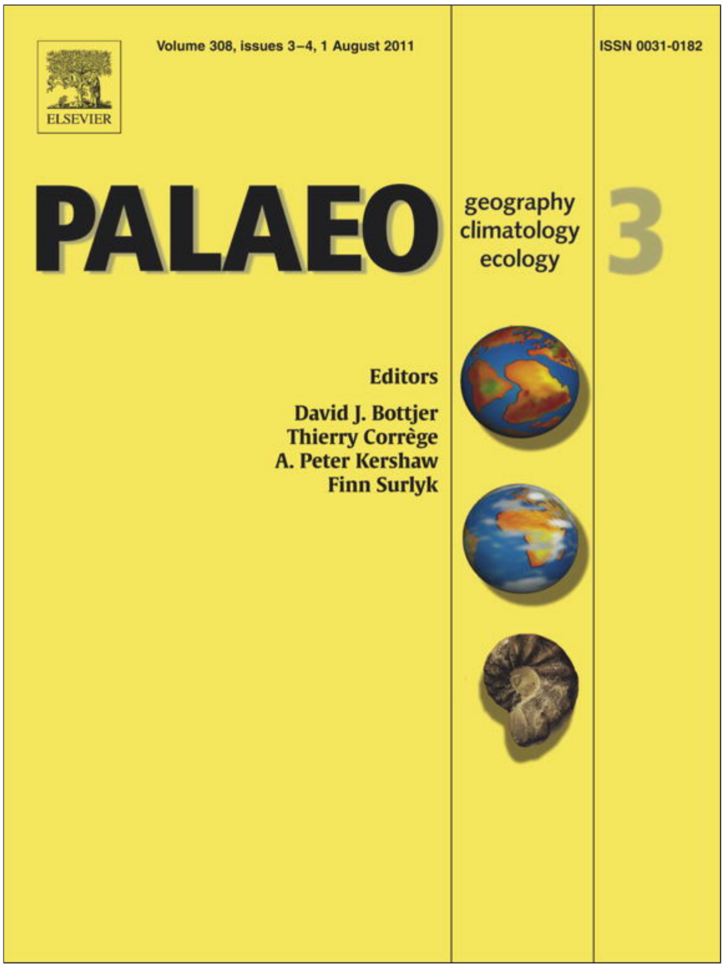
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Stable isotope composition of middle Miocene carbonates of the Frontal Cordillera and Sierras Pampeanas: Did the Paranaense seaway flood western and central Argentina?

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ABSTRACT

The geographic extent, interconnectedness and chronology of the Miocene "Paranaense" epeiric seaway have been the subject of considerable debate. Understanding the timing and location of this marine incursion is significant for documenting sea level changes, paleoclimatic changes, and surface uplift or subsidence. Stable isotope analyses of carbonate strata in the flat-slab segment of the Sierras Pampeanas and high Andean Cordillera, previously purported to be of marine origin, provide evidence that the Paraná seaway did not inundate this portion of west and central Argentina. No unambiguously marine facies or isotopic signatures were recognized for five representative stratigraphic units: the Saguión Formation ESE of Salinas Grande in Córdoba Province; Anta Formation in the Quebrada de la Yesera and Lerma Valley of Salta Province; Del Buey and Del Abra Formations within the Famatina Ranges, La Rioja Province; and Chinches Formation in the Manantiales foreland basin in the Frontal Cordillera, San Juan Province. Paleontologic and lithologic features in support of a marine origin are reconsidered herein. Instead, a lacustrine origin is inferred for these formations, their contemporaneity perhaps related to concurrent global climate conditions and broad tectonic setting. Until more substantive evidence of marine deposition is found, we reject correlation of these units with the Paraná seaway, preserved in the Chaco-Pampean Plain subsurface, and discourage mapping of the seaway as extending into the central Sierras Pampeanas or Andean foreland. Our findings suggest the Miocene Andean foreland was elevated above sea level although it remained as a largely flat-lying area west of the Pampas and Chaco plains, which were inundated by the Paraná seaway.

1. Introduction

Constraining the spatial extent of marine incursions in the rock record by means of facies and isotopic analyses is necessary for documenting sea level fluctuations, paleoclimatic changes, and surface uplift or subsidence. The main objective of this work is to contribute new lithologic interpretations and isotopic proxies to allow further discussion of the setting and paleoclimate of Miocene carbonate beds, interpreted by most previous workers as marine deposits contemporaneous with the Paranaense incursion. These beds are exposed from, in the west, the Frontal Cordillera (high Andes) to, in the east, the Sierras Pampeanas region of Argentina. Both areas constituted part of an extensive foreland basin system by early Neogene (Jordan et al., 2001). While the Frontal Cordillera was associated with foredeep depozones, the Sierras Pampeanas represented the distal foredeep to back-bulge zones (see Dávila et al., 2007). Our data and interpretations provide constraints on the western extent of the Paranaense transgression into this foreland system, which is topographically elevated at present and likely also elevated during the middle Miocene (16–11.6 Ma).

The paleogeography, interconnectedness and chronology of flooding of the Miocene "Paranaense" epeiric seaway have been subjects of considerable debate (e.g. Camacho, 1967; Ramos and Alonso, 1995; Hernández et al., 2005; Lovejoy et al., 2006; Marengo, 2006; Uba et al., 2009). During the Middle and Late Miocene (15–7 Ma), portions of Argentina, Bolivia, Brazil, Colombia, Ecuador, Paraguay, Uruguay and Venezuela were inundated with seaways, variously called the Amazonian and Caribbean in northern South America (Hoorn and Vonhof, 2006; Rebata et al., 2006; Hovikoski et al., 2007), and Paranaense or Entrerrianense in Argentina (Jordan and Alonso, 1987;

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Ramos and Alonso, 1995; Hernández et al., 2005; Hulka et al., 2006; Lovejoy et al., 2006; Marengo, 2006). Eustatic sea level was relatively higher during the Middle Miocene than at present, although not at the magnitudes formerly reported (cf. +150 m sea level maxima of Haq et al., 1987 with +50 m maxima and concordant long term sea level stillstand or gradual fall of Van Sickel et al., 2004).

In Argentina, unequivocal exposures of marine units attributed to the Paranaense ingression are the Miocene Paraná Formation outcropping near Entre Ríos, NE Argentina and the correlative Puerto Madryn–Chenque Formations (marine interval 15.6 –10 Ma, Malumián and Nañez, 1996; Scasso et al., 2001) along coastal Patagonia, also known as the Patagoniense transgression in SE Argentina (Malumián, 1999). These units comprise transgressive sequences with reef and platform limestones containing bivalves and gastropods (Del Rio et al., 2001) or alternatively by greenish shale and silt intervals as in Patagonia and regions east of the Sierras Pampeanas, in the subsurface of the Pampas plain (Marengo, 2006). Sedimentary facies and fossil content have been interpreted as evidence of coastal marine paleoenvironments, and signify multiple times at which relative sea level rise led to Atlantic flooding into the Chaco-Pampean Plain and eastern Patagonia (Martinez, 1988; Hernández et al., 2005; Marengo, 2006). In NW Argentina, calcareous, foraminifera-bearing intervals of the Rio Salí (14 Ma, Bossi and Palma, 1982) and San José Formations, as well as portions of the Yecua Formation (12.4–7.9 Ma, Uba et al., 2009) in southern Bolivia, record multiple, short-duration, marine incursions based on trace fossils, stromatolites, foraminifera and less-depleted isotopic values (e.g. Hernández et al., 2005; Hulka et al., 2006; Uba et al., 2009). It has been suggested that the lacustrine to transitional marine Yecua Formation represents a connecting route between the Amazon and Parana seaways (Uba et al., 2009).

