LATE PALEOZOIC CARBONATES AND GLACIAL DEPOSITS IN BOLIVIA AND NORTHERN ARGENTINA: SIGNIFICANT PALEOCLIMATIC CHANGES

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ABSTRACT: In Bolivia, a marked climatic paleogradient (from west northwest to south) is visible in the Carboniferous depositional systems. In the northwest is the Pangean trend, a warm-water Pennsylvanian and Permian succession (preceded by a Late Devonian glacially derived rock assemblage). To the south is the cold climate Gondwanan trend, a succession of Late Devonian and Pennsylvanian cold-water siliciclastics with glacially influenced deposition. Whereas Devonian through (limited) Mississippian strata are comparable in overall character, a sharp climatic gradient in western South America is established by the earliest Pennsylvanian. The Pangean trend in northwestern Bolivia and Peru continues with warm-water Pennsylvanian and Permian carbonates, evaporites, and mixed siliciclastics of a semiarid, open seaway association (Copacabana Formation). This unit was deposited by marine transgression north (northern Bolivian subsurface and Lake Titicaca area), reaching central Bolivia by the Early Permian (Early Cisuralian). Regionally, the warm Pangean pattern continues into the younger and more restricted overlying Cisuralian and younger Permian and Triassic rocks characterized by restricted marine deposits of both humid and arid association (including red beds). To the south, Early Pennsylvanian rocks in the Gondwanan trend record continental and lacustrine glacial deposition as far north as central Bolivia, with glacial influence strongest in southern Bolivia and northern Argentina. By the Late Pennsylvanian, glacial influence has waned and is restricted to southern Bolivia near the Argentine border. The Copacabana Formation is enigmatic because of the following: (1) its autochthonous succession over cold-water, glaciogenic deposits of the Late Devonian and Mississippian and (2) its apparent coeval deposition with Pennsylvanian (and Permian) glacial diamictites. Although the former can be attributed to paleolatitudinal shift, or a clockwise rotation of Gondwana, what is not easily explained (and much discussed) is the autochthonous continuity of northeastern and central Bolivian carbonate deposits of the northern Peru–Bolivia Basin with southern Pennsylvanian and Permian glaciogenic deposits, which accumulated in the Tarija–Chaco Basin. Given that these cold and warm-water deposits were coeval in time, a severe climate gradient must have existed across Bolivia beginning in Pennsylvanian time. Western Gondwana records steady movement from high latitudes (~55°S) in the Late Devonian to midlatitudes (~40°S) by Pennsylvanian time. Glacial deposits seen in the northwest during the Late Devonian become restricted to the southern Tarija–Chaco Basin by the Late Pennsylvanian. By Early Pennsylvanian (Bashkirian) time, carbonates, evaporites, and siliciclastics were deposited in northwest Bolivia. In central Bolivia, Mississippian diamictites, undated Pennsylvanian siliciclastics, Copacabana lithofacies, and carbonates of the Vitiacua Formation are vertically stacked at a few locations.

KEY WORDS: Pennsylvanian, glaciation, carbonates, Bolivia, paleoclimate shift

INTRODUCTION

During the Late Paleozoic, Bolivia had two principal depocenters (Fig. 1A), the Madre de Dios Basin in the north and the Tarija–Chaco Basin in the south. "Western" Bolivia encompasses the Lake Titicaca area, and the northern Bolivian subsurface (Madre de Dios Basin). Southern Bolivia is part of the Tarija–Chaco Basin that extends into Argentina and Paraguay. It has long been known that Bolivia, in the southern cone of South America (as part of western Gondwana) was at a high paleolatitude during the Early Paleozoic. The region was probably at 55°S paleolatitude (Isaacson and Díaz-Martínez 1995, Scotese 2003) in Early Devonian time and moved in a clockwise rotation (Iannuzzi and Rösler 2000) to the north throughout the Late Paleozoic (Fig. 1B, C). During most of the Devonian, a marine connection between the Bolivian and other areas in South America (Perú, Brazil, Argentina) is interpreted on the basis of common invertebrates, and marine acritarchs, among other fossils (e.g., Isaacson and Sablock 1988; Melo 1988; di Pasquo et al. 2009, 2015a).

Devonian shallow marine depositional systems covered the entire area connecting western and southern Bolivia (Isaacson and Díaz-Martínez 1995). This deposition continued in western Bolivia throughout the Mississippian. In southern Bolivia, limited datable rocks and the extent of Late Devonian (Famennian) and Mississippian (Visean) units point to two phases of uplift associated with the Chañic Orogeny causing significant hiatuses and changes in depositional environments that are most likely due to basin inversion (di Pasquo and

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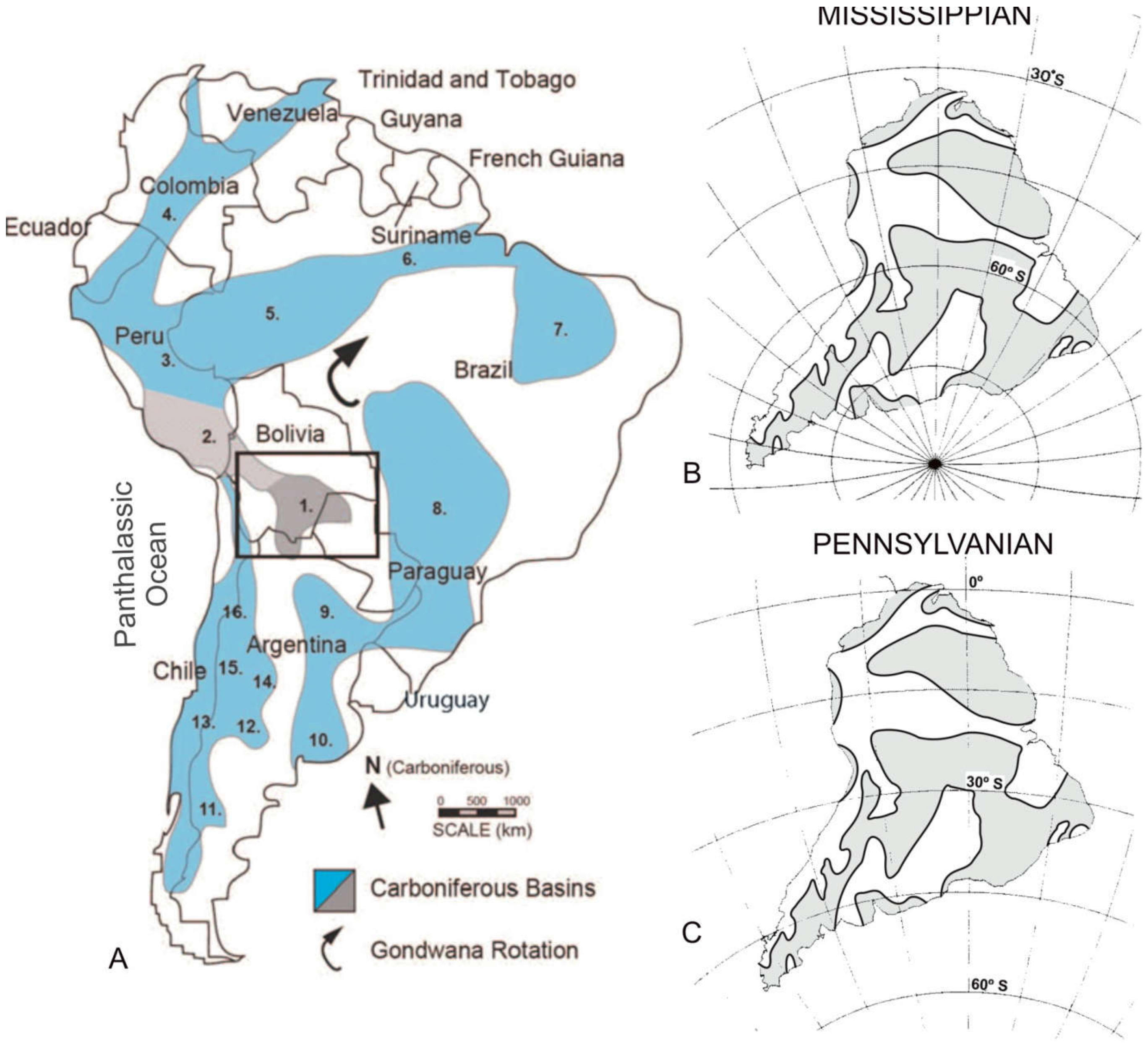

FIG. 1.—**A)** Location of Carboniferous basins in South America (gray and blue), modified from Azcuy and di Pasquo (2000). Gray area is the larger Peru–Bolivia Basin. Dark gray area is the Tarija–Chaco Basin. Light gray area is the Madre de Dios Basin. White areas are highlands. All Carboniferous basins are numbered as follows: (1) Tarija–Chaco, (2) Madre de Dios, (3) Marañon–Ucayali–Acre, (4) Llanos Orientales, (5) Solimôes, (6) Amazonas, (7) Parnaiba, (8) Paraná, (9) Chaco–Paraná, (10) Sauce Grande Colorado, (11) Tapuel–Genoa, (12) San Rafael, (13) Uspallata, (14) Paganzo, (15) Calingasta, (16) Rio Blanco/Navidad–Arizaro. Bold arrow indicates Gondwana clockwise rotation from **B)** Mississippian to **C)** Pennsylvanian (Isaacson and Díaz-Martínez 1995, Azcuy and di Pasquo 2000, Iannuzzi and Rösler 2000).

Azcuy 1997). During the Pennsylvanian, oblique convergence along the western margin of Gondwana caused transtension (Fig. 2) in western and southern Bolivia, with the majority of deposition occurring in a segmented transtensional back-arc setting (López-Gamundí et al. 1992, González Bonorino 1992, Mon and Salfity 1995, Sempere 1995, Tankard et al. 1995, Grader 2003, Grader et al. 2008).

In the Lake Titicaca area (western Bolivia), the northern Bolivian subsurface, and into central Peru and the Brazilian subsurface, Devonian cold-water siliciclastic, glacial dropstones, glacial diamictites, and presumable Early Carboniferous peri-glacial fluvial systems occur (Fig. 3). Above these, and in the same geographic areas, this succession is conformably followed by a succession of carbonate rocks containing warm-water fusulinid faunas (Newell et al. 1953). This has long challenged paleogeographic and paleoclimatic interpretations for western Gondwana. There has been considerable lithologic, stratigraphic, and biostratigraphic work on the carbonates, yet their

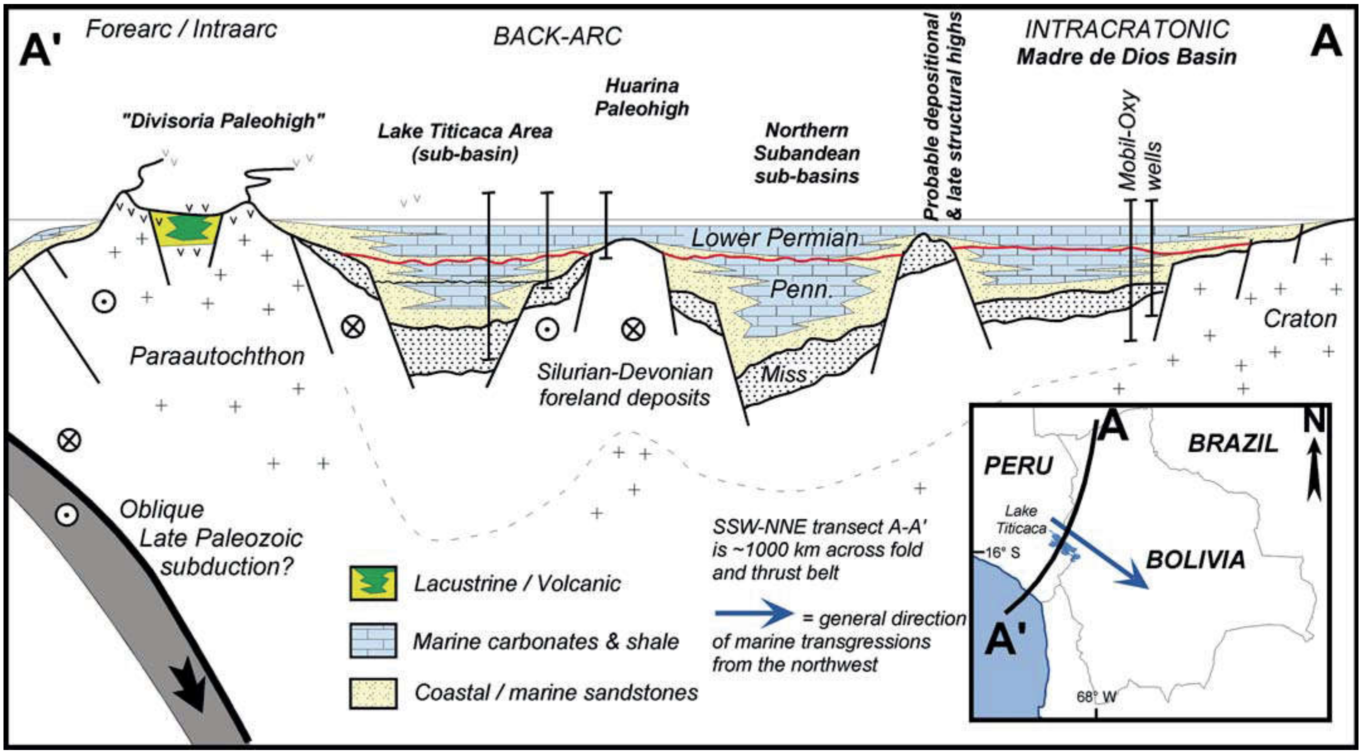

FIG. 2.—Transtensional, prerift setting of the Copacabana Formation showing southwest–northeast primary paleogeographic features (modified from Grader 2003, Grader et al. 2008). Cross-section Y–Y′ crosses primary northwest–southeast paleogeographic features. Stratigraphic sections near Lake Titicaca are significantly older, and generally thinner than sections to the southeast, although local facies and age variations occur (e.g., Copacabana Peninsula vs. Huarina fold and thrust belt). Mobil-Oxy wells in the Madre de Dios Basin have a separate basin history from those in the Cordilleran area, but comparable Early Pennsylvanian successions at both locations allow for comparison between these regions (Isaacson et al. 1995). See Díaz Martínez et al. (2000) and Breitkreuz et al. (1988) for discussion of western forearc and arc-associated deposits. Foreland paleohigh represents both potential syn-depositional Quince Mil Arch (Peru) influence on northern Bolivia and the effects of later reactivation associated with the Madidi structural high. The latter contributed significantly to the concept of a Madre de Dios Basin (Oviedo and Morales 2000).

occurrence in continuous section above cold-water siliciclastics has stimulated much thought.

In southern Bolivia, thick successions of Pennsylvanian diamictites with faceted and striated clasts and few striated surfaces indicate glaciogenic deposition during a cold climate. This contrasts significantly with warm-water faunal assemblages of the Copacabana Formation in western Bolivia, suggesting a steep climatic gradient. Although deposition is continuous across Bolivia at this time, segmentation of the basin restricts depositional areas.

STRATIGRAPHIC FRAMEWORK

Early and Middle Devonian across Bolivia: A Brief Summary

One open question about the Pennsylvanian paleoclimatic gradient across Bolivia is whether the western and southern basins had a marine connection or were separated by a paleogeographic feature at that time, thereby isolating the western and southern regions. We present a synopsis of Devonian events to show that there was a connection at that time.

