Isotopic, paleontologic, and ichnologic evidence for late Miocene pulses of marine incursions in the central Andes

Cornelius E. Uba[1], Claude-Alain Hasler[2], Luis A. Buatois[3], Axel K. Schmitt[4], and Birgit Plessen[5]

[1]Institut für Geowissenschaften, Universität Potsdam, 14476 Potsdam, Germany

[2]Department of Geology and Paleontology, University of Geneva, Boulevard du Pont-d'Arve 40, CH-1211 Geneva, Switzerland

[3]Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5E2, Canada

[4]Department of Earth and Space Sciences, University of California–Los Angeles, Los Angeles, California 90095-1567, USA

[5]Deutsches Geo Forschungs-Zentrum, Potsdam 14473, Germany

ABSTRACT

Recognition of an inferred Miocene marine incursion affecting areas from Colombia through Peru and Bolivia and into Argentina is essential to delineate the South American Seaway. In Bolivia, corresponding strata of inferred marine origin have been assigned to the late Miocene Yecua Formation. We carried out high-resolution $\delta^{13}C$ and $\delta^{18}O$ isotopic studies on 135 in situ carbonates from 3 outcrops, combined with detailed sedimentologic, paleontologic, and ichnologic analysis. Four less negative $\delta^{13}C$ excursion levels were recorded that coincide well with beds containing marine body (barnacle) and trace (*Ophiomorpha*) fossils. These strata are interbedded with red-green beds containing mudcracks, plant roots, gypsum, and trace fossils of the continental *Scoyenia* ichnofacies. Our data are significant in that they show for the first time four possible short-lived marine incursions in the Bolivian central Andes during the late Miocene. The result is constrained by a new U-Pb date of 7.17 ± 0.34 Ma at the top of Yecua strata.

INTRODUCTION

The Miocene paleoenvironmental and paleogeographical history of the central Andes in particular and South America in general has been a matter of intense debate. There have been controversial views on possible marine connection from Colombia through Peru (Amazonia) and Bolivia into Argentina (Paranan) during the Miocene. Several authors proposed a north-south embayment system or seaway, on the basis of tidal signatures and faunal similarities (Räsänen et al., 1995; Lovejoy et al., 2006; Hernández et al., 2005; Hovikoski et al., 2005, 2007; Uba et al., 2005; Hulka et al., 2006). In contrast, Wesselingh et al. (2002), Vonhof et al. (2003), and Hoorn et al. (2006) used stable isotopic, palynologic, and sedimentologic studies to suggest lacustrine and fluvial settings. The proponents of the South American embayment system or seaway invoked the Bolivian late Miocene Yecua strata as the connecting route, thus highlighting its importance in revealing marine incursion in South America. Previously, the Yecua unit has been interpreted on the basis of sedimentology and foraminifera as a long-lived marine deposit (Hernández et al., 2005; Hulka et al., 2006) or a restricted marine-lacustrine deposit (Marshall et al., 1993; Uba et al., 2006). As a result of the different interpretations, the Yecua paleoenvironment and its implications for the South American Seaway remain unresolved.

The aim of this paper is to shed light on the Yecua paleoenvironment and the South American embayment or seaway system. To achieve this, we selected three sections in Bolivia where late Miocene marine and/or lacustrine strata crop out, and conducted sedimentologic, paleontologic, C-O isotopic, and ichnologic studies. Two of these sections have been studied previously and interpreted differently, i.e., ranging from marginal-marine, tidal, lacustrine, to fluvial environments (Marshall et al., 1993; Uba et al., 2005; Hulka et al., 2006). This is the first study in using this integrated approach to unravel the depositional setting of the Yecua Formation.

