The Geological Society of America
Special Paper 441
2008

Late Devonian and Early Carboniferous glacial records of South America

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ABSTRACT

Three glacial episodes are identified in Upper Devonian and Mississippian strata in South America using sedimentologic, stratigraphic, paleontological, bore hole, and outcrop data. The first glacial episode is of late Famennian ("Strunian") age and is interpreted from strata in basins of Brazil, Bolivia, and Peru, where ice sheets and alpine glaciers reached coastal and marine settings. Biostratigraphically, these strata correspond to the Biostratigraphically, these strata correspond to the *Retispora lepidophyta–Indotriradites explanata or* LE Zone and the *Retispora lepidophyta–Verrucosisporites nitidus* or LN Zone. Spore zones of Western Europe. The second glacial episode occurred during the late middle to early late Tournaisian and is recorded in the subsurface of the Solimões Basin (Juruá and Jandiatuba sub-basins) of northwestern Brazil and possibly in Bolivia and Argentina. The third glacial episode is of late Visean age and is currently identified in basins of Brazil and possibly in the area of the former Acre Basin shelf, but data are poor. In Bolivia and Peru, the Ambo Group also displays glacially influenced sediments as well as strata in central western Argentina. These glacial episodes may also have occurred in Africa, but data are still scarce, and the ages of potentially coeval strata are not well constrained. Indirect evidence of these Paleozoic glacial events in Gondwana is suggested by researchers in Western Europe, Asia, and in the United States on the basis of geochemical, stratigraphic, sedimentologic, paleontologic, and eustatic data.

Keywords: Late Devonian, Early Carboniferous, Glacial Record, South America, miospore zones, correlation.

Caputo, M.V., Melo, J.H.G., Streel, M., and Isbell, J.L., 2008, Late Devonian and Early Carboniferous glacial records of South America, *in* Fielding, C.R., Frank, T.D., and Isbell, J.L., eds., Resolving the Late Paleozoic Ice Age in Time and Space: Geological Society of America Special Paper 441, p. XXX–XXX, doi: 10.1130/2008.2441(11). For permission to copy, contact editing@geosociety.org.

INTRODUCTION

The main purpose of this study is to describe and interpret Upper Devonian and Mississippian diamictites deposited in sedimentary basins in South America and to determine whether they were deposited in association with glacial activity. This study discusses the strata in the Solimões, Amazonas, Parnaíba, and Paraná intracratonic basins; the Marajó Basin, a Mesozoic rifted basin; and strata in correlative basins in western South America (Fig. 1).

Devonian and Mississippian glacigenic strata in Brazil occur in both outcrop and in the subsurface. The intracratonic basins enclose mainly Paleozoic sedimentary rocks that were later intruded by Triassic to Early Cretaceous diabase sills and dikes and subsequently buried by Mesozoic to Tertiary rocks. The Mesozoic rifted basins, which opened during the breakup of Gondwana, contain a basement composed of, mainly, Paleozoic sedimentary rocks, and a fill of Mesozoic and Cenozoic strata. Paleozoic strata preserved in the rifted basins strongly suggest that Devonian and Mississippian strata may have originally extended well beyond the present northeastern and southern Brazilian shorelines. On the western side of the Brazilian Shield and the northern side of the Guiana Shield, Devonian and Mississippian sedimentation occurred within intracratonic and foreland

Figure 1. Location of South American basins discussed in the text.

basins from Argentina and Paraguay to Colombia and Venezuela. The Brazilian Acre Basin is confined by the Madre de Dios Basin (Bolivia) and Pastaza Basin (Peru; Fig. 1).

This paper addresses the need to better identify and discriminate the latest Devonian and Mississippian glacial events in South America, the types of glaciers that were present, and the extent and age of the glaciations. Three Devonian and Mississippian glacial episodes are identified, with varying degrees of certainty based on lithological, sedimentologic, stratigraphic, and paleontological evidence. The ages of these events are: (1) latest Famennian, (2) middle late to early late Tournaisian, and (3) late Visean. This paper also presents new palynological data and discusses their implications for biostratigraphic correlation. Although Devonian and/or Mississippian glacigenic strata have also been reported in Africa and North America (cf. Caputo, 1985; Streel et al., 2000a; Cecil et al., 2004), these strata will not be described here.

LATE FAMENNIAN GLACIATION

A glacial episode characterized by glacial, glaciomarine, and glaciofluvial deposits occurs near the top of the Famennian successions in the Marajó, Parnaíba, Amazon, Solimões, and Paraná Basins of Brazil (Caputo, 1984, 1985; Caputo and Crowell, 1985; Loboziak et al., 1995a), and in Bolivia and Peru (Díaz-Martínez, 1995) (Fig. 2).

In the Parnaíba Basin (Fig. 1), glacial signatures contained within latest Famennian strata include: (1) striated pavements overlain by diamictite with striated, faceted, and polished coarse sand– to boulder-sized clasts from a variety of lithologies (Fig. 3); (2) rhythmites, some of which contain dropstones (Carozzi, 1980); (3) exotic basement boulders, up to 1.5 m in diameter, contained within massive diamictite units; and (4) glacially deformed sedimentary rocks (small folded and faulted sandstone bodies in sheared diamictites interpreted as lodgment tills). In the western outcrop belt, coarse-grained cross-stratified sandstone beds containing sparse pebbles, boulders, and microconglomerates often occur below striated pavements (Fig. 3). These strata are interpreted as proglacial outwash deposits. At least, two sheared diamictites with glaciotectonic deformation occur in this region, and these are interpreted as subglacial tillites (Oliveira, 1997). Fine-grained sandstone beds, up to 45 m thick, containing climbing ripple cross-laminations and abundant deformational features, such as balls, pillows, and dish structures, occur between diamictite bodies (Fig. 4). Such sedimentary structures

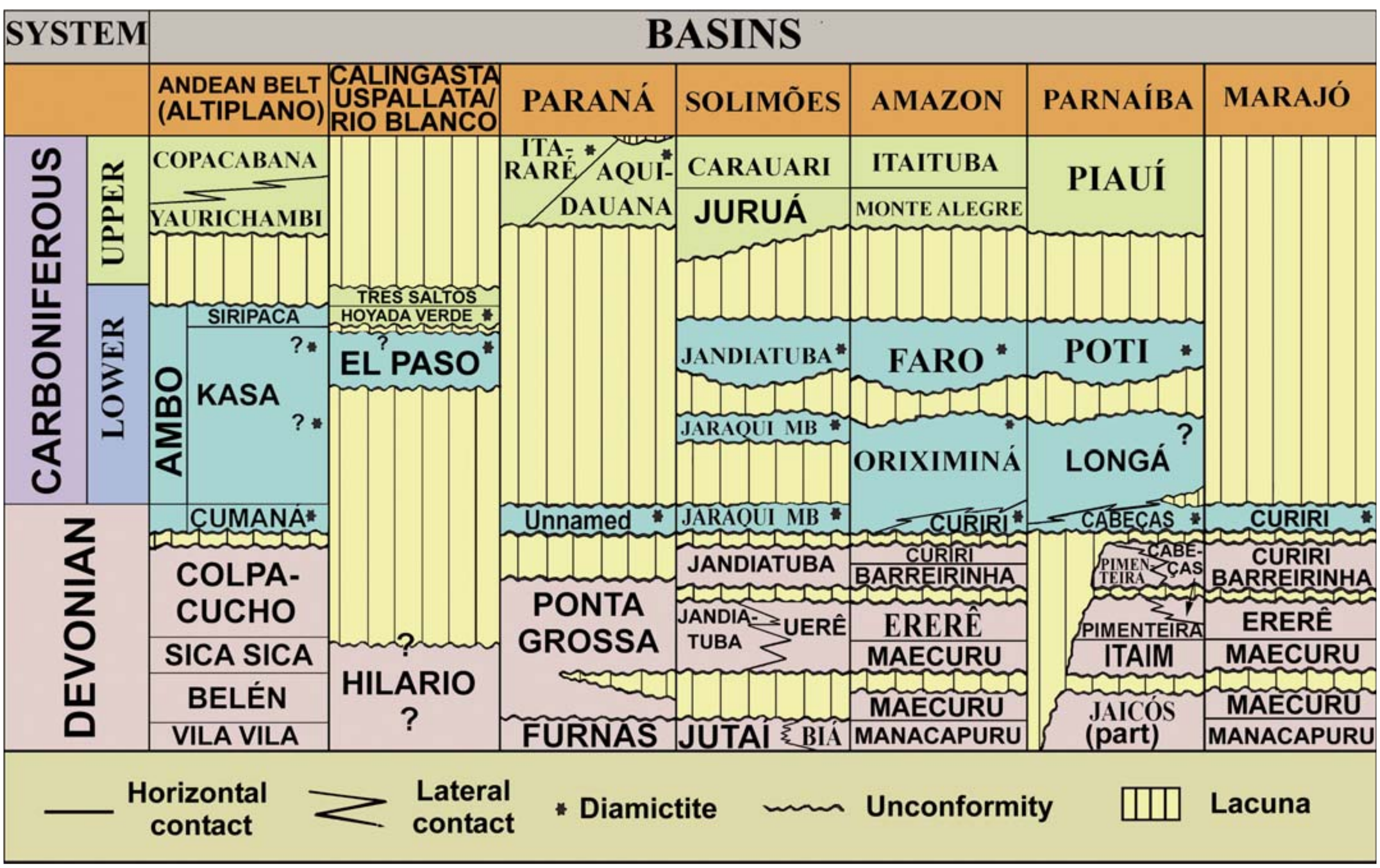

Figure 2. Partial stratigraphic correlation chart for the main basins discussed in the text. The chart is based on recent biostratigraphic data and the identification of glacial and periglacial strata in Brazil (Caputo, 1985), in Bolivia and Peru (Díaz-Martínez et al., 1999), and in Argentina (Gonzáles, 1990).