Being similar in both western and southern Bolivia, basic Devonian stratigraphic data essential for paleogeographic and paleoclimatic reconstructions are well established (Isaacson 1975, 1977; Oller and Sempere, *in* Duarte, 1989; Starck et al. 1993a) and are shown in Figure 4. The bulk of the thick clastic succession in western and central Bolivia is composed of, in descending rank of abundance, siltstone, quartz arenite, mudstone, and shale (Isaacson and Sablock 1988). Feldspathic sandstones are found in southern Bolivia. Lithofacies and isopach maps of the Devonian succession indicates coarser and much thicker sediment in northwestern Bolivia than found to the east and south (Isaacson 1975). This succession is primarily Early Devonian up to Frasnian in age based on many fossil records all along the country up to northern Argentina (see references in Isaacson and Sablock 1990; Babin et al. 1991; Blieck et al. 1996; Limachi et al. 1996; Suárez-Soruco 2000; di Pasquo et al. 2009, 2015a; Troth et al. 2011; Noetinger et al. 2015). Palynomorphs delineate the Famennian–Tournaisian boundary at few localities where diamictites occur (e.g., Lobo Boneta 1987; Vavrdová et al. 1991, 1996; di Pasquo and Azcuy 1997).

WESTERN BOLIVIA

Late Devonian–Earliest Mississippian

Identification of a Late Devonian glacial event in South America not only has major significance with respect to the paleogeography of

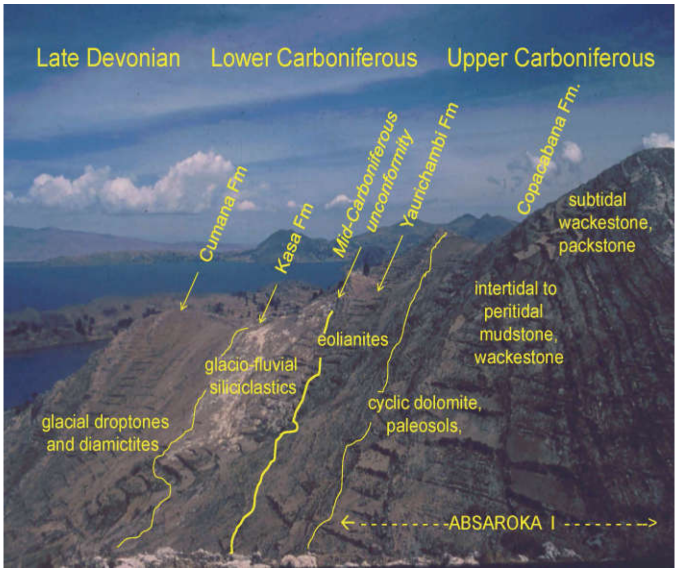

FIG. 3.—View to northwest of conformable Devonian through Pennsylvanian section, Yampupata (Copacabana Peninsula, Lake Titicaca) Bolivia. The Late Devonian Cumaná Formation dropstones and diamictites (Isaacson et al. 1999, 2008; Díaz-Martínez 2004) are overlain by fluvial and glacio–fluvial siliciclastics of the Carboniferous Kasa Formation (Díaz-Martínez 1994, Sempere 1995) and the Yaurichambi Formation (d'Orbigny 1835, Chamot 1965). It is the Copacabana Formation (Grader 2003, Grader et al. 2008) that reflects a significant paleoenvironmental shift from cold-water siliciclastics to warm-water carbonates (rocks types after Dunham 1962).

Gondwana but also may have important consequences and implications for the interpretation of many Late Devonian features of the geological record on a global scale. It is now recognized that the Famennian glaciation in Gondwana occurred over a broad area (Caputo 1985). Caputo (1985) described not only diamictites and dropstones of glacial origin across the Parnaiba, Amazonas, and Solimões basins of Brazil (representing an east–west spread of 3500 km) but also faceted and striated pebbles and glacially striated pavements. Evidence for a Devonian glaciation continues into Bolivia (Díaz-Martínez and Isaacson 1995), both in outcrop in the Lake Titicaca region, and in the subsurface of the Madre de Dios Basin, northern Bolivia (Isaacson et al. 1995). Located above shallow marine shales with dropstones (Colpacucho Formation) and within the Cumaná Formation (Fig. 4) in the northern "altiplano" of Bolivia is a diamictite unit that can be traced for more than 30 km along strike from Isla del Sol to Cumaná (Lake Titicaca area), with a thickness of 60 to 70 m (Díaz-Martínez and Lema 1991). Evidence includes poorly bedded diamictite beds containing large granite boulders as well as faceted and striated clasts composed of quartz arenite, granitoid, quartzite, conglomerate, and intermediate volcanic rock (Díaz-Martínez et al. 1993). Their variable composition, together with some striated and faceted clasts, suggests a glaciated heterogeneous source terrane. There are two major lithofacies associations. The lower is dominated by laminated mudstone with dropstones, and it is interpreted as ice-rafted and suspended sediment deposits. The upper is an erosional based massive, matrix-supported diamictite with deformed sandstone lenses and boulders of up to 2.5 m long. This latter unit is interpreted as being the result of subglacial deposition at the margin of a partly floating ice mass, with resedimentation by postdepositional mass-movement processes (subaqueous slumping), along with partial reworking by currents. There is no evidence for regression and subaerial erosion. The local unconformable and erosional character of the base of the Cumaná Formation resulted from erosional and depositional processes typical of a glacio–marine environment (Isaacson et al. 2008). Paleogeographic reconstruction of the region during the Early Carboniferous (Figs. 1–3) suggests that the Eohercynian orogen in the Cordillera Real is a possible source terrane (Dalmayrac et al. 1980). Early and Middle Carboniferous clastic units of this area (Cumaná and Kasa formations; Fig. 4) show continued glaciation of the source terrane through much of this succession. These thick, widespread diamictite deposits record the local advance and retreat of glaciers into the basin during the Latest Famennian and continue into the Tournaisian, as seen in the Mobil-Oxy wells of northern Bolivia (di Pasquo et al. 2015b, di Pasquo 2015). Coeval deposits in the Subandean regions of Bolivia and northern Argentina suggest glaciers may also have developed further south in the Early Visean (di Pasquo 2006, 2007b, 2007d, 2008).

Timing of glacial deposition in western Bolivia is relatively well constrained by palynomorphs (Vavrdová et al. 1993, Isaacson et al. 1995). It generally begins within the Late Devonian (Famennian) *pusillites–lepidophyta* Palynozone and continues into the Carboniferous. Vavrdová et al. (1993) reported the following taxa: *Retispora lepidophyta*, *Kraeuselisporites explanatus*, *Verrucosisporites nitidus*, and *Lophozonotriletes rarituberculatus* of Late Devonian age, and *Densosporites spitsbergensis* and *Rugospora polyptycha* of Early Carboniferous age. The collections occur within the Late Famennian and Tournaisian LE, LN, and VI palynozones (where LE, *Retispora lepidophyta–Indotriradites explanatus*; LN, *Retispora lepidophyta–Verrucosisporites nitidus*; and VI, *Vallatisporites verrucosus–Retusotriletes incohatus*). Abundant occurrences of *Umbellasphaeridium saharicum* and other acritarch species imply marine connection between Bolivia and coeval North African basins, via Brazil. At the transition from the Devonian to the Carboniferous, relative abundances of marine acritarchs decrease and megaspores increase, suggesting a significant lowering of sea level in the area during this deposition (Vavrdová et al. 1993).

The Bolivian miospore assemblages in altiplano outcrop data show close similarities to sub-Saharan basins (i.e., the Murzúq and Ghadamis basins, Libya, and the Illizi Basin of Algeria) described by Attar et al. (1980), Coquel and Moreau-Benoit (1986), and Vavrdová et al. (1991), among others. The species common to both Bolivia and North Africa are listed in Vavrdová et al. (1991).

New biostratigraphic data from the Mobil-Oxy wells in northern Bolivia show that Devonian palynomorphs are recycled into Tournaisian (Table 1; Appendix 1) sediments (di Pasquo 2015, di Pasquo et al. 2015b); mixed with those taxa that are diagnostic of the Tournaisian–Visean age in South–North America, Europe, and Australia. Interestingly, the reworked species *R. lepidophyta* (Latest Famennian) is abundant, spanning 1432 to 1385 m persisting up to 1151 m, and *Waltzispora lanzonii* and *Cyrtospora cristifera* are only present in the second interval. This new information suggests glacial ice advance, which recycled Late Devonian palynomorphs in the Early Tournaisian.

Therefore, the Cumaná Formation may be the earliest sign of the Late Paleozoic Ice Age in South America, and glaciers in Bolivia, which developed in adjacent mountain ranges, persisted from the Famennian into the Early Visean.

Mississippian

The Kasa Formation (Figs. 3, 4) is commonly assigned a Tournaisian–Visean age and consists of a complex deltaic progradational succession composed of several minor successions deposited on

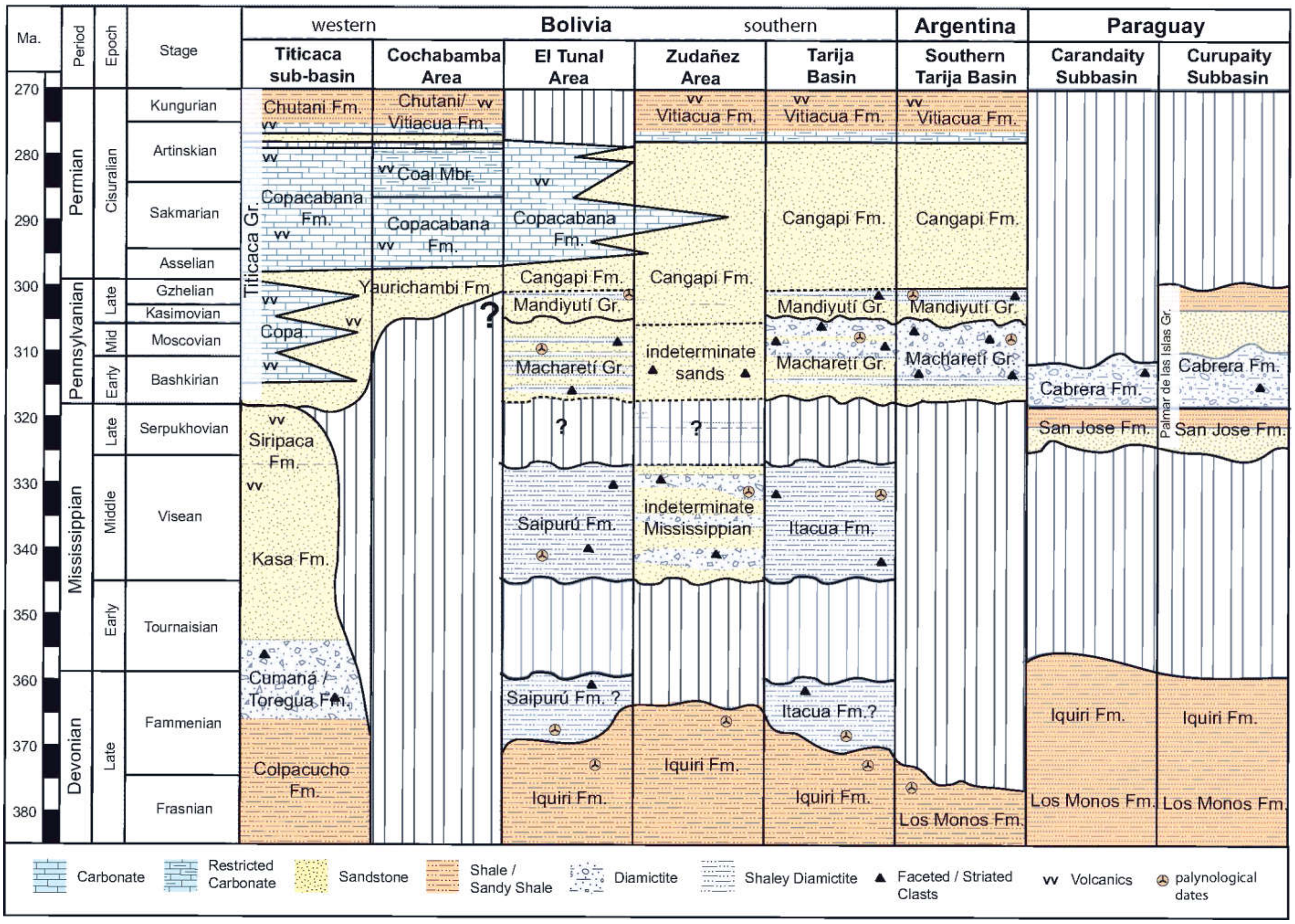

FIG. 4.—Chronostratigraphic formation correlations for Bolivia (western–northern, and southern) and northern Argentina across the Peru–Bolivia basins (Anderson 2011, di Pasquo et al. 2014). Note the lithologic change from siliciclastics to carbonates in western (and northern) Bolivia. In southern Bolivia, cold-water and terrestrial siliciclastics persist through the Late Paleozoic. Note which units are dated through palynology. Triangles show stratigraphic occurrences of glacial lithologies.

a shallow siliciclastic shelf in a retroarc foreland setting (Díaz-Martínez 1994, Isaacson and Díaz-Martínez 1995, Sempere 1995). Provenance analysis of sandstones within the Kasa Formation reveals a compositional trend consisting of arkosic and quartzose petrofacies. The overlying unit, the Siripaca Formation (Fig. 4), contains plant-bearing (notably *Nothorhacopteris*; Iannuzzi et al. 1999) lithologies and paleosols (Díaz-Martínez 1991). It is considered to be Visean to Serpukhovian in age (see Azcuy et al. 2007).

Pennsylvanian

In Bolivia, at the base of the Pennsylvanian succession is the Yaurichambi Formation (d'Orbigny 1835, Chamot 1965), which has several sandstone with eolian characteristics and minor mudstone lithologies reddish in color indicating a range of continental depositional environments (Díaz-Martínez 1991). A portion of the unit is a facies equivalent to the lower Copacabana Formation (Figs. 3, 4). It was deposited in a convergent plate margin setting of western Gondwana and unconformably above a significant erosional event, Serpukhovian in age (Fig. 2; Isaacson and Díaz-Martínez 1995, Díaz-Martínez 1999).

Above the Yaurichambi Formation is the Copacabana Formation (Figs. 2, 5, 6), a carbonate dominated unit deposited in an active back-arc in the central Andes from the Pennsylvanian–Permian. The Pennsylvanian part of the Copacabana Formation is a significant contrast with underlying units, which are Gondwanan glacial and peri-glacial deposits. The Copacabana Formation (and Titicaca Group) consists of diverse carbonates, compositionally immature (but texturally more mature) arkosic and lithic sandstones, shales, tuffs, and evaporates (Grader et al. 2008). Dating and biostratigraphic work included foraminifera (Mamet 1996, Mamet and Isaacson 1997), fusulinids (Sakagami and Mizuno 1994), conodonts (Merino-Rodo 1987, Merino and Blanco 1990), palynomorphs (di Pasquo 2009b, di Pasquo and Grader 2012, di Pasquo et al. 2014), corals (Suárez-Riglos 1984, Wilson 1990), brachiopods (Samtleben 1971, Birhuet 1993), and bryozoans (Sakagami 1995).

Remnant eolian sandstones and cross-bedded, fossiliferous marine sandstones with limestone lithoclasts were sourced from reworked semilithified Copacabana rocks during lowstands and transgressive flooding events (Figs. 2–4; Grader et al. 2000). Many large- and small-scale cycles form warm-water composite sequences in the central Andes. The Pangean second-order transgressive succession in the

TABLE 1.—Indigenous palynomorph occurrences and their ages in the Manuripi X-1 core, Pando Department, northern Bolivia.