The thin carbonate beds on which our study focuses are broadly correlative in age with the Paranaense strata (middle to late Miocene; 16–5 Ma). Previously they have been interpreted as marine deposits on the basis of lithofacies, ichnofacies, fossil content or simply temporal similarity (e.g. Ramos and Alonso, 1995; Pérez et al., 1996; Ottone et al., 1998; Bertolino et al., 2001; Pérez, 2001; Dávila and Astini, 2003a; Fig. 1). Thus they are taken as evidence of extensive marine inundation into the Sierras Pampeanas region and the middle Miocene Andean foredeep, located in what is today the Frontal Cordillera. Although outcrops of these units contain some fauna which are similar to those preserved in the marine Paranaense sediments, such as species of *Corbicula*), modern equivalents of these bivalves are known to inhabit lacustrine and freshwater settings (e.g. Ituarte, 1994). The carbonate strata are also interbedded with low-gradient fluvial overbank, lacustrine and playa lakes deposits, which locally interfinger with coarse-grained synorogenic alluvial strata (e.g. Dávila, 2005). Uncertainty about a marine origin initiates with the lithofacies analyses because, in closed- or sluggish-drainage non-marine foreland basins, carbonate precipitation is possible. This happens when there is oversaturation of carbonate minerals and kinetic barriers to carbonate precipitation are overcome, just as in marine settings. Similar controversy about a marine or terrestrial origin has also arisen for Miocene deposits of more distal foreland scenarios recorded in western Amazonia (S 2°–5°, W 70°–74°) wherein it has been suggested that units once thought to be fluvio-lacustrine contain evidence of occasional marine influence (e.g. Hoorn, 1993; Vonhof et al., 2003; Hoorn and Vonhof, 2006; Rebata et al., 2006; Hovikoski et al., 2007; Uba et al., 2009).

Constraint on the position of a Miocene Paranaense sea level datum is of interest for calibrating paleogeographic, paleoclimate and geodynamic

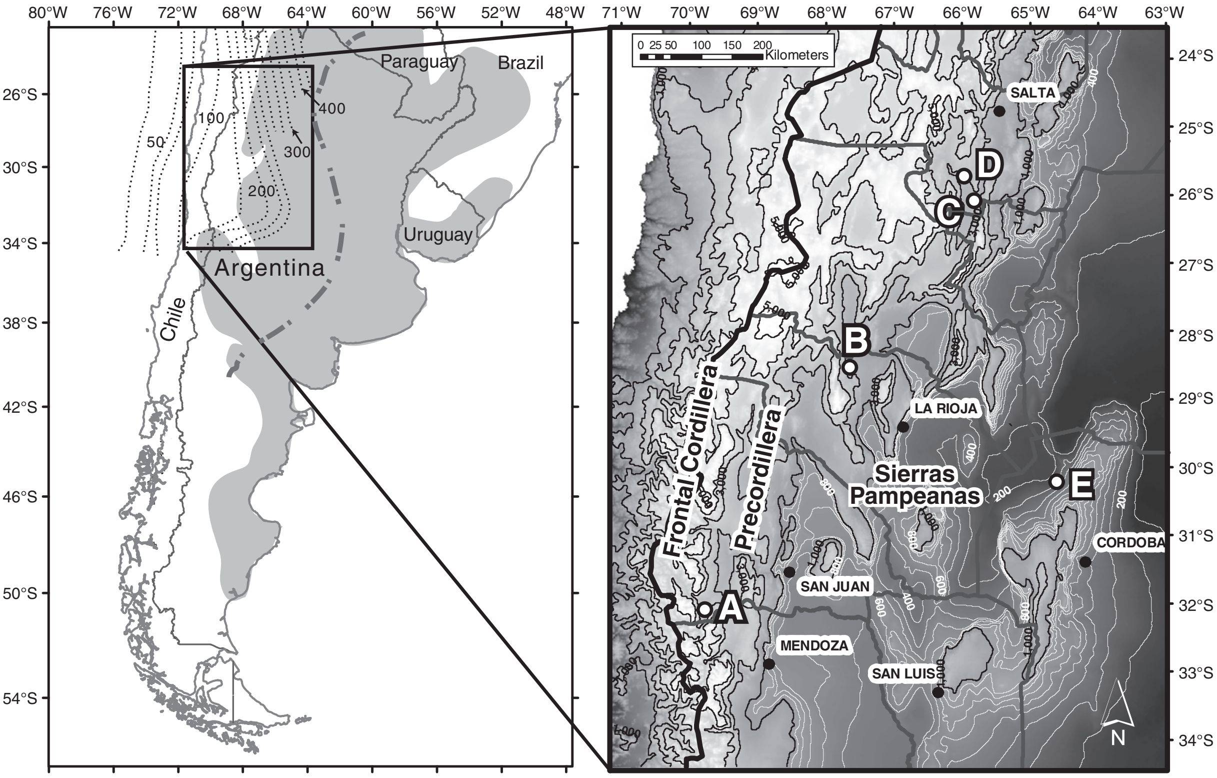

Fig. 1. Left: Map of southern South America illustrating interpreted distribution of Miocene Paraná seaway (grey area, after Ramos and Alonso, 1995; Hernández et al., 2005). Thin dashed lines represent depth contours (meters) of Nazca plate showing flat-slab segment (after Cahill and Isacks, 1992). Thick dashed line represents interpreted westernmost extent of Paraná seaway based on this study; Right: Detail of study area and stratigraphic localities referenced in text (A: Manantiales basin, Chinches Formation; B: Sierras de Famatina, Del Abra and Del Buey Formations, C: Alemania, Anta Formation; D: Quebrada de la Yesera, Anta Formation; E: Sierra de Córdoba, Saguión Formation. Contours are Present day elevations above sea level. Contour interval of white lines is 100 m. Contour interval of black lines is 1000 m.

Table 1
Location, stable isotopic values and age estimates for carbonate units sampled in this study.

Formation	Member	Sample	Locality	Coordinates (WGS 84)	$\delta^{13}C$	$\delta^{18}O$	Age estimate (MA)	Source
Anta		AJ1	Quebrada la Yesera	S 25°59.33′ W 65°45.07′	−6.72	−3.55	15.9–14.2	Reynolds et al. (2000); fission track (zircon) age of interbedded tuff at Alemania (14.5 +/− 1.4); magnetic correlation of concordant top of formation at Rio Piedras (14.2).
Anta		AJ3	Alemania	S 25°36.12′ W 65°35.90′	−6.22	−1.45	15.9–14.2	Reynolds et al. (2000); fission track (zircon) age of interbedded tuff at Alemania (14.5 +/− 1.4); magnetic correlation of concordant top of formation at Rio Piedras (14.2).
Chinches	Tc5	Man-07-50	Manantiales	S 32° 3.34′ W 69° 48.62′	−4.75	−10.89	15.47	Recorrelation of local magnetostratigraphy of Jordan et al. (1996) to Ogg and Smith (2004)
Chinches	Tc5	Man-07-51	Manantiales	As above	−4.93	−12.59	15.42	Recorrelation of local magnetostratigraphy of Jordan et al. (1996) to Ogg and Smith (2004)
Chinches	Tc5	Man-07-53	Manantiales	S 32° 3.33′ W 69° 48.81′	−5.68	−11.59	15.35	Recorrelation of local magnetostratigraphy of Jordan et al. (1996) to Ogg and Smith (2004)
Chinches	Tc5	Man-07-54	Manantiales	As above	−5.86	−10.23	15.3	Recorrelation of local magnetostratigraphy of Jordan et al. (1996) to Ogg and Smith (2004)
Chinches	Tc6	Man-07-86	Manantiales	S32° 5.40′ W69° 51.6′	−2.8	−10.86	9.74	Recorrelation of local magnetostratigraphy of Jordan et al. (1996) to Ogg and Smith (2004)
Del Buey		ED21 (laminar)	Río Durazno	S 28° 39.97′ W 67°42.42′	−0.68	−7.94	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Buey		ED21 (a) laminar	Río Durazno	As above	−0.41	−7.2	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Buey		ED21 (b) laminar	Río Durazno	As above	−1.15	−7.91	Middle Miocene 16–11.6	Dávila (2005); Barreda et al. (2006)
Del Buey		ED21 (c)	Río Durazno	As above	−0.4	−7.27	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Buey		ED21 NOD (nodular)	Río Durazno	As above	−0.02	−7.82	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Buey		S02	Río Durazno	S 28° 39.97′ W 67°42′	−0.26	−8.19	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Abra		S01	Río Durazno	S 28° 39.40′, W 67°42′	−2.27	−7.97	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Abra		S01D	Río Durazno	S 28° 39.40′, W 67°42′	−2.15	−7.81	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Del Abra		FDA 1	Río Durazno	As above	−2.28	−6.95	Middle Miocene 16–11.6	Dávila (2005), Barreda et al. (2006)
Saguión	El Simbolar	MAS1	Río Saguión	S 30° 33.99', W 64°33.11'	−3.63	−7.5	Miocene–Pliocene?	Gordillo and Lencinas (1979), Bertolino et al. (2001)—no biostratigraphic constraint; underlying unit is Cret. Miocene preferred by Bertolino on basis of correlation with Parana ingression
Saguión	El Simbolar	MAS2	Río Saguión	S 30° 33.99′, W 64°33.11′	−4.23	−6.81	Miocene–Pliocene?	Gordillo and Lencinas (1979), Bertolino et al. (2001)—no biostratigraphic constraint; underlying unit is Cret. Miocene preferred by Bertolino on basis of correlation with Parana ingression

