The Lajas Formation in the Neuquén Basin, Argentina, consists of a succession of mainly deltaic deposits. In the Middle Jurassic (170 million years ago), the basin was in western Gondwana roughly at the same paleolatitude as its present location (32°–40°S). Decimeter-scale, interbedded, coarser-grained and finer-grained beds in channelized and nonchannelized deltaic deposits have been interpreted as a product of variability in river discharge. The coarser-grained sandstone beds have erosional bases and contain mudstone clasts; internal cross bedding is commonly directed paleosewards. These beds are interpreted as deposition during river-flood conditions. In contrast, the finer-grained beds are composed of interlaminated sandstone and mudstone, deposited during
interflood periods. Bidirectional ripples and millimeter-scale sand–mud laminae suggest the influence of tides. This sedimentological evidence raises the question of whether these cycles represent annual variability in fluvial input. To answer this question, a simulation using the Fast Ocean Atmosphere Model for the Middle Jurassic was run to equilibrium. The model shows that the paleoclimate of the Neuquén Basin was characterized by a strong seasonal cycle, with a wet winter and a dry summer. Model runs suggest that February mean temperatures were 28°C with 4-mm precipitation (±4 mm standard deviation) per month, whereas August mean temperatures were 8°C with 34-mm precipitation (±17 mm standard deviation) per month. The strong seasonal cycles in the simulation, representing 24% of the variance in the precipitation time series, suggest that the sedimentological cycles represent annual variations. The simulation also suggests a Middle Jurassic climate where increased seasonality of precipitation occurred farther poleward than previously thought.

KEYWORDS: Atmosphere/ocean structure/phenomena; Precipitation; Physical meteorology and climatology; Hydrology; Paleoclimate

1. Introduction

Clastic successions record sedimentary processes (e.g., fluvial, tidal, wave) that are responsible for facies distribution and architecture. These successions can also record paleoclimate information critical for understanding the depositional environment and paleogeography. For example, cycles in sedimentary processes may indicate wet and dry seasons. Such changes associated with seasonal fluctuations of river discharge have been described from modern systems (e.g., Sisulak and Dashtgard 2012; Johnson and Dashtgard 2014) and may be recognized in the geologic record using techniques such as isotope geochemistry (Allen et al. 2007), fossilized trees (Morgans et al. 1999), pollen studies (Dark and Allen 2005), trace fossils (Gingras et al. 2002), and sedimentology (Gugliotta et al. 2015, 2016).

Another technique that can be applied to determine seasonal fluctuations in river discharge is paleoclimate modeling, whereby a climate model is set up with plausible reconstructions of past geographies (i.e., land–sea distribution, ocean bathymetry, continental topography, land cover, and vegetation), atmospheric composition, solar input, and Earth’s orbital parameters as boundary conditions. For time-slice simulations, the model is run to an equilibrium state to determine the climate achieved under these specific boundary conditions and other forcings. Paleoclimate modeling studies have become an increasingly important and popular way to understand Earth’s past climates ever since the first three-dimensional paleoclimate simulations for the supercontinent Pangaea (e.g., Kutzbach and Gallimore 1989).

Combining sedimentological studies and paleoclimatological modeling can result in mutual benefits to both. A better understanding of sediment dynamics can provide important information for verifying paleoclimate model reconstructions, particularly when other approaches (e.g., paleobotanical, isotope geochemistry) are not available, nondiagnostic, or expensive. At the same time, understanding the paleoclimate simulations can help to explain patterns of deposition by providing insight into annual and interannual variations in temperature, rainfall, and snow cover.

In this article, we illustrate how both sedimentological analysis and paleoclimate modeling can be brought together to better understand the paleoenvironment of a sedimentary basin. This study bridges two disciplines of Earth science, incorporating
two different approaches to provide support for interpreting evidence in the geologic record. The aim of this study is to demonstrate a multidisciplinary approach to understanding paleoclimate conditions from the rock record with the additional purpose of improving our understanding of paleoclimate in western Gondwana during the middle Jurassic (170 million years ago), a time for which few paleoclimate model simulations have been performed.