Interval	Age	Indigenous Taxa
1535–1387 m	Tournaisian, with recycled Devonian palynomorphs	*Anapiculatisporites ampullaceus* *Convolutispora harlandii* *Convolutispora ampla* *Convolutispora insulosa* *Cordylosporites papillatus* *Crassispora scrupulosa* *Cristatisporites echinatus* *Cymbosporites loboziakii* *Dibolisporites microspicatus* *Dibolisporites setigerus* *Granulatisporites granulatus* *Foveosporites hortonensis* *Raistrickia ponderosa* *Raistrickia baculosa* *Reticulatisporites waloweekii* *Secarisporites undatus* *Spelaeotriletes balteatus* *Vallatisporites ciliaris* *Vallatisporites microgalearis*
1328–1315 m	Tournaisian–Visean	*Cristatisporites menendezii* *Cristatisporites stellatus* *Crassispora kosankei* *Cristatisporites peruvianus* *Indotriradites viriosus* *Lycospora noctuina* *Punctatisporites lucidulus* *Pustulatisporites multicapitis* *Verrucosisporites morulatus* *Verrucosisporites gobbettii*

Madre de Dios Basin records inherited basement controls and ephemeral pericratonic seaways to the interior of a western landmass. Warm-water marine transgression was from the north (Grader et al. 2008).

Stratigraphic isopachs and paleofault data in Peru suggest localized extension and significant variations in regional subsidence and accommodation of the Copacabana Formation (Sempere et al. 2002). In Bolivia, however, less dramatic facies variations and an overall much thinner, conformable stratigraphic record containing warm-water fossil evidence of all Pennsylvanian–Cisuralian stages is more simply explained by eustatic controls over relatively quiet, epeiric seaways. Additionally, a semiarid climate and nearby source areas produced a consistent supply, by eolian processes, of reworked, sand-sized clastics onto inner carbonate ramps. This reconstruction emphasizes hypothetical extensional fault-enhanced sag basins that received marine influx primarily from the northwest, but it is also likely that these basins received marine transgressions through the arc to the east. With rise and fall of relative sea level and gradual submergence of the Huarina High that segmented the western Bolivian Basin during the Pennsylvanian to Permian, shoreline positions and polarities toward basin centers changed significantly. Figure 2 shows Late Permian evolution of cross-section Y–Y′ and reactivation of the Huarina High (Grader et al. 2008).

Synthesis of Copacabana Formation sequences places them at the core of the “Cuevo Supersequence” (Sempere 1995), an Absaroka-like megasequence (sensu Vail et al. 1991). Silled seaways developed over an inherited northwest–southeast basement lineament between the western Arequipa Massif and eastern Brazilian craton. The Pennsylvanian lower Copacabana Formation is discontinuous, and deposition was fundamentally controlled by an inherited Mississippian paleohigh (Fig. 2). Cyclic siliciclastic–carbonate facies distributions with ash beds were deposited regionally, with accumulation in fault-bound troughs within a back-arc setting. The middle and upper Copacabana Formation (Late Pennsylvanian and Early Permian) is locally variable, but continuous carbonate and evaporite depositional successions over considerable distances are recognized into Peru (Newell et al. 1953) and Brazil (Caputo and Silva 1990, Nascimento et al. 2005). Long-term and widespread flooding (transgressive systems tract [TST]) and aggradational/progradational ramp facies (highstand systems tract [HST]) in western Bolivia suggest deposition on mainly up-dip margins in multiple subbasins. Synchronous glacio–eustatic and climatic controls overprinted an active transtensional(?) to incipient rift tectonic evolution (Fig. 2).

Pennsylvanian (Copacabana Formation) Depositional Paleoenvironments

Characteristic Copacabana deposits include thickly bedded limestone with open marine, warm-water invertebrates, which were deposited on well-oxygenated homoclinal ramps. Accumulations of siliciclastic sediment with an absence of fauna are associated with restricted offshore and lagoonal environments (black shale) and with platform dolomudstones. Dolostones are generally unfossiliferous and associated with algal laminations, red siltstones, artifacts of anhydrite,

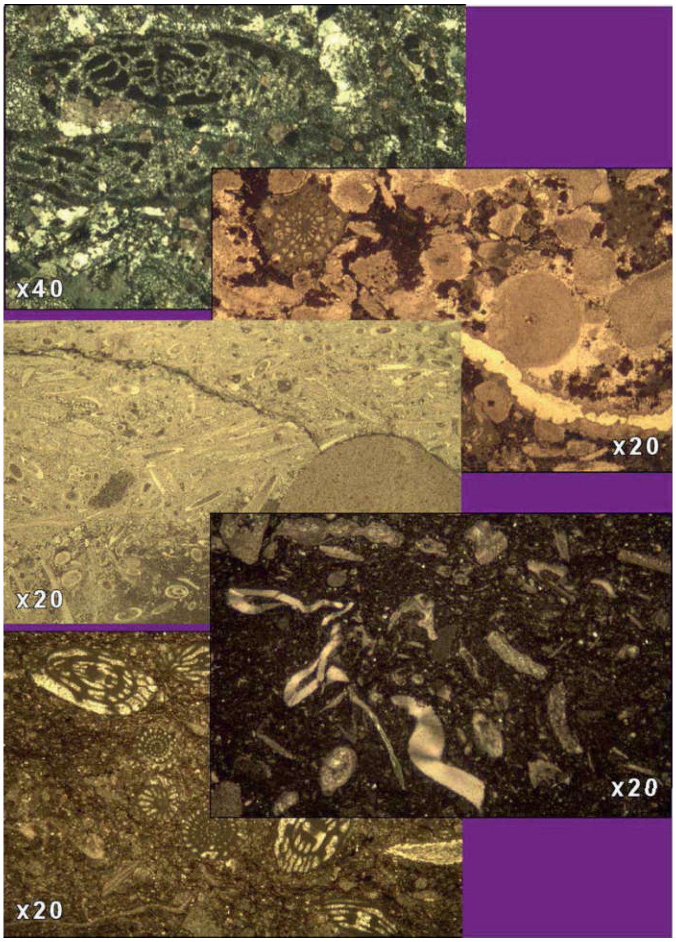

FIG. 5.—Thin sections of representative Copacabana lithologies. Lower two photomicrographs are of lower Copacabana muddy carbonates (wackestones) with small *Profusulina* sp. Other significant bioclasts include echinoderm spines, trilobites, and brachiopods. Upper three photomicrographs show high energy grainstones, encrinites, schwagerinid fusulinids, and *Eoparafusulina* sp.

and well sorted, coarse- to fine-grained volcaniclastic sandstones; these lithofacies are associated with peritidal inner ramp and sabkha environments. Generally, once free of siliciclastic interbeds, carbonate rocks shallow upward (Fig. 5) into in situ marine grainstones and floatstones with diverse fossil assemblages near fairweather wave bases. Further shallowing of these successions resulted in the deposition of grainstones that show significant sorting and reworking of allochems in tidal and shoal environments (Grader 2003).

Fossiliferous limestones with echinoderms (Fig. 6) characterize periods of normal salinity and circulation on the ramp. In Carboniferous units at Cumaná, these facies change up-section into transgressive dark shale deposits with synsedimentary slump beds (distal ramp deposits of the Lake Titicaca Basin). Peritidal, cross-bedded quartz sandstone with blue–green, altered volcaniclastic ash and dolomudstone with silcrete beds punctuate open marine subtidal lithofacies.

The paleoenvironmental record is best summarized as (1) a semirestricted warm seaway to open sea dominated by carbonates and (2) a sand-dominated coastal plain with dune and beach systems, lagoons, and tidal channels. Preserved fluvial facies are mainly restricted to back-arc basin margins. During lowstands, incised semiarid channel systems of the coastal plain may also have acted as conduits of sediment over the exposed Copacabana ramp and are represented in the study area mainly as variable to removed exposure surfaces.

Explosive volcanism within highlands to the west deposited ash beds in marine environments, and these highlands also delivered feldspathic to lithic sandstones to the Copacabana Peninsula and southern Bolivian basins via coastal plain environments (sabkhas with semiarid fluvial and eolian influence). Primarily shallow water carbonate ramp conditions occur with evaporites and heterozoan–photozoan fossil assemblages (Figs. 5, 6), behind wetter arc-associated environments and cool ocean-facing environments to the west (Grader et al. 2008). Warm water delivered by continent-parallel to transcontinental currents connected West Texas and Tethyan faunal provinces with the Andean area (Dunbar and Newell 1946, Newell et al. 1953). The lower and middle Copacabana Formation has calcrete, silcrete, and microkarst paleosols suggesting semiarid, inboard seaway conditions in lower temperate to subtropical latitudes (Rakotosolofo et al. 2006). Copacabana sedimentation rates in Bolivia were relatively low (7–25 m/my) compared with the thicker and shale-rich formation in Peru. Grader (2003) and Grader et al. (2008) described stacked TST/HST systems tracts with significant hiatuses formed in open and restricted to semiarid coastal and marine depositional systems. Twelve third-order, 30- to 100-m sequences have paleosols developed on the marine limestone and extensive siliciclastic lowstand/transgressive shoreline facies above sequence boundaries near the western basin margin. Thick accumulations of progradational carbonate characterize HSTs. More distal, subtidal ramp sequences have fossiliferous packstone/grainstone caps that do not reach subaerial exposure. These sequences are well developed in the northern lowlands and Peru, as well as near Cochabamba (central Bolivia) in one of many seaway-connected depocenters (Fig. 2). Small meter-scale shallowing-upward parasequences and internal autocyclic, icehouse facies mosaics make up the large Copacabana sequences. Overall accumulation patterns and sandstone–carbonate cyclicity are indicative of combined tectonic and high-amplitude, high-frequency glacio–eustatic depositional controls and sequence boundaries that serve as proxies for glaciation events elsewhere in Gondwana (Grader et al. 2000, 2008).

SOUTHERN BOLIVIA–NORTHERN ARGENTINA

Late Devonian–Mississippian

Late Devonian–Mississippian deposits in southern Bolivia, bounded by unconformities, are variably present across the basin, occurring only at a few locations as the Itacua and Saipurú formations (di Pasquo and Azcuy 1997; Azcuy and di Pasquo 2000; di Pasquo 2003, 2007a, 2007b, 2007d, 2008). Although thought to be equivalent units, small differences between them exist across the basin. The Itacua Formation generally consists of mudstone and shale with minor diamictite units. Lower diamictites of the Itacua Formation are sandy and contain faceted and striated clasts, while upper diamictites are shaley with relatively few small granule-sized clasts and more commonly with outsized coarse sand grains (Starck and del Papa 2006, Anderson 2011). To the north, the Saipurú Formation crops out as purple micaceous sandstones and red muddy diamictites. Analysis of these units shows distal delta and submarine fan environments (Suárez-Soruco and Díaz-Martínez 1996, Suárez-Soruco 2000). Significant hiatuses and changes in depositional environments are most likely due to basin inversion caused by the Chañic Orogeny (Starck et al. 1993a, 1993b; di Pasquo and Azcuy 1997; di Pasquo 2003).

FIG. 6.—Marine fossils from open marine bed of Copacabana Formation (Grader 2003). **A)** Articulated productid brachiopods in life position. **B)** partially disarticulated echinoid, indicating normal marine salinity.

The age of the Itacua Formation has been debated, with both Famennian and Visean ages suggested in different studies by different researchers (di Pasquo and Azcuy 1997; di Pasquo 2007b, 2007c, 2008; Wicander et al. 2011). These studies used palynology to determine the age of the Itacua Formation at different locations (Bermejo, Macharetí, Balapuca) in Bolivia. Given the variable extent of the Itacua Formation (and equivalents) across the Tarija–Chaco Basin and its unconformable upper and lower contacts (di Pasquo and Azcuy 1997; di Pasquo 2003, 2006, 2007b, 2007c), it is necessary to date each deposit in different localities where they have been preserved to establish a more accurate correlation of this unit with others such as the Saipurú Formation (di Pasquo 2006, 2007c). It has been suggested that they must not be included in the Macharetí Group (di Pasquo and Azcuy 1997; di Pasquo 2007b, 2007c; Anderson et al. 2010; Anderson 2011), where were placed by Padula and Reyes (1958) and Reyes (1972).

Pennsylvanian

The Pennsylvanian Macharetí and Mandiyutí groups of southern Bolivia constitute a complex succession of sandstones, diamictites, and shales recording glacially influenced deposition (Table 2) in a tectonically active basin (Tarija–Chaco Basin) during the Late Paleozoic Ice Age. The Macharetí Group, which contains the largest extent of glacigenic deposits, consists of four formations, the Tupambi, Itacuami, Chorro, and Taiguati (also known as the Tarija in correlative Argentinian deposits, see Fig. 4), with most deposits containing either minor or extensive evidence of glaciation in the form of diamictites, faceted and striated clasts, and striated surfaces. Overlying this is the Mandiyutí Group, which consists of the Escarpment and San Telmo formations. Glacial evidence is only found in the San Telmo Formation, which occurs in the southern Tarija–Chaco Basin in northern Argentina and southernmost Bolivia (Starck 1995; di Pasquo 1999, 2003; Azcuy and di Pasquo 2000; Starck and del Papa 2006; Anderson 2011; di Pasquo et al. 2017).

The presence of glacial units in the Macharetí and Mandiyutí group has led to their inclusion in several continent-wide studies of the Late Paleozoic Ice Age (e.g., Caputo and Crowell 1985, Eyles et al. 1985, Eyles 1993, Isbell et al. 2003, Caputo et al. 2008), though little study on the glacial significance of these units themselves has been undertaken (Helwig 1972, Starck and del Papa 2006, Anderson 2011). These rocks have been the subject of several basin-wide studies (Ayaviri 1972, Helwig 1972, Reyes 1972, Salinas et al. 1978, Sanjinés-Saucedo 1982, Suárez-Soruco 1986, Weins 1995, Starck and del Papa 2006) owing to the abundance of oil and gas (70% of Bolivia's total oil and gas reserves; McCaslin 1979) within them. However, despite continual interest from industry, these rocks are poorly understood and hotly debated.

Pennsylvanian Depositional Paleoenvironments

Models for the depositional environments of the Macharetí Group have been highly discussed, and interpretations range from continental into deep marine. However, without detailed observation of the deposits, the shift from thick massive diamictites to increasing sandstones and soft sediment deformation has been interpreted as the transition from a glaciated shelf to submarine fan deposits in the northern Tarija–Chaco Basin (e.g., Eyles et al. 1995, Sempere 1995). Instead, other interpretations were based on more careful analysis and provided evidence against a deep marine depositional environment for the Macharetí Group (e.g., López-Gamundí 1986, 1987; Salfity et al. 1987; Starck et al. 1993b; Starck 1995; Díaz-Martínez 1996; del Papa and Martínez 2001; di Pasquo 2002, 2003, 2009a; Starck and del Papa 2006; del Papa and di Pasquo 2007; Anderson 2011; di Pasquo et al. 2017). Some of this evidence is

1. Occurrence of paleosols and rootlets in outcrops across the Tarija–Chaco Basin (Fernández Garrasino 1978, 1979; Salfity et al. 1987; di Pasquo 1999; Azcuy and di Pasquo 2000; Anderson 2011; di Pasquo et al. 2017).
2. *Diplopodichnus biformis* in the Itacuami Formation at Macharetí (Buatois and del Papa 2003, Anderson 2011).
3. Symmetrical ripples and waveform cross-lamination in the Macharetí Group at a few localities (del Papa and Martínez 2001, di Pasquo 2002, del Papa and di Pasquo 2007, Anderson 2011).
4. Few turbidite successions, graded beds, and massive sandstones–facies that dominate submarine fan deposits (López-Gamundí 1986, 1987; Anderson 2011).
5. Plant fragments in the Macharetí Group (di Pasquo 2009a, Anderson 2011).
6. Lack of indigenous marine palynomorphs and pyritization of indigenous miospores in studied sections from northern Argentina and Bolivia (di Pasquo 1999, 2002, 2003, 2009a; del Papa and di Pasquo 2007; di Pasquo and Anderson 2012; Fig. 7; Appendix 1).