reconstructions. For example, the distribution of water masses directly controls the heat capacity and albedo on Earth and ocean current circulation systems are fundamental drivers of climate and sedimentation. Of most concern to the authors is the value of a paleo-sea level datum for interpreting fundamental geodynamics and tectonics across the Andean belt. If a marine origin for these beds could be established, they would provide unequivocal evidence for the amount of middle Miocene to present surface uplift experienced between the Andean foreland (500–1500 m) and the High Cordillera (~3000 m). In particular, the long-wavelength (>300 km, larger than the foreland flexure) topographic response to the coupling of South American lithosphere to oceanic lithosphere is poorly known. For example, it is debatable whether flat-slab subduction caused regional uplift or subsidence (see Dávila et al., 2010). Using flexural and topographic analysis, together with geophysical interpretation, Dávila et al. (2005, 2007, 2010) proposed non-isostatic long-wavelength topographic change or mantle-driven "dynamic topography" (*cf.* Lithgow-Bertelloni and Richards, 1998) along the Argentine pericratonic foreland. This mantle-driven topography is potentially related to subduction of the Juan Fernandez aseismic ridge, which triggered slab flattening since ~18 Ma (Yañez et al., 2001; Kay and Mpodozis, 2002), creating and displacing sublithospheric loads and in turn affecting the foreland topography. In order to test this hypothesis, one needs markers for long-wavelength elevation and elevation change in regions not affected by crustal tectonic loading. The middle Miocene marginal marine deposits of the Paranaense epeiric seaway could provide a regional sea level datum for paleoelevation reconstructions to address this question. However, the scattered nature and minimal documentation of units with inferred marine origin within the Cordillera and the central Sierras Pampeanas regions required field reassessment of their characteristics and extent.

Apart from the geodynamic implications, these Middle Miocene carbonate beds may provide additional information on one of the major climatic events of the Neogene: "the mid-Miocene Climatic Optimum" (Zachos et al., 2001). For example, Dávila (2003, 2005) and Barreda et al. (2006) concluded that fine-grained deposits associated with the carbonate beds signify a wetter-climate paleoflora, compared to the over- and underlying strata. Specifically, in Famatina (NW Sierras Pampeanas), this "wetter-climate" horizon is capped by a thick, Aeolian, sand-dune field (Dávila and Astini, 2003b), which would indicate the re-establishment of semiarid to arid conditions in the foreland (e.g. Jordan et al., 2001).

1.1. Geological setting

The five Miocene carbonate units considered in this study are located above the "flat-slab" segment of the southern Central Andes

(Barazangi and Isacks, 1976; Gutscher, 2002). The strata are located in the eastern- and northwestern-most part of the Sierras Pampeanas (northern Sierras de Córdoba and Famatina, respectively), its northern extension into the Santa Barbara ranges, and in the Andean Frontal Cordillera (Fig. 1). The Sierras Pampeanas and Santa Barbara regions are characterized by a set of intermontane basins bounded by faulted basement blocks referred to as the broken foreland basins of the Central Andes (Jordan and Allmendinger, 1986; Jordan, 1995; Ramos et al., 2002). By the middle Miocene these regions constituted the external part of the foreland, including the interbulge and back-bulge depozones (Dávila et al., 2007). In the Frontal Cordillera, in turn, the middle Miocene Manantiales basin has been interpreted as a proximal foredeep (Jordan et al., 1996), generated by the tectonic loading of the Main Cordillera thrust belt.

The carbonate strata herein analyzed form part of the Saguión, Del Buey and Del Abra, Anta and Chinches Formations, respectively located in the Sierras de Córdoba, Famatina, Sierras de Santa Barbara, and the Frontal Cordillera (see Fig. 1 and Table 1). It should be noted that field reconnaissance of all units described in the literature as "calcareous" in the study area (Fig. 1) was conducted by author Ruskin in 2002 (see Ruskin, 2006). Apart from the units considered herein, the only additional carbonate-rich unit encountered was a rhizolithic paleosol member of the Late Tertiary Estratos de Los Llanos (Ezpeleta et al., 2006; Ruskin, 2006).

The El Simbolar member (10–15 m thick) of the Miocene–Pliocene (Gordillo and Lencinas, 1979) Saguión Formation was interpreted as marginal marine by Bertolino et al. (2001) on the basis of trace fossils (particularly *Diplocraterium* dwelling burrows and *Teichichnus* feeding burrows) and the presence of carbonate beds with thin microstromatolites, which are characteristic of a tidal flat setting. Near the Saguión river valley (S 30° 34′, W 64° 33′), buff-colored stromatolitic units 2–3 m thick are interbedded with reddish fine sandstone, sometimes transitioning laterally into bioturbated sands (Fig. 2). The amount of bioturbation is variable, but tends to be concentrated in sandier facies (Bertolino et al., 2001). The stromatolitic units (samples MAS-1 and 2; see Table 1) are well-laminated, undulatory, and structured as laterally linked hemispheroids, collectively suggestive of a low-energy depositional environment. Algal bed thicknesses vary from 5-mm- laminae to friable layers up to 3 cm thick. The stromatolites are interbedded with gypsum layers.

Tertiary carbonates in the Sierras de Famatina are exposed in the middle Miocene Angulos Group, in the Durazno River valley (near S 28° 40′, W 67° 42′). The Angulos Group is a synorogenic colluvial–alluvial sequence consisting of four units, from base to top, the Del Abra, Del Buey, Santo Domingo and El Durazno Formations (Dávila, 2005), which are interpreted as coeval with the middle Miocene Paranaense incursion (Dávila and Astini, 2003a). Several thin (20 cm) limestone beds, and at least one which is thicker and more regionally extensive, occur within the fluvio-lacustrine Del Buey Formation (Fig. 2; Dávila, 2005; Barreda et al., 2006). The regionally extensive bed (>5 km along strike; samples ED21 and S02) is 70 cm thick, and shows both nodular and laminar structures, with bivalve fragments and gastropods and a *Scoyenia*-like trace fossil association (Dávila, 2005). The carbonate is interbedded with braidplain and lacustrine deposits. Analysis of microspores and algal material from an underlying siltstone layer indicated freshwater lake and lacustrine marginal environments, with no unequivocal remains of marine origin (Barreda et al., 2006).