2. The Lajas Formation in the Neuquén Basin

We examine the deposits of the Lajas Formation, approximately 40 km south from the town of Zapala, Argentina (Figure 1a). The Neuquén Basin is located in west-central Argentina and extends into east-central Chile between 32° and 40°S. It covers an area of more than 137,000 km² (Urien and Zambrano 1993) and is up to 700 km long (north–south) and up to 400 km wide (east–west). The basin is bounded on its north-eastern, eastern, and southern margins by wide cratonic areas, which were the main source areas for the basin-fill sediment during the Jurassic (Uliana and Legarreta 1993), and by a magmatic arc on the active margin of the Gondwanan–South American Plate to the west (Howell et al. 2005). The basin originated as a volcanic rift in the Triassic and evolved into a postrift back-arc basin during the Jurassic (Franzese and Spalletti 2001; Franzese et al. 2003). The basin is filled by more than 7 km of deposits (Vergani et al. 1995), hosting important hydrocarbon reserves (Urien et al. 1995).

The Lajas Formation consists of an approximately 400-m-thick succession of sandstone, mudstone, and heterolithic deposits that accumulated in a variety of
coastal and shallow marine depositional environments (Figure 2). Large parts of these deposits were interpreted to have accumulated in a deltaic setting, primarily controlled by fluvial processes and secondarily assisted by tidal and wave processes (Zavala 1996a,b; Canale et al. 2015; Gugliotta et al. 2015, 2016), although other authors considered that tidal processes dominated through the entire succession (McIlroy et al. 2005).

At the time the Lajas Formation accumulated 170 million years ago, the basin was part of the western margin of Gondwana (Figure 1b) and was located in a similar orientation and latitude to the basin’s present-day configuration (Iglesia Llanos et al. 2006; Iglesia Llanos 2012). Because of the relatively large size of the river channels (sand bodies up to 12 m thick) and the location of the source area (the Patagonian Massif at least 100 km away (Uliana and Legarreta 1993)), the paleorivers reaching the study area likely had relatively large catchment areas. Therefore, vast areas of the proto South American continent were likely drained by rivers with relatively large fluvial systems running from south and southeast to north and northwest.
Palynological studies suggest that the paleoclimate at the time of deposition was warm and mainly arid but with more humid periods (Quattrocchio et al. 2001; Martínez et al. 2002; García et al. 2006; Stukins et al. 2013). Rounded charcoal fragments in the Lajas Formation indicate the occurrence of wildfires (Marynowski et al. 2011).

3. Sedimentological evidence

To document and understand the sedimentary facies of the Lajas Formation, logging and photopanel reconstruction were undertaken (Gugliotta et al. 2015, 2016). The deposits of the Lajas Formation show ubiquitous decimeter-scale, interbedded, coarser-grained and finer-grained beds (Figure 3). These alternations are preserved in channel–bar, crevasse–subdelta, and mouth-bar deposits.
The beds are continuous for up to hundreds of meters and stack in units of a few meters in thickness. The alternation of the two types of beds creates noncyclic rhythmites recently interpreted to be the result of variations in river discharge (Gugliotta et al. 2015, 2016). The coarser-grained beds are mainly composed of sandstone and show erosional bases with mudstone clasts. They are commonly structureless or show seaward-directed, unidirectional trough or planar–tabular cross-stratification and current–ripple cross lamination. In contrast, the finer-grained beds are commonly heterolithic and locally contain mudstone, carbonaceous, or mica drapes, forming millimeter-scale tidal rhythmites with syneresis cracks (similar to desiccation cracks but occurring underwater as the sediments expel water and contract because of a salinity contrast). The finer-grained beds also contain bidirectional ripples, interpreted as due to the influence of tides. The coarser-grained beds have been interpreted as being deposited during river-flood conditions, whereas the finer-grained beds represent low-stage interflood conditions (Gugliotta et al. 2015; Figure 4).

In the river-flood beds, trace fossils are absent or rare, consisting of top–down bioturbation penetrating from the overlying interflood bed. In the interflood beds, a more abundant and diverse suite of trace fossils is present (e.g., *Palaeophycus*, *Ophiomorpha*, *Dactyloidites*, *Thalassinoides*, and *Planolites*) and is associated with an increase in the size of burrows and higher intensity bioturbation.

This evidence from the sedimentary record indicates that fluctuations in river discharge—and hence the strength and regime of the fluvial current—controlled the rate of sedimentation responsible for the alternation between coarse- and fine-grained beds. Additional evidence for the rhythmic pattern is the variation between layers with less and more bioturbation. At the onset of the river floods, erosion dominated (Figure 5a). As the floods waned, coarse-grained beds were deposited (Figure 5b), followed by finer-grained beds showing increasing evidence of tidal influence (Figure 5c). Finally, during the low-river stage, little fluvial input allowed...
the dominance of tidal processes as evidenced by the bidirectional ripples, increasing bioturbation, and reworking of sediments (Figure 5d).

