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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, borehole, 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 *Retispora lepidophyta*–*Indotrivulites explanata* or LE Zone and the *Retispora lepidophyta*–*Verrucosissporites nitidus* (LN) 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 (Juruaá and Jandiatuba subbasins) of northwestern Brazil and possibly in Bolivia and Argentina. The third glacial episode is of late Viséan 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.

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, Paranaíba, 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 glaciogenic 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 northern 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

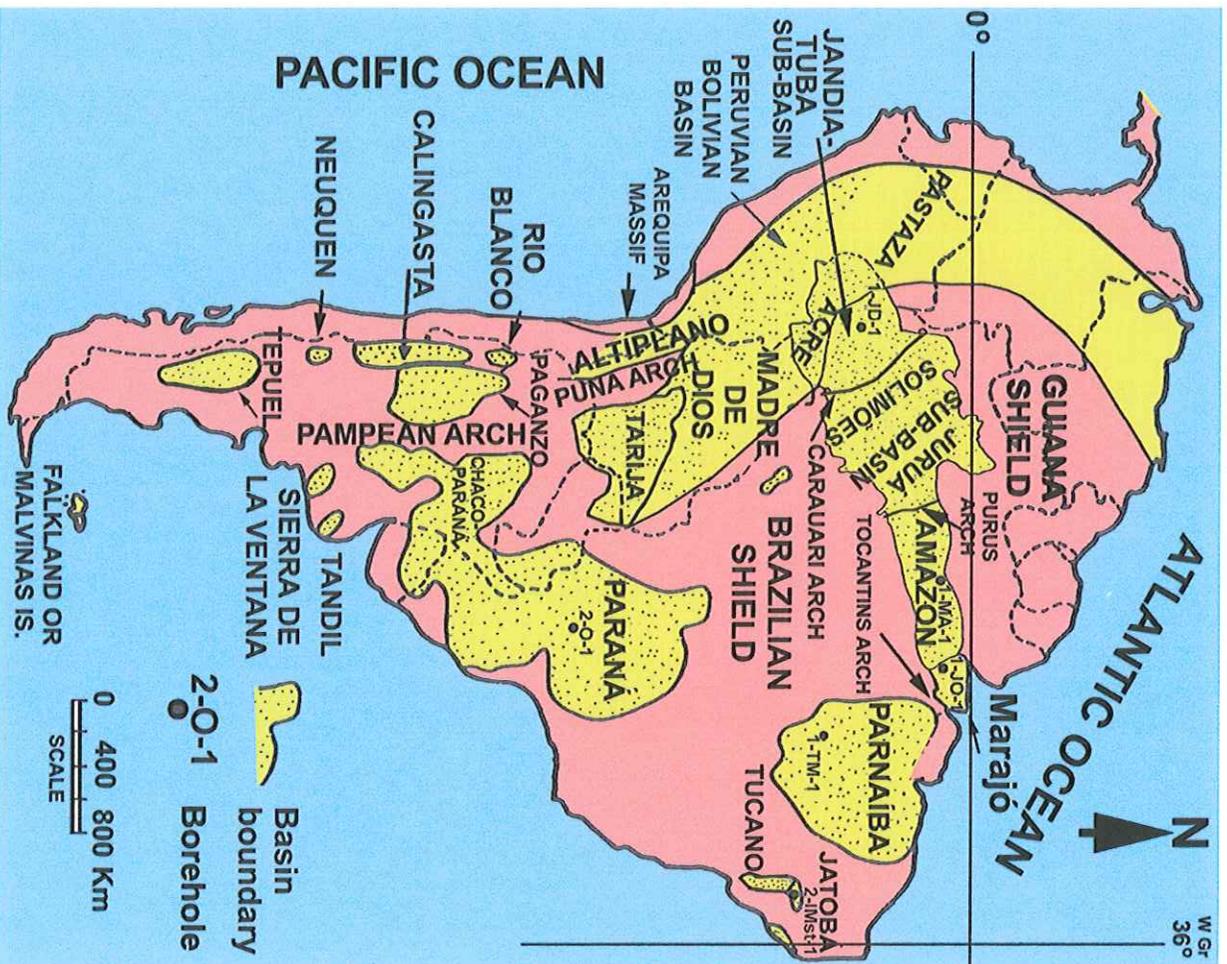


Figure 1. Location of South American basins discussed in the text.

