is represented by a topographic high composed of the Proterozoic Oaxacan Complex, which was exhumed along the NNW-trending Caltepec fault and was drained to the west by a major meandering river called the Tlaxiaco River. Data presented in this work suggest that continental extension during Pangea breakup was accommodated in Mexico not only by NNW-trending faults associated with the development of the Tamaulipas–Chiapas transform and the opening of the Gulf of Mexico, but also by WNW-trending structures. Our work offers a new perspective for future studies that aim to reconstruct the breakup evolution of western equatorial Pangea.

INTRODUCTION

Recognizing that the Earth’s history is punctuated by the cyclic assembly and breakup of supercontinent landmasses is one of the most outstanding developments in the past six decades of research in Earth Science (Hawkesworth et al., 2013; Spencer et al., 2017; Wang et al., 2021). Although the concept of the supercontinent cycle is widely accepted (e.g., Nance and Murphy, 2013), the geodynamic processes that lead to the assembly and breakup of supercontinents are still poorly understood, and indeed, their understanding represents one of the most ambitious frontiers in Earth Science. Pangea is the most recent supercontinent. It formed on Earth at the end of Paleozoic time (e.g., Rogers and Santosh, 2003), and it is probably the best case of study to understand the tectonic processes that produced the breakup and separation of supercontinental masses. However, the kinematics and dynamics of Pangea breakup are still not completely understood in some places, such as continental Mexico. During the early Mesozoic Pangea breakup, Paleozoic and Proterozoic terranes of Mexico were located along the North America–South America divergent plate boundary (e.g., Dickinson and Lawton, 2001). Due to such a paleogeographic position, the Jurassic tectonic evolution of Mexico was influenced by the activity of major normal to lateral faults that represent an invaluable record of the continental attenuation related to Pangea breakup (e.g., Martini and Ortega-Gutiérrez, 2018). However, difficulties arise in recognizing the major faults that accommodated Jurassic continental extension in Mexico because of the deformational overprinting of Cretaceous and Cenozoic shortening, tranpressional, and transtensional episodes that largely obliterate the evidence of previous tectonic events. A sedimentological approach can help to identify major faults that accommodated continental extension during the breakup of Pangea. In effect, the extension associated with Pangea breakup produced the development of several rift basins, some of which are superbly exposed in Mexico (Goldhammer, 1999; Campos-Madrigal et al., 2013; Martini and Ortega-Gutiérrez, 2018). The stratigraphic record of these basins undoubtedly represents a primary archive of information on the tectonic evolution related to Pangea breakup. This is because the internal architecture of an extensional rift basin and its sediment routing are in large part controlled by the exhumation of basement highs along major faults that are the direct expression of the ongoing tectonic process (Gawthorpe and Leeder, 2000; Allen and Allen, 2013). Based on this assumption, the
reconstruction of the internal architecture of Mexican Jurassic rift basins, inte-
grated with the provenance analysis of the different architectural elements, will
allow the tracking of major active faults acting as main basin boundaries, and
consequently, will permit the identification of major structures that accommo-
dated extension during the development of the North America–South America
boundary. In this paper, we present new sedimentologic, petrographic, and U-Pb
geochronologic data that allow the reconstruction of the internal architecture
and sediment routing of the Jurassic Tlaxiaco Basin, which is one of the largest
Jurassic rift basins in southern Mexico related with Pangea breakup. The inte-
gration of our data shows that the Tlaxiaco Basin was limited to the north and
east by two major basement highs that were bounded by two regional-scale
faults with WNW and NNW main trends, respectively. The activity of these faults
profundely controlled the sedimentary architecture and evolution of the Tlaxiaco
Basin. Based on our data, we discuss previous reconstructions of Jurassic conti-
nental extension proposed for southern Mexico and offer a new perspective for
future works that aim to reconstruct the breakup of western equatorial Pangea.

GEOLOGICAL BACKGROUND

In southern Mexico, the stratigraphic record associated with continen-
tal rifting during Pangea breakup is represented by Lower–Middle Jurassic,
continental to shallow-marine successions that are discontinuously exposed
in the surroundings of Tezoatlán, Tlaxiaco, Teconomatlán, and Olinalá (Erben,
1956; Morán-Zenteno et al., 1993; García-Díaz, 2004; Figs. 1 and 2). Based on
stratigraphic similarities, López-Ticha (1985) suggested that these Jurassic
successions were deposited in a single, 200-km-wide, extensional rift basin
named Tlaxiaco Basin (Fig. 1). However, the available data on these succes-
sions are few, and to date, no detailed sedimentologic and provenance study
has demonstrated a physical connection between these depositional areas. The
following briefly summarizes the available data on the Lower–Middle Jurassic
successions in the different areas of the Tlaxiaco Basin.

Tezoatlán Area

The Lower–Middle Jurassic stratigraphic record exposed in the Tezoatlán
area consists of a volcano-sedimentary succession bounded to the north by the
Salado River fault (Fig. 1). The Salado River fault is an Early–Middle Jurass-
ic, WNW-trending, normal sinistral fault, along which the Tezoatlán Jurassic
succession is juxtaposed with the Paleozoic, greenschist-facies metamorphic
rocks of the Acatlán Complex (Martiny et al., 2012; Fig. 1). The lower part of
the Lower–Middle Jurassic succession is composed of mafic and felsic, vol-
canic to very low-grade metavolcanic rocks and volcanioclastic fluviatile deposits
(Diquiyú and Rosario formations; Morán-Zenteno et al., 1993; Zepeda-Martínez
et al., 2018; Fig. 2). Zircon grains in felsitic volcanic rocks return U-Pb ages
between ca. 197 and ca. 184 Ma, which are interpreted as the age of volcanic
activity in the Tezoatlán area (Durán-Aguilar, 2014). U-Pb ages on detrital-zircon
grains from fluvial volcanioclastic deposits show that the magmatic activity in
the Tezoatlán area lasted until ca. 176 Ma (Zepeda-Martínez et al., 2018). Vol-
caniclastic fluviatile deposits are conformably overlain by the Cualac formation
(Fig. 2), which is an informal unit composed of conglomerate, sandstone, and
minor mudstone (Erben, 1956) ubiquitously containing fossil leaves (e.g., Guz-
mán and Velasco-de León, 2014). The Cualac formation is interpreted as a set of
alluvial fans draining, to the south and southwest, the Paleozoic, greenschist-facies
metasedimentary rocks of the Acatlán Complex exposed directly to the north
of the Salado River fault (Zepeda-Martínez et al., 2018). A few authors have tentatively interpreted the Cualac formation as the stratigraphic record of
an estuarine environment (De Anda-García, 2008; Vite-del Ángel, 2014). How-
ever, beds with a clear marine origin have not been reported within the
Cualac formation. The Cualac formation is conformably overlain by the informal
Tecocoyunca group (Erben, 1956; Fig. 2). The lower part of the Tecocoyunca
group is made up of sandstone, coaly mudstone, and coal, with abundant fossil
flora and scarce shallow-marine limestone beds (Erben, 1956; Morán-Zenteno
et al., 1993). These rocks have been interpreted as a flood-plain area that was
occasionally invaded by shallow-marine waters (Erben, 1956; Morán-Zenteno
et al., 1993). Durán-Aguilar (2014) interpreted the lower Tecocoyunca group as
a lateral facies change of the Cualac formation. However, sedimentologic and
petrological evidence indicates that the sandstone and mudstone, which
were tentatively interpreted by Durán-Aguilar (2014) as flood-plain deposits
of the lower Tecocoyunca group interbedded within the Cualac formation, are
rather alluvial deposits of the Cualac formation deposited during low-water
stages (Zepeda-Martínez et al., 2018). The upper part of the Tecocoyunca group
is composed of marine sandstone, mudstone, and limestone with pelecypods
and upper Bajocian (ca. 169 Ma using the Gradstein et al., 2012, time scale)
ammonites (Sandoval and Westermann, 1986; Cantú-Chapa, 1998).