In the Santa Barbara ranges of Salta Province, the Miocene Anta Formation (<15.9–14.2 Ma; Reynolds et al., 2000) has been proposed to record marine influences from the Paranaense Sea on the basis of several oolitic limestones correlated with foraminifera- and mollusk-bearing units to the south and west (Río Salí and San José Formations, respectively; Hernández et al., 2005). At the Quebrada de la Yesera (S 25° 12′, W 65° 45′, Fig. 2), five limestone beds occur within approximately 40 m of well-laminated red and grey mudstones and sandstones. Overlying a trough-cross bedded quartz-pebble conglomerate, the first carbonate bed (sample AJ-1) is ~20 cm thick. The overlying 3 meters consist of coarse, cross-bedded or rippled sandstone, some with mudcracks, and then approximately 10 m of red mudstone. The next limestone bed (AJ-2) is <1 m thick and shows oolitic textures with nuclei of well-rounded quartz grains, and it is overlain by thin rippled sandstones. Three additional limestones (each <1 m thick) are interbedded in the overlying 20 m of redoximorphic and locally pedogenic mudstone (e.g. ped structure development and illuvial horizons; Retallack, 2001). At Quebrada de la Yesera, freshwater fish have been documented (Cione and Casciotta, 1995), thus signifying freshwater lacustrine conditions during at least part of the Anta interval. SE of the Quebrada de la Yesera locality, the Anta Formation is also exposed near the town of Alemania (S 25°36′ W 65° 36′). In this section it consists of 100–150 m of extensively cross-bedded red sandstone with thin interbeds of slightly pedogenic siltstone. The siliciclastic Anta strata include a tuff dated 14.5 ± 1.4 Ma (Reynolds et al., 2000). Thin carbonates (~1 m each; sample AJ-3) occur approximately 100 m above the base and exhibit laminations suggestive of algal accretion, as well as some carbonate intraclasts and ooliths. At Río Piedras (approximately 80 km to the northeast), the Anta Formation consists of claystones, interbedded tuffs, and at least seven oolitic limestone beds (Quattrocchio et al., 2003). Grains from the limestones include analcime, a sodic aluminosilicate of the zeolite group, which is known to be present insome alkaline and saline playa lake sediments (Quattrocchio et al., 2003). The preserved pollen content of the section is also in accord with a saline lake depositional environment (Quattrocchio et al., 2003). Some 120 km NE of Alemania, a 720 m section of Anta Formation is exposed at Arroyo González, with no signs of marine lithofacies (Fig. 2; Reynolds et al., 2000).

In the Manantiales basin, located in the Frontal Cordillera of the south Central Andes (W 69° 45′; S 31° 45′–32° 30′), a section dominated by detrital siliciclastics is referred to as the Chinches Formation (Pérez, 2001). Detailed lithostratigraphic study of the Chinches Formation (Pérez, 1995; Jordan et al., 1996; Pérez, 2001, Fig. 2) characterizes four upward-coarsening cycles, each comprised of a thin basal lacustrine interval of mudstones and limestones that grades upward into fluvial sandstones, and finally capped by alluvial fan/bajada sediments. The carbonate samples for this study were collected from the group IV facies association of Jordan et al. (1996) and Tc5 of Pérez (2001). Although there was a major disagreement in the published stratigraphic thickness of the Chinches Formation between the work of Jordan et al. (1996) and that of Pérez (1995, 2001) based on a difference in interpretation of the degree of deformation in the section, new field observations by author Hoke concur with Jordan et al. (1996) that the stratigraphic thickness totals ~3600 m. Within the Tc5 member, Pérez (1995) recovered a palynological assemblage signifying a warm, dry climate associated with shallow lacustrine sediments. However, within the same interval, planispiral microforaminifera were found and interpreted as marine. This occurrence prompted Pérez et al. (1996) and Pérez (2001) to correlate this unit of the Chinches Formation with the Paranaense ingression, resulting in the westernmost extent of the inferred seaway. This unit has a particular interest for uplift analysis of the Central Andes, given that it is exposed today at ~3 km above sea level (Fig. 1). However the microforaminifera and dinoflagellate specimens of Chinches Formation are poorly preserved and have limited stratigraphic value (Ottone et al., 1998).

1.2. Marine versus lacustrine indicators

On the basis of mineralogy, sedimentology and stratigraphy, it is challenging to differentiate marginal marine facies from lacustrine facies (e.g. Vengosh et al., 1992; Bolhar and Kranendonk, 2007). Among the different methods, paleontologic constraints are likely the

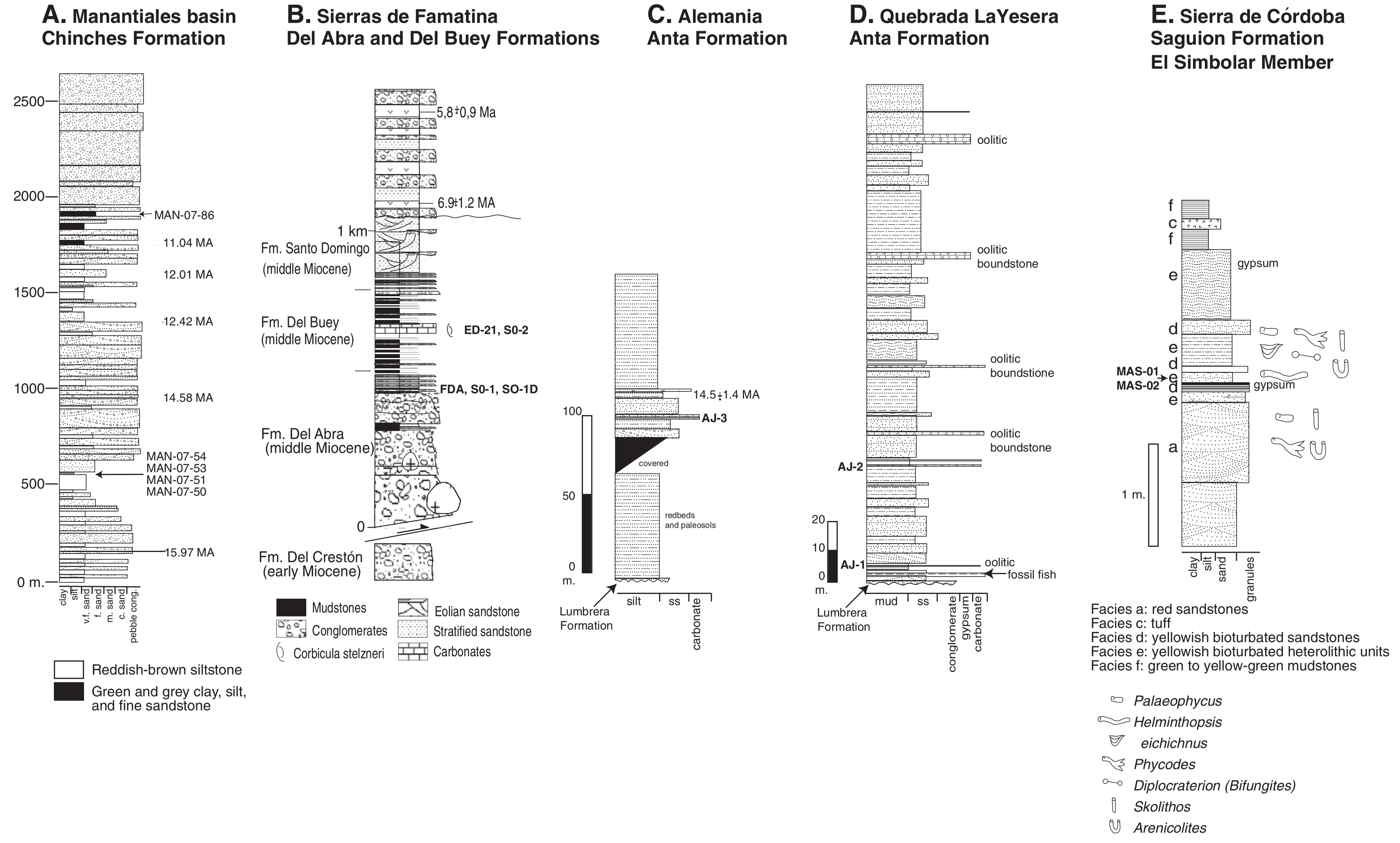

Fig. 2. Generalized stratigraphic sections with locations letter-referenced to Fig. 1. Note separate vertical scale for each section. A. Chinches Formation redrafted from Jordan et al. (1996) and magnetostratigraphic ages recorrelated to Ogg and Smith (2004); B. Del Abra and Del Buey Formations, figure modified from Barreda et al. (2006); C. Anta Formation–Alemania outcrop, modified from Hernández et al. (2005); D. Anta Formation–Quebrada de la Yesera outcrop, redrafted from Cione and Casciotta (1995); E. Saguión Formation, El Simbolar member, redrafted from Bertolino et al. (2001).