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 Viséan. This paper also presents new palynological data and discusses their implications for biostratigraphic correlation. Although Devonian and/or Mississippian glaciogenic strata have also been reported in Africa and North America (cf. Caputo, 1985; Strel 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

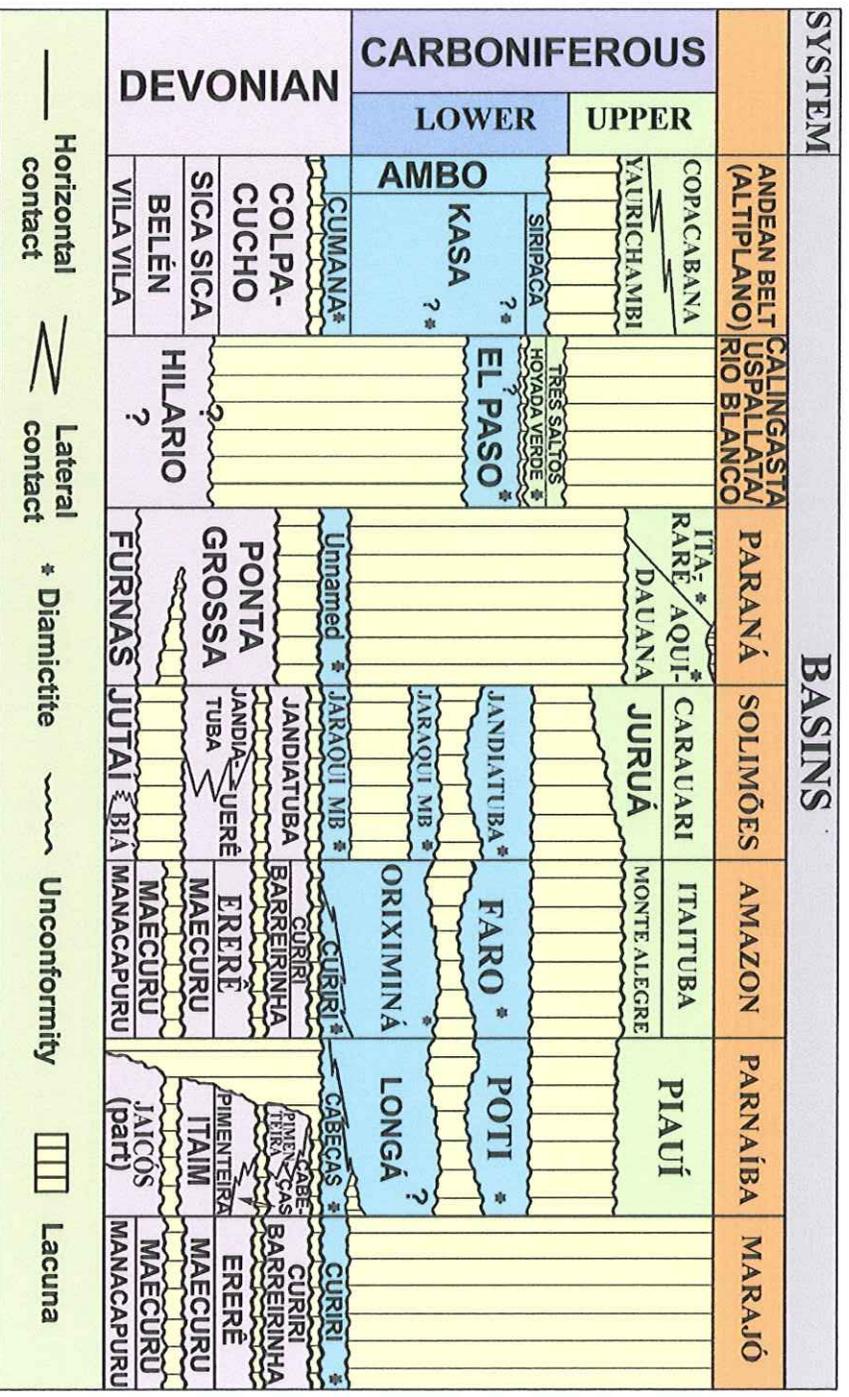


Figure 2. Partial stratigraphic correlation chart for the main basins discussed in the text. The chart is based on recent biostratigraphic data and the identification of glacial and periglacial strata in Brazil (Caputo, 1985), in Bolivia and Peru (Díaz-Martínez et al., 1999), and in Argentina (González,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