Tlaxiaco Area

Based on lithological, stratigraphical, and paleontological similarities,
Lower–Middle Jurassic sedimentary rocks of the Tlaxiaco area have been
assigned to the Cualac formation and overlying Tecocoyunca group originally
defined in the Tezoatlán area (Erben, 1956; Carrasco-Ramírez et al., 2016; Fig. 2).
As in the Tezoatlán area, the Cualac formation in the Tlaxiaco area has been
tentatively interpreted as the stratigraphic record of coalesced alluvial fans
(Corro-Ortiz and Ruiz-González, 2011), whereas the overlying Tecocoyunca
group has been preliminarily interpreted as the deposit of a meandering river
and adjacent flood-plain areas that evolved into a shallow-marine environment
during a major transgressive event (Erben, 1956; Carrasco-Ramírez et al., 2016).
Almost all previously published works on these units are focused on their
paleontological content, which includes a well-preserved Jurassic flora domi-
nated by Bennettitales, Cycadales, and Podozamitales (Lozano-Carmona and
Velasco-de León, 2016), as well as dinosaur footprints (Rodríguez-de la Rosa
Figure 1. Geologic map of southern Mexico, showing the extent and location of the Jurassic sedimentary clastic successions and the major metamorphic and plutonic basement complexes. The extension of the Tlaxiaco Basin according to López-Ticha (1985) is denoted by the brown dashed line. The yellow dashed lines represent the northern and eastern boundaries of the Tlaxiaco Basin defined in this work. The red rectangles show the areas of the maps in Figures 3, 4, and 12. Rose diagrams show paleocurrent directions obtained from the Cualac formation (blue rose diagrams) and the lower Tecocoyunca group (red rose diagrams) deposits at the studied areas. Map modified from Martini et al. (2020).
et al., 2018). No detailed sedimentological study has been published on these Jurassic units. The provenance of these clastic rocks is also poorly understood.

**Tezocatlán Area**

Clastic deposits in the Tecomatlán area have been tentatively correlated with the Cualac formation and Tecocoyunca group based on similarities in lithology and the Jurassic floral content (Silva-Pineda, 1969; Hernández-Vulpes and Rodríguez-Calderón, 2012; Fig. 2). However, to date, no sedimentological and provenance study has been carried out on these clastic rocks.

**Olinalá Area**

The Jurassic stratigraphic record exposed in the Olinalá area consists of a volcano-sedimentary succession similar to the one described in the Tezocatlán area (Fig. 2). The oldest rocks consist of volcanic deposits (Las Lluvias Ignimbrite; Corona-Esquível, 1981) with zircon grains that yield U-Pb ages between ca. 179 and ca. 177 Ma (Campa-Uranga et al., 2004). Volcanic rocks are overlain by fluviol and shallow-marine clastic deposits that, based on lithological, stratigraphic, and paleontological similarities, have been assigned to the Cualac formation and the Tecocoyunca group (Marshall, 1986; García-Díaz, 2004). A detailed sedimentological and provenance analysis of these clastic deposits in the Olinalá area is presently not available. Differing from the Tezocatlán area in which available paleontological data bracket the beginning of marine transgression to upper Bajocian time (ca. 169 Ma using the Gradstein et al., 2012, time scale; Sandoval and Westermann, 1986), the age of ammonites from the marine upper part of the Tecocoyunca group in the Olinalá area vary from Bathonian to Callovian (ca. 168 to ca. 166 Ma using the Gradstein et al., 2012, time scale; Westermann et al., 1984).

**METHODS**

**Field Work**

The integration of our field observations with previously published data allowed the construction of four geologic maps of the Lower–Middle Jurassic...
successions exposed in the Tezoatlán, Tlaxiaco, Tecomatlán, and Olinalá areas (Figs. 3A, 3B, 4A, and 4B). We measured representative stratigraphic columns (Figs. 5A–5I), determined lithofacies assemblages, and identified architectural elements and main stratigraphic surfaces according to the hierarchy scheme of Miall (2006). This scheme upgrades the original scheme of DeCelles et al. (1991), which was specifically designed for alluvial fan deposits. A summary of the surface hierarchy observed in the study area is given in Table 1. A synthesis of the main lithofacies and architectural elements is presented in Tables 2 and 3. Additionally, we measured paleocurrent directions to reconstruct the fluvial drainage pattern and improve the provenance analysis. Paleocurrent data were corrected for bedding dip according to Collinson et al. (2006) and for clockwise tectonic rotation according to the paleomagnetic data of Böhnel (1999).

Whole-Rock Sandstone Petrography

Along the measured stratigraphic columns, we selected 58 samples of medium- to coarse-grained sandstone for whole-rock compositional analysis (Figs. 5A–5I). We counted between 371 and 493 points for each sample by using the Gazzi-Dickinson method (Gazzi, 1966; Dickinson, 1970). Whole-rock petrographic thin sections were stained for easy recognition of potassium feldspar. Following Garzanti and Vezzoli (2003), metamorphic lithic grains were classified based on their protolith composition and metamorphic rank. Grain parameters (Zuffa, 1985; Garzanti and Vezzoli, 2003) are defined in Table 4, and sandstone modal compositions are presented in File A in the Supplemental Material.

U-Pb Geochronology

We integrated the sandstone compositional analysis with detrital-zircon U-Pb geochronology to reinforce our provenance analysis. Zircons were dated by U-Pb laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at Laboratorio de Estudios Isotópicos, Centro de Geociencias, Universidad Nacional Autónoma de México, following the methodology and data treatment reported by Solari et al. (2018). Individual zircon ages were obtained with a Resolution M-50 Excimer laser, operating at a 193 nm wavelength and coupled to a Thermo ICap Qc quadrupole ICPMS. We selected the analyzed zircons randomly by handpicking to avoid a possible age bias toward certain groups (e.g., shape, color, and dimension). Standard zircon 91500 (ca. 1065 Ma, Wiedenbeck et al., 1995) was used as the primary standard, whereas Plesiochrome zircon (ca. 337 Ma, Sláma et al., 2008) was employed as the control standard, yielding, in the course of the present analytical sessions, a mean 206Pb/238U age of 339.8 ± 1.3 Ma (MSWD 2.4, n = 47) in agreement with published values, especially for non-annealed standard zircons (e.g., Solari et al., 2015). We consider the 206Pb/238U age for younger zircons (Spencer et al., 2016). Raw data

Figure 3. Geologic maps of the (A) Tezoatlán and (B) Tlaxiaco areas. The location of each map is shown in Figure 1. Maps show locations of the measured stratigraphic columns (orange arrows), main paleocurrent directions (yellow arrows), and U-Pb geochronologic samples (white stars).

1Supplemental Material. File A: Point-counting raw data and recalculated parameters for whole-rock sandstone petrography. File B: Details of analytical methodology and analytical results for individual zircon ages. Please visit https://doi.org/10.1130/GEOS.S14428712 to access the supplemental material, and contact editing@geosociety.org with any questions.
were reduced by employing Iolite software v. 3.6 (Paton et al., 2011) and the VizualAge data reduction scheme of Petrus and Kamber (2012). Errors are quoted at the 2σ level. A representation of the statistical distribution for the visualization of data was made by employing a Kernel density estimator (KDE; e.g., Vermeesch, 2018), which is a more robust alternative to the probability density plot. This is because a KDE does not explicitly take into account the analytical uncertainties. The bandwidth used for the construction of a statistical distribution of data varies according to the local density (adaptive Kernel density estimation). Sample locations are given in Figures 3–5. The maximum depositional age (MDA) of samples is constrained by the weighted mean of the youngest cluster defined by at least three zircon grains overlapping in age at 2σ (Dickinson and Gehrels, 2009). If a cluster is not defined, the MDA is determined on the basis of the youngest concordant zircon grain, according to Spencer et al. (2016) and Copeland (2020). We use multidimensional scaling (MDS) maps based on the Kolmogorov-Smirnov statistics (Vermeesch, 2013) to compare the detrital-zircon U-Pb age signature of the analyzed samples from the Cualac formation and lower Tecocoyunca group with the available data from Paleozoic and Proterozoic complexes, which represent potential source terranes. Clusters in MDS maps represent samples with similar age spectra, whereas samples with different age spectra plot far apart. To help identify the first- and second-order similarities, each sample is connected to its most similar sample by a solid line and its second most similar sample by a dashed line.