TABLE 2.—Summary of lithofacies codes, descriptions, and interpretations for the Macharetí and Mandiyutí Groups, with emphasis on glacial and peri-glacial occurrences (Anderson 2011). Lithofacies codes modified after Evans and Benn (2004) and Miall (1978).

Facies	**Overall description of lithofacies association**	**Interpretation of depositional environment**	**Units**
Dmm (Dml)	Thick massive diamictite with gradational changes from muddier to sandier diamictites	Proximal glacial (waterlain or lodgement till)	Macharetí (Tarija, Taiguati) San Telmo
Dmm, Dmm(c), Dms(c) (Sm,St)	Massive diamictite with sand channels and lenses	Proximal glacial (reworking of diamictite by sub-glacial outflow)	Macharetí (Tarija, Taiguati)
Dmm(c) (Scr)	Massive diamictite with evidence of reworking	Proglacial sediment gravity flows	Macharetí (Tarija, Taiguati)
Dml, Fmd	Mudstone with outsized sand and rare clasts	Distal glacial (suspended sediment plumes and rainout)	Itacua, Macharetí (Itacuami), San Telmo
Sd, Dmm(c)	Deformed sandstones with shale based scours, slumps and olistoliths in massive resedimented diamictite	Submarine fan/ slope resedimentation	Central Bolivia
Dmm(c), Sd Guf, Sl, Se, St, Su(c), St(c), Scr, Dmm, Dmm(c))	Diamictite with discontinuous and deformed sand beds	Prodelta and delta front sediment gravity flows	Macharetí San Telmo
St, Se (Ser, St(r), Se(r), Sr, Sh, Sd, Scr, Sm, Su, Gms)	Channel sands and lenticular sand bodies and resedimentation	Delta Front	Macharetí Escarpment

Dmm: Diamictite, clay-boulder (poorly sorted), massive, matrix supported with scattered clasts
Dml: Diamictite, clay-sand (moderately sorted), crude lamination
Dmm(c): Diamictite, clay-boulder (poorly sorted), sand lenses, ripples, small (<20cm) trough cross-bedding
Dmm(r): Diamictite, clay-boulder (poorly sorted), flame structures, fracture heal structures, convolute bedding, slumped and disembodied sands
Dms(c): Diamictite, clay-boulder (moderately sorted), stratified, matrix supported, sand lenses and channels
Gms: Gravel, medium sand to pebble (moderately sorted), crudely stratified or cross-bedded
Guf: Gravel, medium sand to pebble (moderately sorted), fining upward
St: Sandstone, fine-coarse sand (moderately to well sorted), trough cross-bed sets (up to 2 m)
Sp: Sandstone, fine-coarse sand (moderately to well sorted), planar cross-bedding
Shc: Sandstone, fine sand (moderately to well sorted), hummocky cross-bedding
Sr: Sandstone, very fine to medium sand (moderately to well sorted), ripple cross-lamination (unidirectional)
Sr(b): Sandstone, very fine to medium sand (moderately to well sorted), ripple cross-lamination (bi-directional) 11 Wave-form ripples
Scr: Sandstone, very fine to medium sand (moderately to well sorted), climbing ripples
Sfl: Sandstone, very fine to medium sand (moderately to well sorted), flaser cross-bedding or cross-lamination
Sh: Sandstone, fine-medium sand (moderately to well sorted), horizontally bedded a) No shale partings, minor ripple cross-laminations b) Shale partings, minor ripple cross laminations
Sl: Sandstone, fine sand (moderately to well sorted) with laminations
Se: Sandstone, fine sand to cobble (moderately sorted), scour and fill, conglomerate lags, trough cross-bedding, fining upward
Ser: Sandstone, fine sand to cobble (moderately sorted), scour and fill, minor conglomerate lags, ripple cross laminations, fining upward
Su: Sandstone, fine sand to granule (moderately sorted), scour and fill, broad shallow sand lenses, minor conglomerate lags and trough cross bedding

7. No marine invertebrates in the Macharetí Group except for few records in the Taiguati Formation (see Rocha-Campos et al. 1977, di Pasquo 1999, Anderson 2011, di Pasquo et al. 2017).

Faceted and striated clasts within the diamictites (Fig. 8) confirm a glacial origin to several units within the Macharetí and Mandiyutí groups, recording at least six major glacial ice advances. Glacial, cold climate influence slightly decreases to the north and through time (Fig. 4) in the Tarija–Chaco Basin, also reflecting the northward clockwise rotation of Gondwana throughout the Late Paleozoic (Fig. 1B, C). Thick diamictites in southern Bolivia and glacial pavements (Starck and del Papa 2006) support the presence of an ice sheet in northern

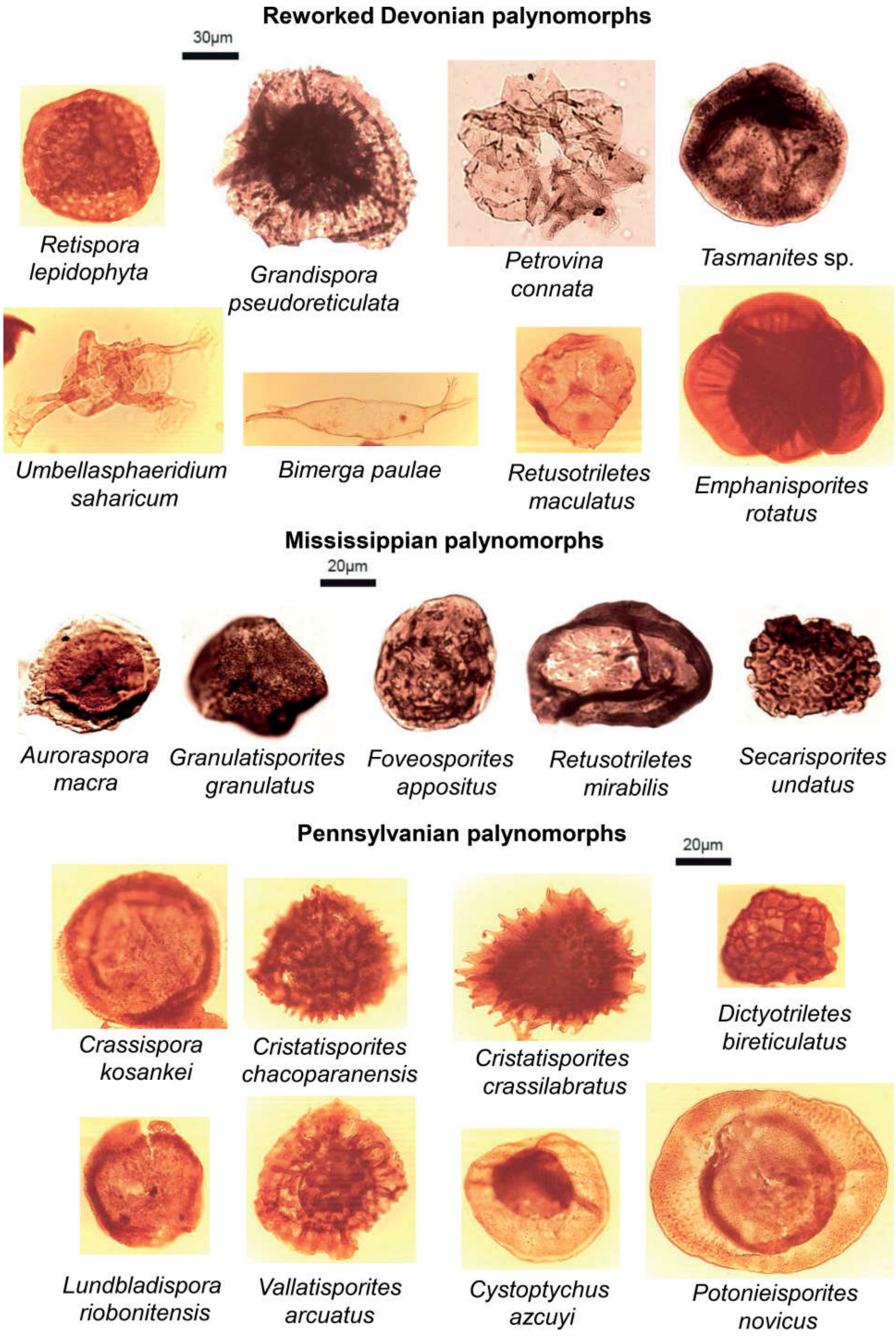

FIG. 7.—Selected palynomorphs (Appendix 1) from the Macharetí and Mandiyutí groups (from di Pasquo 1999, 2003, 2009a; del Papa and di Pasquo 2007; di Pasquo et al. 2001, 2017).

Argentina and southern Bolivia that periodically entered the basin. In northern sections the addition of glacial sediments is likely from mountain glaciers that covered highs during that time. The greater angularity of clasts in northern diamictites and greater variability in lithofacies in northern sections also supports this interpretation (Anderson et al. 2010, Anderson 2011).

Common deformation features, including synsedimentary slumps, folds, and faults and thick beds of climbing ripples throughout both the Macharetí and Mandiyutí groups indicate high sedimentation rates throughout deposition (Starck 1995; Azcuy and di Pasquo 2000; di Pasquo et al. 2001, 2017; Anderson 2011). Reconstructions of unit thicknesses and depositional environments across the region show a series of depocenters within the larger Tarija–Chaco Basin (smaller basins' depocenters within the Late Paleozoic foreland), indicating a change in shelf geometry and primary tectonic stresses within the area during that time (Starck et al. 1993b, Sempere 1995). Basin

FIG. 8.—Faceted and striated clasts. **A, B)** Clasts within the Taiguati Formation (upper Macharetí Group; Fig. 3). **C, D)** Clasts within the Tarija Formation (upper Macharetí Group) (Anderson 2011).

reconstructions from Devonian through Pennsylvanian time indicate basin inversion during the Late Devonian to Mississippian (e.g., Dalenz Farjat et al. 2002, Anderson 2011). Pennsylvanian Basin reconstructions show a change in basin type from a simple foreland basin deepening to the north in the Devonian to a dissected back-arc basin in the Pennsylvanian with at least three depocenters or subbasins (Sempere 1995, Azcuy and di Pasquo 2000, Suárez-Soruco 2000, Anderson 2011).

Paleosols have been described throughout the sandstones and even within the diamictites of both the Macharetí and Mandiyutí groups, confirming that these units were deposited within a largely continental basin (Fernández Garrasino 1987, Azcuy and di Pasquo 2000, del Papa and di Pasquo 2007, Anderson 2011). However, minor marine incursions, as evidenced by the presence of brachiopods, occurred during deposition of the upper Macharatí Group (*Levipustula levis* Maxwell; Rocha-Campos et al. 1977) and the upper San Telmo Formation (*Orthotetid* indet.; Anderson 2011, di Pasquo et al. 2017). The occurrence of *Levipustula levis* in the Macharetí Group questions previous basin reconstructions, which separate the Tarija–Chaco Basin from basins to the south and supports a connection to southern basins (di Pasquo et al. 2017). No other evidence exists to support a connection between these basins, although similar sedimentation patterns occur across Gondwana due to glacial influence. A connection to Argentinian basins (where *L. levis* also occurs) is only possible across the Pampean Arch, which is thought to have acted as a positive element throughout the Paleozoic (Reyes 1972, Sempere 1995, Tankard et al. 1995, Ramos 2008).

In southernmost Bolivia, where the Macharetí Group can be divided into distinct formations (Figs. 4, 9), a pattern of repeating deltaic and glacial depositional systems can be seen that roughly follow the lithologic units. This pattern likely reflects changes in the glacial mode, with glacial advance represented by diamictites and glacial retreat or interglacial periods represented by fluvial-dominated deltaic deposits (Schulz et al. 1999, Starck and del Papa 2006, del Papa and di Pasquo 2007, Anderson 2011).

In the northern Tarija–Chaco Basin, a greater variability in lithofacies associations is seen. While sandstone facies dominate the lower Macharetí Group and diamictite facies become more common in the upper Macharetí Group, the same repeating patterns of lithofacies associations that were seen in southern basin sections cannot be traced across the northern depositional areas. The increase in resedimentation to the north coinciding with greater variability in the facies likely reflects an increase in tectonic activity or greater topographic variability chiefly during interglacial periods (Anderson 2011).

Integration of lithofacies associations and palynology in the Macharetí Group across the basin demonstrates the predominance of glacial and deltaic facies across the depositional area in largely lacustrine and shallow marine settings (di Pasquo 2003, Anderson 2011). Palynomorphs indicative of marine settings (i.e., pyritized acritarchs) have been found in the Macharetí and Mandiyutí groups, however, only as reworked types (Fig. 7; di Pasquo and Azcuy 1997, 1999; di Pasquo et al. 2001; di Pasquo 2003, 2007d, 2009a; del Papa and di Pasquo 2007). Predominance of terrestrial palynomorphs from lycophytes, sphenophytes, pteridophytes, and gymnosperms, along with trace fossils and plants, supports deposition of both the Macharetí and Mandiyutí groups in largely terrestrial environments. Green algae, especially *Botryococcus*, is found in these groups, and the lack of pyritization of the indigenous palynomorphs support deposition in mainly continental settings (e.g., lacustrine, fluvial, and brackish; di Pasquo and Azcuy 1999; di Pasquo et al. 2001; di Pasquo 2003, 2009a; del Papa and di Pasquo 2007).

Pennsylvanian Biostratigraphy

Numerous results have been given for the age of the Macharetí and Mandiyutí groups, spanning from the Early to Late Pennsylvanian mostly based on palynology (Díaz-Martínez 1996; di Pasquo and Azcuy 1997; di Pasquo 1999, 2003, 2007d, 2009a) and plant fossils (di Pasquo 2009a). Owing to few chronostratigraphically useful macrofossils, even sparse productive palynological samples, and difficulties in lithologic correlations, these groups need still more studies to confirm coeval deposition of carbonates in northwest Bolivia and glacial units in the south.

A biostratigraphic framework for the Macharetí and Mandiyutí groups of northern Argentina and southern Bolivia using numerous (165+) indigenous species and their stratigraphic ranges was carried out by di Pasquo (1999, 2003). This work has established a Pennsylvanian Superzone, *Kraeuselisporites volkheimerii–Circumplicatipollis plicatus* (VP), which is divided into five palynozones based on first appearance. These are the *Cassispora kosankei–Cystoptychus azcuyi* (KA), the *Raistrickia radiosa–Apiculatasporites spinulistratus* (RS), and *Dictyotriletes bireticulatus–Cristatisporites chacoparanaensis* (BC) palynozones of Early to Middle Pennsylvanian age and the *Converrucosisporites micronodosus–Reticulatisporites reticulatus* (MR) and *Marsupipollenites triradiatus–Lundbladispora braziliensis* (TB) palynozones of Late Pennsylvanian age (Fig. 7). The chronostratigrapy supported by these palynozones largely follows the lithostratigraphic framework for the units (Fig. 9; Appendix 1; di Pasquo 2002, 2003, 2007d, 2009a).