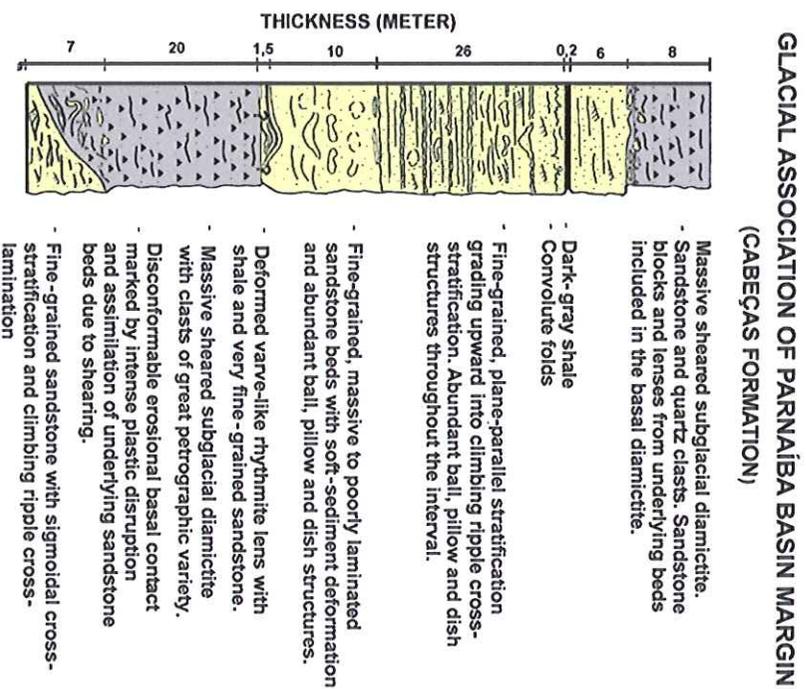


Figure 4. Glacial association of western Parnaíba Basin.

and Paranaíba 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 glacial 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 mudrocks and to clast-free laminated mudrocks (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 run-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 Amazon Basin and from the southwest (Brazilian Shield) in the southern part of the basin (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 Caruarú 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 Petróbras' 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