FIELD OBSERVATIONS

Cualac Formation

The base of the Cualac formation is a seventh-order surface. Along this surface, the Cualac formation unconformably overlies Paleozoic metamorphic rocks of the Acatlán Complex and conformably overlies volcanic and volcanioclastic fluvial deposits of the Las Lluvias Ignimbrite and the Rosario formation (Fig. 2). The Cualac formation is composed of pebble to cobble conglomerate, conglomeratic to coarse-grained sandstone, minor medium- to fine-grained sandstone, and mudstone that are arranged in a fining- and thinning-upward succession (Figs. 5A–5C and 5F–5H). The thickness of the Cualac formation is...
Figure 5. Measured stratigraphic columns of the Cualac formation and lower Tecocoyunca group. The location of each column is given in the maps in Figures 3 and 4. For a detailed description of the different lithofacies and architectural elements, see Tables 2 and 3. n = number of paleocurrent individual measurements at the site. (Continued on following page.)
TABLE 1. SYNTHESIS OF BOUNDING-SURFACE HIERARCHY OBSERVED IN THE CUALAC FORMATION AND LOWER TECOCOYUNCA GROUP ACCORDING TO MIALL (2006)

| Bounding surfaces | Bounding surface characteristics | Interpretation |
|-------------------|----------------------------------|----------------|
| 1°                | Cross-bed set bounding surface. Lithofacies above and below the surface are the same. Little or no internal erosion is apparent at these boundaries. | Continuous sedimentation of trains of bedforms under similar flow conditions |
| 2°                | Coset bounding surface. Lithofacies above and below the surface are different. The surface is usually not marked by significant bedding truncation or other evidence of erosion. | Changes in flow conditions or a change in flow direction, but no significant time break |
| 3°                | Crosscutting erosion surface within macroforms. This surface dips at low angle in the direction of accretion, and commonly is draped with mudstones. Succeeding strata commonly contain a basal intraclast breccia. Facies assemblages above and below the surface are similar. | Macroform growth increment (lateral or downstream accretion) |
| 4°                | Bounding surfaces that enclose complex packages of channel facies; erosional bases or flat to convex-upward accretionary upper surfaces. | Erosion and migration of channels and/or accretion and burial of macroforms |
| 5°                | Bounding surfaces that enclose major sand sheets; they are generally flat to slightly concave-upward. | Major channel scour (channel base) |
### TABLE 2. SYNTHESIS OF LITHOFAcies OBSERVED IN THE CUALAC FORMATION AND LOWER TECOCOYUNCA GROUP

| Lithofacies | Description | Interpretation | References |
|-------------|-------------|---------------|------------|
| Coal (C)    | Centimeter- to meter-thick, tabular sheets of coal interbedded with centimeter- to meter-thick, tabular to lenticular bodies of coaly mudstone. This lithofacies is commonly interbedded with lithofacies Fl. | Vegetated swamp deposit formed under humid climatic conditions. | Makaske, 2001; Miall, 2006 |
| Laminated sandstone, siltstone, and mudstone (Fl) and siltstone, claystone (Fsm) | Centimeter- to meter-thick, tabular sheets of horizontally interlaminated mudstone, siltstone and very fine-grained sandstone. These lithofacies contain leaf impressions, plant roots perpendicular to bedding, trunk molds, and thin sheets of coal. Fsm lithofacies differs from the Fl lithofacies because of the absence of sandstone beds. | Deposit of the suspended load of very low-velocity river currents associated with overflow and flooding events. | McLean and Jerzykiewicz, 1978; Miall, 2006 |
| Ripple cross-laminated sandstone (Sr) | Centimeter- to meter-thick strata of very fine to medium-grained sandstone displaying unidirectional ripple cross lamination. Convolute lamination, load casts, and flame structures are locally present. Commonly, this lithofacies transitionally overlies sandstone deposits of the Sp lithofacies and is overlain by drapes of lithofacies Fl. Locally, decimeter-thick, lens-shaped sandy bodies of lithofacies Sr cut coarse-grained deposits of lithofacies Gt. | Beds formed by migration of ripple trains under lower flow regime. Channel-fill deposits of chute and other minor channels formed during low-water stage. | Jopling and Walker, 1968; Allen, 1984; Miall, 2006 |
| Planar- and trough-cross-bedded sandstones (Sp and St) | Decimeter- to meter-thick lenses of fine- to very coarse-grained sandstone displaying trough- and planar-cross-bedding (St and Sp, respectively). Cross-bedding has a dip that varies from 15° to 25°and displays sharp, angular to sigmoidal upper and lower terminations. This lithofacies transitionally overlies lithofacies Gp and is overlain by lithofacies Gt and Fl. | Transverse and linguoid sand bars. | Saunderson and Lockett, 1983; Miall, 2006 |
| Horizontally bedded sandstone (Sh) | Decimeter- to meter-thick strata of very fine to coarse-grained sandstone with upper plane bedding and lamination. Primary current lineation is observed on bedding planes. Intraclasts are locally present near the base of strata. Lithofacies Sh forms sandy tabular bodies that are laterally continuous for hundreds of meters. Lithofacies Sh displays a sharp erosional base and is transitionally overlain by lithofacies St, Sp, and Sr. | Deposit formed during single events in which flow conditions remain in the critical stage for periods of many hours (e.g. flash flood events). | Miall, 2006 |
| Planar- and trough-cross-bedded conglomerate (Gp and Gt) | Decimeter- to meter-thick, lens-shaped bodies of moderately to well-sorted conglomerate displaying trough to planar cross bedding (Gt and Gp, respectively). These lithofacies display a concave-upward erosional base and are overlain by lithofacies St and Sp. The erosional base is locally followed by a lag deposit of coarser grain size than the cross-bedded fill. Clast imbrication is ubiquitous. | Transverse conglomeratic bars. | Allen, 1984; Miall, 2006 |
| Clast-supported, horizontally stratified conglomerate (Gh) | Decimeter-thick, lens-shaped conglomerate deposits showing crude horizontal bedding and, locally, clast imbrication. The vertical accretion of these beds forms multistory units that reach several meters in thickness. | Longitudinal conglomeratic bars. | Miall, 2006 |
| Matrix-supported, massive conglomerate (Gmm) | Centimeter- to meter-thick, matrix-supported, poorly sorted conglomerate characterized by the lack of clast framework. Clasts vary in size from a few tens of decimeters to a few centimeters. The matrix is dominantly composed of sandstone and siltstone. Lithofacies Gmm displays a sharp, non-erosional base. | High-strength, pseudoplastic debris-flow deposit. | Schultz, 1984; Miall, 2006 |
| Clast-supported, massive conglomerate (Gcm) | Centimeter- to decimeter-thick, clast-supported, poorly sorted conglomerate deposits. Clasts vary in size from a few centimeters to a dozen centimeters. This lithofacies is characterized by the complete lack of internal organization. The base of lithofacies Gcm is sharp and varies from locally erosive to non-erosive. | Low-strength, pseudoplastic debris-flow deposit. | Miall, 2006 |
### TABLE 3. SYNTHESIS OF ARCHITECTURAL ELEMENTS OBSERVED IN THE CUALAC FORMATION AND LOWER TECOCOYUNCA GROUP