STUDY AREA

The study area is situated along the Piray River (Angostura), and along the new Abapó and Camiri highway (Agua Buena, Fig. 1), where the Yecua Formation has good outcrops. In addition to these outcrops, we studied the Abapó section along the Grande River to complement the observation from the other two sections (see the GSA Data Repository[1]). The upper Miocene deposit is as thick as 250 m, and is included stratigraphically within the Yecua Formation; it is correlated to the Pebas, Ipururo, and Nauta Formations (Peru), the Solimoes Formation (Brazil), and the Anta Formation (Argentina) (e.g., Hernández et al., 2005; Hoorn, 2006; Hulka et al., 2006; Rebata et al., 2006; Hovikoski et al., 2007). The Yecua strata consist of mudstone, sandstone, and limestone arranged in repeated 1–8-m-thick sequences. In addition, many Miocene fossils from these outcrops, such as foraminifera, ostracods, gastropods, and bivalves,

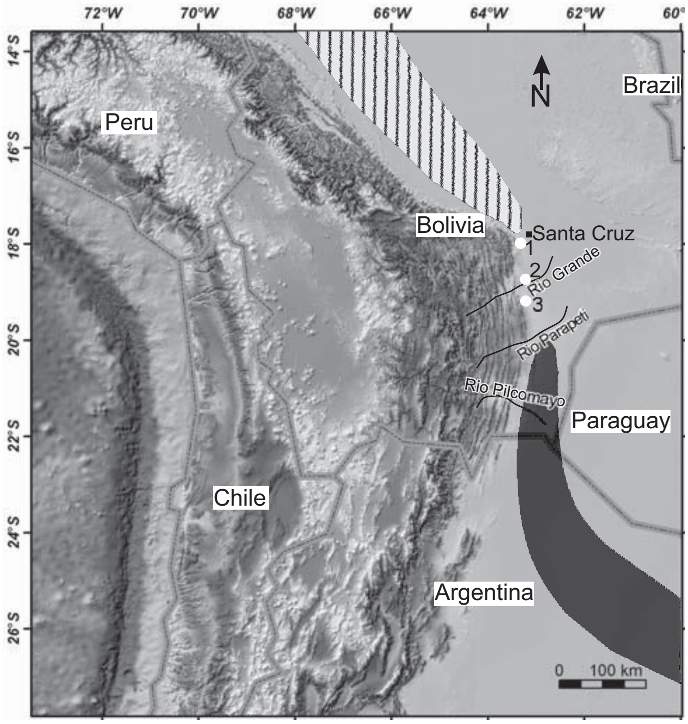


Figure 1. Digital elevation map of central Andes with location of study area and measured sections. 1—Angostura (x: 0445136, y: 7991158); 2—Abapó (x: 0455369, y: 7907089); 3—Agua Buena. Vertical shaded area represents northern arm of the South American marine ingression (modified from Räsänen et al., 1995); gray area indicates extent of Paranan Sea (after Marshall et al., 1993).

[1]GSA Data Repository item 2009202, Figure DR1 (summary of stratigraphic profile, paleontologic data, $\delta^{18}O$ and $\delta^{13}C$ curves, and interpreted paleoenvironments from the Abapó section), and Table DR1 (analytical method and results of the C-O isotope analysis on paleosol carbonates), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

have been documented (e.g., Marshall et al., 1993; Hernández et al., 2005; Hulka et al., 2006). The formation is estimated to be 12.4–8 Ma old on the basis of U-Pb chronologic dates (Uba et al., 2007).

METHODS

The data set consists of sedimentologic, stable isotopic, paleontologic, and ichnologic analysis. A detailed sedimentologic analysis was carried out at the three sections, and hand samples were collected at ~1–5 m intervals for petrography and geochemistry. Thin sections and polished slabs of representative samples of mostly limestone lithofacies were made and screened under microscopy to determine fossil components. We selected 135 samples consisting predominantly of micritic limestone and carbonates from paleosols (alluvial sediments) for isotopic analysis. Between 0.2 and 2 mg of each of the powdered samples were analyzed using the Finningan GasBenchII with carbonate option coupled to a DELTAplusXL mass spectrometer at the Deutsches GeoForschungs-Zentrum, Potsdam. (For the C-O analytical methods and results, see footnote 1.) The size and type of ichnotaxa of burrows were documented. In addition, zircons from a volcanic ash at the top of the Yecua strata at the Angostura section were dated by the U-Pb method using the Cameca IMS (ion mass spectroscope) 1270 at the University of California Los Angeles.