best differentiators of nonmarine and marine settings, but still can lead to contradictory interpretations. Although some fauna (e.g. corals, echinoderms, articulate brachiopods, bryozoans and cephalopods) are diagnostic of a narrow range of salinity conditions ("stenohaline" organisms), certain other biota may be adapted to broad temperature and salinity ranges that overlap environments. For example, the presence of foraminifera, often presented as evidence of marine conditions, is not a unique indicator of either salinity or water depth (the parameters also used to define shallow epicontinental seaways; Heckel, 1972; Johnson and Baldwin, 1986). Numerous species of Quaternary foraminifera have adapted to large variations in the salinity of Australian and Canadian lakes (e.g. Cann and de Deccker, 1981; Patterson and McKillop, 1991; Boudreau et al., 2001). Foraminiferal assemblages in shallow marine conditions also can adapt to variable salinity (e.g. Fontes et al., 1985; Sellwood, 1986; Walsh, 2002). Without constraints of the salinity tolerances of a particular species throughout its fossil record, the presence (or absence) of foraminifera is not a robust indicator of marine or freshwater conditions.

Although ichnofacies may assist in differentiating marine from continental strata, it is difficult to interpret depositional systems from incomplete trace associations and without an integrated analysis considering lithofacies (e.g. Hasiotis, 2007). For example, in El Simbolar Member of the Saguión Formation (see Bertolino et al., 2001), the presence of *Teichichnus, Phycodes* and *Rhizocorralium* was interpreted as evidence of sublittoral settings. Yet other ichnogenera in the El Simbolar Member (*Diplocraterium* and *Arenicoles*) can be found in sandy lacustrine shorelines (*Skolithos* ichnofacies) as well as semi-consolidated onshore strata (*Glossifungites* ichnofacies; Buatois and Mángano, 1998).

1.3. Stable isotopes

Chemostratigraphy is a preferred method to solve uncertainties of paleogeography and paleoenvironments such as the Paranaense deposits. Ratios of stable isotopes of carbon and oxygen provide a means of assessing the depositional origin of carbonates in the geologic record. Modern marine carbonates are generally characterized by δ^{13}C and δ^{18}O values near zero (a range of −2‰ to 2‰ versus Peedee Belemnite standard, PDB, is common for both elements; Ghosh et al., 2001; 0–3‰ in Hoefs, 2009). Moreover, the isotopic composition of seawater throughout the Cenozoic is well known (e.g. Veizer et al., 1999; Zachos et al., 2001). For the Miocene to Pliocene time interval, global seawater δ^{13}C ranges from +1 to +3 and δ^{18}O from −1.5 to +1‰ (Fig. 2). Isotopic values for various continental and marine carbonates have been assembled in Fig. 3 to be compared with our results. Continental carbonates possess C and O isotopic ratios that are affected by mixing of water from different sources with distinctive isotopic fractionation values (e.g. meteoric waters, continental runoff, marine waters), which are challenging to constrain in the geologic record (Vonhof et al., 2003; Bolhar and Kranendonk, 2007). The δ^{13}C isotopic signatures for freshwater carbonates are generally depleted by −6 to −12‰ compared with those of marine carbonates due to influx of low δ^{13}C from CO_2 derived from soil respiration or organic matter degradation and meteoric sources. δ^{13}C values for lacustrine waters shift toward negative values in response to short residence times (e.g. open hydrologic conditions; Talbot, 1990). Oxygen isotopic ratios are quite susceptible to environmental alteration because they are affected by temperature, evaporation,

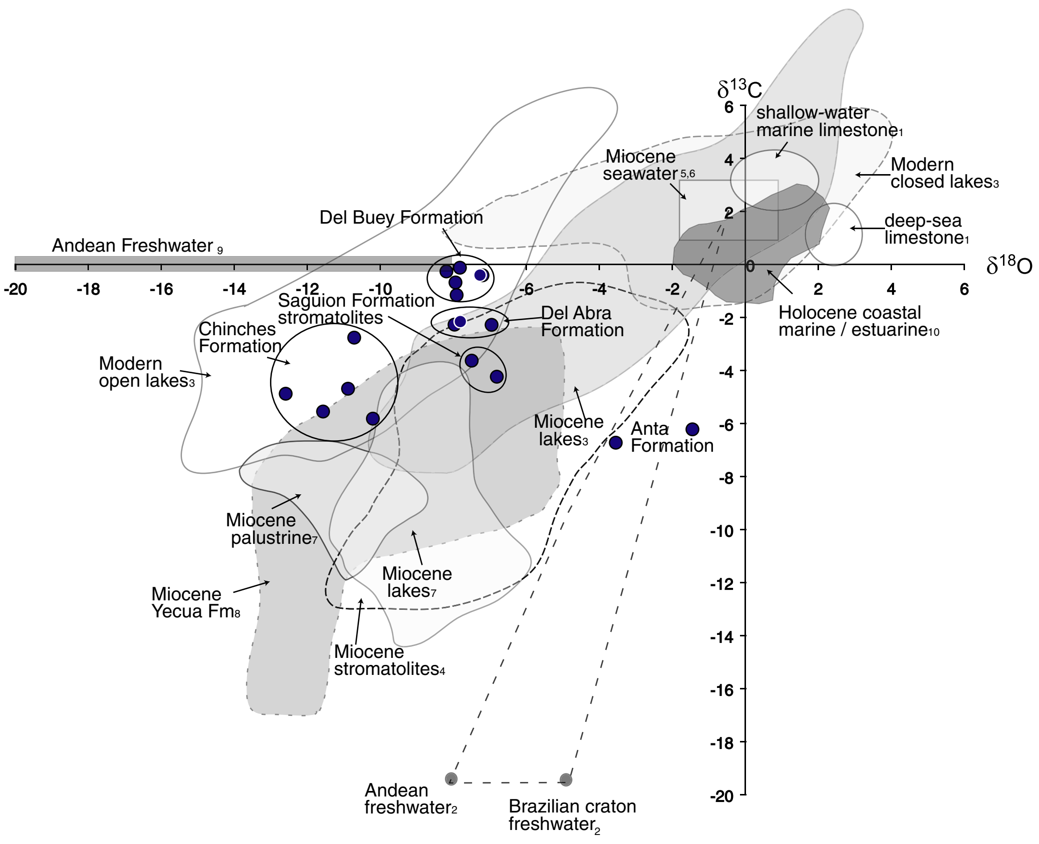

Fig. 3. δ^{13}C and δ^{18}O isotopic values of carbonates sampled in this study as compared with fields for various Miocene to Recent nonmarine and marine water and carbonate systems, after: 1. Milliman, 1974; 2. Longinelli and Edmond, 1983; 3. Talbot, 1990; 4. Talbot, 1994; 5. Veizer et al., 1999; 6. Zachos et al., 2001; 7. Garzione et al., 2006; 8. Uba et al., 2009; 9. Hoke et al., 2009; 10. Aguirre et al., 1998.