| Architectural element | Lithofacies assemblages | Description | Interpretation | References |
|------------------------|-------------------------|-------------|---------------|------------|
| Floodplain fines (FF)  | Most representative: Fl Minor to subordinate: Fsm, Sr, C | Composed of tens of meter-thick tabular beds composed of rhythmically interbedded Fl, Fsm, Sr, and C lithofacies. Typically, FF deposits occur as beds with lateral extension of tens to hundreds of meters. Trunk molds, fossil leaves, plant roots, and dinosaur footprints are present. | Deposit of overbank sheet flow, floodplain ponds and swamps. | Willis and Behrensmeyer, 1994; Miall, 2006 |
| Crevasse-splay deposits (CS) | Most representative: St, Sp Minor to subordinate: Sr | Centimeter- to meter-thick deposits composed of St, Sp, and Sr lithofacies that are arranged in sets of clinoforms that dip downstream. Clinoforms are bounded by third-order accretionary surfaces. The base of element CS is a fourth-order erosional surface. Its top is a fourth-order surface draped by fine-grained deposits of the FF element. Intraclasts of mudstone are ubiquitous near the base of element CS. | Fan-shaped, sandy deposits that form adjacent to the margins of a main channel and invade the back-swamp area during major crevasse events. | Farrel, 1987; Smith et al., 1989; Miall, 2006 |
| Lateral-accretion deposits (LA) | Most representative: St, Sp Minor to subordinate: Gt, Gp, Sr | Meter-thick, dominantly sandy body composed of lithofacies St, Sp. Well-sorted granule to pebble conglomerate with cross bedding (Gt and Gp lithofacies) can be present near the base of the element, whereas Sr lithofacies are present at its top. These lithofacies are typically arranged in a fining-upward succession and form sets of clinoforms bounded by third-order and fourth-order accretionary surfaces that dip 15° to 25°. Paleocurrent directions are suborthogonal (90°–60°) to the dip of clinoforms. The base of element LA is an erosional flat surface of fifth-order. At its top, element LA transitionally grades into element FF. | Bank-attached, sandy bar developed in a high-sinuosity fluvial system (i.e. point-bar). | Allen, 1970; Bristow, 1993; Miall, 2006 |
| Downstream-accretion macroforms (DA) | Most representative: Gt, Gp, St, Sp Minor to subordinate: Sr | Meter-thick sandy to sandy-conglomeratic bodies composed of lithofacies Gt, Gp, St, Sp, and minor amounts of Sr that are arranged in sets of clinoforms. Clinoforms internally show a fining-upward succession and are bounded by third-order accretionary surfaces that vary in dip from 10° to 25°. Paleocurrent directions form an angle of 60° or less with the dip of clinoforms. The base of element DA is a fourth-order erosional surface. At its top, element DA transitionally grades into element FF. | Mid-channel, sandy to sandy-conglomeratic set of bars that grow by downstream accretion. | Miall, 2006 |
| Gravel bars and bed forms (GB) | Most representative: Gt, Gp Minor to subordinate: Gh, St, Sp, Sr | Element GB consists of decimeter- to meter-thick lenses and wedges of dominantly conglomerate (lithofacies Gt, Gp, and Gh) and minor sandstone (St, Sp, and Sr) organized between third-order, convex-upward to planar bounding surfaces. Conglomeratic lenses and wedges typically cut into each other both laterally and vertically. In the observed outcrops, the base of the GB element is a fourth-order surface, locally showing conspicuous basal scour. The top of element GB is represented by a fourth-order surface draped by a few decimeters to meters of horizontally to ripple-cross-laminated siltstone and mudstone (Fl and Sr) with ubiquitous fossil leaves. | Mid-channel, dominantly conglomeratic set of bars that grow by downstream accretion. | Leopold and Wolman, 1957; Ashmore, 1991; Miall, 2006 |
| Sedimentary-gravity-flow deposits (SG) | Most representative: Gmm, Gcm | Decimeter- to meter-thick, narrow, elongate lobes or multistory sheets composed of Gmm and Gcm conglomerate deposits. Element SG typically displays irregular to planar, non-erosive bases. | Sedimentary-gravity-flow deposit. | Schultz, 1984; Blair and McPherson, 1992; Miall, 2006 |
on the order of ~100 m in the eastern Tlaxiaco Basin (Tezoatlán and Tlaxiaco areas). In its western part (Olinalá area), we estimate a thickness of ~1300 m by using trigonometry. In the Cualac formation, we recognized ten lithofacies that are arranged into two different architectural elements. For a detailed description of lithofacies, the reader is referred to Table 2.

**Element Gravel Bars and Bedforms**

Most of the Cualac formation consists of decimeter- to meter-thick, lens-shaped conglomerate deposits that are bounded at the base by third-order erosional surfaces and cut into each other both laterally and vertically (Figs. 6A and 6B). Conglomerate deposits are clast-supported, poorly sorted, and typically display trough and planar cross-bedding (lithofacies Gt and Gp), imbricate clasts, and, locally, crude horizontal bedding (GH; Figs. 5F–5H). Conglomeratic facies locally grade upward into cross-bedded, conglomeratic to coarse-grained sandstone (St and Sp) and eventually, medium- to fine-grained sandstone with ripple cross-lamination (lithofacies Sr) draped by horizontally laminated siltstone and mudstone (lithofacies FI). According to Miall (2006), these deposits correspond to the Gravel Bars and Bedforms (GB) architectural element, which represents in-channel longitudinal and transverse gravel bars. The base of the GB element is a fourth-order surface, locally showing conspicuous basal scour (Figs. 6A and 6B). The top of element GB is represented by a fourth-order surface draped by a few decimeters to meters of horizontally to ripple cross-laminated siltstone and mudstone (FI and Sr) with ubiquitous fossil leaves. Paleocurrent directions measured on cross-bedded deposits (Gt, Gp, St, and Sp) are dominantly directed to the SW and SE (Figs. 3–5), with a few data pointing to the W and E directions.

**Element Sediment-Gravity-Flow Deposits**

Deposits of the GB element are locally interbedded with decimeter- to meter-thick, matrix- to clast-supported, poorly sorted, massive to inverse grading conglomeratic deposits (Gmm, Gcm, and Gci; Figs. 5B, 5C, 5E–5H, and 6A). Often, these deposits contain tabular clasts aligned parallel to bedding and display a sharp non-erosional base. According to Miall (2006), these characteristics are typical of the architectural element Sediment-Gravity-Flow Deposits (SG), which represents deposits emplaced by high- to low-strength debris flows.

**Lower Tecocoyunca Group**

The lower Tecocoyunca group is composed of fine to conglomeratic sandstone, mudstone, and minor granule conglomerate that conformably overlie the Cualac formation in transitional contact (Figs. 5A, 5E, and 5H). The precise age of this transitional contact in the diverse studied areas is presently unknown. Centimeter- to meter-scale, normal syn-sedimentary faults and associated growth strata can be observed at different outcrops. A systematic kinematic analysis of these faults is presently not available. Bed-by-bed measurement and sampling of the lower Tecocoyunca group are possible only at a few localities because of deformation related to post-sedimentary faulting. Based on the lithofaciesassociation and three-dimensional architecture of deposits, we recognized four main elements in the lower Tecocoyunca group.

**Element Floodplain Fines**

The lower Tecocoyunca group is mostly composed of alternating and horizontally laminated coaly mudstone, coal, and siltstone (FI and Fsm) and fine-grained...
Rose diagram showing paleocurrent directions obtained from cross bedding and clast imbrication (black). The great circle (red) shows the trend and dip of the third-order accretionary surfaces of the architectural elements.

Figure 6. (A) Photograph of the Cualac formation in the Tlaxiaco area, showing the typical geometry of the architectural elements Gravel Bars and Bedforms (GB) and Sediment-Gravity-Flow Deposits (SG). The conglomerate deposits of GB show lens-shaped beds that cut into each other both laterally and vertically, whereas the conglomerate deposits of SG show a sharp and non-erosional relationship with the underlying deposit. (B) Photograph of the Cualac formation in the Tezoatlán area, showing GB and FF elements, as well as its bounding surfaces. (C) Photograph of meter-thick sheet-like deposits of the Floodplain Fines (FF) of the lower Tecocoyunca group in the Tlaxiaco area. (D) Plant roots perpendicular to bedding are present in the lower Tecocoyunca group deposits.
sandstone with ripple cross-lamination (Sr), which form meter- to decameter-thick, sheet-like deposits that are laterally continuous for several hundreds of meters (Fig. 6C). Trunk molds, fossil leaves, and rootlet traces (Fig. 6D) are ubiquitous in these rocks. Dinosaur footprints are locally present. According to Miall (2006), these deposits correspond to the Floodplain Fines (FF) element, which represents deposits of overbank sheet flow, floodplain ponds, and swamps.