It must be said that the age assessment of samples is hindered by the presence of reworked Devonian and Mississippian palynomorphs (notably *R. lepidophyta*; Fig. 7), throughout the Pennsylvanian palynozones. This reworking makes analysis of samples quite difficult, especially in poorly productive samples; however, it is not uncommon in glacial deposits (e.g., Stephenson 2008) like those of the Macharetí and Mandiyutí groups (di Pasquo and Azcuy 1997; di Pasquo 2003, 2009a). In fact, reworked palynomorphs are useful to ascertain the time interval and nature of deposition during a hiatus. For example, the presence of reworked Mississippian (Visean) species of palynomorphs indicates that deposition had to have occurred during the Mississippian (Visean) in southern Bolivia, for which few deposits have been recognized (di Pasquo 2003, 2007b). In addition, the lack of reworked palynomorphs of certain ages may indicate a period of nondeposition (di Pasquo and Azcuy 1997, di Pasquo 2003). Using

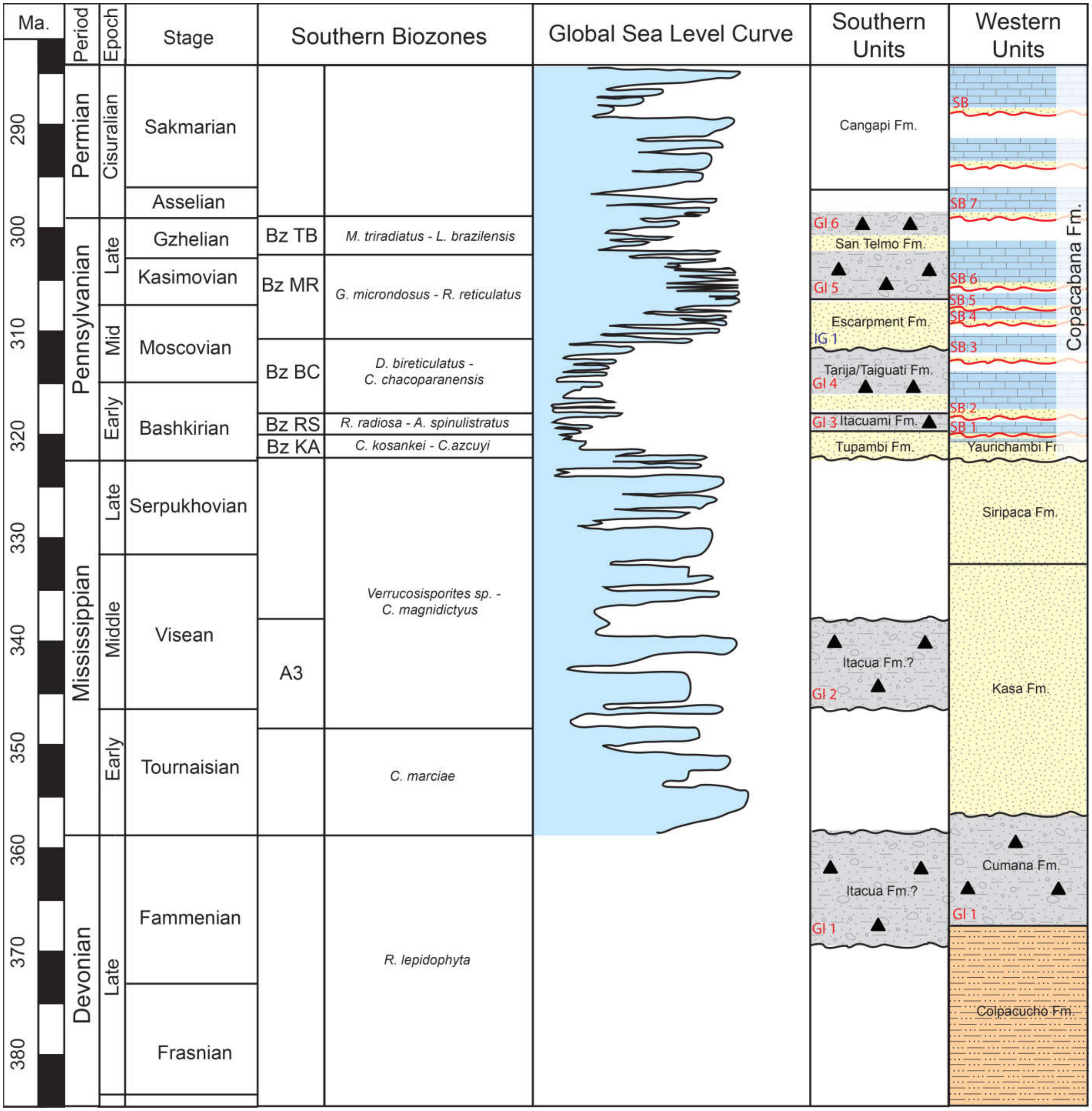

FIG. 9.—Chronostratigraphy and sequences of the western and southern units. Biozones of the Macharetí and Mandiyutí groups of the Tarija–Chaco Basin in northern Argentina and southern Bolivia (di Pasquo 2003, 2007d). Global sea level curve (Ross and Ross 1987), glacial intervals (GI) and Interglacial Periods (IG) for the southern units (Anderson 2011), and sequence boundaries (SB) for northern units (Grader et al. 2008) are shown. Triangles show stratigraphic occurrences of glacial lithologies.

this information, researchers have hypothesized two phases of tectonic uplift in the Late Devonian and a final phase in the Late Mississippian (di Pasquo and Azcuy 1997; Figs. 4, 9).

DISCUSSION

Western Bolivia

Overall warming-upward and restricted to open marine trends occur in the Pennsylvanian part of the Copacabana Formation (Fig. 4), based on lithofacies associations and paleoecology. Three field-recognizable Copacabana members are identified (Grader 2003). The disconformity between the lower and middle members is a second-order sequence boundary, but depositional stacking patterns are masked due to high-amplitude small-scale cyclicity and repetition of lithofacies at multiple scales (typical of icehouse strata). The lower Copacabana Member is Bashkirian to Moscovian (Early Pennsylvanian; Mamet and Isaacson 1997, di Pasquo 2009b, di Pasquo et al. 2016), the middle member is Kasimovian to Asselian–Sakmarian (Pennsylvanian–Permian; see Grader et al. 2008, di Pasquo et al. 2014), and the Upper Member is Sakmarian–Artinskian (Late Early Permian; Mamet 1996, di Pasquo and Grader 2012, di Pasquo et al. 2014).

The Upper Copacabana Member is significantly less cyclic compared with the other two members, suggesting that global climate was transitional between first-order icehouse and greenhouse climate modes (Grader et al. 2008). This is supported by slower patterns of change (e.g., thick rhythmic limestone–shale deposits) in basinal rocks of the subsiding Cochabamba subbasin (Apillapampa facies), as well as in thick accumulations of shoaling carbonates, marginal to the southern Peru and northern Subandean basins in the Copacabana Peninsula and submerged Huarina High areas. The very fossiliferous part of the Permian sequence is a distinct facies, and overlying subtidal units represent the last of widespread open marine Copacabana deposition before first-order turn-around and establishment of the regressive limb of the Cuevo Supersequence (and Late Permian rifting). Late Artinskian nodular dolostones, shales, and evaporites of the uppermost Copacabana Formation are interpreted as a diagenetic and silicified mappable transitional facies deposited below an unconformity. Grader et al. (2008) described six probable glacial ice advances through sequence proxies in these Pennsylvanian (306.5, 308, 309, 311 and 318 million years ago [Ma]) and Permian (283, 293, 299 Ma) deposits. Similar deposits without marine invertebrates overlie this unconformity and are laterally equivalent to sandstones with thin chert conglomerates and recycled Copacabana lithoclasts (Figs. 4, 9).

Southern Bolivia

Numerous compressional and extensional phases along the western margin of Gondwana caused several cycles of basin inversion and deposition in the area over which the Carboniferous Tarija–Chaco Basin formed (Sempere 1993, 1995; Tankard et al. 1995; Jacques 2004; Ramos 2008). Devonian compressional tectonism with complex Late Paleozoic extension and transpression affected basin formation and deposition in western Bolivia since formation of the supercontinent (~1000 Ma). The structures that led to and resulted from formation of the original basin (Puncoviscana and Tucavaca) were continually reactivated throughout the Paleozoic due to changes in the stress regime along the western margin of Gondwana (Dalenz-Farjat et al. 2002). Deposition of Carboniferous units in the Tarija–Chaco Basin of southern Bolivia were subject to Late Devonian–Mississippian basin inversion, with the majority of deposition occurring in a segmented transtensional back-arc setting during the Pennsylvanian (Suárez-Soruco 2000, Azcuy and di Pasquo 2000, Anderson 2011).

Glacial cycles throughout Earth's history follow a cyclic pattern related to cyclical changes in Earth's orbital parameters (eccentricity, obliquity, and precession; Broecker and Denton 1990, Eyles 1993, Hambrey 1994). Interestingly, however, most glacial deposits are coeval with tectonic events (Eyles 1993, 2007) either due to the formation of highs (easier to glaciate) or basins (easier to preserve) in a cause or effect manner. Such is the case for glacial deposits of Late Devonian, Mississippian, and Pennsylvanian age in Bolivia, with earlier deposits (Late Devonian and Mississippian) coeval with initial uplift of the Puna, Asunción, and Michicola highs and a probable basin inversion event (Starck and del Papa 2006). Devonian tectonic quiescence is interrupted in the Late Devonian and Mississippian by a reorganization of stresses along the western margin of Gondwana and later renewal of subduction causing uplift of the Puna, Michicola, and Asunción arches during the Chañic Orogeny. Few restricted deposits of Late Devonian and Mississippian units are found in the Tarija–Chaco Basin and demonstrate active tectonism during this time (submarine fans and common resedimented units). Extensive unconformities across the region and local angular unconformities and metamorphism suggest inversion of the Tarija–Chaco Basin (Tankard et al. 1995).

Later (Pennsylvanian) more extensive glacial deposits are coeval with extension and formation of the Tarija–Chaco Basin. Decrease in glacial units, and therefore glaciation as a depositional control, throughout the Pennsylvanian is likely due to both the migration of Bolivia toward lower latitudes and the decreased rate of uplift or erosion of highs across the area (Azcuy and di Pasquo 2000, Anderson 2011). Integration of facies analyses and biostratigraphy of Late Devonian–Carboniferous units reveals as many as six glacial cycles, one in the Late Devonian, one in the Mississippian, two in the Early–Middle Pennsylvanian (Macharetí Group), and two in the Late Pennsylvanian (Mandiyutí Group) (Fig. 9; Anderson 2011).

Numerous models on the age and depositional environments of the Macharetí and Mandiyutí groups throughout their study are due largely to the lack of and difficulty in obtaining age data and the significant lateral variability in thickness and facies of these units across the Tarija–Chaco Basin. Detailed palynology of deposits across the basin in previous studies confirms a Pennsylvanian age for the Macharetí and Mandiyutí groups with minor Late Devonian and Mississippian restricted units (di Pasquo 2002, 2003, 2007d, 2008, 2009a; di Pasquo and Vergel 2008; di Pasquo and Noetinger 2008; di Pasquo and Anderson 2012). Sedimentology and depositional analysis of facies in the Macharetí and Mandiyutí groups support deposition in largely terrestrial glacio–lacustrine and fluvio–deltaic depositional environments with minor marine incursions in the upper units of both the Macharetí and Mandiyutí groups (di Pasquo 1999, 2003; del Papa and di Pasquo 2007; Anderson 2011; di Pasquo et al. 2017). Lithostratigraphy and limited marine faunal associations (brachiopod fragments and gastropod *Mourlonia balapucensis*) in the Macharetí and Mandiyutí groups support a southern source for marine incursions across either the Puna or southwestern Subandean range (di Pasquo et al. 2017). Similar glacially influenced terrestrial dominated depositional environments and marine incursions during deglaciated periods are recognized in Pennsylvanian deposits farther south, in the Paganzo and Rio Blanco basins of Argentina, where *L. levis* and *Mourlonia* species are also found (Azcuy et al. 2007, Cisterna and Sterren 2010).

In summary, deposition in the Early Pennsylvanian Tarija–Chaco Basin started with the Macharetí Group, a siliciclastic unit consisting largely of interbedded sandstones and diamictites. Sedimentology and facies analysis of this group reveals a repeating pattern of glacial and fluvio–deltaic facies across the basin with strong climatic (diamictites, glacial pavements, and faceted and striated clasts), tectonic (resedimentation and soft sediment deformation of units), and eustatic (brachiopods in largely terrestrial deposits) controls to deposition (Anderson 2011). Its correlation and basin reconstructions (isopach maps) reveal segmentation of the basin into several subbasins with recognizable structurally controlled highs across the basin consistent with deposition in a transtensional back-arc setting. Abundant soft sediment deformation structures across the basin, though especially in the north, indicate active tectonism during deposition.

Consistency of fluvial facies across the Tarija–Chaco Basin during deposition of the Escarpment Formation (Mandiyutí Group) reflects a period of tectonic quiescence and infilling of paleovalleys over an unconformity (Azcuy and di Pasquo 2000). No glacial units are found in the lower Mandiyutí Group (Figs. 4, 9) across the basin, indicative of an interglacial period (Anderson 2011). Resumption of glacial activity in the upper Mandiyutí Group in southern Bolivia is coincident with renewal of tectonic activity and subsidence in the southern subbasin. Brachiopod occurrences suggest that marine incursions came from the south beyond northern marine environments of the Copacabana Formation (di Pasquo et al. 2017). A general change in color gray to red and a likely transitional contact with aeolian facies of the Cangapi Formation suggest an overall change from cold, humid climates, to warm, dry conditions (Azcuy and di Pasquo 2000, Starck and del Papa 2006).

Western to Southern Bolivia Climatic Gradient

Warm-water carbonates of the Copacabana Formation in western Bolivia contrast sharply with the glacigenic deposits in southern Bolivia. The proposed climatic gradient between cold-water glacial deposits in southern Bolivia and warm-water carbonate deposits in northern Bolivia depends largely on the age and nature of each of these deposits and the tectonic framework of the basin. As western Bolivia records a warming of the Copacabana waters throughout the Pennsylvanian, southern Bolivia records a waning of glaciation and restriction of glacial units to the south. Throughout the Pennsylvanian, Gondwana moves north in a clockwise rotation (Fig. 1B, C). This rotation is likely reflected in the changes in spatial extent of the carbonates and glacials.

During the Early and Middle Pennsylvanian in western Bolivia, the lower Copacabana Member was deposited with a limited lateral extent in the Lake Titicaca region (Grader et al. 2008). These carbonates, sands, and shales record an open marine setting with cool to warm “Bryoderm” or “Heterozoan” faunal associations. At the same time, the Macharetí Group in southern Bolivia records thick successions of sands and glacigenic diamictite. Striated surfaces in northern Argentina and southern Bolivia document the presence of an ice sheet in the southern part of the Tarija–Chaco Basin (Starck and del Papa 2006). Northern deposits of the Macharetí Group are strongly influenced by active tectonism and paleohighs and are likely deposited by mountain glaciers.

By the Late Pennsylvanian, deposits of the Copacabana Formation show a marked increase in fossils, containing abundant fusulinids and more corals and bryozoans (Grader 2003, Grader et al. 2008). The marked increase in fossil content denotes a warming of the Copacabana Basin in the Late Pennsylvanian and Early Permian. During this time, the Mandiyutí Group in southern Bolivia records a widespread fluvial sandstone unit (Escarpment Formation) and, finally, glacial diamictites (San Telmo Formation) that are restricted to the south (di Pasquo et al. 2017).