seasonality of precipitation, latitude, and continentality (e.g. Cerling and Quade, 1993). Talbot (1990) showed that lacustrine water δ^{18}O shifts toward positive values in response to increasing evaporation and residence time, whereas increasing latitude, altitude and continentality result in more negative values. We can qualitatively address the likelihood of a marine versus continental paleoenvironment based on comparison of the new Sierras Pampeanas and NW Argentina data to compiled isotopic results from well-constrained depositional systems (Fig. 2, compiled from Milliman, 1974; Hudson, 1977; Talbot, 1990, 1994; Veizer et al., 1999; Zachos et al., 2001; Garzione et al., 2006; Uba et al., 2009). We can also consider the likely isotopic values of a three end-member water system of Miocene seawater, Andean freshwater and cratonic freshwater (Longinelli and Edmond, 1983; Veizer et al., 1999; Zachos et al., 2001; Hoke et al., 2009). We also include values from Holocene shelly faunas of the Rio de la Plata estuary (Aguirre et al., 1998), which might represent a good comparison because of geographic proximity and because this was likely the ancient inlet of the Miocene Paranaense sea tongue (see Hernández et al., 2005).

There are, however, exceptions to the general trend of positive or near-zero marine isotopic values and negative (depleted) freshwater isotopic signatures. For example, saline waters may be enriched in δ^{13}C up to +13‰ PDB in settings where evaporative brines, anoxic sediments, diagenetic CO_2, travertine minerals or methane inputs are concentrated (e.g. Valero-Garcés et al., 1999). Conversely, it is possible for marine carbonates to yield negative isotopic values in response to restricted circulation, meteoric input, coastal runoff, and local-scale carbon cycle processes (e.g. Patterson and Walter, 1994; Gomez et al., 2007; Hoefs, 2009). Recently, Uba et al. (2009) interpreted marginal marine conditions for intervals of the Yecua formation with δ^{13}C values of −2 to −8‰ PDB and δ^{18}O = −5 to −11.5‰ PDB, but corresponding to beds with barnacles, stromatolites, foraminifera and *Ophiomorphia* ichnofossils. As with all of the above tools for paleoenvironmental interpretation, C and O isotopic values should corroborate other lines of evidence, not be taken alone as evidence of marine or nonmarine deposition.

2. Methods and materials

We sampled 18 limestone beds from 5 formations in the Sierras Pampeanas and Frontal Cordillera, some of them interpreted by previous investigators as lacustrine or marginal marine deposits. The locations and coordinates of the sample localities are depicted in Fig. 1 and Table 1 respectively. The samples provided materials for thin section examination and for stable isotopic (δ^{13}C and δ^{18}O) analysis. In order to interpret the isotopic signal as either a primary feature of the depositional environment or as diagenetic secondary signals, we carried out petrographic screening in order to determine component microfacies and to aid in paleoenvironmental analysis. Thin sections were prepared by Spectrum Petrographics (Vancouver, WA) and by the authors at CENAC (CICTERRA-Universidad Nacional de Cordoba) and subsequently studied with a binocular microscope under plane- and cross-polarized light at magnifications of 4x to 40x.

For stable isotopic analysis, most of the micritic carbonate samples were analyzed at the University of Colorado Institute of Arctic and Alpine Research Stable Isotope Lab with a dual inlet Finnegan MAT Delta Plus mass spectrometer. Results are given in delta notation relative to the Vienna Pee Dee Belemnite standard (V-PDB), where $\delta_{sample} = [(R_{sample}/R_{V\text{-}PDB}) - 1] \times 100$, with precision better than 0.1‰ for both carbon and oxygen. Micritic calcite was utilized for isotopic analyses (see below). An additional 5 samples from Famatina (Dávila, 2003, unpublished PhD thesis) and 5 from Frontal Cordillera are included in this work. The Famatina carbonates were analyzed for stable isotopic ratios at the Geological Institute of the Swiss Federal Institute of Technology (Zurich), whereas the Frontal Cordillera samples were analyzed at the University of Rochester Stable Isotope Laboratory on a Thermo-Finnegan Delta XP with a gas bench peripheral. Results on the individual analyses reported here all have analytical precision of ≤0.1‰. However, several replicate analyses of samples MAN-07-50 (n = 4, 1σ δ^{13}C = 0.3‰, σ δ^{18}O = 0.8‰) and MAN-07-86 (n = 3, 1σ δ^{18}O = 0.9‰) yield higher uncertainties than single analyses.

2.1. Analysis

2.1.1. Petrography and sedimentology

In Famatina, the carbonates of the Del Buey Formation can be separated into two different facies: (a) nodular carbonates (sample ED21 NOD) and (b) laminar carbonates (samples ED21a,b, c and SO-2). The nodular limestones were interpreted as pedogenetic calcretes, based on calcitic rhizonconcretions and rhizoliths, prismatic structures and peds (Dávila, 2005), which indicate illuvial–eluvial processes, typical of pedogenesis (Retallack, 2001). The laminar carbonates, in turn, represent a tabular and laterally extensive facies, formed of thin (1–3 mm) and convex (amplitude <30 mm and wavelength <20 cm) lamination. Via microscopy, the laminae reveal an alternation of peloidal packstones (<100 µm pellet diameter) and agglutinated micrite (*grumeleuse* structure of Demicco and Hardie, 1994). The micrite and microsparite and the *grumeleuse*-clotted structure were interpreted as cryptomicrobial fabrics (Demicco and Hardie, 1994). Further evidence of organic activity is represented by bioturbation and brackish-water bivalves (*Corbicula*; Ituarte, 1994). Abundant meniscate burrow fills are interpreted as *Scoyenia* ichnofacies. This ichnofacies is commonly developed at the margins of water bodies. The carbonate strata are associated with proximal alluvial deposits (conglomerates and sandstone sheet-flood beds), which most likely signify a terrestrial origin (Dávila, 2005). However, Dávila (2005) and Barreda et al. (2006) did not discard the possibility of a marginal marine setting due to the age correlation with the Paranaense incursion.

A thin section of a rock sample from the limestone bed in the upper Del Abra Formation (SO1), in Famatina, revealed a primary micritic matrix (90–95%) with some amorphous hematite accumulations. Framework grains included subhedral twinned and zoned plagioclase with edges altering to clay, anhedral micas, and sparry calcite, the latter appearing as skeletal fragments and concentrated in elongate zones. Abundant gastropods are present in this level in outcrop; however, in thin section, skeletal fragments comprise <1% of the area. The overlying Del Buey Formation sample (SO-2) was observed to be of similar micritic composition to the Del Abra sample (SO-1), albeit with a greater quartz content (15–20%). The abundance of micritic carbonate as groundmass mineral in these samples is in accord with deposition in quiet-water conditions where winnowing of fine-grained material (e.g. by waves or bottom-currents) was minimal. Micritic calcite is also inferred to be a primary precipitate and appropriate for isotopic analyses.

Samples from the Saguión Formation stromatolitic facies (MAS-1, MAS-2) in the Sierras de Córdoba, were analyzed for micromorphic characteristics. Under cross-polarized light and 10x magnification, mudstone laminations are found to be predominantly micritic carbonate and mud with accessory muscovite grains visible. Minor amounts of chlorite are also present in the groundmass. Of the calcareous groundmass, minor sparite recrystallization (5–10%) was observed on some boundaries of laminations with quartz grains. These areas were correspondingly avoided in favor of primary micritic calcite for isotopic analyses.