Figure 3. Striated pavement underlying the uppermost Famennian tillite (in the background) of the Cabeças Formation in the Parnaíba Basin.

suggest accumulation in a delta-front environment. In the subsurface (1-TM-1 well), the occurrences of massive diamictites and dropstone-bearing rhythmites suggest rain-out deposition of debris from meltwater plumes and icebergs; both facies contain acritarchs and other marine microfossils that indicate accumulation in a glaciomarine setting.

In the Parnaíba Basin, glacigenic strata occur in the upper part of the Cabeças Formation in both the subsurface (wells drilled by the Brazilian state-owned oil company, Petrobras) and in outcrops (Fig. 2). In the western outcrop belt, diamictites rest unconformably on sandstones within the Cabeças Formation, on older Paleozoic strata, and on crystalline basement rocks. The occurrence of the unconformity beneath the diamictites, and a moderate stratigraphic lacuna across the rest of the basin during the latest Devonian, is evidence for a concomitant sea-level drop during this glacial event. In more distal depositional areas, fossiliferous marine diamictite overlies striated pavements cut on fine-grained delta-front sandstones. This suggests advance of grounded ice below sea level. Striations with a N15–27°E orientation indicate that ice advanced from the northeastern portion of the Brazilian Shield into the southwest part of the Parnaíba Basin.

In the rifted Marajó Basin, diamictite occurs in strata of the latest Famennian Curiri Formation (Figs. 1 and 2; Petrobras Jacarezinho well 1-JO-1). Below the Cretaceous unconformity, an argillaceous-silty, micaceous, gray massive diamictite section with scattered sand-sized grains, granules, cobbles, and pebbles is present. The diamictite is thought to be glacially derived like those in the adjacent Amazon Basin because, at the time of deposition, before faulting, the Marajó Basin was part of the Amazon

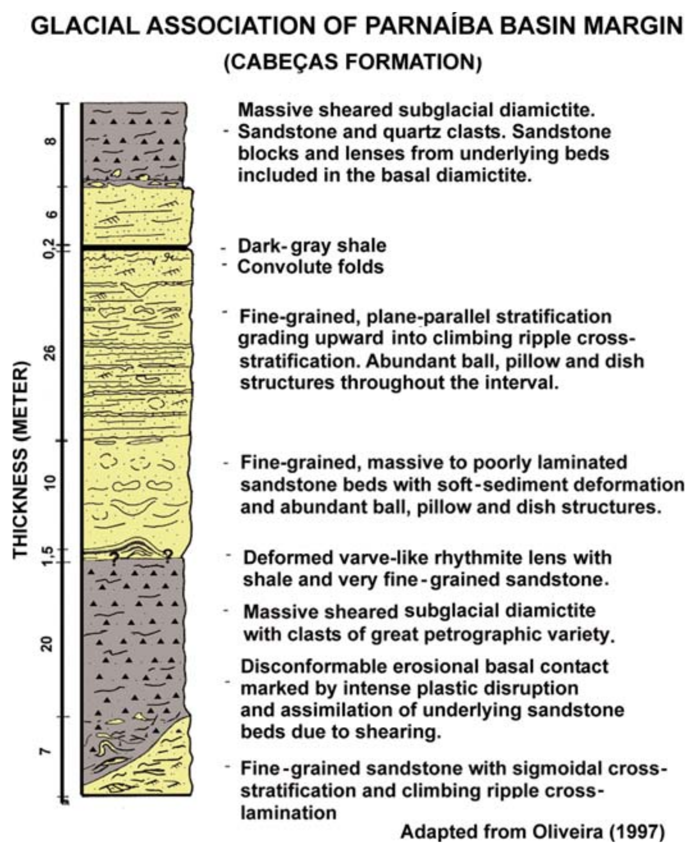

Figure 4. Glacial association of western Parnaíba Basin.

and Parnaíba Basins (see Fig. 1). These basins were connected before the breakup of Gondwana (Caputo, 1984).

In the Amazon Basin (Fig. 1), diamictites interfinger with and overlap shoreface to offshore black siltstones. The strata of the Curiri Formation (Fig. 2) are exposed in two belts that extend for ~500 km along the northern and southern margins of the basin. In these belts and in the subsurface, massive, fine-grained (clay and silt matrix) diamictite units contain striated pebbles and boulders (Fig. 5) as well as deformed elongate sandstone bodies. Striations and a flatiron shape of some clasts indicate a glacigenic origin. The Curiri diamictite beds are present in two bodies and are separated by sandstone and shale beds. Some diamictite intervals change basinward to dropstone-bearing laminated mud rocks and to clast-free laminated mud rocks (Caputo, 1984). Lenticular bodies composed of very fine– to fine-grained cross-laminated and cross-bedded sandstone beds are generally deformed and mixed with diamictite masses. The sandstones contain scattered pebbles, diamictite pieces, microfolds, and microfaults. Massive marine diamictite facies were deposited by rain-out of mud from suspended sediment together with ice-rafted debris. In the northwestern part of the basin, large intercalated deformed sandstone bodies (30 km long), detected in the subsurface, are interpreted as having accumulated in submarine channels. These units are also interpreted to have terminated in subaqueous fan and related turbidite deposits (Carozzi, 1979). The orientation of submarine channels and the geometry of diamictite lobes (100 × 40 km) as identified from borehole data indicate that paleoflow in the western portion of the basin was from the northwest (Guiana Shield) in the northern part of the area and from the southwest (Brazilian Shield) in the southern part of the region (Carozzi, 1979).

In the Jandiatuba and Juruá subbasins of the Solimões Basin (Fig. 1), diamictites are restricted to the subsurface. Famennian diamictites extend across a wide area of the Solimões Basin from the southern border of the Jandiatuba subbasin onto the Carauari High, and throughout the Juruá subbasin. These diamictites are used as a marker in boreholes in both subbasins. The diamictites are composed of a dark-grayish, massive silty-clayey matrix supporting clasts up to pebble size of quartz, quartzite, shale, and crystalline rocks. These clasts vary considerably in size and roundness. Sandstone bodies are lenticular and show deformational features such as folds and small faults. Shale interbeds also occur. These uppermost Devonian diamictites and shales are rich in coeval marine microfossils. These strata are the same age as glaciomarine strata in the Amazon Basin, and rock textures (diamictites) suggest that strata in the Solimões Basin were also deposited under glaciomarine to glacially influenced conditions.

In the subsurface of the Paraná Basin (Southern Brazil in Petrobras' Ortigueiras well 2-O-1), Loboziak et al. (1995a) identified an apparently in situ uppermost Famennian palynoflora (*Retispora lepidophyta–Verrucosisporites nitidus* or LN Zone) within gray diamictites that disconformably rest on Frasnian shales in the upper part of the Ponta Grossa Formation (Fig. 2). The diamictite bed is made of sand-, granule-, and pebble-sized clasts dispersed in a massive micaceous, silty

Figure 5. Nonparallel glacial striae on clasts from Curiri Formation, Upper Devonian (Amazon Basin). Cuiabá-Santarém Highway, ~7 km north from the intersection with the Transamazonian Highway.

and clayey groundmass. These strata were formerly considered to be part of the Upper Pennsylvanian to Early Permian Itararé Group. The frequent occurrence of reworked palynomorphs of Givetian-Frasnian age confirms the unconformable contact between the latest Famennian diamictite and the underlying Frasnian Ponta Grossa Formation.