With the above information, when the greatest extent of glaciation occurred in the Late Bashkirian to Early Moscovian during deposition of glacial erosional surfaces and massive diamictite in the Macharetí Group as far north as Macharetí (central Tarija–Chaco Basin), the Copacabana Formation was restricted to northern subbasins of the Madre de Dios Basin (ca. 1000 km away from current Macharetí Group glacial deposits) and displayed cool to warm faunal associations. Though glacial deposition in the northern Tarija–Chaco Basin during this time may suggest a much steeper gradient, glacial deposits in this area are contributed from mountain glaciers and may not represent a climatic gradient within the basin. Similar settings occur in New Zealand today with mountain glaciers depositing sediments into carbonate environments (Griggs et al. 1983, Orpin et al. 2006).

Also important to discussion on this possible paleoclimatic gradient is whether or not the western (Madre de Dios) and southern (Tarija–Chaco) basins were connected during deposition of carbonate and glacial units. Deposition of the Macharetí and Mandiyutí groups under deposits of the Copacabana Formation at El Tunal (central Bolivia; Fig. 4) indicate that the basin was connected during the Early Permian, perhaps as early as the Late Pennsylvanian, and flow indicators suggest that waters in the Macharetí and Mandiyutí groups flowed north throughout deposition (Anderson 2011). Basin reconstructions (Ayaviri 1972, di Pasquo and Grader 2012) point to a possible high between the two basins during this time. More work is needed to establish how well the Tarija–Chaco and Madre de Dios basins were connected throughout the Pennsylvanian.

Although a physical connection between the western and southern deposits is unclear, five regionally correlative sequence boundaries are recorded in the Pennsylvanian Copacabana Formation (Grader et al. 2008) that have been shown to correlate with Gondwanan glaciations in South America (Crowell 1999, Fielding et al. 2008). Major Pennsylvanian sequence boundaries appear to coincide with major ice advances and their associated sea-level lowerings (Fig. 9).

Several works on the Macharetí and Mandiyutí groups have recognized two major glacial cycles, with one cycle in the Macharetí Group and one in the Mandiyutí Group (Helwig 1972, Sempere 1995, Schulz et al. 1999, Viera and Hernández 2001, Starck and del Papa 2006). Further study of the sedimentology, lithostratigraphy, and facies of the Macharetí and Mandiyutí groups (Anderson 2011) have divided the glacial cycles of these units into four cycles of glaciation in the Pennsylvanian (and two others, one in the Late Devonian and one in the Mississippian; Fig. 9). At least two glacial advances are recorded in the Macharetí Group in massive diamictite of the Itacuami and Taiguati formations. Diamictite of the Itacuami Formation contains dropstones, outsized clasts, and *Diplopodichnus biformis*, indicating deposition in a distal glacio–lacustrine setting (Buatois and del Papa 2003). Thick massive diamictites of the Tarija Formation containing glacial pavements in northern Argentina (Starck et al. 1993b) are the best evidence of glacial deposition directly into the Tarija–Chaco Basin and represent the greatest extent of glaciation in all Carboniferous deposits of the area (del Papa and di Pasquo 2007).

Diamictites of the San Telmo Formation are only recorded in southern Bolivia and northern Argentina. At Balapuca (southern Bolivia) and in northern Argentina where the San Telmo Formation is thickest and can be divided into three members, two glacial advances are noted (Anderson 2011). Massive diamictites of the Caiguami Member represent the greatest extent of glaciation in the San Telmo Formation with possible glacial sedimentation directly into the basin. Minor diamictite units in the Yaguacua Member of the San Telmo Formation likely represent resedimentation of diamictite in glacio–deltaic deposits (Starck and del Papa 2006).

Fluvial and deltaic deposits occur between all of the above glacial units. Fluvio–deltaic deposits of the Macharetí Group (Tupambi and Chorro formations) are interbedded with glacial units and represent glacial retreat facies. Ubiquitous deposition of fluvial and delta front facies in the Escarpment Formation across the Tarija–Chaco Basin represents an interglacial period in the Middle Pennsylvanian. Renewal of glaciation is represented by diamictite of the San Telmo Formation with fluvio–deltaic facies representing glacial retreat and interglacial and postglacial facies. Four Copacabana sequence boundaries broadly correspond to glacial cycles in southern Bolivia (Fig. 9) in the Bashkirian (SB1; Itacuamí Formation), Early and Middle Moscovian (SB2 and 3; Tarija–Taiguati Formation), and the Moscovian–Kasimovian boundary (SB5; first cycle in San Telmo). SB4 corresponds to the Escarpment Formation, which is thought in southern Bolivia to represent an interglacial period. Differences in timing of sequence boundaries and glacial cycles may exist for several reasons: (1) Age of northern Bolivian deposits is better constrained (foraminifera, fusulinids, conodonts, and palynomorphs) than southern deposits (palynomorph); (2) Most glacial sediments are deposited during glacial retreat rather than advance; (3) Because timing of glaciations across Gondwana are not ubiquitous (Isbell et al. 2003) and northern Bolivian deposits, known to have a marine connection to the north, may reflect larger glaciations in other parts of Gondwana; and (4) Sequence boundaries and glacial cycles reflect autocyclic controls differently between the western and southern Bolivia, perhaps due to different tectonic constraints between them or a separation of the basins.

Finally, seasonal to arid conditions in the Latest Pennsylvanian–Cisuralian Copacabana Formation are suggested by mixed fluvial and eolian facies in the correlative Cangapi Formation to the southeast (Fig. 4).

CONCLUSIONS

The question of sharp paleoclimate changes across a narrow paleolatiudinal range is addressed. That is, coeval carbonates and glacials occurring over approximately 4° latitude change is striking.

1. The Carboniferous depositional systems in the central Andes (Bolivia portion) followed the configuration of the Devonian marine basin with no apparent structural highs separating the west and south.
2. Deposits of Late Devonian and Early Mississippian are better preserved and more evident in the west and north (and into Brazil), than in the south mostly by erosion. These deposits show glacial signals that reveal a significant Late Devonian climate change, with evidence for this event in several Brazilian basins, Peru, parts of Africa, and the Appalachian Basin in the USA.
3. In the Mississippian, sparse deposits of the Tournaisian (Mobil-Oxy wells) and Early Visean (central and southern Bolivia) show evidence of glaciation. Scarcity of Mississippian deposits is likely due to erosion or nondeposition (elevated and/or glaciated areas).
4. In Pennsylvanian time, warm marine carbonates developed in western Bolivia (and Brazil), with evidence of transgression from the north. This succession (the Copacabana Formation) has five sequence boundaries, which have been interpreted to be responses to coeval glaciation farther south. Climate indicators in the Copacabana Formation (coastal plain sandstones with evaporites and microkarst features) are interpreted to represent a long period of semiarid conditions.
5. In the south (and in northern Argentina) Pennsylvanian units are either glacial or periglacial in origin.
6. The paleoclimatic gradient may not be a function of paleogeographic separation of the two regions but appears to be a result of Gondwana’s clockwise rotation into lower paleolatitudes.

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REFERENCES

Anderson H. 2011. Sedimentology and lithostratigraphy of the carboniferous Tarija–Chaco Basin, southern Bolivia: Geodynamic and Paleoclimatic evolution [unpublished PhD dissertation]: University of Idaho, Moscow, 509 p.

Anderson H, Grader G, Di Pasquo M, Isaacson P. 2010. Ice-proximal stratigraphy and active tectonics: An example from southern Bolivia: *Geological Society of America. Abstracts with Programs* 42(3):52.

Attar A, Fournier J, Candilier AM, Coquel R. 1980. Etude palynologique du Dévonien terminal et du Carbonifère inferieur du bassin d’Illizi (Fort-Polignac) Algérie. *Revue de l’Institut Français du Pétrole* 35:585–618.

Ayaviri A. 1972. El sistema Carbónico en el Sureste Boliviano. *Anales Academia Brasileira Ciências* 44 (Suppl):51–60.

Azcuy C, Beri A, Bernardes-De-Oliveira MEC, Carrizo HA, Di Pasquo MM, Díaz Saravia P, González C, Iannuzzi R, Lemos V, Melo JHG, Pagani A, Rohn R, Rodríguez Amenábar C, Sabattini N, Souza PA, Taboada A, Vergel MM. 2007. *Bioestratigrafía del Paleozoico Superior de América del Sur: primera etapa de trabajo hacia una nueva propuesta cronoestratigráfica*: Publicación Especial 11, Serie D: Asociación Geológica Argentina. p. 9–65.

Azcuy CL, Di Pasquo M. 2000. Carbonífero y Pérmico de las Sierras Subandinas, Cordillera Oriental y Puna. *In* Caminos R (Editor). Geología Argentina. *Instituto de Geología y Recursos Minerales, Anales* 29(11):239–260.

Babin C, Racheboeuf PR, Le Hérissé A, Suárez Riglos M. 1991. Donées nouvelles sur les Goniatites du Dévonien de Bolivia. *Geobios* 24:719–724.

Birhuet R. 1993. Bioestratigrafía de la Formación Copacabana (Carbonífero superior–Pérmico inferior) en base al Phylum Brachiopoda [unpublished PhD thesis]: Universidad Mayor de San Andrés, La Paz, Bolivia.

Blieck A, Gagnier PY, Bigey FP, Edgecombe GD, Janvier P, Loboziak S, Racheboeuf PR, Sempere T, Steemans P. 1996. New Devonian fossil localities in Bolivia. *Journal of South American Earth Sciences* 9(5/6):295–308.

Breitkreuz C, Bahlburg H, Zeil W. 1988. The Paleozoic evolution of northern Chile: Geotectonic implications. *In* Bahlburg H, Breitkreuz C, Giese P (Editors). *The Southern Central Andes*: Lecture Notes in Earth Sciences 17: Springer-Verlag, Berlin. p. 87–102.

Broecker WS, Denton DH. 1990. What drives glacial cycles? *Scientific American* 262:48–56.

Buatois LA, Del Papa CE. 2003. Trazas fósiles de la Formación Tarija, Carbonífero Superior del norte Argentina: aspectos icnológicos de la transgresión postglacial en el oeste de Gondwana. *In* Buatois LA, Mángano MG (Editors). *Icnología: hacia una convergencia entre Geología y Biología*, Publicación Especial 9: Asociación Paleontológica Argentina, Buenos Aires. p. 119–130.

Caputo MV. 1985. Late Devonian glaciation in South America. *Palaeogeography, Palaeoclimatology, Palaeoecology* 51:291–317.

Caputo MV, Crowell JC. 1985. Migration of glacial centers across Gondwana during Paleozoic Era. *Geological Society of America Bulletin* 96:1020–1036.

Caputo MV, Melo JHG, Streel M, Isbell JL. 2008. Late Devonian and Early Carboniferous glacial records of South America. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Resolving the Late Paleozoic Ice Age in Time and Space*, Special Paper 441: Geological Society of America, Boulder, Colorado. p. 161–173.

Caputo MV, Silva OB. 1990. Sedimentacâo e tectonica na Bacia do Solimôes. *In* Raja Gabaglia GP Milani EJ (Editors). *Origem e evolucâo da bacias sedimentares*: Petrobras, Rio de Janeiro. p. 169–193.

Chamot GA. 1965. Permian section at Apillapampa, Bolivia and its fossil content. *Journal of Paleontology* 39(6):1112–1124.

Cisterna GA, Sterren AF. 2010. *Levipustula* fauna in central-western Argentina and its relationships with the Carboniferous glacial event in the southwestern Gondwanan margin. *In* López-Gamundí OR, Buautois LA (Editors). *Late Paleozoic Glacial Events and Postglacial Transgressions in Gondwana*, Special Publication 468: Geological Society of America, Boulder, Colorado. p. 133–147.

Coquel R, Moreau-Benoit A. 1986. Les spores des séries struniennes et tournaisiennes de Libye occidentale. *Revue de Micropaléontologie* 29:17–43.

Crowell JCV. 1999. *Pre-Mesozoic Ice Ages: Their Bearing on Understanding the Climate System*, Memoir 192: Geological Society of America, Boulder, Colorado. 106 p.

Dalenz-Farjat A, Alvarez L, Hernández RM, Albariño LM. 2002. Cuenca Siluro–Devónica del Sur de Bolivia y del Noroeste Argentino: algunas interpretaciones, in 5th Congreso de Hidrocarburos, Mar del Plata, CD Trabajos Técnicos, p. 1–21.

Dalmayrac B, Laubacher G, Marocco R, Martínez C, Tomasi P. 1980. La Chaîne d'Amérique du sud hercynienne: Évolution de la structure et d'un orogène intracratonique. *Geologische Rundschau* 69:1–21.

Del Papa C, Di Pasquo M. 2007. Paleoenvironmental interpretation and palynology of outcrop and subsurface sections of the Tarija Formation (Late Carboniferous), northwestern Argentina. *Journal of South American Earth Sciences* 23:99–119.

Del Papa CE, Martínez L. 2001. Sedimentación lacustre glaci-dominada en la Formación Tarija (Carbonífero), sierra de Aguaragüe, noroeste argentino. *Revista de la Asociación Argentina de Sedimentología* 8(1):61–76.

Di Pasquo MM. 1999. Palinología, Bioestratigrafía y Correlación de las asociaciones presentes en los Grupos Macharetí y Mandiyutí, Neopaleozoico de la Cuenca Tarija, provincia de Salta, Argentina [unpublished PhD dissertation]: Universidad de Buenos Aires, 480 p.

Di Pasquo MM. 2002. The *Crassispora kosankei–Cystoptychus azcuyi* Palynozone of the Late Carboniferous Tupambi Formation, Tarija Basin, northern Argentina. *Review of Palaeobotany and Palynology* 118:47–76.

Di Pasquo MM. 2003. Avances sobre palinología, bioestratigrafía y correlación de los grupos Macharetí y Mandiyutí, Neopaleozoico de la Cuenca Tarija, provincia de Salta, Argentina. *Ameghiniana* 40:3–32.

Di Pasquo MM. 2006. Puesta al día de la información paleontológica del Carbonífero y Pérmico de la cuenca Tarija, Norte de Argentina y Sur de Bolivia, in 13th Simposio Argentino de Paleobotánica y Palinología (Bahía Blanca), Resúmenes, p. 19.

Di Pasquo MM. 2007a. Asociaciones palinológicas en las formaciones Los Monos (Devónico) e Itacua (Carbonífero Inferior) en Balapuca (Cuenca Tarija), sur de Bolivia. Parte 1. Formación Los Monos. *Revista Geológica de Chile* 34:97–137.

Di Pasquo MM. 2007b. Asociaciones palnológicas en las formaciones Los Monos (Devónico) e Itacua (Carbonífero Inferior) en Balapuca (Cuenca Tarija), sur de Bolivia. Parte 2. Asociaciones de la Formación Itacua e interpretación estratigráfica y cronología de las formaciones Los Monos e Itacua. *Revista Geológica de Chile* 34:163–198.

Di Pasquo MM. 2007c. State of the art of the Devonian palynological records in the northern Argentina, southern Bolivia and northwestern Paraguay, in Field Meeting of the IGCP 499-UNESCO "Devonian Land–Sea Interaction: Evolution of Ecosystems and Climate" (DEVEC), San Juan, Serie Correlación Geológica, Special Issue: INSUGEO, Universidad Nacional de Tucumán. p. 70–73.