**Element Crevasse-Splay Deposits**

Element FF is rhythmically interbedded with ~1–3-m-thick, coarse- to fine-grained, cross-bedded to ripple cross-laminated sandstone deposits (St, Sp, and Sr), which are arranged in a 10° to 15° downstream-dipping clinoform set showing a fining-upward succession. These sandstone deposits display a fourth-order sharp erosional basal surface and toward the top, transitionally grade into the overlying FF element. The sandstone ubiquitously contains mudstone intraclasts and displays convolute lamination, load casts, flame structures, pseudo-nodules, and abundant bioturbation. According to Miall (2006), we interpret these deposits as the architectural element Crevasse-Splay Deposits (CS), which represents fan-shaped sandy deposits introduced into floodplain areas during major crevassing events.

**Element Lateral-Accretion Deposits**

In the Olinalá and Tlaxiaco areas, element FF is interbedded with 9–11-m-thick, conglomeratic to sandstone bodies composed of a set of decimeter- to meter-thick clinoforms bounded by third- to fourth-order accretionary surfaces with a dip of ~20° (Fig. 7A). The base of the clinoform set is a fifth-order, flat erosional surface, whereas its top is transitional to the overlying

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**Figure 7. Photographs of the lower Tecocoyunca group.**

(A) The characteristic geometry of Lateral-Accretion Deposits (LA), which is composed of sets of clinoforms and the paleocurrent direction, with the dip direction of clinoforms typically more nearly perpendicular (>60°). The base of LA element is an erosional fifth-order bounding surface. (B) The typical geometry of the Downstream-Accretion Macroforms (DA) element, where the paleocurrent direction and the dip direction of clinoforms typically are within ~60° of each other.
FF element. In their lower part, clinoforms are composed of clast-supported and well-sorted granule to pebble conglomerates showing trough and planar cross bedding (Gt and Gp). Rip-up mud clasts are ubiquitous in these conglomerates. Conglomeratic deposits grade upward into coarse-grained sandstone beds with trough cross bedding (St), which in turn progressively grade into medium-grained sandstones with planar cross bedding (Sp) and fine-grained sandstone to siltstone with ripple cross lamination (Sr; Fig. 5D). Paleocurrent directions obtained from deposits showing cross bedding (St and Sp) point toward the NE, NW, SE, and SW quadrants and are suborthogonal to the dip of clinoforms. According to Miall (2006), we interpret these deposits as the element Lateral-Accretion Deposits (LA), which is the typical point bar described for meandering rivers (e.g., Allen, 1970).

**Element Downstream-Accretion Macroforms**

In the Olinalá and Tlaxiaco areas, a few conglomeratic to sandstone bodies interbedded with element FF show a lithofacies assemblage and geometry that are similar to those of element LA. However, in these few conglomeratic to sandstone bodies, paleocurrent directions form an angle of 0°–60° with the dip of clinoforms (Fig. 7B). According to Miall (2006), this three-dimensional architecture is typical of the element Downstream-Accretion Macroforms (DA), which represents in-channel, downstream-accretion sandy bars.

**WHOLE-ROCK SANDSTONE PETROGRAPHY**

**Cualac Formation**

We collected 19 medium- to coarse-grained sandstone samples representative of the Cualac formation. Results from these 19 samples were integrated with detrital modes previously reported by Zepeda-Martínez et al. (2018) for the Tezoatlán area. Selected samples are moderately to poorly sorted sandstones, with angular to subangular grains surrounded by a very thin film of clay and opaque minerals. The analyzed samples vary in composition from quartzose to quartzo-lithic sandstone (Fig. 8A). In order of decreasing abundance, they are composed of monocrystalline quartz (97.8%–31.5% of the total framework grains), metamorphic lithic grains (68.3%–1.9%; Fig. 8B), polycrystalline quartz (0.7%–0%), and heavy minerals such as tourmaline, rutile, epidote, zircon, and prehnite (0.7%–0%). Solid-state deformation and recrystallization structures in quartz such as undulatory extinction, subgrain domains, and shape-preferred orientation suggest a low-grade metamorphic origin for this component. Metamorphic lithic grains are rank 2–4 metapelitic and metapsammitic/metafelsitic fragments (Figs. 8C and 8D) that, according to Garzanti and Vezzoli (2003), correspond to the subgreenschist and greenschist-facies metamorphic facies. Metapelitic grains are composed of micaschist and display a penetrative continuous foliation at the submillimeter scale defined by tiny flakes to well-developed crystals of aligned white mica (Fig. 9A). Metapsammitic/metafelsitic grains vary from quartz-rich metasandstone to quartz-micaschist with a main foliation that is moderately to highly penetrative at the submillimeter scale and is expressed by the alignment of elongated quartz, flakes of clay minerals in grains of rank 2 and white mica in grains of ranks 3 and 4 (Figs. 10B–10D).

**Lower Tecocoyunca Group**

Analyzed samples from the Lower Tecocoyunca group are moderately to very well sorted sandstones, with subrounded to well-rounded grains in a matrix made up of clay and opaque minerals. The analyzed samples are quartzose and litho-quartzose sandstones (Fig. 8A) and are composed of monocrystalline quartz (96.8%–63.7%); metamorphic lithic grains (24.1%–0%); volcanic lithic grains (175%–0.2%; Fig. 8B); plagioclase (4.3%–0%); K-feldspar showing mesoperthitic texture (2.5%–0%; Fig. 9E); heavy minerals such as zircon, rutile, tourmaline, epidote, apatite, and orthopyroxene (1.8%–0%; Fig. 9F); and polycrystalline quartz (0.8%–0%). Quartz in the lower Tecocoyunca group is mostly included in polycrystalline planarite grains that display a polygonal granoblastic texture with triple junctions (Fig. 9G), which is typical of high-grade metamorphic rocks (Garzanti and Vezzoli, 2003; Passchier and Trouw, 2005). Quartz in these high-grade planeritic fragments ubiquitously contains several needle-shaped rutile inclusions (Fig. 9H). Metamorphic lithic grains are metapsammitic/metafelsitic and metapelitic fragments of ranks 2 and 3 of Garzanti and Vezzoli (2003; Fig. 8D), corresponding to subgreen schist- and greenschist-facies conditions. Metapsammitic/metafelsitic grains are composed of quartz-sericite and quartz-white mica schists with a moderately to highly penetrative foliation at the submillimeter scale. Quartz in these metapsammitic/metafelsitic metamorphic lithic grains does not contain rutile inclusions. Metapelitic grains are mostly composed of sericite and white mica schist with a penetrative continuous foliation at the submillimeter scale. Volcanic lithic grains are felsitic and are characterized by a porphyritic texture, with quartz, plagioclase, and minor K-feldspar phenocrysts in a quartzo-feldspathic microcrystalline groundmass (Fig. 9I).