Using spores (Fig. 6), Loboziak et al. (1994a, 1994b, 2000) and Streel et al. (2000a, 2000b) located the diamictites in a biostratigraphic interval correlative with the *Retispora lepidophyta–Indotriradites explanatus* (LE) and *Retispora lepidophyta–Verrucosisporites nitidus* (LN) biozones of Western Europe, i.e., palynozones *Retispora lepidophyta* (Rle) and *Retispora lepidophyta–Vallatisporites vallatus* (LVa), according to the Gondwanan zoning by Melo and Loboziak (2003). These biozones correspond to the last two million years of the Devonian. However, the vertical distribution of the diamictites suggests that glaciation ended just prior to the Devonian-Mississippian boundary.

The Peru-Bolivia foreland basin (Fig. 1), the southern and southwestern parts of which continue into Argentina and Paraguay as the Tarija or Chaco-Tarija Basin (Díaz-Martínez et al., 1999), contains uppermost Devonian diamictites. Strata of the Cumaná Formation of latest Famennian age (Fig. 2), which crop out in the Altiplano and Eastern Cordillera regions of the Andes, are the best studied Devonian units in western Gondwana. The Cumaná Formation includes basal shales with dropstones, massive diamictite with striated and faceted clasts, and quartz sandstones containing soft-sediment folds. These strata have been interpreted as glacially influenced sediments, and they have been recognized

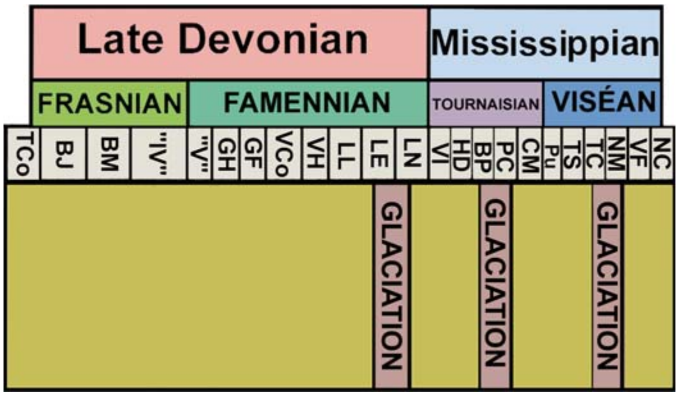

Figure 6. Western European miospore zones and corresponding stratigraphic intervals where Devonian–Early Carboniferous (Mississippian) glacial and periglacial imprints are observed in Western Gondwana and adjacent European regions. Devonian biozones are according to Streel et al. (1987) and Maziane et al. (1999); Early Carboniferous biozones are after Clayton et al. (1977), Higgs et al. (1988a, 1988b), and Riley (1993). Acronyms for miospore zones are as follows (in ascending stratigraphic order): TCo—*Samarisporites triangulatus—Chelinospora concinna*, BJ—*Verrucosisporites bulliferus—Cirratriradites jekhovskyi*, BM—*Verrucosisporites bulliferus—Lophozonotriletes media*, "IV" and "V"—phase zones (informal palynozones), GH—*Grandispora gracilis–Samarisporites sp. cf. A. hirtus*, GF—*Grandispora gracilis–Grandispora famenensis*, VCo—*Rugospora versabilis–Grandispora cornuta*, VH—*Apiculiretusispora verrucosa–Vallatisporites hystricosus*, LL—*Retispora lepidophyta–Knoxisporites literatus*, LE—*Retispora lepidophyta–Indotriradites explanatus*, LN—*Retispora lepidophyta–Verrucosisporites nitidus*, VI—*Vallatisporites verrucosus–Retusotriletes incohatus*, HD—*Kraeuselisporites hibernicus–Umbonatisporites distinctus*, BP—*Spelaeotriletes balteatus–Rugospora polyptycha*, PC—*Spelaeotriletes pretiosus–Raistrickia clavata*, CM—*Schopfites claviger–Auroraspora macra*, Pu—*Lycospora pusilla,* TS—*Knoxisporites triradiatus–Knoxisporites stephanephorus*, TC—*Perotrilites tessellatus–Schulzospora campyloptera*, NM—*Raistrickia nigra–Triquitrites marginatus*, VF—*Tripartites vetustus–Rotaspora fracta*, NC—*Bellispores nitidus–Reticulatisporites carnosus*.

in several studies in the Altiplano (Díaz-Martínez, 1991; Díaz-Martínez et al., 1993a; Isaacson and Díaz-Martínez, 1995; Díaz-Martínez, and Isaacson, 1994; Isaacson et al., 1995).

Late Famennian strata, equivalent to strata in the Cumaná Formation, are given different formational names across western South America. In Subandean basins and the low plains areas, coeval strata are known as the Itacua (Central Cordillera), the Saipuru (Eastern Cordillera), and the Toregua (Madre de Dios Basin) Formations.

The Saipuru Formation (Eastern Cordillera) contains diamictites with faceted and striated clasts in its lower part, and, based on palynomorphs (*Retispora lepidophyta* zone), it is of latest Famennian age (Suárez-Soruco and López-Pugliessi, 1983).

Although no direct evidence of glaciations is currently known in the Devonian and Mississippian of Colombia and Venezuela, it is possible that glacigenic strata may occur in the subsurface of these countries (Fig. 1). Venezuela is located on the northern side of the Guiana Shield, which is the location of a proposed Famennian glacial center that fed ice to the northern margins of the Solimões and Amazon Basins. In Venezuela, Stover (1967) dated the Carrizal Formation as Late Devonian–Early Carboniferous. This sequence reaches a thickness of ~3000–5000 m and was deposited in coastal to neritic marine settings. It consists of fine- to coarse-grained sandstones intercalated with conglomerates and shales. Much work is needed on Devonian strata in these Andean countries to determine if they contain a glacial signature.

Frakes et al. (1992), Sablock (1993), Williams (1995), Lópes-Gamundí (1997), and Isbell et al. (2003) have hypothesized that Upper Devonian strata in west-central and northern South America were deposited by alpine glaciers. However, the widespread occurrence of latest Famennian glacigenic strata in marine settings suggests that glaciation is better explained by more extensive glaciation, possibly by multiple ice sheets and or ice caps. Although Williams (1995) reported that uplift occurred along the southern margins of the Amazon and Parnaíba Basins, there is no evidence of such Devonian intraplate tectonism in those areas, or in the area of the Guiana Shield, which was also a glacial center located to the north of the Amazon and Solimões Basins. Devonian intraplate tectonics in central Western Gondwana are very difficult to validate on the basis of currently available evidence. Therefore, a preserved record of alpine glaciation is unlikely in Brazil, but alpine glaciation may have occurred in western South America (cf. Isaacson and Díaz Martínez, 1995).

A severe biotic crisis at the end of the Famennian occurred within the Western European biostratigraphic interval LN (Streel et al., 2000a) after an anoxic event. Coeval glaciation could have promoted a eustatic fall and a more vigorous circulation of cold bottom waters in the world oceans, (associated with climatic cooling), which may have facilitated a rise of toxic waters to the surface (Wilde and Berry, 1984; Caputo, 1995). Such a scenario could have contributed to the elimination of ~20% of genera and 20% of the families of marine invertebrates at that time (Streel et al., 2000a).

Data presented here provide positive evidence for the latest Famennian glaciation in the Parnaíba, Amazon, Marajó, and Peru-Bolivia Basins. Possible or problematic records include strata in the Solimões and Paraná Basins. In these areas, possible glacigenic strata are buried, making it difficult to determine their origin. It is clear that many of the units mentioned here still need more field and sedimentological work.

MIDDLE TO EARLY LATE TOURNAISIAN GLACIATION

The second Gondwanan glacial episode recorded in South America may have occurred during the late middle to early late Tournaisian. However, documentation of this episode is poor and sparse. Presently, Tournaisian glacigenic strata are identified in the subsurface of the Solimões Basin of Brazil (Loboziak et al., 1994a, 1994b, 1995b).

Paleozoic strata in the Solimões Basin (Fig. 1) are covered by Tertiary beds, and unfortunately, many of the new borehole data for the Solimões Basin are proprietary, and little has been published. Tournaisian diamictites occur in the upper part of the Jaraqui Member of the Jandiatuba Formation (Fig. 2) and are crudely stratified. Clasts are unoriented and consist of angular to rounded quartz, shale, sandstone, and igneous pebbles. Some diamictite units are deformed or show significant dips. These strata rest disconformably on underlying Famennian diamictites and older strata. The diamictites are best developed throughout much of the Juruá subbasin and are less frequent in the Jandiatuba subbasin. Diamictites from cores and sidewall cores in the Juruá subbasin (Jaraqui Member of the Jandiatuba Formation) contain fossil palynomorphs of late middle to early late Tournaisian age, which are equivalent to the *Spelaeotriletes balteatus–Rugospora polyptycha* (BP) and *Spelaeotriletes pretiosus–Raistrickia clavata* (PC) biozones of Western Europe (Loboziak et al., 1994a, 1994b, 1995b). These zones correspond to the Gondwanan *Spelaeotriletes balteatus–Neoraistrickia loganii* (BL) and *Spelaeotriletes pretiosus–Colatisporites decorus* (PD) palynozones sensu Melo and Loboziak (2003), respectively. Except for reworked Devonian marine microfossils, Tournaisian diamictites contain mainly miospores, and scarce autochthonous acritarchs may occur in some Tournaisian diamictites. Latest Famennian diamictites have a widespread distribution in the basin, and part of these rocks were almost invariably eroded and recycled into the Tournaisian diamictites. Because of reworked uppermost Devonian sediments and palynomorphs, Tournaisian strata are sometimes very difficult to identify using palynology.