RESULTS

Angostura Section

This 250-m-thick section exposes a complete succession of the Yecua Formation, and consists of interbedded gray-green limestone, green-purple-red mudstone, and light brown to yellow sandstone that extend laterally for several kilometers. The locally sandy limestone beds are 10–100 cm thick and parallel laminated. The 10–40-cm-thick limestone beds mostly occur in the lower and middle interval of the section. The 20-cm- to 7-m-thick mudstone intervals are dominantly horizontal laminated, and contain plant roots (Fig. 2A), poorly to moderately developed paleosoils, mudcracks (Fig. 2B), and flaser, lenticular, and wavy bedding. The mudstone is interbedded with 40–100-cm-thick, rippled, medium- to coarse-grained, calcareous, parallel-laminated sandstone that locally contain fragments of bivalves and ostracods. At the upper part of the section, the sandstone beds locally show erosive surfaces.

This section contains foraminifera, bivalves, ostracods, and gastropods (Hulka et al., 2006; Hernández et al., 2005). In addition to some of these fossils, we identified barnacles and the foraminifera *Ammonia* (Figs. 2C and 2D). The bioturbation intensity increases upsection, but with low-diversity assemblages in the finer-grained mudstone. The trace fossils observed include *Ophiomorpha* (Fig. 2E) and other crustacean burrow systems, *Palaeophycus*, and *Taenidium* (Fig. 2F); the latter is abundant in the upper part. The $\delta^{13}C$ values fluctuate between −3.2‰ and −16.7‰, and the $\delta^{18}O$ between −6.5‰ and −13.7‰ (see the Data Repository). Whereas $\delta^{18}O$ is more prone to diagenetic alteration, the $\delta^{13}C$ signal is more difficult to alter (Banner and Hanson, 1990). At this section, the new U-Pb dating of zircon yields an age of 7.17 ± 0.34 Ma for the top of the Yecua Formation (Fig. 3).

Agua Buena Section

At Agua Buena (Fig. 2G), which is at the southernmost end of the study area, only a 130 m thickness of the Yecua unit is exposed. The strata consist of 10–50-cm-thick, sharp-based, parallel-laminated, green-gray limestone; 0.5–5-m-thick, red-green, horizontally laminated mudstone; and 20–60-cm-thick, light brown to light green, planar to lenticular fine- to coarse-grained sandstone. In the middle part of the section, an intercalation of coquina-rich, wedge-shaped, quartzose, low-angle cross-bedded coarse-grained sandstone and subordinated thin-bedded green-gray mudstone (Fig. 2G) overlies the barnacle-containing unit (Figs. 2C and 2G). The sedimentary structures observed include wavy and flaser bedding, climbing ripples, and trough cross-stratification. Soft-sediment deformation structures are common in the upper half of the section.