For the samples from the middle Miocene Anta Formation, the most prevalent micromorphic features are subspherical mature ooids. Sample AJ-1 is predominantly micritic mudstone, with patchy spar replacement (<5% area) and occasional peloidal accumulations. Sample AJ-2 appears oolitic in thin section, as in outcrop. Subrounded to well-rounded quartz grains exist both as ooid nuclei and 'floating' in the micritic mud matrix, where they are somewhat larger in diameter (0.75 mm) than the ooids themselves (~0.5 mm). Note that insufficient carbonate material was obtained from this sample for isotopic analysis. Sample AJ-3 consists of ~70% micritic mud, ~20% subhedral quartz and opaque minerals and ~10% relict ooids and peloids lacking the strong form and abundance of sample AJ-2. Sparitic calcite orthochems were not observed in AJ-3.

The abundance of micritic carbonate as groundmass mineral in samples from the Anta and Saguión Formations is in accord with deposition in quiet-water conditions where winnowing of fine-grained material (e.g. by waves or bottom-currents) was minimal. Micritic calcite is also inferred to be a primary precipitate. The sparry calcite observed in sample MAS-2 is in association with the coarser-grained quartzose laminations as a cement phase, whereas sparite within the otherwise micritic groundmass (e.g. AJ-1) may represent diagenetic replacement or secondary void fill.

In the Manantiales Basin, carbonate beds within the Chinches Formation have been correlated to the magnetostratigraphy of Jordan et al. (1996; Fig. 2). In a facies association of Jordan et al. (1996), previously interpreted as lacustrine with possible deltaic influence, samples MAN-07-50 and MAN-07-51 are carbonate nodules from a calcic argilliosol and calcic protosol, respectively. Directly above, a 50 cm thick massive grey limestone (MAN-07-052) partially grades into an overlying 50 cm thick, massive, red calcareous mudstone (MAN-07-53). MAN-07-54 comes from an organic matter rich calcareous siltstone, 40 m above the limestone. Approximately 1375 m up in the section, a single 20 cm thick limestone bed, MAN-07-86, is exposed between meter-thick green siltstones.

2.1.2. Isotopic data

Carbon and Oxygen isotopic results from the Anta, Chinches, Del Abra, Del Buey, and Saguión Formations are summarized in Table 1 and compared to isotopic fields defined for various carbonate-precipitating environments (Fig. 3). Note that all of the samples are characterized by negative values (i.e. depleted relative to PDB standard) for both isotopic systems.

Within the strata in the Famatina Ranges, a small enrichment in δ^{13}C values occurs upsection between the Del Abra and Del Buey Formations, though both units are still depleted in comparison to standard marine carbonate values. The Del Abra Formation samples yield a small range of δ^{13}C values, from −2.15 to −2.28‰. The range of δ^{18}O values is slightly larger, from −6.95 to −7.97‰. Samples collected upsection within the Del Buey Formation exhibit the least depleted δ^{13}C signals (−0.02 to −1.15‰), whether from laminar or nodular accumulations. Note the most depleted value (−1.15‰) is from a darker grey level (ED21 b) interlayered with lighter grey layers (ED21 a and c). The δ^{18}O values of the six Del Buey Formation samples are again within a small range (−7.2 to −8.2‰) and comparable to the Del Abra Formation values.

The stromatolitic carbonates from the Saguión Formation exhibit greater depletion of δ^{13}C (−3.63‰ to −4.23‰) values. The samples δ^{18}O values are again similar, from −6.81‰ to −7.51.

Isotopic analyses of two of the Anta Formation oolitic limestones from Salta Province yield the least depleted δ^{18}O values (−1.45 to −3.55‰) of all sampled units, but also the most depleted δ^{13}C values (−6.22 to −6.72‰).

The 5 samples from the Chinches Formation of the Manantiales Basin exhibit the most depleted δ^{18}O values (−10.23 to −12.59‰) of the sampled units. Chinches Formation δ^{13}C values (−2.8 to −5.86‰) are depleted similar to those of the other carbonate units.

3. Discussion

By comparison with other isotopic studies of marine and nonmarine carbonates (Fig. 3), the Miocene limestones sampled in this study yield δ^{13}C and δ^{18}O values comparable to those recorded for nonmarine environments.

δ^{13}C values of Del Buey Formation are only slightly depleted from common values for marine carbonates, but are depleted by −7.2 to −7.9‰ with respect to δ^{18}O. The Del Buey samples plot in a field similar to those observed in modern open lakes (Fig. 3). As mentioned above, since lacustrine water δ^{18}O values shift toward negative values in response to increasing latitude, altitude and continentality and since hydrologically open lakes commonly have small variation among δ^{18}O values (Talbot, 1990), it is likely that the Del Buey carbonates reflect hydrologically open lakes receiving an influx of isotopically depleted (i.e. meteoric and fluvial) waters. The difference of carbon isotopic composition between sample ED21b as compared to ED-21a and ED21c is likely related to the contrast in organic productivity as might be inferred from the color of the laminations. δ^{13}C values may have been enriched via evaporation during periods of hydrologic closure. This is in agreement with the depositional interpretation by Dávila (2005) and Barreda et al. (2006) of a continental playa lake, based on associated pedogenic carbonates (ED21-Nod), interbedded braidplain silts and sands and associated palynology.

The Del Abra carbonate isotopic values are similar to those obtained from other Miocene lakes as well as modern hydrologically open lakes. As with the overlying Del Buey samples, δ^{18}O values vary slightly between samples, suggesting hydrologic through-flow of depleted (i.e. continental) source waters. Because the Famatina belt was concurrently uplifting (e.g. Dávila and Astini, 2007), depletion of δ^{18}O may also be due to Raleigh distillation of atmospheric water vapor as a result of increasing altitude/decreasing air-mass temperature (e.g. Siegenthaler and Oeschger, 1980). Greater depletion of δ^{13}C versus the overlying unit may be a consequence of a shorter residence time or difference in vegetative cover or overall humidity within the catchment area (Talbot, 1990). These samples were taken from a formation in which colluvial and proximal alluvial facies interfinger (Dávila, 2005).

The stromatolitic carbonates of the Saguión Formation in the central Sierras Pampeanas yield isotopic values comparable to other Miocene stromatolites (e.g. Talbot, 1994). The depleted values are also comparable to lacustrine carbonates. It should be noted that the Saguión Formation isotopic values are within the range defined as "marginal marine" for the Yecua Formation of Bolivia (Uba et al., 2009) from Yecua horizons that include not only stromatolites but also additional saline-water fossils and ichnofossils. As will be discussed below, the presence of stromatolites does not preclude a saline lake origin.

The isotopic values recorded in the Anta Formation carbonates, though depleted, are more ambiguous in the context of depositional environmental interpretation. As an approximation of isotopic values expected in a mixed system of potential marine and freshwater sources, a three end-member system of δ^{13}C and δ^{18}O for present-day Andean runoff, Brazilian cratonic runoff and Miocene seawater is proposed (Fig. 3; Longinelli and Edmond, 1983; Veizer et al., 1999; Zachos et al., 2001). These are proxy values (e.g. continental source isotopic compositions are not constrained for the Miocene) and to know the proportion of water mixing would require ^{87}Sr/^{86}Sr ratios (e.g. Hulka, 2005). However, their mixing model may be appropriate for comparison to the Anta Formation samples, in that this is the northernmost of the sites and closest to the Brazilian craton where the mixing model was calibrated. If any of our sample locations were interconnected with marine incursions in western Amazonia, the Anta locations have the greatest likelihood. Indeed, the Anta isotopic values do plot within the mixing polygon and are somewhat closer to the marine end-member than continental sources (Fig. 3). It is noteworthy that the Anta Formation δ^{13}C values (−6.22 to −6.72‰) are quite similar, even though the strata from which the samples were collected 45 km apart and not physically connected. This could indicate a well-mixed system receiving a large fraction of isotopically "uniform" source water. Therefore, isotopic values of Anta Formation do not entirely preclude the possibility that the bodies of water that precipitated the carbonates may have received influx from a marine source, which would tend to drive values toward zero per mil.