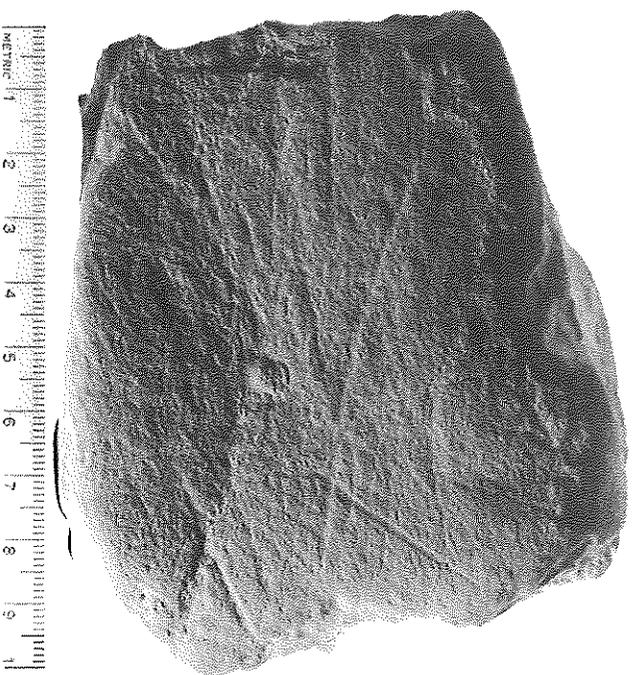


Figure 5. Nonparallel glacial striae on clasts from Curiri Formation, Upper Devonian (Amazon Basin), Curitiba-Santarém Highway, ~7 km north from the intersection with the Transamazonian Highway.

and clayey groundmass. These strata were formerly considered to be part of the Upper Pennsylvanian to Early Permian Ileraté 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 Streef et al. (2000a, 2000b) located the diamictites in a biostratigraphic interval correlative with the *Retispora lepidophyta*–*Indotrivahies explanatus* (LE) and *Retispora lepidophyta*–*Verrucosisporites nitidus* (LN) biozones of Western Europe, i.e., palynozones *Retispora lepidophyta* (Rle) and *Retispora lepidophyta*–*Vallanisporites vallanus* (LVa), according to the Gondwanan zoning by Melo and Loboziak (2003). 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

Late Devonian										Mississippian								
FRASNIAN			FAMENNIAN			<small>TOURNAISIAN</small>			VISÉAN									
TCO	BJ	BM	"V"	"VH"	GH	GF	VG	VH	LE	LN	VH	HD	BC	CM	PS	TCM	VM	NC
GLACIATION										GLACIATION								

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 Steel 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—*Samariisporites triangulatus*—*Chelinospora concinna*, BJ—*Verrucosisporites bulliferus*—*Cirratrivulvites jekhovskyi*, BM—*Verrucosisporites bulliferus*—*Lophosporites media*, "V" and "V"—phase zones (informal palynozones), GH—*Grandispora gracilis*—*Samariisporites* sp. cf. *A. hirtus*, GF—*Grandispora gracilis*—*Grandispora famennensis*, VCo—*Rugospora versabilis*—*Grandispora cornuta*, VH—*Apiculiretusispora verrucosa*—*Vallanisporites hystericus*, LL—*Retispora lepidophyta*—*Knoxisporites literatus*, LE—*Retispora lepidophyta*—*Indotriletes explanatus*, LN—*Retispora lepidophyta*—*Verrucosisporites nitidus*, VI—*Vallanisporites verrucosus*—*Retusotriletes inchoatus*, HD—*Kraeuselisporites hibernicus*—*Umbonatisporites distinctus*, BR—*Speleotriletes balteatus*—*Rugospora polyphycha*, PC—*Speleotriletes pretiosus*—*Raistrickia clavata*, CM—*Schopflies claviger*—*Auroraspora macra*, Pu—*Lycospora pusilla*, TS—*Knoxisporites triradiatus*—*Knoxisporites stephanephorus*, TC—*Perotriletes tessellatus*—*Schulzospora campyloptera*, NM—*Raistrickia nigra*—*Triquitries marginatus*, VF—*Triparities vetustus*—*Rotasporea fracta*, NC—*Bellisporites 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 Cumana Formation, are given different formational names across western South America. In Subandean basins and the low plains areas, coeval strata are known as the Iracua (Central Cordillera), the Saipuru (Eastern Cordillera), and the Torregua (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-Pugliesi, 1983).

Although no direct evidence of glaciations is currently known in the Devonian and Mississippian of Colombia and Venezuela, it is possible that glacial 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), Lopes-Gamundi (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 glacial 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 Paratiba 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 (Steel 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 (Strel et al., 2000a).