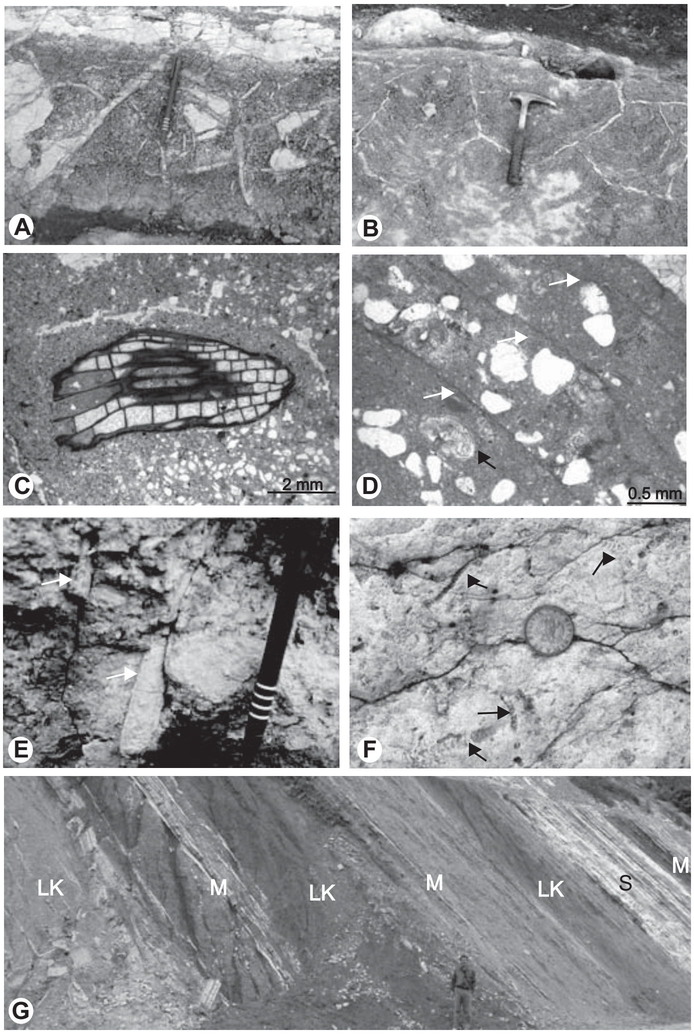
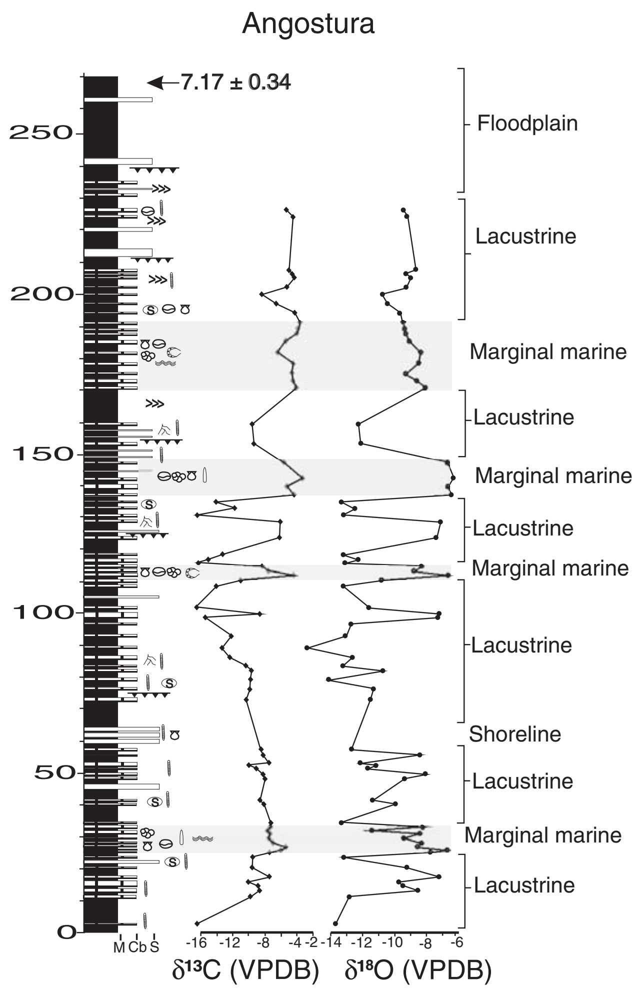


Figure 2. Outcrop and petrographic photos. A: Plant roots from Angostura. B: Mudcracks from Angostura. Hammer is 33 cm long. C: Tangential section of barnacle's plate showing longitudinal tubes (opening toward left), and longitudinal and tangential septa. D: Detrital quartz and foraminifera (*Ammonia*, black arrows) trapped within stromatolite growing laminae (white arrows). E: *Ophiomorpha* from Agua Buena (white arrow) showing typical pelletoidal wall. F: *Taenidium* from Angostura (black arrows) characterized by meniscate backfilled structure. Diameter of coin is ~2.5 cm. G: Cross-section view of Agua Buena (person for scale is 1.82 m tall). Lk—lake, M—shallow marine, S—shoreface.