In the nearby Amazon Basin, Tournaisian diamictites of the Oriximiná Formation (Fig. 2) are restricted to the subsurface, and, to date, no diamictites have been identified in outcrops. They are made up of a hard, dark-grayish, structureless massive clay matrix supporting coarse-grained sand grains, granules, and pebbles of quartz, quartzite, shale, and crystalline rocks. The nature of these diamictites is problematic, but a glacial derivation cannot be discarded. Because the Famennian and Tournaisian diamictites often occur together, additional subsurface sampling studies and more detailed paleontological examinations are necessary in order to discriminate these strata and deduce their origin in the basin.

In western South America, Frakes and Crowell (1972) and Lopez-Paulsen et al. (1992) mentioned the presence of Tournaisian glacially derived strata in Peru, Bolivia, and Argentina. However, Díaz-Martínez (2007, personal commun.) suggests that there is no credible evidence for Tournaisian glaciation in Peru or western Bolivia. Therefore, this area is problematic and requires further investigation.

The lower Kasa Formation, overlying the Cumaná Formation in the Eastern Cordillera (Figs. 1 and 2), also contains diamictites interbedded within deltaic sequences. These diamictites are interpreted as massive sediment gravity flows and reworked sediments. The presence of rare dropstones and glacially striated and faceted Clasts in strata of the lower Kasa Formation is problematic and suggests possible glaciation in the source area, or reworking of Devonian diamictites (Díaz-Martínez and Isaacson, 1994; Díaz-Martínez, 1995). Unfortunately, there are no detailed Tournaisian biostratigraphic zonations according to Western European palynozones that could be established for the Kasa Formation and that could be used to compare these strata with Brazilian Tournaisian biozones.

VISEAN GLACIATION

The third glacial pulse, also from the Mississippian, is recorded in strata of the Poti Formation (Caputo, 1985; Caputo et al., 2006a, 2006b) of the Parnaíba Basin, the Faro Formation of the Amazon Basin, and the Jandiatuba Formation of the Solimões Basin. Visean glacigenic strata have also been reported in western Argentina (Limarino et al., 2006).

In Brazil, late Visean glaciation is less evident than the Late Devonian glacial episode because most of the glacigenic formations are restricted to the subsurface (e.g., strata in the Solimões and Amazon Basins). However, in the Parnaíba Basin, diamictites of the Poti Formation occur in outcrops (Figs. 1 and 2; Andrade, 1972, Caputo et al., 2006a, 2006b).

The Poti Formation is up to 170 m thick in the western outcrop belt, and it is up to 320 m thick in the subsurface of the central part of the basin. According to Andrade (1972), the formation is composed of two units. The lower unit is up to 120 m thick, and it consists of very fine– to coarse-grained, cross-bedded sandstone containing unoriented dispersed clasts up to boulder size. The clasts are composed of shale, quartz, quartzite, gneiss, and granite, while many sand grains are feldspathic. This succession contains occasional oligomictic conglomeratic wedges, which include angular to subangular pebbles and rare silty-argillaceous interbeds. Strata in the middle portion of the formation include a silty-shaly interval, which grades laterally into fine-grained sandstone.

The upper unit, ~50 m thick, consists of shale, siltstone, sandstone, and diamictite. The section is composed of cream-gray and pinkish-violet shales and micaceous, calciferous siltstones. Occasional interbeds of fine- to medium-grained pinkish quartz-sandstones also occur. Carbonized plant remains occur in the siltstones and shales. Diamictite units are observed to grade laterally into the distal mud rock succession. Clasts in the diamictites are mainly characterized by angular quartz grains, mica schist, quartzite, gneiss, sandstone pebbles, and boulders disseminated within a compact silty-argillaceous, micaceous, and sometimes calciferous massive matrix. Some clasts are flat, while others are elongated. This diamictite section, ~35 m thick, with striated pebbles and boulders, is also exposed in the Tocantins River, upstream from the town of Carolina, Brazil (Barbosa et al., 1966). Only cores from shallow wells show dark-gray diamictites, while in deep wells inside the basin, laminated strata contain dropstones. Interbeds of massive sandstones separate the diamictite units. Small plant fragments and small sandstone blocks are also included in the diamictite beds. These beds locally show deformation, which includes small folds and faults. Additional evidence for glacigenic or cold-climate conditions in strata of the Poti Formation includes: (1) vertical sandstone wedges, possibly formed as permafrost patterned ground, (2) synsedimentary soft-sediment deformations in the lower Poti member, now attributed to ice-collapse structures, (Kegel, 1954; Caputo, 1985), (3), some dispersed irregular and angular broken sand grains seen within diamictite thin sections obtained from cores, and (4) dropstones (up to boulder size) within fine-grained suspension deposits attributed to debris rafted by floating ice (Della Fávera and Uliana, 1979; Caputo et al., 2006a).

The paleoenvironmental interpretation of the Poti Formation in outcrop areas suggests a proglacial outwash setting for the sandstones of the lower unit. The presence of extrabasinal cobbles and boulders (mainly of quartz and quartzite) in the sandstones derived from basement exposures hundreds of kilometers away suggests that these clasts were carried by streamborne ice rafts. The intermediate shales in the lower part of the Poti Formation may have been deposited in deltaic to shallow-marine environments, whereas diamictites at the top of the Poti are interpreted as glacially derived. The shales on the top of the upper unit would have been deposited in delta-plain settings; they have pelites and sandstones that contain fossil land plant assemblages and a very thin (1-cm-thick) coal bed. The presence of a "Paraca-type" macroflora in the upper part of the formation is indicative of climatic improvement (Iannuzzi and Pfefferkorn, 2002) during interglacial and postglacial times. Lithofacies and the terrestrial macroflora suggest a predominantly continental to transitional (fluvial-deltaic) environment for much of the Poti Formation in the western outcrop belt of the basin. However, brief marine incursions are characterized by storm facies (hummocky cross-stratification) in the lower unit and at the top of the upper unit (Della Fávera, 1990), and by the presence of *Edmondia*, a marine bivalve (Kegel, 1954) in the central and eastern parts of the basin in the lower unit. However, marine palynomorphs do not occur in this unit or in correlative units in the Amazon and Solimões Basins (Melo and Loboziak, 2000, 2003).

Melo and Loboziak (2000) assigned a late Visean age (coeval with the Holkerian and Asbian stages of the British Isles) to the Poti Formation and correlated it with two Western European palynozones: *Perotrilites tessellatus–Schultzospora campyloptera* (TC) and *Raistrickia nigra–Triquitrites marginatus* (NM). Melo and Loboziak (2003) related this formation to the late Visean Mag palynozone (*Cordylosporites magnidictyus* zone), placed by them in the Faro Formation of the Amazon Basin. Iannuzzi and Pfefferkon (2002) confirmed a late Visean–earliest Serpukhovian age for the Poti Formation macroflora, which is dominated by pteridosperms, and some associated arboreal lycopsids and sphenopsids.

In the Amazon Basin, the Faro Formation (Fig. 2) is present in the central part of the basin, without reaching the Paleozoic outcrop belts on the basin margins, and it consists mainly of two thick sandstone bodies and two shale bodies. Deformed sandstone bodies and gray, diamictite, of possible glacial derivation, with sand grains, granules, and pebbles in a micaceous siltic-argillaceous matrix are present close to the base of the formation (e.g., in core 27 of Petrobras well 1-MA-1). Although the origin of the diamictite level has not been studied in detail, the diamictites may result from glacial activity. This interpretation is subject to revision as new well data become available.

Much like its equivalent in the Parnaíba Basin, the Faro Formation contains great amounts of carbonized plant fragments as well as very thin coal layers in the upper shale unit. However, these fossil plant records are limited to the subsurface of the basin and still lack systematic studies. The Faro Formation rests disconformably on the Tournaisian Oriximiná Formation, and it is unconformably overlain by the middle Pennsylvanian Monte Alegre Formation. The age of the Faro Formation is late Visean (palynozone Mag, equivalent to the European TC-NM biozones), according to Melo and Loboziak (2003).