4. Sedimentary layers likely represent annual cycles

Given these rhythmic deposits representing variations in sediment supply, the question is whether they are the result of seasonal variations in climate. Other authors have interpreted river-flood and interflood alternations in ancient deltaic deposits as the result of seasonality in the paleorivers (e.g., Dalrymple et al. 2015; Jablonski and Dalrymple 2016). The evidence for seasonal cycles in sedimentation is as follows.

First, nearly 95% of modern rivers show annual discharge fluctuations (Gugliotta et al. 2016, their Figure 1), and ancient rivers are not anticipated to be any different. The depositional record in modern seasonal rivers bears a striking resemblance to the sedimentology in ancient river deposits (e.g., Dark and Allen 2005; Allen et al. 2007; Choi 2011; Sisulak and Dashtgard 2012; Johnson and Dashtgard 2014). Therefore, by analogy, we expect the annual cycle to be the most likely cause of these alternations.
Second, the differences in river flow and discharge between the low and high river stages in modern systems, as well as the differences implied by the sedimentology of the Lajas Formation, are an order of magnitude. Decadal and longer-duration cycles are more subtle than this, where the variability of the annual mean in a decadal cycle is commonly of the same order of magnitude. The most obvious and largest alternations that result in deposits of sand with erosional bases and normal grading are most likely to represent annual fluctuations in discharge.

Third, the alternation of two types of beds (coarser and finer grained) requires a process in which two different conditions alternate (A–B–A–B–A–B–...), in this case interpreted as being high- and low-discharge states of the river. Such regular alternation is most likely explained by the annual cycle between a wet season and a dry season. The decadal, centennial, millennial, or Milankovitch cycles are not binary, so they cannot explain the A–B couplets. Such longer-duration cycles might be identified by analyzing the thickness of multiple A–B couplets and understanding their variations. Such an interpretation requires a detailed statistical analysis of the beds as was done by Jablonski and Dalrymple (2016). However, Jablonski and Dalrymple (2016) still interpreted the decimeter-scale alternations of coarser- and finer-grained beds (A–B) as parts of an annual cycle.

Fourth, if the recorded cycles represent longer-duration cyclicity, then the depositional environment would have needed to stay unchanged for time periods over which autocyclic processes are known to operate in deltas. To record a centennial cycle would require the same depositional barform to be active for at least a few hundred years, which is unlikely, given the historical evidence for river dynamics. To fully preserve longer-duration cycles, the subsidence rate would need to be greater than is reasonable. For example, given a mean flood/interflood bed thickness, full preservation of a 0.25-m-thick succession over 300 years would require 75 m of accommodation generation. Even allowing for erosion of sedimentary layers, such conditions are extremely unlikely to persist in a channel or mouth bar of a deltaic system. This preservation problem becomes even greater for longer-duration cycles such as 20 000-yr Milankovitch precession cycles. Thus, shorter-term cycles are more likely to be represented in the rock record in fluvial sedimentary environments.

Fifth, another point is whether these cycles record intra-annual, shorter-term periodicity due to heavy precipitation events. In rivers with relatively large drainage basins, the sedimentary effects of individual rainfall events are dampened by the drainage system itself (e.g., Allen and Chambers 1998). Such rivers show one river flood per year as the result of the longer-term annual variation in runoff. In contrast, in systems with small drainage areas, flow generally responds to individual rainfall events (Gonzalez-Hidalgo et al. 2010, 2013), causing multiple river floods in a single year. Such rivers are often characterized by intense floods with flashy discharge and show specific sedimentary features, such as abundant, pedogenically modified mud partings, abundance of upper flow-regime sedimentary structures, and in situ trees (Fielding 2006; Fielding et al. 2009, 2011; Gulliford et al. 2014; Wilson et al. 2014). These features are not recognized in the Lajas Formation. The presence of preserved bar elements further supports seasonal rather than flashy discharge fluctuations (Fielding et al. 2009, 2011).