Data presented here provide positive evidence for the latest Famennian glaciation in the Paratiba, Amazon, Marajó, and Peru-Bolivia basins. Possible or problematic records include strata in the Solimões and Parará Basins. In these areas, possible glacial 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 glacial strata are identified in the subsurface of the Solimões Basin of Brazil (Lobozziak 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 Jaragu Member of the Jandamba 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 Jandamba subbasin. Diamictites from cores and sidewall cores in the Juruá subbasin (Jaragu Member of the Jandamba Formation) contain fossil palynomorphs of late middle to early late Tournaisian age, which are equivalent to the *Speleorhizales baltheatus–Rugospora pohlypcha* (BP) and *Speleorhizales prenosus–Rastrickia clavata* (PC) biozones of Western Europe (Loboziak et al., 1994a, 1994b, 1995b). These zones correspond to the Gondwanan *Speleorhizales baltheatus–Neorastriackia joganii* (BL) and *Speleorhizales prenosus–Colanispories decorus* (PD) palynozones sensu Melo and Loboziak (2003), respectively. Except for reworked Devonian marine microfossils (which may be locally abundant), Tournaisian diamictites contain mainly miospores and land plant debris. However, scarce, possibly autochthonous acritarchs (mostly simple acanthomorphs) may occur in some Tournaisian diamictites and shales. 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-Pausen et al. (1992) mentioned the presence of Tournaisian glacially derived strata in Peru, Bolivia, and Argentina. However, Diaz-Martinez (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 (Diaz-Martinez and Isaacson, 1994; Diaz-Martinez, 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 Poi Formation (Caputo, 1985; Caputo et al., 2006a, 2006b) of the Paranaíba Basin, the Faro Formation of the Amazon Basin, and the Jandamba Formation of the Solimões Basin. Visean glacial 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 glacialic formations are restricted to the subsurface (e.g., strata in the Solimões and Amazon basins). However, in the Paranaíba Basin, diamictites of the Poi Formation are exposed in outcrops (Figs. 1 and 2; Andrade, 1972; Caputo et al., 2006a, 2006b).

The Poi 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 in outcrop, 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 mudrock 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 glacial 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) drop-stones (up to boulder size) within fine-grained suspension deposits attributed to debris rafted by floating ice (Della Fàvera 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 in the upper part are interpreted as glacially derived. The shales on the top of the upper unit would have been deposited in delta-plain settings; they have pebbles and sandstones that contain fossil land plant assemblages and a very thin (1-cm-thick) coal bed. The presence of a "Paracarya" macroflora in the upper part of the formation is indicative of climatic improvement (Lannuzzi 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 Fàvera, 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 Viséan age (coeval with the Holkerian and Asbian stages of the British Isles) to the Poti Formation and correlated it with two Western European palynozones: *Perotrites tessellatus-Schulzospora campyloptera* (TC) and *Raistrickia nigra-Triquirites marginatus* (NMD). Melo and Loboziak (2003) related this formation to the late Viséan Mag palynozone (*Cordylasporites magnidictyus* Zone), placed by them in the Faro Formation of the Amazon Basin. Lannuzzi and Pfefferkorn (2002) confirmed a late Viséan-earliest Serpukhovian age for the Poti Formation macroflora, which is dominated by pteridospores, 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 sand-

stone 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 Paranaíba 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 unconformably on the Tomraisan Orximiná Formation, and it is unconformably overlain by the middle Pennsylvanian Monte Alegre Formation. The age of the Faro Formation is late Viséan (palynozone Mag, equivalent to the European TC-NMD 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-AM). These rocks tentatively suggest that crudely stratified diamictites represent deposition from sediment gravity flows and icebergl rafting. Here, Melo and Loboziak (2003) identified a miospore assemblage of doubtless late Viséan 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 unconformably on late upper Famennian shales attributed to the same Jandiatuba Formation. Therefore, this late Viséan 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 reedimentation 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 kellybelenensis* paleoflora (Suárez-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 flow deposits (Díaz-Martínez, 1995). However, the striated clasts could be the result of reworking of older glacial 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 Viséan–early Serpukhovian by Iannuzzi and Pfefferkorn (2002), and it correlates well with the uppermost shales of the Kaka, Poti, and Faro Formations.