In the Solimões Basin (Jandiatuba subbasin), crudely stratified diamictites containing quartz granules and pebbles immersed in an abundant dark clayey and sandy matrix occur in the top of the Jandiatuba Formation (Fig. 2), at the base of core 1 of Petrobras well Jandiatuba (1-JD-1). These rocks tentatively suggest that crudely stratified diamictites represent deposition from sediment gravity flows and iceberg rafting. Here, Melo and Loboziak (2003) identified a miospore assemblage of doubtless late Visean age (biozone Mag) in an interval that extends from the base of core 1 at 2185.25 m (just underneath the Pennsylvanian unconformity with the Juruá Formation) down to interval 2208/2217 m, where it rests disconformably on late upper Famennian shales attributed to the same Jandiatuba Formation. Therefore, this late Visean section is situated in the same biostratigraphic interval as the Poti and Faro Formations (Melo and Loboziak, 2000, 2003). The lateral persistence of correlative diamictite-bearing strata throughout northern Brazilian sedimentary basins is compatible with glacial derivation.

The Kaka Formation, the upper unit of the Retama Group from the northern Subandean, equivalent to the Kasa and Siripaca Formations of the Ambo Group in the Altiplano and in the Eastern Cordillera regions, contains glaciomarine sediments and abundant resedimentation features (Figs. 1 and 2; Suárez-Soruco, 2000). This unit is composed of a succession of diamictites with a silty-sandy matrix, intercalated with shale and sandstone beds. Shale levels of the upper Kaka Formation contain the *Nothorhacopteris kellaybelenensis* paleoflora (Suáres-Soruco, 2000).

Azcuy and Ottone (1987) attributed an Early Carboniferous age to palynological assemblages from the upper part of the Kaka Formation, whereas the Late Devonian palynomorphs found in the section have been regarded as reworked.

The upper part of the Kasa Formation of the Ambo Group consists of sandstone with large-scale cross-bedding interbedded with shale and fine-grained sandstones that fill paleochannels. Its maximum thickness is estimated to be from 1000 to 1400 m. This unit also contains several diamictites that are generally less than 10 m thick. However, in the Peninsula section of the Lake Titicaca region, a diamictite body as thick as 26 m has been found. The matrix consists of muddy sand with small rounded to subrounded clasts and abundant plant fragments. Sandstone beds within these diamictites show convolute deformation and load casts.

According to Díaz-Martínez (1995) there is no evidence of direct contact with ice in these sediments. Glacial features were not found, so the diamictite could be the product of mass transport, but glaciation in adjacent areas is suggested by the presence of rare dropstones and glacially striated and faceted clasts in gravity flows (Díaz-Martínez, 1995). However, the striated clasts could be the result of reworking of older glacigenic deposits by mass movement (Díaz-Martínez, 2007, personal commun.) and dropstones could be the result of ice rafting by plants or sea ice.

The upper unit of the Ambo Group, the Siripaca Formation (Fig. 2), is mainly made of mudstone interbedded with sandstone and coal seams. This unit was dated as late Visean–early Serpukhovian by Iannuzzi and Pfefferkorn (2002), and it correlates well with the uppermost shales of the Kaka, Poti, and Faro Formations.

Unfortunately, no detailed Carboniferous biostratigraphic zonations according to Western European palynozones could be established for the Kasa and Siripaca Formations. However, the Upper Saipuru Formation, in the south Subandean region, contains many diamictite beds of late Visean age (*Reticulatisporites magnidictyus* Zone = *Cordylosporites magnidictyus* Zone), as determined by Suárez-Soruco and López-Pugliessi (1983). The Saipuru Formation is bounded by unconformities according to Suárez-Soruco and Lópes-Pugliessi (1983), but there are also internal unconformities in the unit, because several biostratigraphic zones are missing in the section. Probable discontinuities are also present within the Kasa Formation and below the Cumaná Formation of the Ambo Group.

In the Calingasta-Uspallata–Río Blanco Basin, in the central region of the Precordillera (central western Argentina), Gonzáles (1990) described three glacigenic levels in the San Eduardo Group. He reported two levels as being possibly as old as late Visean. The oldest is displayed in the El Paso Formation, ~10 m above a regional unconformity. A 25-m-thick diamictite consists of a massive diamictite charged with polished and striated clasts probably accumulated in direct contact with ice (Gonzáles, 1990). Below the diamictite, ~10-m-thick coarse-grained sandstone and conglomerate beds may be a proglacial outwash deposit. The actual age of the base of the El Paso Formation is not known (Gonzáles 1990), and the unit is likely glaciomarine. A second diamictite level lies more than 100 m above the basal diamictite. This 27-m-thick diamictite displays abundant polished and faceted boulders bearing glacial striae, which suggest deposition in close contact with ice (Gonzáles, 1990). Gonzalez reports this unit to be as old as late Visean to Serpukhovian based on the occurrence of fossils of the *Rugosochonetes-Bulahdelia* zone (Gonzáles, 1990). The El Paso Formation is unconformably overlain by sandstones in the Tres Saltos Formation. The age of the El Paso strata is problematic, and they may be as young as Namurian (Bashkirian). The unit displays a facies succession similar to the well-studied Bashkirian Hoyada Verde Formation, which is exposed in the core of an anticline 1.5 km to the north of exposures of the El Paso Formation. Strata in the Hoyada Verde Formation also contain two diamictite levels spaced ~100 m apart, and the formation is also unconformably overlain by Tres Saltos sandstones (cf. Gonzáles, 1990; Henry et al., this volume). Further investigation is needed to determine if these units are in fact two separate successions.

Visean data presented here show that there is a glacial record in the Parnaíba Basin. The Amazon and Solimões Basins have possible glacial records, whereas Díaz-Martínez questions whether there is a Visean glacial record in Peru and Bolivia. Argentina has a Visean alpine glacial record of unknown extent (Limarino et al., 2006). There is a growing body of work to suggest that Visean glaciation occurred in this region, and there is considerable evidence for Namurian glaciation in western Argentina. In this area, Namurian glacigenic deposits are contained in fjords (Kneller, et al., 2004; Dykstra et al., 2006), and paleocurrents show radial ice flow away from the proto-Precordillera (Henry et al., this volume). It is clear that many of the units mentioned here still need more field, sedimentological, and paleontological work.

THE FAR-AFIELD RECORD OF DEVONIAN AND MISSISSIPPIAN GLACIATION

Latest Famennian

According to Isaacson et al. (1999) a rapid sea-level drop of ~100–140 m occurred in North America, central Europe, and southern China in the latest Famennian due to a large buildup of ice sheets in Gondwana and elsewhere. This low sea-level stand produced subaerial exposure of Famennian and Frasnian-age carbonate rocks, resulting in karstification and extensive carbonate breccias, shallow-water, and evaporite deposits in the western United States. In siliciclastic seas, the occurrence of significant progradational sandstone bodies within shale-dominated successions marks an important facies change near the Devonian-Carboniferous boundary. Regressive beds, facies changes, and unconformities of global extent are expected during times of extensive glaciation like that of the latest Famennian.

Geochemical evidence based on ^{18}O and ^{13}C stable isotope studies supports the hypothesis that increased organic carbon burial and oceanic anoxia triggered mass extinction, glaciation, and eustatic sea-level fall at the Devonian-Carboniferous boundary (Caputo, 1995; Kaiser et al., 2006).

Late Middle Tournaisian

Saltzman (2002), based on ^{18}O and ^{13}C stable isotope studies of Mississippian sections in Idaho and Nevada (USA), observed a significant sea-level lowering that he attributed to a late middle to early late Tournaisian glaciation in Gondwana. A pronounced positive $\delta^{13}C$ excursion within the Tournaisian late *crenulata-isostichia* conodont Zone (Buggisch and Joachimsky, 2006) gave rise to the assumption that a major Tournaisian buildup of ice sheets occurred in Gondwana.

Matchen and Kammer (2006) considered the Black Hand Sandstone of the Cuyahoga Formation in east-central Ohio to be an incised valley fill deposit of Kinderhookian-Osagean (Tn2-Tn3) boundary age. They interpreted that glaciation in Gondwana to be the cause of a glacio-eustatic sea-level fall that provoked incision of the Cuyahoga Formation, followed by deposition of the Black Hand Sandstone.

Visean

Studies of oxygen and carbon isotopic composition of Dinantian (Mississippian) brachiopods shells from Western Europe also indicate sea-level changes that could reflect the growth and decline of ice masses, particularly in the late Tournaisian and middle to late Visean (Bruckschen and Veizer, 1997). Additional indirect evidence of glaciation includes preserved upper Visean fourth-order sequences within carbonate ramp deposits and the occurrence of deep incised valleys in the Illinois Basin (USA; Smith and Read, 2000). This evidence of sea-level fall in North America is roughly correlative with evidence from glacigenic strata in Gondwana.