For these five reasons, the evidence from the geologic record is that these cycles in sedimentation are due to cycles in runoff and sedimentation on the annual time scale.
5. Paleoclimate model simulation

For further testing of the hypothesis that the cycles in sedimentation are annual, we use a paleoclimate model simulation of the Middle Jurassic to investigate annual variations in precipitation over the basin. Additional assumptions that would need to hold to achieve this result include the following: First, because of the coarse resolution of paleoclimate models and uncertainty in the paleoclimate, the rivers should have had large catchment areas of low-gradient plains such that the fluvial discharge would be directly related to the precipitation and be adequately resolved. This condition fits the interpreted regional paleogeography described in section 2. Second, there should be an absence of substantial snowfall accumulation in the model so that the discharge fluctuations are only the result of the precipitation and not of snowmelt. This assumption will be tested below.

5.1. Model methods

The paleoclimate simulation uses the Fast Ocean Atmosphere Model (FOAM; Jacob et al. 2001), a coupled general circulation model derived from the National Center for Atmospheric Research Community Climate Model, version 2 (NCAR CCM2; Hack et al. 1993), and optimized for efficient and fast simulations. FOAM has two-way interactions between the atmosphere and ocean general circulation models as well as an interactive sea ice model. Topography, vegetation, and land surface type are fixed. Our control simulation was initialized by interpolating the Middle Jurassic paleogeographic reconstruction at 170 million years ago (Colorado Plateau Geosystems 2014) to the model grid (cf. Figures 1b and 6a). Because of the uncertainty in the paleobathymetry and for simplicity, the ocean depths were set to 110 m on continental shelves and 3100 m in the deep ocean. Paleovegetation follows the classification of Matthews (1983) and was assumed to be a function of latitude (Figure 6b), which is the default assigned by the model boundary condition generator Slarti. Other past paleoclimate experiments using FOAM have typically used one fixed vegetation classification (e.g., Donnadieu et al. 2006b; Zhang et al. 2011) in the absence of any data of past biomes or vegetation models, so our simulation potentially provides a more realistic assumption about the past vegetation.

Atmospheric concentrations of greenhouse gases in the control simulation were set as follows: 3000 ppm for carbon dioxide, consistent with 8 times its present value (Ward 2006, p. 30); 306 ppb for nitrous oxide, set at preindustrial levels because of lack of any proxy records; and 7.5 ppm for methane, set from a ratio of $2.5 \times 10^{-3}$ methane to carbon dioxide concentrations in the atmosphere, which assumes the same ratio as preindustrial in the absence of any other information about the paleomethane concentration.

The horizontal grid spacing in the atmosphere was 4.5° in latitude and 7.5° in longitude (about 500 km by 800 km near the equator) with 18 levels, and the horizontal grid spacing in the ocean and sea ice models was operating at 1.4° latitude and 2.8° longitude with 24 levels. The time step in the atmosphere was 20 min. The solar constant was set at 1340 W m$^{-2}$ [2% less than present day, consistent with Donnadieu et al. (2006a)], and the rotation rate of the Earth was its present value of 7.292 $\times$ 10$^{-5}$ s$^{-1}$. The model was run for 130 years in order for
the control simulation to reach equilibrium, as defined by the stabilization of the global-mean annual-mean temperature over time. The next 30 years of simulation were analyzed as the equilibrium time-slice climate control simulation in this article.

To determine the sensitivity of the control simulation to greenhouse gas concentrations, we refer to previous literature. To our knowledge, only one previous paleoclimate simulation of the Middle Jurassic has been performed (Donnadieu et al. 2006a), which offers few maps of the meteorological conditions from their simulation. For comparison, we rely on one simulation from the Lower Jurassic (Chandler et al. 1992) and the simulations of the Upper Jurassic by two different research groups: Ross et al. (1992) and Moore et al. (1992a,b) versus Valdes and
Sellwood (1992), Valdes (1993), Sellwood et al. (2000), and Sellwood and Valdes (2006, 2008). These simulations have considerably less carbon dioxide than our simulations (cf. 280–1160 and 3000 ppm) but are within the large uncertainty in suspected carbon dioxide concentrations occurring during this time and the discrepancies with proxies (Figure 10 in Ekar et al. 1999; Figure 2 in Royer et al. 2004). To test the sensitivity of the Middle Jurassic simulation to the greenhouse gas concentrations, we performed a simulation with the carbon dioxide concentration reduced to 1080 ppm and the methane concentration reduced to 2.7 ppm. This simulation did not yield a qualitatively different precipitation pattern as our control simulation (not shown), despite the global-mean temperature being nearly 5°C lower than our control simulation, so we believe our results to be relatively insensitive to large changes in greenhouse gas concentrations.