In addition to some of the fossils previously recorded (see Hernández et al., 2005; Hulka et al., 2006), we identified centimeter-scale columnar agglutinated stromatolites (Fig. 2D), barnacles, and the genus *Ammonia* (Fig. 2D), which is extremely abundant in this section. Bioturbation is generally low and the dominant ichnogenus is *Ophiomorpha*. The ichnogenus *Taenidium* occurs near the top of the section. Isotopic analysis shows $\delta^{13}C$ values ranging between −2.25‰ and −15.1‰, whereas the $\delta^{18}O$ fluctuates between −4.96‰ and −11.1‰. It is interesting that the C-O results from micritic limestone are similar to the $\delta^{13}C$ and $\delta^{18}O$ values obtained by Hulka (2005) from foraminifera and ostracods calcite at the same outcrops.



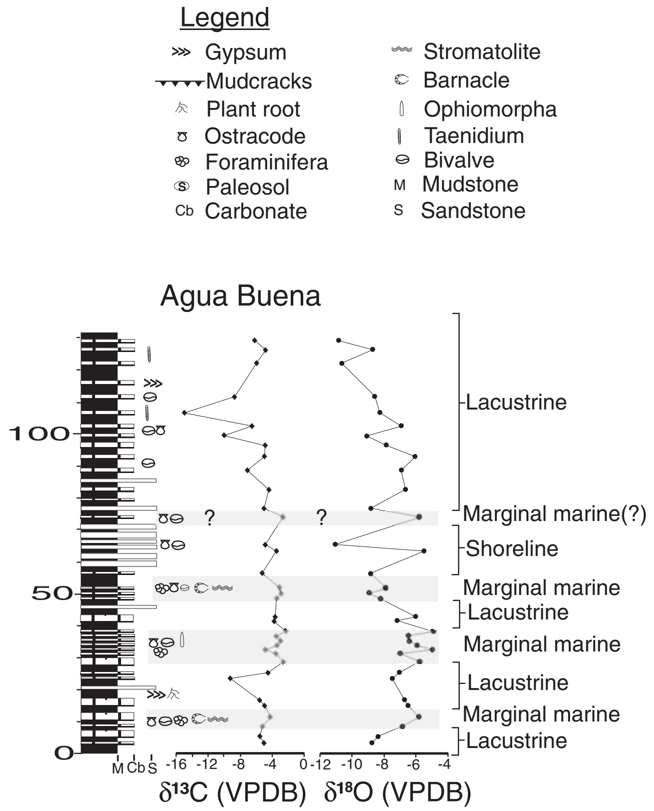


Figure 3. Summary of stratigraphic profiles, paleontologic data, $\delta^{18}O$ and $\delta^{13}C$ curves, and interpreted paleoenvironments from Angostura and Agua Buena sections. Note shaded areas that show marine levels. New U-Pb zircon age of 7.17 ± 0.34 Ma ago is indicated; VPDB—Vienna Peedee belemnite.

DISCUSSION AND CONCLUSIONS

Yecua Paleoenvironment

Sedimentologic, isotopic, paleontologic, and ichnologic analyses from the three sections allow the interpretation of the Yecua unit as repeated intercalations of marginal-marine, lacustrine, and shoreline deposits (Fig. 3). A marginal-marine setting is supported by the presence of barnacles, which are exclusively marine (Foster, 1987) as well as Neogene in age (Donovan, 1989; Doyle et al., 1996). This interpretation is further supported by the presence of stress-tolerant elements, such as stromatolites, *Ammonia*, and the ichnofossil *Ophiomorpha*. In particular, the latter two do not occur in fresh water (Pemberton and Wightman, 1992; Riding, 2000; Nikulina et al., 2007). The extremely low diversity of the trace-fossil suites and the presence of *Ammonia* indicate brackish-water conditions rather than normal-marine salinities. The brackish-water interpretation for these deposits is further supported by the close association of fluvio-lacustrine and marginal-marine trace fossils and sedimentary facies (e.g., Hovikoski, et al., 2007). The late Miocene marine incursion into the central Andes is further enhanced by the relatively good correlation of the less negative $\delta^{13}C$ (between −3.8‰ and −2‰) excursion levels with the shallow-marine fauna and trace fossils (Fig. 3). Although the $\delta^{13}C$ data for the interpreted marine incursion do not show the typical positive values, the trend is significant. Furthermore, Krull et al. (2004) and Gomez et al. (2007) showed that C-O values for shallow-marine carbonates could be negative.