Butts (2005) recorded a major global lowstand just below the mid-Carboniferous boundary at the *Cavusgnathus naviculus–Adentognathus unicornis* conodont zone boundary, which is consistent with a new phase of glaciation in the Gondwana continent during the Namurian, but it is unknown in Brazil.

DISCUSSION AND CONCLUSION

Rygel et al. (2006) concluded that at least seven distinct glacio-eustatic episodes from Tournaisian to Late Permian time can be recognized in the entire Gondwana continent. If the latest Famennian glaciation is also taken into account, then one additional glacial episode can be considered.

The Upper Devonian glacigenic strata discussed herein indicate that glaciation affected much of South America (from Venezuela or northern Brazil to central Argentina). Large areas of Africa (Caputo and Crowell, 1985) and adjacent areas, such as the Appalachian Basin, also experienced latest Devonian glaciation (Cecil et al., 2002, 2004).

Although many geologists are skeptical about the occurrence of latest Devonian glaciation in the Appalachian Basin (Cecil et al., 2002, 2004), it is reasonable to expect glaciation at high elevations and low latitudes during glacial events. Strata of the Spechty Kopf Formation of Pennsylvania and equivalent strata in Maryland and West Virginia contain massive diamictite, bedded siltstone with dropstones, rhythmites, pyramid-shaped clasts, and some striated and faceted clasts (Cecil et al., 2004). Spechty Kopf strata occupy the *Retispora lepidophyta–Indotriradites explanatus* (LE) Palynozone (Woodrow and Richardson, 2008). These features and age suggest glacigenic deposition in latest Famennian in North America. At the Late Devonian time, Western Gondwana (ancestral Peru, Equador and Colombia) was in conctat or very close to Eastern Laurentia (Dalziel, 2007).

In Western Gondwana and adjacent lands, continental glaciation was initiated in latest Devonian. Less obvious was the extent of ice during the Early Mississippian as sediments of possible glacial derivation of Tournaisian age have only been recognized in Brazil. A growing body of evidence for late Viséan glaciation is beginning to appear, and although the glacigenic strata are widespread, evidence at the present time only supports the occurrence of widely scattered glacial centers.

The possible alternation of glacial and interglacial phases in each episode may have originated transgressive-regressive successions of nonmarine, nearshore, and offshore clastic and evaporite cyclothems outside the glaciated areas. In northern South America, the last glacial event in Visean time was succeeded by lower middle Pennsylvanian basal sandstones and younger limestone and evaporite cyclothems controlled by climate and glacial eustasy (Itaituba and Nova Olinda Formations in Brazil and Tarma and Copacabana Formations in western South America; Caputo, 1984). Glaciation continued elsewhere in Gondwana according to the model of migration of glacial centers across Gondwana during the Paleozoic Era (Caputo and Crowell, 1985; Díaz-Martínez et al., 1993b). During the supercontinent's drift, northwestern Gondwana moved toward the tropics, and Eastern Gondwana moved toward the South Pole.

Frakes et al. (1992) divided the past 600 m.y. history of Earth's climate into times of warm and cool modes. They placed the Silurian to Mississippian interval in a warm mode, without considering the Early Silurian, Late Devonian, and Mississippian glaciations in Gondwana. The Devonian warm climate mode ended by late Famennian time, as indicated by the available direct evidence of glaciation obtained from Western Gondwanan basins.

Glacial centers and sediment source areas for basins in Peru and western Bolivia could have been located on the east by a continental highland (Brazilian Shield) and on the west by a land mass (part of the Arequipa Massif) and the Puna Arch to the south. These areas may have furnished fine- to very coarse–grained clastics to the basins of western South America.

In western South America, the source areas were not related to metamorphism and magmatism (Díaz-Martínez, 1995), and no tectonic folding or angular unconformity was recorded during the Ambo Group sedimentation. Possibly the Eastern Cordillera, also considered a possible eastern source area for sediments in the Altiplano region, had not yet been formed during the inferred Eohercynian orogeny. The precise time of the beginning of this tectonism is obscured by later tectonism, deformation, and erosion (Williams, 1995). Sempere (1995) also considered the inferred Late Devonian–Mississippian Eohercynian orogeny to be of little significance in the area. He also suggested that the tectonism, metamorphism, and plutonism considered as evidence for the Late Devonian–Early Carboniferous orogenesis is now dated as Late Triassic. In southern Bolivia, the very thick Ordovician siliciclastic rocks of the Eastern Cordillera show folds and slaty cleavage, which had previously been attributed to either the Late Ordovician Oclóyic or to the Late Devonian to

Early Carboniferous Eohercynian orogenies. K/Ar age determinations from phyllosilicates of these Ordovician slates provided ages within the 320–290 Ma interval (Pennsylvanian–Early Permian), indicating late Hercynian orogenic activities in that region (Jacobshagen et al., 2002).

The orogenic activity in the area during the latest Devonian–Early Carboniferous period has also been deduced from the frequent and abundant supposed synorogenic massive gravity flows and redeposited sediments (Díaz-Martínez, 1995), but the increased sedimentary pile may also have been produced by continental and alpine glaciation on a deep subsiding basin floor.

We observed that, in Western Gondwana, the glacial erosion of basement and sediments previously deposited in the margins of basins furnished a large volume of coarse clastics to the basins and that coarse material derived from tectonic uplift during latest Devonian to latest Visean time forms only a minor proportion in the Huarina fold belt and Eastern Cordillera. Isaacson and Díaz-Martínez (1995) highlighted, that after the deposition of the Ambo Group, took place a period of uplift followed by intense deformation and subaerial erosion in the Altiplano, during the Serpukhovian and Bashkirian time.

The studied three glacial intervals are separated by erosional unconformities, and only the Visean glacial episode has an unconformity on the upper shales of the Poti, Faro, Siripaca, and upper Kaka Formations deposited without glacial influence. Relative sea-level changes were more important than tectonism in the Upper Devonian–Mississippian sedimentary accumulation, because angular unconformities have not been described in the studied sections, and erosional unconformities are relatively synchronous in the examined Solimões and Andean sections.

The presence of reworked palynomorphs suggests that during glaciation and sea-level falls, much older sediment was removed from the margins of basins and incorporated into glacial- and nonglacial-derived strata.

ACKNOWLEDGMENTS

We gratefully acknowledge Petrobras and Themag Co. for permission to publish this contribution. We also thank Enrique Díaz-Martínez, and Blaine C. Cecil for constructive criticism and peer review of the manuscript.

REFERENCES CITED

Andrade, S.M., 1972, Geologia do Sudeste de Itacajá, Bacia do Parnaíba (Estado de Goiás) [Ph.D. dissertation]: São Paulo, Universidade de São Paulo, Escola de Engenharia de São Carlos, 87 p.

Azcuy, C.L., and Ottone, E.G., 1987, Datos palinológicos de la Formación Retama em la Encañada de Beu, Río Alto Beni (Bolivia): IV Congreso Latinoamericano de Paleontologia, Santa Cruz, Memorias, v. 1, p. 235–249.

Barbosa, O., De Ramos, J.R.A., Gomes, F.A., and Hembold, R., 1966, Geologia Estratigráfica, Estrutural e Econômica da Área do "Projeto Araguaia": Departamento Nacional de Produção Mineral, Divisão de Geologia e Mineralogia, Monografia 19, 94 p.

Bruckschen, P., and Veizer, J., 1997, Oxygen and carbon isotopic composition of Dinantian brachiopods: Paleoenvironmental implications for the Lower Carboniferous of Western Europe: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 132, p. 243–264, doi: 10.1016/S0031-0182(97)00066-7.

Buggisch, W., and Joachimsky, M.M., 2006, Mississippian climate in the light of oxygen and carbon isotopes of conodonts and carbonate rocks [abs.]: Geological Society of America Abstracts with Programs, v. 38, no. 7, p. 267.

Butts, S.H., 2005, Latest Chesterian (Carboniferous) initiation of Gondwanan glaciation recorded in facies stacking patterns and brachiopod paleocommunities of the Antler foreland basin, Idaho: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 223, p. 275–289, doi: 10.1016/j.palaeo.2005.04.010.

Caputo, M.V., 1984, Stratigraphy, Tectonics, Paleoclimatology and Paleogeography of Northern Basins of Brazil [Ph.D. dissertation]: Santa Barbara, University of California–Santa Barbara, XIX + 583 p.

Caputo, M.V., 1985, Late Devonian glaciation in South America: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 51, p. 291–317, doi: 10.1016/0031-0182(85)90090-2.

Caputo, M.V., 1995, Anti-greenhouse effect as a glaciation and biotic crisis triggering agent: The Late Devonian and Early Carboniferous glacial cases: Academia Brasileira de Ciências, Rio de Janeiro: Resumo das Comunicações, v. 67, no. 3, p. 390.