5.2. Model results

Despite the uncertainties in the paleogeography of the Middle Jurassic, the control model simulation reasonably reproduces the global-mean, annual-mean surface air temperature. The global-mean temperature at equilibrium for the simulation was 19°C or about 5°C above a year 2015 simulation. This 5°C difference is consistent with reconstructions of temperature at 170 million years ago showing an anomaly of 5°C with ±2°C uncertainty above the 1960–90 mean (Royer et al. 2004). These results are also consistent with the 5°C temperature anomalies in previous paleoclimate simulations of Pangaea (e.g., Kutzbach and Gallimore 1989; Chandler et al. 1992) but are larger than the 3°C anomaly from Donnadieu et al. (2006a), although still within the error bars of the reconstructions.

The mean surface air temperature from the control simulation in February and August illustrates the warmth of Earth at this time (Figure 7). During February (Southern Hemisphere summer), mean temperatures exceed 45°C at 30°S over Gondwana with a strong gradient poleward to mean temperatures of about 30°C over the Neuquén Basin (Figure 7a), consistent with the geologic evidence described in section 2. By August (Southern Hemisphere winter), the region of highest temperatures have moved equatorward (exceeding 40°C at 10°S), with mean temperatures over the basin of 10°–15°C (Figure 7b). These temperatures are comparable with those in the simulations by Chandler et al. (1992) for the Lower Jurassic, except in the southernmost landmass in the late winter [minimum temperature −15°C in August for the present study in Figure 7b vs −35.2°C in June–August for Chandler et al. (1992) in their Figure 5]. Temperatures in Figure 7 are also consistent with those in Valdes and Sellwood (1992, their Figure 2) and Sellwood and Valdes (2006, their Figures 3a,b) for the Upper Jurassic, although theirs have more detail because of their higher resolution. At the grid point of the Neuquén Basin (37.7°S, 22.5°W), mean February temperatures were 28°C (±2°C standard deviation) and mean August temperatures were 8°C (±3°C standard deviation; not shown).

The band of high precipitation amounts associated with the intertropical convergence zone (ITCZ) and the band of low precipitation amounts associated with the subtropical descent in the Hadley cell also undergoes a seasonal shift
(Figure 8), consistent with previous research (e.g., Loope et al. 2001; Ziegler et al. 2003). Over the Neuquén Basin in February, the precipitation rate can be less than 0.1 mm day$^{-1}$ (3.5 mm month$^{-1}$; Figure 8a), whereas in August, the subtropical descent has moved equatorward, leaving the Neuquén Basin at the poleward edge of the strong gradient in precipitation (ranging from less than 0.05 mm day$^{-1}$ on its equatorward edge to more than 1 mm day$^{-1}$ on its poleward edge; 1.5 to 30 mm month$^{-1}$; Figure 8b). This precipitation mainly falls in the form of rain, as no winter snow and ice accumulate near the basin in the model (Figure 9), consistent with Valdes and Sellwood (1992, their Figure 2), Valdes (1993, his
Figure 6), and Sellwood and Valdes (2008, their Figure 4). With little to no snow cover around the basin in the model, we can interpret the discharge fluctuations in the sedimentary record to be primarily the result of the seasonal rainfall and not because of the melting of a snowpack. The lack of a deep snowpack on Gondwana is consistent with other paleoclimate simulations from the Jurassic (e.g., Chandler et al. 1992; Moore et al. 1992a). Thus, the strong annual cycle in rainfall in the control simulation likely explains the strong cycles in sedimentation (Figures 3–5).

**Figure 8.** Mean precipitation rate (mm day$^{-1}$) in (a) February and (b) August from the control simulation. This field is created from the mean of all daily total precipitation amounts for that month over the 30-yr period of analysis of the control simulation.
To further illustrate this strong annual cycle, the precipitation amount from the control simulation at the point for the Neuquén Basin is calculated (Figure 10). Precipitation in February averages 4 mm month$^{-1}$ ($\pm$4 mm standard deviation) compared to August with a maximum of 34 mm month$^{-1}$ ($\pm$17 mm standard deviation). This annual cycle in precipitation is strong, with the August “mean $-1$ standard deviation” curve exceeding the January “mean $+1$ standard deviation” curve (Figure 10). This cycle is apparent at five of the eight surrounding points (Figure 11). The exceptions are the three points to the east with a weak annual cycle due to a strong west–east gradient in continentality due to the basin being on the western edge of the continent. Nevertheless, all nine points show that precipitation is at its minimum early in the year and maximum later in the year (Figure 11).