Di Pasquo MM. 2007d. Update and importance of the Carboniferous and Permian paleontological records of the Tarija Basin. *In* Díaz-Martínez E, Rábano I (Editors). *European Meeting on Paleontology and Stratigraphy of Latin American, Madrid*, Serie Cuadernos del Museo Geominero 8, Instituto Geológico y Minero de España, Madrid. p. 107–112.

Di Pasquo MM. 2008. Nueva información palinológica sobre el límite Devónico–Carbonífero en Bolivia: Las Formaciones Iquirí e Itacua en la quebrada Macharetí, in 12th Simposio de Paleobotánica y Palinología, Florianópolis, Boletín de resúmenes, 50 p.

Di Pasquo MM. 2009a. Primer registro de megafloras y palinología en estratos de la Formación Tarija (Pennsylvaniano), Arroyo Aguas Blancas, Provincia de Salta, Argentina: Descripción de dos especies nuevas. *Andean Geology* 36(1):95–123.

Di Pasquo MM. 2009b. The Pennsylvannian palynoflora from the Pando X-1 Borehole, northern Bolivia. *Review of Paleobotany and Palynology* 157:266–284.

Di Pasquo MM. 2015. First record of *Lagenicula mixta* (Winslow) Wellman et al. in Bolivia: Biostratigraphic and paleobiogeographic significance. *16th Simposio Argentino de Paleobotánica y Palinología, La Plata, Ameghiniana, Suplemento* 52(4):41–42.

Di Pasquo MM, Amenábar CR, Noetinger S. 2009. Middle Devonian microfloras and megafloras from western Argentina and southern Bolivia. Its importance in the palaeobiogeographical and palaeoclimatical evolution of western Gondwana. *In* Königshof P (Editor). *Devonian Change: Case Studies in Palaeogeography and Palaeoecology*, Special Publication 314: The Geological Society, London. p. 191–211.

Di Pasquo MM, Anderson H. 2012. Palynological record of Devonian and Pennsylvanian units in the Espejos Range, western Santa Cruz de la Sierra, central Bolivia, in 45th Annual Meeting of AASP (The Palynological Society) and CIMP (Commission Internationale de la Microflore du Paléozoïque Subcommissions), Lexington, Abstracts, p. 19–20.

Di Pasquo MM, Azcuy CL. 1997. Palinomorfos retrabajados en el Carbonífero Tardío de la Cuenca Tarija (Argentina) y su aplicación a la Datación de eventos diastróficos. *Revista Universidade Guarulhos, Geociências* 2 (no. especial):28–42.

Di Pasquo MM, Azcuy CL. 1999. Interpretación paleoambiental del Grupo Mandiyutí (Carbonífero Superior): Evidencias palinológicas, sedimentológicas y tafonómicas. *Ameghiniana* 36:71–81.

Di Pasquo MM, Azcuy CL, Starck D. 2001. Palinología de la Formación San Telmo (Carbonífero Superior) en la sierra San Antonio, provincia de Salta, Argentina. *Ameghiniana* 38:85–98.

Di Pasquo MM, Grader G. 2012. Palynology and paleoenvironment of the Asselian–?Artinskian Copacabana Formation at Apillapampa near Cochabamba, Bolivia. *Palynology* 36:264–276.

Di Pasquo MM, Grader GW, Isaacson P, Souza PA, Iannuzzi R, Díaz-Martínez E. 2014. Global biostratigraphic comparison and correlation of an early Cisuralian palynoflora from Bolivia. *Historical Biology* 27(7):868–897.

Di Pasquo MM, Isaacson P, Anderson H. 2017. Record of a Pennsylvanian Cisuralian marine transgression, southern Bolivia: A short-lived event in western Gondwana? *Palaeogeography, Palaeoclimatology, Palaeoecology* https://doi.org/10.1016/j.palaeo.2017.05.026

Di Pasquo MM, Isaacson P, Grader GW, Hamilton MA, Soreghan GS. 2016. Palynostratigraphy of the Yaurichambi and Copacabana formations in the Manuripi X-1 core, Madre de Dios Basin, northern Bolivia: First constraints from U-Pb dating of volcanic ash, in International Palynological Congress and International Organisation of Palaeobotany Conference IPC/IOPC, Salvador de Bahia. *Boletín de la Asociación Latinoamericana de Paleobotánica y Palinología* 16:110.

Di Pasquo MM, Noetinger S. 2008. Resultados preliminares del análisis palinológico del Pozo San Antonio X-1 (Salta) entre 2544 y 1293 m de profundidad, in 17th Congreso Geológico Argentino, Jujuy, Actas 1, p. 347–348.

Di Pasquo MM, Noetinger S, Isaacson PE, Grader G, Starck D, Morel E, Anderson Folnagy H. 2015a. Mid–Late Devonian assemblages of herbaceous lycophytes from northern Argentina and Bolivia: Age assessment with palynomorphs and invertebrates and paleobiogeographic importance. *Journal of South American Earth Sciences* 28(7):913–929.

Di Pasquo MM, Vergel MM. 2008. Primer registro palinológico del Pennsylvaniano del Norte de la Sierra de Zenta, provincia de Jujuy, Argentina, in 12th Simposio de Paleobotánica y Palinología, Florianópolis, Boletín de resúmenes, 51 p.

Di Pasquo MM, Wood GD, Isaacson PE, Grader G. 2015b. Palynostratigraphic reevaluation of the Manuripi-X1 (1541–1150 m interval), Madre de Dios Basin, northern Bolivia: Recycled Devonian species and their implication for the timing and duration of Gondwanan glaciation. *Simposio Argentino de Paleobotánica y Palinología, La Plata, Ameghiniana, Suplemento* 52(4):104–105.

Díaz-Martínez E. 1991. Litoestratigrafía del Carbonífero del Altiplano de Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales Bolivianos* 12(2):295–302.

Díaz-Martínez E. 1994. Late Devonian and Carboniferous of the Altiplano of Bolivia: Stratigraphy, sedimentology and paleogeographic evolution [unpublished PhD dissertation]: University of Idaho, Moscow, 208 p.

Díaz-Martínez E. 1996. Síntesis Estratigráfica y Geodinámica del Carbonífero de Bolivia, in Congreso Geológico de Bolivia, Tarija, Memorias, p. 355–361.

Díaz-Martínez E. 1999. Estratigrafía y paleogeorafía del Paleozoico Superior del norte de los Andes Centrales (Bolivia y sur del Peru). *Boletín de la Sociedad Geológica del Peru* 5:19–26.

Díaz-Martínez E. 2004. La glaciación del Devónico superior en Sudamérica: estado del conocimiento y perspectivas. *Congreso Peruano de Geología,* *Lima, Resúmenes Extendidos, Sociedad Geológica del Perú, Publicación Especial* 6:440–443.

Díaz-Martínez E, Isaacson PE. 1995. Late Devonian glacially-influenced marine sedimentation in western Gondwana: the Cumaná Formation, Altiplano, Bolivia. *In* Embry AF, Beauchamp B, Glass DJ (Editors). *Pangea: Global Environments and Resources*, Memoir 17: Canadian Society of Petroleum Geology, Calgary, Alberta. p. 511–522.

Díaz-Martínez E, Isaacson PE, Christensen KL, Vavrdová M, Antelo Pérez B. 1993. Significance of Late Devonian Diamictite, Lake Titikaka, Bolivia. *International Congress of Carboniferous and Permian Stratigraphy and Geology, Buenos Aires, Comptes Rendus* 1:293–304.

Díaz-Martínez E, Lema JC. 1991. Diamictitas glaciomarinas en el Carbonífero del Altiplano norte de Bolivia: Sedimentología e interpretación de ambientes sedimentarios. *Congreso Geológico de Chile, Viña del Mar, Actas* 1:268–271.

Díaz-Martínez E, Mamet B, Isaacson PE, Grader GW. 2000. Permian marine sedimentation in northern Chile: New evidence from the Juan de Morales Formation and regional paleogeographic implications. *Journal of South American Earth Sciences* 13:511–525.

D'Orbigny AD. 1835. Voyage dans l'Amérique Méridionale de 1826 à 1833. *Géologie* 3(3), 289 p., *Paléontologie* 3(4), 188 p.

Duarte RG. 1989. Estratigrafía de detalle del Formación Copacabana y Mesozoico Inicial: Formaciones Sayari y Ravelo del área Oeste de Cochabamba [Tesis de Grado]: Universidad Mayor de San Andrés, La Paz, 89 p.

Dunbar CO, Newell ND. 1946. Marine Early Permian of the central Andes and its fusuline faunas. *America Journal of Science* 244(6):377–402.

Dunham RJ. 1962. Classification of carbonate rocks according to depositional texture. *In* Ham WE (Editor). *Classification of Carbonate Rocks, A Symposium*, Memoir 1: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 108–121.

Evans DJA, Benn DI. 2004. *A Practical Guide to the Study of Glacial Sediments*: Hodder Arnold, London. 266 p.

Eyles CH, Eyles N, Miall AD. 1985. Models of Glaciomarine sedimentation and their application to the interpretation of ancient glacial sequences. *Palaeogoegraphy, Palaeoclimatology, Palaeoecology* 51:15–84.

Eyles N. 1993. Earth's glacial record and its tectonic setting. *Earth Science Reviews* 35:1–248.

Eyles N. 2007. Glacio-epochs and the supercontinent cycle after ∼3.0 Ga: Tectonic boundary conditions for glaciation. *Paleogeography, Paleoclimatology, Paleoclimatology* 258:89–129.

Eyles N, González Bonorino G, França A, Eyles C, Lopez Paulsen O. 1995. Hydrocarbon-bearing late Paleozoic glaciated basins of southern and central South America. *In* Tankard A, Suárez S, Welsink H (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 165–183.

Fernández Garrasino CA. 1978. Algunos rasgos sedimentarios y estratigráficos de las llamadas "Areniscas del Palmar" (Carbónico de la cuenca de Tarija, Chaco Salteño) y esquemas evolutivos paleoambientales del Grupo Macharetí, Argentina. *Reunión Nacional El Paleozoico de Argentina, San Miguel de Tucumán, Acta Geológica Lilloana* 14(Suplemento):49–52.

Fernández Garrasino CA. 1979. Algunos rasgos estratigráficos y sedimentológicos de las llamadas "Areniscas del Palmar", Formación Tarija, Carbónico del Chaco Salteño. *Petrotecnia* 12:25–29.

Fernández Garrasino CAF. 1987. Sinópsis petrolera. *In* Archangelsky S (Editor). *El Sistema Carbonífero en la Republica Argentina*: Academia Nacional Ciencias, Córdoba. p. 321–323.

Fielding CR, Frank TC, Birgenheier LP, Jones MC, Roberts J. 2008. Stratigraphic imprint of the late Paleozoic ice age in eastern Australia: A record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society* 165:129–140.

González Bonorino G. 1992. Carboniferous glaciation in Gondwana. Evidence for grounded marine ice and continental glaciation in southwestern Argentina. *Palaeogeography, Palaeoclimatology, Palaeoecology* 91:363–375.

Grader GW. 2003. Carbonate-Siliciclastic Sequences of the Pennsylvanian and Permian Copacabana Formation, Titicaca Group, Andes of Bolivia [unpublished PhD dissertation]: University of Idaho, Moscow, 359 p.

Grader GW, Isaacson PE, Díaz-Martínez E, Pope MC. 2008. Pennsylvanian and Permian Sequences in Bolivia: Direct responses to Gondwana Glaciation. *In* Fielding CR, Frank TD, Isbell JL (Editors). *The Late Paleozoic Gondwanan Ice Age: Timing, Extent, Duration and Stratigraphic Records*, Special Paper 441: Geological Society of America, Boulder, Colorado. p. 143–160.

Grader GW, Isaacson PE, Rember B, Mamet B, Díaz-Martínez E, Arispe O. 2000. Stratigraphy and depositional setting of the late Paleozoic Copacabana Formation in Bolivia. *Zentralblatt Geologie und Paläontologie* 1(7/8):723–741.

Griggs GB, Carter L, Kennett JP, Carter RV. 1983. Late Quaternary marine stratigraphy southeast of New Zealand. *Geological Society of America Bulletin* 94:791–797.

Hambrey M. 1994. *Glacial Environments*: University College Press, London. 295 p.

Helwig J. 1972. Stratigraphy, sedimentation, paleogeography, and paleoclimates of Carboniferous (Gondwana) and Permian of Bolivia. *American Association of Petroleum Geology, Bulletin* 56:1008–1033.

Iannuzzi R, Díaz-Martínez E, Suárez-Soruco R. 1999. Los elementos florísticos de la Formación Siripaca (Grupo Ambo, Bolivia) y su contexto bioestratigráfico. *Pesquisas* 26(1):21–40.

Iannuzzi R, Rösler O. 2000. Floristic migration in South America during the Carboniferous: Phytogeographic and biostratigraphic implications. *Paleogeography, Palaeoclimatology, Palaeoecology* 161:71–94.

Isaacson PE. 1975. Evidence for a western extracontinental land source during the Devonian Period in the central Andes. *Geological Society of America Bulletin* 86:39–46.

Isaacson PE. 1977. Devonian stratigraphy and brachiopod paleontology of Bolivia. Part A: Orthida and Strophomenida. *Palaeöntographica, Abteilung A* 155:133–192.

Isaacson PE, Díaz-Martínez E. 1995. Evidence for a Middle and Late Paleozoic Foreland Basin and Significant Paleolatitudinal Shift, Central Andes. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 231–249.

Isaacson PE, Díaz-Martínez E, Grader G, Kalvoda J, Babek O, Devuyst FX. 2008. Late Devonian Glaciation in Gondwana. *In* Soreghan GS, Montañez IP (Editors). Geosystems: Investigations of the Late Paleozoic Tropical Earth System. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Special Issue 268:126–142.

Isaacson PE, Hladil J, Jianwei S, Kalvoda J, Grader G. 1999. Late Devonian (Famennian) glaciation in South America and marine offlap on other continents. *In* Feist R, Talent JA, Daurer A (Editors). *North Gondwana: MidPaleozoic Terranes, Stratigraphy and Biota*, vol. 54: Abhandlungen der Geologischen Bundesantstalt, Vienna, p. 239–257.

Isaacson PE, Palmer BA, Mamet BL, Cooke JC, Sanders DE. 1995. Devonian Carboniferous Stratigraphy in the Madre de Dios Basin, Bolivia: Pando X1 and Manuripi X1 Wells. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 501–509.

Isaacson PE, Sablock PE. 1988. Devonian System in Bolivia, Peru, and Northern Chile. *In* McMillan NJ, Embry AF, Glass DJ (Editors). *Devonian of the World*, Memoir 14: Canadian Society of Petroleum Geologists, Calgary, Alberta. p. 719–728.

Isaacson PE, Sablock PE. 1990. Devonian palaeogeography and palaeobiogeography of the central Andes. *In* McKerrow WS, Scotese CR (Editors). *Palaeozoic Palaeogeography and Biogeography*, Memoir 12: Geological Society, London. p. 431–435.

Isbell JL, Miller MF, Wolfe KL, Lenaker PA. 2003. Timing of Late Paleozoic Ice Age in Gondwana: Was glaciation responsible for the development of northern hemisphere cyclothems? *In* Chan MA, Archer AW (Editors). *Extreme Depositional Environments: Mega End Members in Geologic Time*, Special Paper 370: Geological Society of America, Boulder, Colorado. p. 5–24.

Jacques JM. 2004. The influence of intraplate structural accommodation zones on delineating petroleum provinces of the Sub-Andean foreland basin. *Petroleum Geoscience* 10:1–19.