Caputo, M.V., and Crowell, J.C., 1985, Migration of glacial centers across Gondwana during Paleozoic Era: Geological Society of America Bulletin, v. 96, p. 1020–1036, doi: 10.1130/0016-7606(1985)96 <1020:MOGCAG>2.0.CO;2.

Caputo, M.V., Streel, M., Melo, J.H.G., and Vaz, L.F., 2006a, Glaciações neodevonianas e eocarboníferas na América do Sul, *in* Sociedade Brasileira de Geologia, 43° Congresso Brasileiro de Geologia: Anais, Simpósio/Sessão Técnica 2, p. 103.

Caputo, M.V., Melo, J.H.M., and Vaz, L.F., 2006b, Late Devonian and Early Carboniferous glaciations in South America [abs.]: Geological Society of America Abstracts with Programs, v. 38, no., p. 266.

Carozzi, A.V., 1979, Petroleum geology in the Paleozoic clastics of the Middle Amazon Basin, Brazil: Journal of Petroleum Geology, v. 2, no. 1, p. 55–74.

Carozzi, A.V., 1980, Tectonic control and petroleum geology of the Paleozoic clastics of the Maranhão Basin, Brazil: Journal of Petroleum Geology, v. 2, no. 4, p. 389–410.

Cecil, C.B., Skema, V., Stamm, R., and Dulong, F.T., 2002, Evidence for Late Devonian and Early Carboniferous global cooling in the Appalachian Basin: Geological Society of America Abstracts with Programs, v. 34, no. 7, p. 500.

Cecil, C.B., Brezinski, D.K., and Dulong, F., 2004, The Paleozoic record of changes in global climate and sea level: Central Appalachian Basin, *in* Southworth, S., and Burton, W., eds., Geology of the National Capital Region: Field trip Guidebook: U.S. Geological Survey Circular 1264, p. 77–135.

Clayton, G., Coquel, R., Doubinger, J., Gueinn, K.J., Loboziak, S., Owens, B., and Streel, M., 1977, Carboniferous miospores of Western Europe: Illustration and zonation. Mededelingen Rijks Geologische Dienst, v. 29, p. 1–71.

Dalziel, I.W.D., 2007, Earth before Pangaea—Our ever changing Earth: Scientific American, Special edition, no. 20, p. 16–23.

Della Fávera, J.C., 1990, Tempestitos da Bacia do Parnaíba [Ph.D. dissertation]: Porto Alegre, Universidade Federal do Rio Grande do Sul, 2 vols., 400 p.

Della Fávera, J.C., and Uliana, M.A., 1979, Bacia do Maranhão—Possibilidades de Treinamento em Facies e Ambientes Sedimentares: Petrobras Report 103-3945, 211 p.

Díaz-Martínez, E., 1991, Litoestratigrafía del Carbonífero del Altiplano de Bolivia: Revista Técnica de Yacimientos Petroliferos Fiscales Bolivianos, v. 12, p. 295–302.

Díaz-Martínez, E., 1995, Regional correlation with late Paleozoic events in Bolivia, *in* 2° Simpósio Sobre Cronoestratigrafia da Bacia do Paraná, Instituto Latino-Americano de Estudos Avançados – Universidade Federal do Rio Grande do Sul: Porto Alegre: Boletim de Resumos Expandidos, p. 98–100.

Díaz-Martínez, E., and Isaacson, P.E., 1994, Late Devonian glacially-influenced marine sedimentation in Western Gondwana: The Cumaná Formation, Altiplano, Bolivia, *in* Embry, A., Beauchamp, B., and Glass, D.G., eds., Pangea: Global Environments and Resources: Canadian Society of Petroleum Geology Memoir 17, p. 511–522.

Díaz-Martínez, E., Palmer, B.A., and Lema, J.C., 1993a, The Carboniferous sequence of the Northern Altiplano of Bolivia: From glacial-marine to carbonate deposition, *in* Archangelsky, S., ed.: Buenos Aires, XII International Congress on Carboniferous-Permian, Comptes Rendus, v. 2, p. 203–222.

Díaz-Martínez, E., Isaacson, P.E., and Sablock, P.E., 1993b, Late Paleozoic latitudinal shift of Gondwana: Stratigraphic, sedimentologic and biogeographic evidence from Bolivia: Lyon, Document des Laboratoires de Géologie, v. 125, p. 119–138.

Díaz-Martínez, E., Vavrdová, M., and Isaacson, P.E., 1999, Late Devonian (Famennian) glaciation in Western Gondwana: Evidence from central Andes, *in* Feist, R., Talent, J.A., and Daurer, A, eds., North Gondwana: Mid-Paleozoic Terranes, Stratigraphy and Biota: Wien, Jahrbuch der Geologischen Bundesamts, v. 54, p. 238–247.

Dykstra, M., Kneller, B., and Milana, J.P., 2006, Deglacial and postglacial sedimentary architecture in a deeply incised paleovalley-paleofjord; the Pennsylvanian (Late Carboniferous) Jejenes Formation, San Juan, Argentina: Geological Society of America Bulletin, v. 118, p. 913–937, doi: 10.1130/B25810.1.

Frakes, L.A., and Crowell, J.C., 1972, Late Paleozoic glacial geography between the Paraná Basin and the Andean geosyncline: Anais da Academia Brasileira de Ciencias, v. 44, p. 139–145.

Frakes, L.A., Francis, J.E., and Syktus, J.I., 1992, Climates Modes of the Phanerozoic—The History of the Earth's Climate over the Past 600 Million Years: New York, Cambridge University Press, 274 p.

González, C.R., 1990, Development of the Late Paleozoic glaciation of the South American Gondwana in western Argentina: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 79, p. 275–287.

Higgs, K.T., Clayton, G., and Keegan, J.B., 1988a, Stratigraphic and Systematic Palynology of the Tournaisian Rocks of Ireland: Geological Survey of Ireland Special Paper 7, 93 p.

Higgs, K.T., McPhilemy, B., Keegan, J.B., and Clayton, G., 1988b, New data on palynological boundaries within the Irish Dinantian: Review of Palaeobotany and Palynology, v. 56, p. 61–68, doi: 10.1016/0034-6667(88)90074-7.

Iannuzzi, R., and Pfefferkorn, H.W., 2002, A pre-glacial, warm-temperate floral belt in Gondwana (late Visean, Early Carboniferous): Palaios, v. 17, p. 571–590.

Isaacson, P.E., and Díaz-Martínez, E., 1995, Evidence for a middle and late Paleozoic foreland basin and significant paleolatitudinal shift, central Andes, *in* Tankard, A.J., Suarez, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir 62, p. 231–250.

Isaacson, P.E., Palmer, B.A., Mamet, B.L., Cooke, J.C., and Sanders, D.E., 1995, Devonian-Carboniferous stratigraphy in the Madre de Dios Basin, Bolivia: Pando X-1 and Manuripi X-1 wells, *in* Takard, A.J., Suárez-Soruco, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir 62, p. 501–509.

Isaacson, P.E., Hladil, J., Shen, J.W., Kalvoda, J., Díaz-Martínez, E., and Grader, G., 1999, Late Devonian glaciation in Gondwana: Setting the stage for Carboniferous eustasy: Subcommission on Devonian Stratigraphy Newsletter, v. 16, p. 37–46.

Isbell, J.L., Miller, M.F., Wolfe, K.L., and Lenaker, P.A., 2003, Timing of late Paleozoic glaciation in Gondwana: Was glaciation responsible for the development of Northern Hemisphere cyclothems?, *in* Chan, M.A., and Archer, A.W., eds., Extreme Depositional Environments: Mega End Members in Geologic Time: Geological Society of America Special Paper 370, p. 1–20.

Jacobshagen, V., Müller, J., Wemmer, K., Ahrendt, H., and Manutsoglu, E., 2002, Hercynian deformation and metamorphism in the Cordillera Oriental of southern Bolivia, Central Andes: Tectonophysics, v. 345, p. 119–130, doi: 10.1016/S0040-1951(01)00209-8.

Kaiser, S.I., Steuber, T., Becker, R.T., and Joachimsky, M.M., 2006, Geochemical evidence for major environmental change at the Devonian-Carboniferous boundary in Carnic Alps and the Rhenish Massif: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 240, p. 146–160, doi: 10.1016/j.palaeo.2006.03.048.

Kegel, F., 1954, Lamelibrânquios da Formação Poti (Carbonífero Inferior) do Piauí: DNPM, Divisão de Geologia e Mineralogia, Notas Preliminares e Estudos, Boletim 88, 14 p.

Kneller, B., Milana, J.P., Buckee, C., and Al Ja'aidi, O.S., 2004, A depositional record of deglaciation in a paleofjord (Late Carboniferous [Pennsylvanian] of San Juan Province, Argentina); the role of catastrophic sedimentation: Geological Society of America Bulletin, v. 116, p. 348–367, doi: 10.1130/B25242.1.