**ZIRCON U-Pb GEOCHRONOLOGY**

**Cualac Formation**

We selected five samples from the Cualac formation exposed in the Tlaxiaco (MI-0318-3 and NU-0318-1; Figs. 5B and 5C), Tecomatlán (Tmt-0219-16; Fig. 4A), and Olinalá (T and CU-05b; Fig. 5H) areas for detrital-zircon U-Pb geochronology. Results from these five samples are integrated with the detrital-zircon U-Pb data (samples 13C and 23C; Fig. 5A) previously reported by Zepeda-Martínez et al. (2018) for the Tezoatlán area. In the Tecomatlán area, 0.5 km to the northwest of Peña Colorada (Fig. 4A), some conglomeratic deposits were tentatively
correlated with the Cualac formation by previous works (Hernández-Vulpes and Rodríguez-Calderón, 2012). However, conglomeratic deposits at Peña Colorada have volcanic clasts that are absent in the Cualac formation. Therefore, we collected a sample from the matrix of conglomeratic deposits at Peña Colorada (Tmt-0219-19, Fig. 4A) to verify its possible correlation with the Cualac formation. We performed between 87 and 97 point-ablation analyses for each sample and obtained concordant to slightly discordant ages (percentages of discordia vary from −4.9–1 1.7; Supplemental File B [footnote 1]). Zircons from samples 13C, 23C, MI-0318-3, ÑU-0318-1, Tmt-0219-16, T9, and CU-05b return similar age distributions, characterized by two main age groups of ca. 1380–870 and ca. 790–330 Ma (Figs. 10A–10G). The MDA for samples 13C, 23C, MI-0318-3, ÑU-0318-1, Tmt-0219-16, T9, and CU-05b are ca. 183.9, ca. 252.0, ca. 332.5, ca. 267.6, ca. 407.5, ca. 478.6, and ca. 463.0 Ma, respectively (Figs. 10A–10G). Sample Tmt-0219-19 from the Peña Colorada conglomerate displays three main age groups of ca. 1400–880, ca. 500–450 Ma, and ca. 60–50 Ma and a MDA of ca. 49.6 Ma (Fig. 10K). The MDS map shows that the Cualac formation samples have first-order distances with greenschist-facies metasedimentary samples from the Acatlán Complex, whereas they do not share any similarity with granulite-facies rocks of the Oaxacan Complex (Galaz et al., 2013; Zepeda-Martínez et al., 2018; Martini et al., 2020; Fig. 11).

Lower Tecocoyunca Group

We selected six samples from the lower Tecocoyunca group exposed in the Tezoatlan (Tec-0916–3; Fig. 5A), Tlaxiaco (TB-0817-2, TLA-013; Figs. 5B and 3B), Tecomatlán (Tmt-0219-13; Fig. 4A), and Olinalá (OL-0618-T3, OL-1018-1; Figs. 4B and 5I) areas for detrital-zircon U-Pb geochronology. We performed between 83 and 97 point-ablation analyses for each sample and obtained concordant to slightly discordant ages (percentages of discordia vary from −4.9–1 1.7; Supplemental File B [footnote 1]). Zircons from samples 13C, 23C, MI-0318-3, ÑU-0318-1, Tmt-0219-16, T9, and CU-05b return similar age distributions, characterized by two main age groups of ca. 1380–870 and ca. 790–330 Ma (Figs. 10A–10G). The MDA for samples 13C, 23C, MI-0318-3, ÑU-0318-1, Tmt-0219-16, T9, and CU-05b are ca. 183.9, ca. 252.0, ca. 332.5, ca. 267.6, ca. 407.5, ca. 478.6, and ca. 463.0 Ma, respectively (Figs. 10A–10G). Sample Tmt-0219-19 from the Peña Colorada conglomerate displays three main age groups of ca. 1400–880, ca. 500–450 Ma, and ca. 60–50 Ma and a MDA of ca. 49.6 Ma (Fig. 10K). The MDS map shows that the Cualac formation samples have first-order distances with greenschist-facies metasedimentary samples from the Acatlán Complex, whereas they do not share any similarity with granulite-facies rocks of the Oaxacan Complex (Galaz et al., 2013; Zepeda-Martínez et al., 2018; Martini et al., 2020; Fig. 11).

Lower Tecocoyunca Group

We selected six samples from the lower Tecocoyunca group exposed in the Tezoatlan (Tec-0916–3; Fig. 5A), Tlaxiaco (TB-0817-2, TLA-013; Figs. 5B and 3B), Tecomatlán (Tmt-0219-13; Fig. 4A), and Olinalá (OL-0618-T3, OL-1018-1; Figs. 4B and 5I) areas for detrital-zircon U-Pb geochronology. We performed between 83 and 97 point-ablation analyses for each sample. The analyzed grains return ages

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**Sandstone provenance subdivisions** (Dickinson and Suczek, 1979)
- Continental block provenance
- Recycled orogen provenance
- Magmatic arc provenance

**Metamorphic ranks** (Garzanti and Vezzoli, 2003)
- R1: metamorphic lithic grain of rank 1 (zeolite facies)
- R2: metamorphic lithic grain of rank 2 (prehnite-pumpellyte facies)
- R3: metamorphic lithic grain of rank 3 (low-temperature greenschist facies)
- R4: metamorphic lithic grain of rank 4 (high-temperature greenschist facies)

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**Figure 8. Detrital modes for sandstones from the Cualac formation and lower Tecocoyunca group analyzed in this work.** (A) QtFL diagram (after Garzanti, 2016) showing the classification of studied sandstones. Sandstone provenance fields proposed by Dickinson and Suczek (1979) are shown for reference. (B) LmLvLs diagram (after Garzanti et al., 2001) displaying the abundances of metamorphic, sedimentary, and volcanic lithic grains. (C) LmfLmpLvL diagram showing the abundances of metapsammitic/metafelsitic, metapelitic grains, and felsitic volcanic lithic grains. (D) R1R2-3R4 diagram (Garzanti and Vezzoli, 2003) showing the abundances of the different metamorphic grains according to metamorphic rank. Abbreviations: Qt—total quartz; F—total feldspar; L—total lithic grains; Lm—total metamorphic lithic grains; Lv—total volcanic lithic grains; Ls—total sedimentary lithic grains; Lmf—metapsammitic and/or metafelsitic lithic grain; Lmp—meta pelitic lithic grain; Lvf—felsitic volcanic lithic grain; R1—metamorphic lithic grains of rank 1; R2-3—metamorphic lithic grains of ranks 2 and 3; R4—metamorphic lithic grains of rank 4. See Table 4 and Supplemental File A (text footnote 1) for a detailed description of the framework components.
that vary from concordant to slightly discordant (percentages of discordia vary between −4.8%–11.9%; Supplemental File B). Zircon grains from the analyzed samples yield similar age distributions that are characterized by two main age groups of ca. 1400–880 and ca. 300–240 Ma (Figs. 10L–10Q). Subordinate grains return ages in the ranges of ca. 1700–1470, ca. 670–350, and ca. 191–173 Ma. The MDA for samples Tec-0916-3, TB-0817-2, TLA-013, Tmt-0219-13, OL-0618-T3, and OL-1018-1 are ca. 179.3, ca. 260.0, ca. 176.5, ca. 189.7, ca. 257.5, and ca. 173.2 Ma, respectively (Figs. 10L–10Q). The MDS map shows first-order distances between the analyzed lower Tecocoyunc group sandstone samples and the granulite-facies metamorphic rock of the Oaxacan Complex (Solari et al., 2014; Fig. 11).

**The Axutla Fault**

In the Tecomatlán area, the contact relationship between the Jurassic succession and Paleozoic metamorphic rocks of the Acatlán Complex is represented by a major fault zone that we describe here for the first time and name the Axutla fault. This structure can be recognized in the field and in satellite images. It has a trend of N290–315° and a dip of 90°–70° to the southwest (Fig. 12). The distribution of the exposures of this structure allows us to follow the Axutla fault trace for ~25 km from Tecomatlán to Axutla (Fig. 12). Generally, horizontal to moderately dipping Jurassic strata become progressively more inclined as they get closer to the fault (Fig. 4A). Along the fault trace, Jurassic strata are subvertical and trend parallel to the main structure. The core of the fault zone is represented by a ~30–100-m-thick breccia composed of blocks of metamorphic rocks from the Acatlán Complex up to some meters in size. Between Tecomatlán and Axutla, two rhyolitic domes are aligned along the trace of the Axutla fault (Fig. 12). Establishing the kinematics of the Axutla fault is difficult because two, and in some cases, even three, superposed kinematic indicators can be observed at each outcrop of this structure, suggesting a complex history of reactivation at different times. Some kinematic indicators suggest normal to normal sinistral movements, although structures indicating a dextral
Metasedimentary rocks: sample G-02 (Zepeda-Martínez et al., 2018)

\[
\begin{align*}
\text{MDA} &= 49.6 \pm 1.5 \text{ Ma} \\
\text{MSWD} &= 3.5
\end{align*}
\]