Limachi R, Goitia VH, Sarmiento D, Arispe O, Montecinos R, Diaz Martinez E, Dalenz-Farjat A, Liachenco N, Pérez Leyton MA, Aguilera E. 1996. Estratigrafía, Geoquímica, Correlaciones, Ambientes Sedimentarios y Biostratigrafía del Silúrico–Devónico de Bolivia. *Congreso Geológico de Bolivia, Tarija, Memoria* 1:183–197.

Lobo Boneta J. 1987. El Límite Devónico–Carbonifero en el Subandino Sur de Bolivia. *Revista Técnica de Yacimientos Petroliferos Fiscales Bolivianos* 10(3–4):213–217.

López-Gamundí OR. 1986. Sedimentología de la Formación Tarija, Carbonífero de la sierra de Aguarague, provincia de Salta. *Revista de la Asociación Geológica Argentina* 41:334–355.

López-Gamundí OR. 1987. Depositional models for the glaciomarine of Andean Late Paleozoic basins of Argentina. *Sedimentary Geology* 52:109–126.

López-Gamundí OR, Limarino CO, Césari SN. 1992. Late Paleozoic paleoclimatology of central west Argentina. *Paleogeography, Paleoclimatology, Paleoecology* 91:251–261.

Mamet B. 1996. Late Paleozoic small foraminifers (endothyrids) from South America (Ecuador and Bolivia). *Canadian Journal of Earth Sciences* 33(3):452–459.

Mamet B, Isaacson P. 1997. Bashkirian (Early Pennsylvanian) Small Foraminifers from Bolivia. *International Congress on the Carboniferous and Permian (Warsaw), Proceedings* 2C:319–329.

McCaslin JC. 1979. Bolivia's Carboniferous system draws interest. *Oil and Gas Journal* 77(10):199.

Melo JHG. 1988. The Malvinokaffric realm in the Devonian of Brazil. *In* McMillan NJ, Embry AF, Glass DJ (Editors). *Devonian of the World*, Memoir 14: Canadian Society of Petroleum Geologists, Calgary, Alberta. p. 669–703.

Merino D, Blanco J. 1990. Conodontos de la Formación Copacabana (Carbonífero superior–Pérmico inferior) en la sección de Huarachani-Pacobamba, Departamento de La Paz, Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales Bolivianos* 11:109–116.

Merino-Rodo D. 1987. Estudio bioestratigráfico de los conodontos de la Formación Copacabana (Carbonífero Superior-Pérmico Inferior) en Yaurichambi (La Paz–Bolivia): IGCP-Proj. 211, Annual Meeting, Santa Cruz, Bolivia, p. 64–65.

Miall AD. 1978, Lithofacies types and vertical profile models in braided river deposits: A summary. *In* Miall AD (Editor). *Fluvial Sedimentology*, Memoir 5: Canadian Society of Petroleum Geologists, Calgary, Alberta. p. 597–604.

Mon R, Salfity JA. 1995. Tectonic evolution of the Andes of Northern Argentina. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 269–283.

Nascimento S, Scomazzon AK, Moutinho LP, Lemos VB, Matsuda NS. 2005. Conodont biostratigraphy of the lower Itaituba Formation (Atokan Pennsylvanian), Amazonas Basin, Brazil. *Revista Brazileira de Paleontologia* 8(3):193–202.

Newell ND, Chronic J, Roberts TG. 1953. *Upper Paleozoic of Peru*, Memoir 58: Geological Society of America, Boulder, Colorado. 230 p.

Noetinger S, Di Pasquo MM, Isaacson P, Aceñolaza GF, Vergel MM. 2015. Integrated study of fauna and microflora from the Early Devonian (Pragian–Emsian) of northwestern Argentina. *Historical Biology* 28(7):913–929.

Orpin AR, Alexander C, Carter L, Walsh JP. 2006. Temporal and spatial complexity in post-glacial sedimentation on the tectonically active, Poverty Bay continental marine of New Zealand. *Continental Shelf Research* 26:2205–2224.

Oviedo C, Morales R. 2000. Compendio de Geología de Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales Bolivianos* 18:(1–2):145–167.

Padula EL, Reyes FC. 1958. Contribución al Léxico Estratigráfico de las Sierras Subandinas. *Boletín Técnico Yacimientos Petrolíferos Fiscales Bolivianos* 1(1):9–70.

Rakotosolofo NA, Tait JA, Carolotto V, Cárdenas J. 2006. Palaeomagnetic results from the Early Permian Copacabana Group, southern Peru: Implication for Pangaea palaeogeography. *Tectonophysics* 413:287–299.

Ramos VA. 2008. The basement of the Central Andes: The Arequipa and related Terranes. *Annual Review of Earth and Planetary Sciences* 36:289–324.

Reyes FC. 1972. On the Carboniferous and Permian of Bolivia and Northwestern Argentina. *Anales Academia Brasileira Ciências* 44:261–277.

Rocha-Campos AC, Carvalho RG, Amos AJ. 1977. A Carboniferous (Gondwana) fauna from Subandean Bolivia. *Revista Brasileira de Geociências* 7:287–303.

Ross CA, Ross JRP. 1987. Permian sequence stratigraphy and fossil zonation. *In* Embry AF, Beauchamp B, Glass DJ (Editors). *Pangea: Global Environments and Resources*, Memoir 17: Canadian Society of Petroleum Geologists, Calgary, Alberta. p. 219–232.

Sakagami S. 1995. Upper Paleozoic bryzoans from the Lake Titicaca region, Bolivia. *Transactions Proceedings of Palaeontological Society of Japan* 180:226–281.

Sakagami S, Mizuno Y. 1994. Discovery of middle Pennsylvanian fusulinids and conodonts from the Copacabana Group in the Lake Titicaca region. *Proceedings of the Palaeontological Society of Japan* 174:484–494.

Salfity J, Azcuy CL, López-Gamundí O, Valencio DA, Vilas JF, Cuerda A, Laffitte G. 1987. El Sistema Carbonífero en la República Bolivia. *In* Archangelsky S (Editor). *El Sistema Carbonífero en la República Argentina*: Academia Nacional de Ciencias, Córdoba. p. 15–40.

Salinas C, Oblitas, Vargas C. 1978. Exporación del Sistema Carbonífero en la Cuenca Oriental de Bolivia. *Revista Técnica de Yacimientos Petrolíferos Fiscales Bolivianos* 7:5–27.

Samtleben C. 1971. Zur Kenntnis der Produktiden und Spiriferiden des bolivianischen Uunterperms. *Geologigisches Jahrbuch*, p. 111.

Sanjinés-Saucedo G. 1982. Estratigrafía del Carbónico, Triásico y Cretácico boliviano en el borde oriental de las Sierras Subandinas Centrales. *Congreso Latinoamericano de Geología, Buenos Aires* 1:301–318.

Schulz A, Santiago M, Hernández R, Galli C, Alvarez L, Del Papa C. 1999. Modelo estratigráfico del Carbónico en el sector sur de la Cuenca de Tarija. *Congreso de Exploración y desarrollo de Hidrocarburos, Mar del Plata* 2:695–711.

Scotese CR. 2003. PALEOMAP Project: http://www.scotese.com. Accessed October 9, 2017.

Sempere T. 1993. Paleozoic to Jurassic Evolution of Bolivia. *Second ISAG* 21–23(9):547–550.

Sempere T. 1995. Phanerozoic Evolution of Bolivia and Adjacent Regions. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 207–230.

Sempere T, Carlier G, Soler P, Fornari M, Carlotto V, Jacay J, Arispe O, Cárdenas J, Rosas S, Jiménez N. 2002. Late Permian–Middle Cretaceous lithospheric thinning in Peru and Bolivia and its bearing on Andean-age tectonics. *Tectonophysics* 345:153–181.

Starck D. 1995. Silurian–Jurassic Stratigraphy and Basin Evolution of Northwestern Argentina. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 251–267.

Starck D, Del Papa C. 2006. The northwestern Argentina Tarija Basin Stratigraphy, depositional systems and controlling factors in a glaciated basin. *Journal of South American Earth Sciences* 22:169–184.

Starck D, Gallardo E, Schulz A. 1993a. The pre-Carboniferous unconformity in the Argentine portion of the Tarija Basin. *International Congress of Carboniferous-Permian, Buenos Aires 1991, Comptes Rendus* 2:373–384.

Starck D, Gallardo E, Schulz A. 1993b. Neopaleozoic stratigraphy of the Sierras Subandinas Occidentales and Cordillera Oriental, Argentina. *International Congress of Carboniferous-Permian, Buenos Aires 1991, Comptes Rendus* 2:353–372.

Stephenson MH. 2008. A review of the palynostratigraphy of Gondwana Late Carboniferous to Early Permian glacigenic successions. *In* Fielding CR, Frank TD, Isbell JL (Editors). *Resolving the Late Paleozoic Ice Age in Time and Space*, Special Paper 441: Geological Society of America, Boulder, Colorado. p. 317–310.

Suárez-Riglos M. 1984. Introducción a los conodontes del Permocarbonico de Bolivia, in Congreso Latinoamericano de Paleontologia, México, Memorias, p. 125–129.

Suárez-Soruco R. 1986. The Carboniferous System of Bolivia: A brief summary, in Meeting of the Carboniferous Working Group, Córdoba, Abstracts, p. 11–26.

Suárez-Soruco R. 2000. Compendio de Geología de Bolivia. *Revista Técnica Yacimientos Petrolíferos Fiscales Bolivianos* 18(1–2):1–213.

Suárez-Soruco R, Díaz-Martínez E. 1996. Léxico Estratigráfico de Bolivia. *Revista Técnica Yacimientos Petrolíferos Fiscales Bolivianos* 17(1):227.

Tankard AJ, Uliana MA, Welsink HJ, Ramos VA, Turic M, França AB, Milani EJ, De Brito Neves BB, Eyles N, Skarmeta J, Santa Ana H, Wiens F, Cirbian M, Lopez Paulsen O, Germs GJB, DeWit MJ, Machacha T, Miller RM. 1995. Tectonic controls of basin evolution in southwestern Gondwana, *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 5–52.

Troth I, Marshall JEA, Racey A, Becker RT. 2011. Devonian sea-level change in Bolivia: A high palaeolatitude biostratigraphical calibration of the global sea level curve. *Palaeogeography, Palaeoclimatology, Palaeoecology* 304:3–20.

Vail PR, Audemard F, Bowman SA, Eisner PN, Perez-Crus C. 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology an overview. *In* Einsele G, Ricken W, Seilacher A (Editors). *Cycles and Events in Stratigraphy*: Springer, Berlin. p. 617–659.

Vavrdová M, Bek J, Dufka P, Isaacson PE. 1996. Palynology of the Devonian (Lochkovian to Tournaisian) sequence, Madre de Dios Basin, northern Bolivia. *Vestnik Ceskeho geologickeho ustavu* 71(4):333–349.

Vavrdová M, Isaacson PE, Díaz Martínez E, Bek J. 1991. Palinología del límite Devónico-Carbonífero entorno al Lago Titikaka, Bolivia: resultados preliminares. *Revista Técnica Yacimientos Petrolíferos Fiscales Bolivianos* 12(2):303–313.

Vavrdová M, Isaacson PE, Díaz-Martínez E, Bek J. 1993. Devonian–Carboniferous boundary at Lake Titikaka, Bolivia, preliminary palynological results. *Congreso Estratigrafía y Geología del Carbonífero y Pérmico, Comptes Rendus* 1:187–199.

Viera AF, Hernández RM. 2001. Carboniferous stratigraphic analysis in the Subandean foothills and plains of the Tarija Basin, Bolivia, in American Association of Petroleum Geologists, Annual Meeting, abstract.

Weins F. 1995. Phanerozoic tectonics and sedimentation in the Chaco basin of Paraguay, with comments on hydrocarbon potential. *In* Tankard AJ, Suárez R, Welsink HJ (Editors). *Petroleum Basins of South America*, Memoir 62: American Association of Petroleum Geologists, Tulsa, Oklahoma. p. 185–206.

Wicander R, Clayton G, Marshall JEA, Troth I, Racey A. 2011. Was the latest Devonian glaciation a multiple event? New palynological evidence from Bolivia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 305:75–83.

Wilson EC. 1990. Permian corals of Bolivia. *Journal of Paleontology* 64(1):60–78.

Appendix 1

List of species (with authors) mentioned in the text

Spores

Anapiculatisporites ampullaceus (Hacquebard) Playford 1964

Apiculatasporites spinulistratus (Loose) Ibrahim 1933

Converrucosisporites micronodosus (Balme and Hennelly) Playford and Dino 2002

Convolutispora ampla Hoffmeister, Staplin and Malloy 1955

Convolutispora harlandii Playford 1962

Convolutispora insulosa Playford 1978

Cordylosporites papillatus (Naumova) Playford and Satterthwait 1985

Crassispora kosankei (Potonié & Kremp) Smith and Butterworth 1967

Crassispora scrupulosa Playford, 1971 emend. Playford and Satterthwait 1988

Cristatisporites chacoparanaensis Ottone 1989

Cristatisporites crassilabratus Archangelsky and Gamerro 1979

Cristatisporites echinatus Playford 1962

Cristatisporites menendezii (Menéndez and Azcuy) Playford 1976

Cristatisporites peruvianus Azcuy and di Pasquo 2005

Cristatisporites stellatus (Azcuy) Gutiérrez and Limarino 2001

Cymbosporites loboziakii Melo and Playford 2012

Cyrtospora cristifera (Luber) emend. Van der Zwan 1979

Densosporites spitsbergensis Playford 1963

Dibolisporites microspicatus Playford 1978

Dibolisporites setigerus Playford and Satterthwait 1986

Dictyotriletes bireticulatus (Ibrahim) Potonié and Kremp emend. Smith and Butterworth 1967, morphon (in di Pasquo 2003, 2009a)

Foveosporites hortonensis (Playford) Azcuy 1975

Granulatisporites granulatus Ibrahim 1933

Indotriradites viriosus Melo and Playford 2012

Kraeuselisporites explanatus (Luber) Azcuy and di Pasquo 2005

Kraeuselisporites volkheimerii Azcuy 1975

Lundbladispora braziliensis (Pant y Srivastava) Marques Toigo and Pons 1974 emend. M. Toigo and Picarelli 1984

Lycospora noctuina Butterworth and Williams 1958

Punctatisporites lucidulus Playford and Helby 1968

Pustulatisporites multicapitis Bertelsen 1972

Raistrickia baculosa Hacquebard 1957

Raistrickia ponderosa Playford 1964

Raistrickia radiosa Playford and Helby, 1968

Reticulatisporites reticulatus (Ibrahim) Ibrahim 1933

Reticulatisporites waloweekii Ravn 1991

Retispora lepidophyta (Kedo) Playford 1976

Rugospora polyptycha Neves and Ioannides 1974

Secarisporites undatus Playford and Satterthwait 1986

Spelaeotriletes balteatus (Playford) Higgs 1975

Tumulispora (Lophozonotriletes) rarituberculata (Luber) Potonié 1966

Vallatisporites arcuatus (Marques Toigo) Archangelsky and Gamerro 1979

Vallatisporites ciliaris (Luber) Sullivan 1964

Verrucosisporites gobbettii Playford 1962

Verrucosisporites morulatus (Knox) emend. Smith and Butterworth 1967

Verrucosisporites nitidus (Naumova) Playford, 1964 emend. Turnau 1994

Waltzispora lanzonii Daemon 1974

Pollen grains

Circumplicatipollis plicatus Ottone and Azcuy 1988

Cystoptychus azcuyi di Pasquo 2002

Marsupipollenites triradiatus Balme and Hennelly 1956

Acritarchs

Umbellasphaeridium saharicum Jardiné et al. 1972