Limarino, C., Tripaldi, A., Marenssi, S., and Fauqué, L., 2006, Tectonic, sea-level, and climatic controls on late Paleozoic sedimentation in the western basins of Argentina: Journal of South American Earth Sciences, v. 33, p. 205–226.

Loboziak, S., Melo, J.H.G., Quadros, L.P., Daemon, R.F., and Barrilari, I.M.R., 1994a, Biocronoestratigrafia dos palinomorfos do Devoniano Médio–Carbonífero Inferior das bacias do Solimões e Parnaíba: Estado da arte, *in* Petrobras, Sintex II—2 Seminário de Interpretação Exploratória: Rio de Janeiro, Atas, p. 51–56.

Loboziak, S., Melo, J.H.G., Quadros, L.P., Daemon, R.F., Barrilari, I.M.R., and Streel, M., 1994b, Devonian-Dinantian miospore biostratigraphy of the Solimões and Parnaíba Basins (with considerations on the Devonian of the Paraná Basin): Rio de Janeiro, Petrobras/Cenpes, 2 vols. (Petrobras internal report).

Loboziak, S., Melo, J.H.G., Steemans, P., and Barrilari, I.M.R., 1995a, Miospore evidence for pre-Emsian and latest Famennian sedimentation in the Devonian of the Paraná Basin, South Brazil: Anais da Academia Brasileira de Ciências: Resumo das Comunicações, v. 67, p. 391–392.

Loboziak, S., Melo, J.H.G., Quadros, L.P., Daemon, R.F., Barrilari, I.M.R., and Streel, M., 1995b, Biocronoestratigrafia de miósporos do Devoniano Médio–Carbonífero Inferior das bacias do Solimões e Parnaíba (estado da arte): Anais da Academia Brasileira de Ciências: Resumo das Comunicações, v. 67, p. 394–395.

Loboziak, S., Caputo, M.V., and Melo, J.H.G., 2000, Middle Devonian–Tournaisian miospore biostratigraphy in the southwestern outcrop belt of the Parnaíba Basin, north-central Brazil: Revue de Micropaleontologie, v. 43, no. 4, p. 301–318, doi: 10.1016/S0035-1598(00)90154-5.

López-Paulsen, O., López-Pugliessi, O, Suárez-Soruco, R., and Oler-Veramendi, J., 1992, Estratigrafia, facies, ambientes y tectónicas fanerozoicas em um sector de la Cordillera de los Andes, Sucre, Chuquisaca, Abstract: Santa Cruz, Primera Conferencia Internacional de las cuencas Fanerozoicas del Gondwana Sudoccidental, 56 p.

López-Gamundí, O.R., 1997, Glacial-postglacial transition in the late Paleozoic basins of southern South America, *in* Martini, I.P., ed., Late Glacial and Postglacial Environmental Changes: Quaternary, Carboniferous-Permian, and Proterozoic: Oxford, UK, Oxford University Press, p. 147–168.

Matchen, D.L., and Kammer, T.W., 2006, Incised valley fill interpretation for Mississippian Black Hand Formation sandstone, Appalachian Basin, USA: Implications for glacial eustasy at Kinderhookian-Osagean (Tn2-Tn3) boundary: Sedimentary Geology, v. 191, p. 89–113, doi: 10.1016/j.sedgeo.2006.02.002.

Maziane, N., Higgs, K.T., and Streel, M., 1999, Revision of the Late Famennian miospore zonation scheme in eastern Belgium: Journal of Micropaleontology, v. 18, p. 17–25.

Melo, J.H.G., and Loboziak, S., 2000, Viséan miospore biostratigraphy and correlation of the Poti Formation (Parnaíba Basin, northern Brazil): Review of Palaeobotany and Palynology, v. 112, p. 147–165, doi: 10.1016/S0034-6667(00)00043-9.

Melo, J.H.G., and Loboziak, S., 2003, Devonian–Early Carboniferous miospore biostratigraphy of the Amazon Basin, northern Brazil: Review of Palaeobotany and Palynology, v. 124, p. 131–202, doi: 10.1016/S0034-6667(02)00184-7.

Oliveira, M.J. de, 1997, Caracterização Faciológica de Sedimentos Glaciais da Formação Cabeças na Borda Sudoeste da Bacia do Parnaíba [M.S. thesis]: Belém, Universidade Federal do Pará, Centro de Geociências, 142 p.

Riley, N.J., 1993, Dinantian (Lower Carboniferous) biostratigraphy and chronostratigraphy in the British Isles: Journal of the Geological Society of London, v. 150, no. 3, p. 427–446.

Rygel, M.C., Fielding, C.R., Frank, T., and Birgenheier, L., 2006, The magnitude of Carboniferous-Permian glacio-eustatic fluctuations: A review: Geological Society of America Abstracts with Programs, v. 38, no. 7, p. 315.

Sablock, P.E., 1993, A warm to cold paleoclimate change in Gondwana (Devonian through Carboniferous): A consequence of coupled continental shift and onlap, *in* Archangelsky, S., ed.,: Buenos Aires, Comptes Rendus, XII International Congress on the Carboniferous and Permian, v. 1, p. 355–367.

Saltzman, M.R., 2002, Carbon and oxygen isotope stratigraphy of the Lower Mississippian (Kinderhookian–Lower Osagean), western United States: Implications for seawater chemistry and glaciation: Geological Society of America Bulletin, v. 114, no. 1, p. 96–108, doi: 10.1130/0016-7606(2002)114<0096:CAOISO>2.0.CO;2.

Sempere, T., 1995, Phanerozoic evolution of Bolivia and adjacent regions, *in* Tankard, A.J., Suárez-Soruco, R., and Welsink, H.J., eds., Petroleum basins of South America: American Association of Petroleum Geologists Memoir 62, p. 207–230.

Smith, L.B., Jr., and Read, J.F., 2000, Rapid onset of late Paleozoic glaciation on Gondwana: Evidence from Upper Mississippian strata of the Mid-continent, United States: Geology, v. 28, no. 3, p. 279–282, doi: 10.1130/0091-7613(2000)28<279:ROOLPG>2.0.CO;2.

Stover, L.E., 1967, Palynological dating of the Carrizal Formation of eastern Venezuela: Associación Venezolana de Geólogos Mineros y Petroleros Boletin (Instituto de Estudios de Poblacion y Desarrollo [Dominican Republic]), v. 10, p. 288–301.

Streel, M., Higgs, K., Loboziak, S., Riegel, W., and Steemans, P., 1987, Spore stratigraphy and correlation with faunas and floras in the type marine Devonian of the Ardennes-Rhenish regions: Review of Palaeobotany and Palynology, v. 50, p. 211–229, doi: 10.1016/0034-6667(87)90001-7.

Streel, M., Caputo, M.C., Loboziak, S., and Melo, J.H.G., 2000a, Late Frasnian–Famennian climates based on palynomorph analyses and the question of the Late Devonian glaciations: Earth-Science Reviews, v. 52, p. 121–173, doi: 10.1016/S0012-8252(00)00026-X.

Streel, M., Caputo, M.V., Loboziak, S., Melo, J.H.G., and Thorez, J., 2000b, Palynology and sedimentology of laminites and tillites from the latest Famennian of the Parnaíba Basin, Brazil: Geologica Belgica, v. 3, no. 1/2, p. 87–96.

Suárez-Soruco, R., and López-Pugliessi, M., 1983, Formación Saipuru, nuevo nombre formacional para representar a los sedimentos superiores del Ciclo Cordillerano (Devónico Superior–Carbónico Inferior), Bolivia: Revista Técnica de Yacimientos Petrolíferos Fiscales de Bolivia, La Paz, v. 9, no. 1–4, p. 189–202.

Suárez-Soruco, R., ed., 2000, Compendio de geología de Bolivia: Revista Técnica de Yacimientos Petroliferos Fiscales Bolivianos, Cochabamba, v. 18, no. 1-2, 213 p.

Wilde, P., and Berry, W.B.N., 1984, Destabilization of the oceanic density structure and its significance to marine extinction events: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 48, p. 143–162, doi: 10.1016/0031-0182(84)90041-5.

Williams, K.E., 1995, Tectonic subsidence analysis and Paleozoic paleogeography of Gondwana, *in* Takard, A.J., Suárez-Soruco, R., and Welsink, H.J., eds., Petroleum Basins of South America: American Association of Petroleum Geologists Memoir 62, p. 79–100.

Woodrow, D.L., and Richardson, J.B., 2006, What WAS Going on in the Late Devonian?: http://www.searchanddiscovery.net/documents/2006/06091eastern/abstracts/woodrow.htm (last accessed 30 January 2008).

Manuscript Accepted by the Society 19 November 2007