To confirm that the annual cycle is the dominant signal in the modeled Neuquén Basin, the time series of monthly precipitation at the grid point is decomposed through Fourier analysis (Figure 12). The amplitude maxima of 0.21 at 12-month periodicity and 0.03 at 6-month periodicity indicates that the annual and semi-annual cycles together explain 24% of the variance in the time series of monthly precipitation at the Neuquén Basin grid point.

5.3. Comparison to current climate and the geologic record

A warm, arid summer with a mild, wet winter simulated by the paleoclimate model is reminiscent of a Mediterranean climate. Such a climate is also consistent with the palynological evidence (Quattrocchio et al. 2001; Martínez...
et al. 2002; García et al. 2006; Stukins et al. 2013). The presence of rounded charcoal fragments in the formation (Marynowski et al. 2011) is consistent with a dry warm season in which lightning strikes from dry thunderstorms (i.e., thunderstorms in which the rain evaporates before reaching the ground) could start wildfires.

5.4. Comparison to previous simulations

Our result differs from that in Chandler et al. (1992, their Figure 8), who did not find any continental locations in the tropics and subtropics with precipitation rates exceeding 1 mm day$^{-1}$. Moore et al. (1992a, their Figure 11) also produced a much drier continental climate. This discrepancy is possibly due to the rather coarse resolution of their model (7.83° latitude by 10° longitude with nine levels), which shows less spatial detail than our simulation, and is also apparent in the temperature fields, although that would not explain the similarity to the Moore et al. (1992a) simulation. Also, Hallam’s (1985, his Figures 6 and 7) schematics of seasonally wet areas for the Lower and Upper Jurassic do not reach as far poleward as the Neuquén Basin. Were such an arid environment to occur throughout the year, as depicted in these studies, annual cycles of the intensity observed in the geologic record of the Neuquén Basin would be unlikely. Indeed, the Lower–Middle Jurassic simulation of Donnadieu et al. (2006a, their Figure 5d) shows nearly no runoff at the location of the Neuquén Basin (<10 cm yr$^{-1}$). Thus, the control simulation presented in this paper appears to be an improvement over previously published simulations and shows consistency with the geologic record in the Neuquén Basin. In addition, this article provides further support for the argument

Figure 10. Annual cycle in mean precipitation amount (mm, thick black solid line) plus and minus one standard deviation of the daily amounts (mm, thin red dashed lines) over the Neuquén basin.
raised by Sloan and Barron (1990) and Chandler et al. (1992) that equable climates still had large temperature gradients and annual temperature changes over middle and high-latitude continents, questioning whether the term “equable climate” is appropriate.

Figure 11. Annual cycle in monthly mean precipitation amount (mm, black solid line) over the Neuquén Basin (labeled center) plus the eight surrounding points (labeled by their cardinal direction).

Figure 12. Fourier decomposition of the monthly precipitation amount as a function of period (months) over the Neuquén Basin. The y axis labeled amplitude represents the fraction of variance explained for each period.
6. Conclusions

The Lajas Formation of the Neuquén Basin, Argentina, provides a Middle Jurassic (170 million years ago) record of mainly fluvial-dominated, tidal-influenced delta sedimentation. Constituent channelized and nonchannelized deltaic deposits contain decimeter-scale, interbedded sandstone and heterolithic facies interpreted as river-flood and interflood deposits, respectively. The interflood deposits show tidal influence consistent with the low-river stage. To test the hypothesis that the river-flood–interflood cycles represent annual fluvial discharge fluctuations, a paleoclimate model was run to simulate the climate of the Middle Jurassic. The paleoclimate model simulation depicts a global circulation consistent with the reconstructions of paleoclimate at the time through geologic evidence. February mean temperatures were 28°C with 4-mm precipitation (±4 mm standard deviation) per month, whereas August mean temperatures were 8°C with 34-mm precipitation (±17-mm standard deviation) per month. These strong annual fluctuations in rainfall and humidity across the basin derived from the paleoclimate simulations are consistent with previously published palynological evidence and the charcoal fragments caused by wildfires. Therefore, the interbedding of the river-flood beds and interflood beds in the Lajas Formation is likely explained by annual variations in sediment supply with river floods during the wet season in the Southern Hemisphere cool season and the interflood period during the dry season in the Southern Hemisphere warm season. The simulation also suggests a Middle Jurassic climate where increased seasonality of precipitation occurred farther poleward than previously thought. Finally, this article shows the importance of integrated cross-disciplinary collaborative research.

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