Tezozomoc area: sample Tmt-0219-19

\[
\begin{align*}
\text{MDA} &= 93.3 \pm 4.1 \text{ Ma} \\
\text{MSWD} &= 3.4
\end{align*}
\]

Tezozomoc area: sample Tec-0916-3

\[
\begin{align*}
\text{MDA} &= 49.6 \pm 1.5 \text{ Ma} \\
\text{MSWD} &= 3.4
\end{align*}
\]

Tezozomoc area: sample Tmt-0219-13

\[
\begin{align*}
\text{MDA} &= 189.7 \pm 5.5 \text{ Ma} \\
\text{MSWD} &= 3.4
\end{align*}
\]

Figure 10. Kernel density estimator plots showing the statistical distribution of zircon ages for sandstones from the Cualac Formation, Lower Tezozomoc Group, greenschist-facies metasedimentary samples of the Acatlán Complex, Carboniferous–Permian intrusive bodies that cut the rocks of the Oaxacan Complex, and granulite-facies metamorphic rocks of the Oaxacan Complex. Histograms (gray rectangles) are also shown for comparison. The open circles at the base of each plot represent the age for each analyzed zircon grain. The maximum depositional ages (MDAs) of sandstone samples 13C, TB-0817-2, OL-0618-13 (A, M, and P, respectively) are constrained by the weighted mean of the youngest cluster defined by at least three zircon grains overlapping in age at 2σ. The MDA of samples 23C, MI-0318-3, NU-0318-1, Tmt-0219-16, T-9, CO35b, Tmt-0219-19, Tec-0916-3, TLA-013, Tmt-0219-13, and OL-1018-1 (B–G, K–L, N–O, and Q) are determined on the basis of the youngest concordant zircon grain.
DISCUSSION

Depositional Environments of the Tlaxiaco Basin

The Cualac formation is dominated by the architectural element GB, which is locally interbedded with element SG. These elements are typical of high-energy and steep-gradient fluvial environments characterized by unstable channels such as braided rivers and alluvial fans (Miall, 2006). The scattered exposure of the Cualac formation does not permit an exhaustive reconstruction of the paleocurrent pattern at the regional scale. However, based on the ~230° dispersion angle of the available paleocurrent data in the Tezoatlán and Olinalá areas and the ~150° dispersion angle in the Tlaxiaco area, we tentatively interpret the Cualac formation as the stratigraphic record of a coalescing alluvial fan system, which was originally proposed by Morán-Zenteno et al. (1993). We do not exclude the possibility that at least the distal part of some of these alluvial fans transitionally changed into a transverse braided river. Displacement are also observed. Therefore, the kinematics of the Axutla fault remains unresolved. Directly to the east of Tecomatlán, the Axutla fault is cut by the N-S-trending, dextral Tetla fault (Ortega-Gutiérrez et al., 2018; Fig. 1). These metasedimentary rocks contain zircons with U-Pb ages defining two main groups of ca. 1370–870 and ca. 800–340 Ma (Galaz et al., 2013; Zepeda-Martínez et al., 2018; Martini et al., 2020; Figs. 10H–10J), which match well with the two U-Pb zircon groups of ca. 1351–868 and ca. 794–336 Ma obtained for the Cualac formation (Figs. 10A–10G). The MDS map shown in Figure 11 supports this U-Pb zircon age similarity, showing that samples from the Cualac formation plot close to samples from the Acatlán Complex. Therefore, we suggest that the metasedimentary rocks of the Acatlán Complex exposed to the north of the study areas are the source of the Cualac formation. Conglomeratic deposits of Peña Colorada (Fig. 4A), which were tentatively correlated with the Cualac formation, display three main age groups of ca. 1400–880, ca. 500–450 Ma, and ca. 60–50 Ma (Fig. 10K). The MDA of these deposits is ca. 49.6 Ma. Therefore, we exclude any possible correlation of the Peña Colorada conglomerate with the Cualac formation. Samples from the lower Tecocoyunca group ubiquitously contain quartz with rutile inclusions and a polygonal granoblastic texture with triple junctions, as well as minor mesoperthitic K-feldspar, suggesting their derivation from a high-temperature (>700 °C) metamorphic source (Passchier and Trouw, 2005; Cherniak et al., 2007; Winter, 2014). In southern Mexico, rutile-bearing quartz and mesoperthitic K-feldspar have been reported exclusively in Proterozoic granulites of the Oaxacan Complex (e.g., Ortega-Gutiérrez et al., 2018; Fig. 1). The occurrence of detrital orthopyroxene in samples from the lower Tecocoyunca group supports such a provenance interpretation, as this mineral phase is ubiquitous in granulites from the Oaxacan Complex (Ortega-Gutiérrez et al., 2018). Derivation from the Oaxacan Complex is also supported by detrital-zircon
grains from the lower Tecocoyuncan group, which yield U-Pb ages defining a main group of ca. 1395–900 Ma (Figs. 10L–10Q), matching well with the ca. 1400–880 Ma U-Pb zircon age range from the Oaxacan Complex (Solari et al., 2014; Fig. 10R). This U-Pb zircon age similarity is also shown in the MDS map (Fig. 11), where samples from the lower Tecocoyuncan group show close distances with samples from the Oaxacan Complex. A second group of zircons with ages between ca. 290 and ca. 250 Ma are likely derived from Carboniferous–Permian (ca. 290–255 Ma) plutonic bodies that cut Proterozoic rocks of the Oaxacan Complex (Ortega-Obregón et al., 2014; Figs. 1 and 10S). Minor felsitic volcanic and greenschist- to subgreenschist-facies metasedimentary lithic grains are present in samples from the lower Tecocoyuncan group. As suggested by the occurrence of few zircons with U-Pb ages between ca. 191 and ca. 173 Ma (Figs. 10L, 10N, 10O, and 10Q), volcanic lithic grains were likely derived from the Jurassic synrift magmatism that accompanied the lithospheric attenuation of Pangea (Martini and Ortega-Gutiérrez, 2018). Low-grade metasedimentary lithic grains are tentatively derived from the metasedimentary rocks of the Acatlán Complex. This interpretation is supported by the occurrence of a few tourmaline grains, as this mineral phase is absent in the Oaxacan Complex and ubiquitous in metamorphic rocks of the Acatlán Complex (Ortega-Gutiérrez et al., 2018).

Main Boundaries and Internal Architecture of the Tlaxiaco Basin

Based on our sedimentological data and provenance analysis, we interpret the Cualac formation as a set of alluvial fans that drained fans to the SE and SW from the adjacent metasedimentary rocks of the Acatlán Complex exposed to the north (Fig. 13A). It is well known that alluvial fans necessarily require high-relief source areas to form; therefore, they occur in tectonically active regions (Dade and Verdeyen, 2007; Meek et al., 2020) and form major accumulations along major active faults bounding sedimentary basins (e.g., Gawthorpe and Leeder, 2000; Miall 2006). In the study area, alluvial fan deposits of the Cualac formation are exposed directly to the south of the Axutla fault that we document in this work and the Salado River fault that was previously documented by Martiny et al. (2012). No exposure of the Cualac formation has been documented north of these faults. Moreover, alluvial fan deposits are distributed along a main WNW-trending line that coincides with the trend of these two major fault segments (Fig. 14). All these aspects suggest that the Axutla and Salado River faults likely represent the northern boundary of the Tlaxiaco Basin (Figs. 1 and 13A). At present, the Axutla and Salado River faults are two different segments separated by the N-trending Tetla fault (Fig. 1). However, the development of alluvial fan deposits with the same sedimentological
According to these considerations, the stratigraphy and internal architecture of the Tlaxiaco Basin was controlled by two major faults: the WNW-trending Salado River–Axutla fault and the NNW-trending Caltepec fault. (A) The Cualac formation represents the stratigraphic record of a coalescing alluvial fan system that drained the greenschist-facies metasedimentary samples of the Acatlán Complex exposed to the north of the Tlaxiaco Basin along the Salado River–Axutla fault. (B) The lower Tecocoyunca group represents the stratigraphic record of the Tlaxiaco River, a meandering river with local mid-channel bars, and its adjacent overbank areas, which were mainly sourced by granulite-facies metamorphic rocks of the Oaxacan Complex, exposed to the east of the Tlaxiaco Basin along a NNW-trending Caltepec fault. For a certain time, the fan system and the Tlaxiaco River interacted, as suggested by the transitional stratigraphic contact between the Cualac formation and lower Tecocoyunca group. (C) The alluvial fans of the Cualac formation were progressively buried by overbank deposits of the Tlaxiaco River because of the deactivation of the Salado River–Axutla fault. Yellow arrows indicate main paleocurrent directions. Abbreviations: OL—Olinalá; TE—Tecomatlán; TZ—Tezoatlán; TL—Tlaxiaco; SRAF—Salado River–Axutla fault; CF—Caltepec fault.