Unfortunately, detailed Carboniferous biostratigraphic zonation according to Western European palytozones are still in revision for the Kasa and Siripaca formations. However, the Upper Saipuru Formation, in the south Subandean region, contains many diamictite beds of late Viséan age (*Reticularisporites magniticivus* Zone = *Cordylasporites magniticivus* Zone), as determined by Suárez-Soruco and López-Pugliesi (1983). The Saipuru Formation is bounded by unconformities according to Suárez-Soruco and López-Pugliesi (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), González (1990) described three glacial levels in the San Eduardo Group. He reported two levels as being possibly as old as late Viséan. 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 (González, 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 (González 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 (González, 1990). Gonzalez reports this unit to be as old as late Viséan to Serpukhovian based on the occurrence of fossils of the *Rugosochonetes-Bulabdelia* Zone (González, 1990). The El Paso Formation is unconformably overlain by sandstones of the Tres Saltos Formation. The age of the El Paso strata is problematic, and they may be as young as Namurian (Bashkiran). The unit displays a facies succession

similar to the well-studied Bashkiran 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. González, 1990; Henry et al., this volume). Further investigation is needed to determine if these units are in fact two separate successions.

Viséan data presented here show that there is a glacial record in the Pamamba Basin. The Amazon and Solimões basins have possible glacial records, whereas Díaz-Martínez questions whether there is a Viséan glacial record in Peru and Bolivia. Argentina has a Viséan alpine glacial record of unknown extent (Limarino et al., 2006). There is a growing body of work to suggest that Viséan glaciation occurred in this region, and there is considerable evidence for Namurian glaciation in western Argentina. In this area, Namurian glacial 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-FIELD RECORD OF DEVONIAN AND MISSISSIPPIAN GLACIATION

Latest Famennian

According to Isacson 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 siliclastic 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

Salzman (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 $\delta^{13}\text{C}$ excursion within the Tournaisian late *crenulata-isorichia* conodont Zone (Bugjisch 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.

Viséan

Studies of oxygen and carbon isotopic composition of Dmanetan (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 Viséan (Bruckschen and Velzer, 1997). Additional indirect evidence of glaciation includes preserved upper Viséan fourth-order mixed carbonate-siliciclastic sequences within carbonate-dominated 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 glaciogenic strata in Gondwana.

Butts (2005) recorded a major global lowstand just below the mid-Carboniferous boundary at the *Cavusgnathus naviculus*–*Adentognathus unicomis* 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 glaciogenic 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 Spechy 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). Spechy Kopf strata occupy the *Retispora lepidophyta*–*Indotrivadias explanatus* (LE) Palynozone (Woodrow and Richardson, 2008). These features and age suggest glaciogenic deposition in latest Famennian in North America. At the Late Devonian time, West-

ern Gondwana (ancestral Peru, Ecuador and Colombia) was in contact or very close to Eastern Laurentia (Datzel, 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 glaciogenic 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 Viséan time was succeeded by lower middle Pennsylvanian basal sandstones and younger limestone and evaporite cyclothems controlled by climate and glacial eustasy (Itatuba and Nova Olinda formations in Brazil and Tarna 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; Diaz-Martinez 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 (Diaz-Martinez, 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 Oclóvic or to the Late Devonian to Early Carboniferous Eohercynian orogenies. However, 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 Viséan time forms only a minor proportion in the Huarina fold belt and Eastern Cordillera. Isacson 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 Viséan glacial episode has an unconformity on the upper shales of the Potú, Faro, Siripacá, 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.

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