The facies with mudcracks, primary gypsum, plant roots, and paleosoils are interpreted as lacustrine and alluvial-plain deposits. They locally contain ostracods and freshwater bivalves, and no foraminifera or other marine fossils were observed. This interpretation is further supported by the presence of elements of the freshwater *Scoyenia* ichnofacies (*Taenidium*). Sedimentologic and ichnologic evidence indicates periodic subaerial exposure (e.g., Buatois and Mángano, 2007). In addition, this facies shows higher negative $\delta^{13}C$ values, which range between −16.7‰ and −5‰.

The coarse-grained quartzose coquina-rich sandstone facies represents high-energy conditions, consistent with those of nearshore areas. This interpretation is further supported by the presence of the marine bivalve *Tellina* (Hulka, 2005), associated with barnacles, and the ichnogenus *Ophiomorpha*. The coarsening-upward successions may suggest shoreline progradation, encompassing deposition in shoreface to foreshore settings under wave activity.

Our interpretation for the Yecua Formation is in agreement with that of Marshall et al. (1993), who suggested lacustrine and shallow-marine settings. In addition, our data partly agree with Hulka (2005), who suggested short-lived marginal marine, shoreline, and coastal environments. In contrast, the data presented here disagree with Hernández et al. (2005), who postulated a long-lived open marine setting in Bolivia during the late Miocene.

It is interesting that our data allow us for the first time in the central Andes to (1) distinguish marine from fluvio-lacustrine conditions for late Miocene rock, and (2) document probably four short-lived marine ingressions. Although the C-O isotopic data are far from conclusive, the correlation of the less negative excursion levels with marine fauna and ichnofossils may strongly suggest periods of short-lived marine systems in the central Andes during the late Miocene. Furthermore, the occurrence of continental ichnofossils and sedimentologic features close to marine fauna and ichnofossils in the Yecua strata probably indicates that marginal-marine–influenced strata represent short-lived cycles. Similar observations have been documented in the Pebas Formation in Peru (Hovikoski et al., 2007).

Alternatively, the alternation of environments may reflect tectonic subsidence and pulses of progradation into a steady sea level. However, the thicknesses of these sections (as much as 250 m) argue for the interpretation of multiple transgressions.

Implications for the Miocene South American Paleogeography

Our data allow the documentation of pulses of marine ingressions into the Bolivian central Andes. In light of the Miocene South American embayment or seaway controversy, the result from this study supports the proposal of a South American marine transgression (Räsänen et al., 1995; Hernández et al., 2005; Hovikoski et al., 2005; Uba et al., 2005; Hulka et al., 2006). In addition, the data partly support the lacustrine interpretation (Wesselingh et al., 2002; Vonhof et al., 2003; Hoorn, et al., 2006), although within the framework of repeated transitional marginal marine-freshwater systems (e.g., Hoorn, 2006, Lovejoy et al., 2006). It is important that the result presented here improves on the previous suggestion by Vonhof et al. (2003) of one marine incursion level. Although our data have some uncertainty, they show that the Bolivian central Andes foreland basin may have undergone more than one marine ingression (Lovejoy et al., 2006), and probably as many as four transgressions during the late Miocene.

The data presented herein, however, cannot reconcile the debate on the pathway of the marine ingression into the central Andes. Nonetheless, we suggest two possible scenarios: (1) a northeastern source through Amazonia as proposed by Hulka et al. (2006), since Hovikoski et al. (2007) showed the unlikelihood of a northern connection (through southern Peru and northern Bolivia), and (2) a southern connection from the Paranan Sea through southern Bolivia.

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