The Chinches Formation carbonates have the most depleted $\delta^{18}O$ values, plotting in a range similar to that of modern open lakes. The inter-sample variability of $\delta^{18}O$ is small (<2.4‰) and combined with depleted $\delta^{13}C$ values, these carbonates are interpreted to reflect continental runoff waters with short residence times. The very negative $\delta^{18}O$ values imply that the source of meteoric waters is from an area of mountainous terrain. Today, at the latitude of the Chinches Formation, meteoric water in the low elevation plains on both sides of the range has values of approximately −5‰ (IAEA/WMO, 2006). The younger sample (MAN-07-86, 10.1 Ma) is somewhat less depleted in $\delta^{13}C$ (−2.8‰) versus the four samples dated ~14 Ma, albeit with comparably depleted $\delta^{18}O$ (−10.68‰). This may reflect increasingly evaporitic or restricted lakes upsection within the Chinches Formation.

On the basis of our results, it is prudent to affirm that further isotopic studies are needed to constrain Miocene $\delta^{13}C$ and $\delta^{18}O$ values from Andean freshwater and cratonic runoff, as well as $^{87}Sr/^{86}Sr$ ratios for these sources and for any included microfossil content in order to determine the proportion of mixture between the water inputs. The use of trace elements such as Boron can also differentiate marginal marine from continental conditions (e.g., Vengosh et al., 1992; Aguirre et al., 1998). Nonetheless, all of the analyzed samples are isotopically depleted with respect to marine carbonates and seawater, and most critically, are not associated with any unambiguously marine sedimentologic or paleontologic indicators.

A marine origin for these Neogene intervals in the Sierras Pampeanas, Santa Barbara system and Frontal Cordillera is questionable for numerous reasons. First, the facies associations and vertical organization of facies of the calcareous beds do not show a typical arrangement of transgressive sequences. Limestones are restricted to meter-thick beds amid much thicker alluvial to fluvial successions (e.g., Dávila, 2005). They are not laterally traceable into deeper water facies in the central Sierras Pampeanas intermontane basins, nor are carbonates of distinctly marine facies encountered in well cuttings (e.g. Alvarez et al., 1989; Fisher et al., 2002). Secondly, the sedimentologic features of the proposed carbonates (bioturbated mudstones, algal bioherms, oolitic and laminar carbonates) are not uniquely diagnostic of a littoral depositional setting. These features are also commonly found in modern and ancient lacustrine settings (Dean and Fouch, 1983; Allen and Collinson, 1986). In fact, detailed sedimentological and palynological examination of the Del Buey Formation led to reinterpretation of the continuous laminar carbonate beds as perennial lake deposits (Dávila, 2005; Barreda et al., 2006). Furthermore, there is a complete absence of any tidal features described for any of these units so far, though admittedly the tidal range in ancient epicontinental seaways is subject to debate (e.g. Higgs et al., 2006).

Third, the fossil assemblages do not unequivocally support marine conditions. Freshwater fish collected in the Anta Formation make a marine origin for at least some of the limestone beds particularly suspect. Other fossils collected from the proposed “Paranaense” units are foraminifera, which have been shown to be present in lacustrine systems and tolerant of variable salinity water (Cann and de Deccker, 1981; Patterson and McKillop, 1991; Boudreau et al., 2001). Without supporting data to confirm the range of paleotemperatures and paleosalinities in which these species could live, marine influence cannot be assured based only on the presence of foraminifera. A similar argument holds for the use of trace fossils, whereby fairly complete ichnofacies and detailed descriptions are needed for confident paleoenvironmental interpretation. Fourth, based on $\delta^{13}C$ and $\delta^{18}O$ isotopic values, a lacustrine origin is interpreted as more likely than marginal marine deposition.

If the Sierras Pampeanas and Frontal Cordillera Neogene carbonate horizons are not of marine origin, what is their sedimentological and isotopic significance? The carbonate units of the Del Buey, Anta, Chinches and Saguión Formations are lithologically unique compared to the Tertiary stratigraphy of their areas. These limestones are interbedded with laminar and often pedogenic siltstones and mudstones (e.g. Dávila and Astini, 2003a; Dávila, 2005; Barreda et al., 2006) or lacustrine deposits (e.g. Quattrocchio et al., 2003). It is suggested that these middle Miocene lacustrine intervals in the northern and central Sierras Pampeanas were formed under a climate that was more humid than in earlier Neogene times. In Famatina, palynological studies (Barreda et al., 2006) interpreted subtropical conditions during the middle Miocene (deposition of the Del Buey Fm). This evidence is in accord with depleted O isotopes values, close to −8‰ (see ED21, ED21a, b, c and d). A change from semiarid to more humid conditions would be indicated also by contrasting the relatively enriched Del Buey $\delta^{13}C$ values (−0.02 to −1.1‰) with the depleted values (−2.2‰) of the underlying Del Abra. It is important to note that overlying the Del Buey Formation, a thick eolian succession (Santo Domingo Formation, Dávila and Astini, 2003b) is evidence of the return to relatively arid conditions (Dávila and Astini, 2003b) which have dominated the Andean foreland to the Present. Cessation of eolian deposits at 14 Ma in the Bermejo Basin, south of Famatina, has been interpreted as a paleoclimate change to less arid conditions (Jordan et al., 2001). Similar lithologic as well as paleontologic shifts 15-10 Ma from arid to humid conditions have been suggested in northwestern Argentina (Hernández et al., 1999; Starck and Anzótegui, 2001; Strecker et al., 2007). Whether these sedimentary systems were responding to local climate changes driven by Andean orogeny or to global changes is still debated (e.g. Alonso et al., 2006). However, they are of the same age as a major episode of global oceanic cooling, beginning ~14 Ma (Zachos et al., 2001). A middle Miocene $\delta^{18}O$ increase is associated with deep-water cooling and two ice-growth events that resulted in the development of the present East Antarctic ice sheet (Shackleton and Kennett, 1975).

Regarding the limestone beds of Sierras Pampeanas and the Cordillera as more compatible with lacustrine settings, a flat paleotopography may be deduced for the Middle Miocene foreland paleogeography. This is consistent with recent work (e.g., Dávila et al., 2007) that suggests a planation stage and development of forebulge to back-bulge depocenters in this part of the foreland, prior to Mio-Pliocene foreland partitioning and formation of the broken foreland landscape. We infer that the middle Miocene foreland, where the Sierras Pampeanas region is now located, was more elevated than surrounding regions where the transgression had influence (e.g. eastern Argentina in the subsurface Pampean Plains). This might relate to a thicker Sierras Pampeanas crust inherited from earlier orogenies or alternatively to a middle Miocene surface uplift, likely related to mantle dynamic processes driven by slab flattening (i.e. “positive” dynamic topography). The latter conclusion is in agreement with recent numerical approaches in the Sierras de Cordoba and the Argentine Pampas (Dávila et al., 2010), which have proposed dynamic uplift across the Andes to the Sierras Pampeanas and dynamic subsidence along the Pampas plains. A similar scenario has been described in Peru, where subduction of the Nazca ridge, associated with flat subduction, triggered the formation of the Fitzcarrald Arch, a positive topographic feature more elevated than the Amazonian foreland (Regard et al., 2009).

4. Conclusion

Given our observations and summary of available datasets, it seems that although parts of eastern and southern Argentina were certainly inundated by the Paranaense seaway during the Miocene, we find no evidence that marine water flooded the coeval Andean foreland, in the Sierras Pampeanas and the Frontal Cordillera of central Argentina. A period of climatic change resulting in regional lacustrine deposition is equally likely. Until more substantive evidence supporting marine deposition can be found, we reject correlation of the Saguión, Anta, Chinches and Del Buey Formations with the Paranaense seaway and caution against broadly mapping the flooding into the central Sierras Pampeanas and the Cordillera.

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