The stratigraphic transitional relationship of the Cualac formation with the overlying lower Tecocoyunca group indicates that the alluvial fans that developed along the northern boundary of the Tlaxiaco Basin were abandoned, probably because the Salado River–Axutla fault became inactive, and were progressively buried by overbank deposits of the Tlaxiaco River between ca. 173 Ma, the age of the youngest zircon grains in the lower Tecocoyunca group (this work), and the Bajocian–Bathonian age (ca. 170–168 Ma, Gradstein et al., 2012) of the overlying transgressive marine deposits (Westermann et al., 1984; Marshall, 1986; Sandoval and Westermann, 1986; Figs. 13B and 13C). Available sedimentologic and provenance data suggest that the Tlaxiaco River was a major meandering fluvial system that drained high-grade metamorphic rocks of the Oaxacan Complex to the west into the Tlaxiaco Basin (Fig. 13C). This indicates that, at least during the development of the Tlaxiaco River, the Oaxacan Complex was a major topographic high that bounded the Tlaxiaco Basin to the east (Fig. 13C). Such a scenario is supported by theapatite and titanite fission-track data of Abdullin et al. (2020), which indicate that the Oaxacan Complex was episodically exhumed between Late Triassic and Middle Jurassic time along the Caltepec fault (Figs. 1 and 13C) as a result of crustal extension associated with Pangea breakup. Based on these data, we interpret the Caltepec fault as the eastern boundary of the Tlaxiaco Basin (Fig. 13C). According to these considerations, the stratigraphy and internal architecture of the Tlaxiaco Basin, at least in the areas explored in this work, were largely controlled by two major faults, the Salado River–Axutla and Caltepec faults, which represent the northern and eastern boundaries of the Tlaxiaco Basin, respectively. These faults produced the exhumation of different crustal blocks at different times. The Salado River–Axutla fault activated first and produced the exhumation of the Acatlán Complex along the northern boundary of the Tlaxiaco Basin, resulting in the deposit of the Cualac formation fan system.
(Fig. 13A). Subsequently, the Salado River–Axutla fault progressively became inactive, and the Caltepec fault was activated, producing the exhumation of the Oaxacan Complex along the eastern boundary of the Tlaxiaco Basin and the development of the Tlaxiaco River and associated overbank areas (Figs. 13B and 13C). For a certain time, the Cualac fan system and the Tlaxiaco River interacted, as suggested by the transitional stratigraphic contact between the Cualac formation and lower Tecocoyunca group (Fig. 13B).

**Tectonic Implications**

Our data indicate that the Salado River–Axutla and Caltepec faults are major structures that controlled the geometry and internal depositional architecture of the Tlaxiaco Basin during Early–Middle Jurassic time. This indicates that the Salado River–Axutla and Caltepec faults took part in the process of continental attenuation related to Pangea breakup. The Caltepec fault has a NNW trend that is similar to the trend of other major normal faults (e.g., Oaxaca, Texcalapa, and El Sabino faults; Alaniz-Álvarez et al., 1996; Campos-Madrigal et al., 2013; Fig. 1) that developed between eastern Mexico and the Yucatán block during Early–Middle Jurassic time (Fig. 14A). These faults are the early manifestation of the development of a major transform boundary, the Tamaulipas–Chiapas transform, which by the end of Middle Jurassic time produced the anticlockwise rotation of the Yucatán block (YB) and the opening of the Gulf of Mexico (Pindell and Kennan, 2009).

Figure 14. (A) Paleogeographic reconstruction of the western equatorial margin of Pangea during Early–Middle Jurassic time, showing the paleogeographic position of southern Mexico in a more northwestern position (Anderson and Schmidt, 1983; Pindell, 1985) and the location of major NNW-trending faults in southern Mexico, which are the early manifestation of the development of the Tamaulipas–Chiapas transform boundary (TCT). Our data suggest that continental extension during Pangea breakup was also accommodated by NNW-trending faults and indicate that sinistral displacements in Mexico represent an excellent solution to the North America–South America overlap problem in the reconstruction of Pangea. (B) By the end of Middle Jurassic time, the TCT produced the anticlockwise rotation of the Yucatán Block (YB) and the opening of the Gulf of Mexico (Pindell and Kennan, 2009).
hand, recognizing the Salado River–Axutla fault as a major Lower–Middle Jurassic structure controlling the evolution of adjacent sedimentary basins shows that continental extension during Pangea breakup was also accommodated by WNW-trending faults. Therefore, our work offers a new perspective for researchers that aim to reconstruct the kinematics of Pangea breakup in Mexico. The existence of major Jurassic faults in Mexico with a WNW trend and a normal sinistral displacement was tentatively suggested by some authors (Anderson and Schmidt, 1983; Dickinson and Lawton, 2001; Pindell and Kennan, 2009). According to them, these faults would have placed south and central Mexico to the NW of its present location during Early and Middle Jurassic time, avoiding the large overlap between North and South America in the Pangea reconstruction (Fig. 14A). However, the existence of these Jurassic WNW-trending faults has been challenged by several authors during the past two decades, and the idea of sinistral block motion in Mexico during Pangea breakup has been largely downplayed (e.g., Iriondo et al., 2005). The kinematics of the Salado River–Axutla fault during Early–Middle Jurassic time is difficult to establish because of the superposition of kinematic indicators suggesting different motions (Martiny et al., 2012; this work). The kinematic indicators superposition advocates for the complex history with multiple reactivation episodes overprinted. Considering that the Tlaxiaco Basin is a rift basin, as indicated by the regional tectonic setting under which it developed, at least a normal displacement is required to accommodate the up to ~1300-m-thick alluvial fan deposits of the Cualac Formation along the northern boundary of the basin. At present, a possible lateral kinematic component cannot be excluded for the Salado River–Axutla fault, making this structure the subject of interest of future studies that aim to explore the potential of sinistral displacements in Mexico as a valid solution to the North America–South America overlap in the reconstruction of Pangea.

CONCLUSIONS

Our results indicate that the geometry and tectono-sedimentary evolution of the Early–Middle Jurassic Tlaxiaco Basin was influenced by the activity of two major faults. The WNW-trending Salado River–Axutla fault bounded the basin to the north and produced the exhumation of the Paleozoic Acatlán Complex, which was drained to the southeast and southwest by a set of alluvial fans. Subsequently, the NNW-trending Caltepec fault produced the exhumation of the Proterozoic Oaxacan Complex, which formed a prominent topographic bounding the Tlaxiaco Basin to the east. The Tlaxiaco River drained the Oaxacan Complex to the west into the Tlaxiaco Basin and progressively buried the previously formed alluvial fan set. U-Pb ages and biostratigraphic data bracket the activity of the Salado River–Axutla and Caltepec faults between ca. 176 and ca. 188 Ma. Therefore, our work shows that the continental attenuation produced during Pangea breakup was accommodated not only by NNW-trending faults associated with the development of the Tamaulipas-Chiapas transform, but also by a WNW-trending fault. Due to the difficulty in determining its kinematics, the potential of the WNW-trending Salado River–Axutla fault in producing sinistral block displacements that can solve the North America–South America overlap problem in the Pangea reconstruction is unknown and must be clarified in future works.

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