Late Paleozoic Sedimentation and Volcanism in the Central Andes: Geotectonic Setting and Stratigraphy

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Abstract. During the Late Paleozoic, the Gondwana supercontinent reached its maximum expansion, encompassing Australia, India, Antarctica, and part of South Africa, the central and southern part of South America. The western margin of Gondwana, represented in the vast Upper Paleozoic basins of South America, is an important link to reconstruct the Gondwana history because South American basins exhibit a complete Late Paleozoic stratigraphic record. Thus, sedimentological studies reconstruct not only the timing of different glacial episodes but also the transition to semiarid and arid climatic conditions toward the Permian. The extensive magmatic activity registered in the Central Andes during the Late Paleozoic is among the most important recorded in the Gondwana supercontinent.

Introduction

Late Permian-Triassic rifting diachroneously developed in the Eastern Cordillera of Peru and extended into Bolivia in the Late Triassic-Middle Jurassic. The main axis of the rift system appears to coincide with the axis of the Eastern Cordillera in both countries. Current research in southern Peru and Bolivia shows that Mesozoic Bolivian basins were mostly connected to Peruvian basins, and not to southern, Argentine-Chilean basins. Reconstruction of the rift system in map view shows that it splits into two branches at about 19°S (Fig. 1). The southeastern, "Entre Ríos branch" extends into the Chaco Subandean belt and dies out in the Bolivia-Argentina border area. The southern, "Tupiza branch" strikes (presently) N10°E and apparently extends into Argentina Puna.

In map view, this geometry is reminiscent to the present-day Red Sea rift system, which to the north splits into the now inactive Suez Gulf and the active Aqaba Gulf rift and Dead Sea wrench-fault system (Fig. 2).
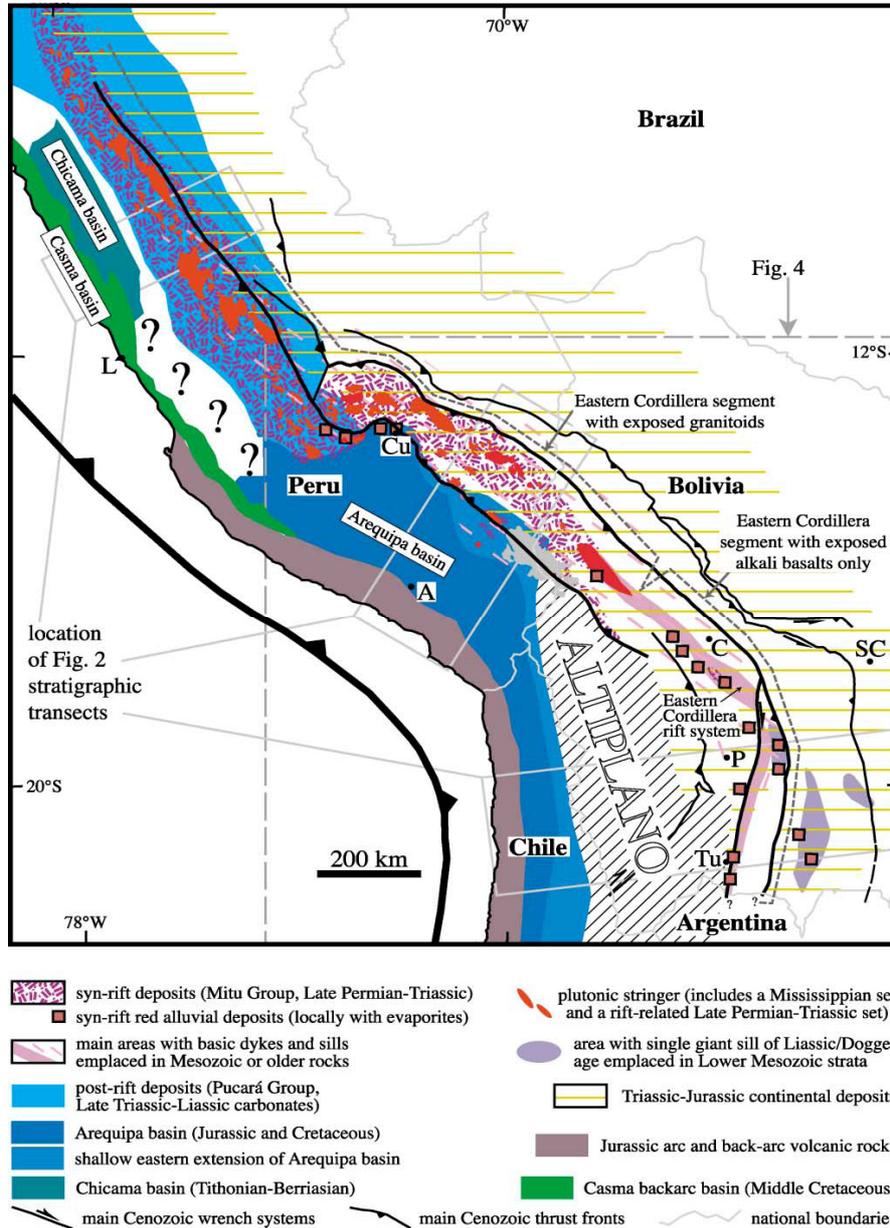

Fig. 1. Synopsis of the main Mesozoic geologic elements of Peru and Bolivia. The axis of the Late Permian– Middle Jurassic rift system is defined by occurrences of the Mitu Group, coeval granitoids, and basic dyke swarms, and approximately coincides with the axis of the Eastern Cordillera of Peru and Bolivia. Localities: A: Arequipa, C: Cochabamba, Cu: Cusco, L: Lima, P: Potosı´, SC: Santa Cruz, Tu: Tupiza. (From Sempere et el., 2002).

In Peru, late Paleozoic continental sedimentation and volcanism is represented by Mitu Group, which is mostly known from the Eastern Cordillera of central and southern Peru and accumulated in subsident grabens, reflecting Late Permian-Triassic rifting (Kontak et al., 1985). In the grabens produced by rifting, conformable or deformed Late Paleozoic strata were generally preserved below the Mitu Group, whereas they were eroded out from the neighbouring rift shoulders. Intense magmatism commonly occurred at depth beneath the floor of the grabens, and predominantly alkaline volcanic and plutonic rocks point to a Late Permian-Middle Jurassic age for the Rifting.
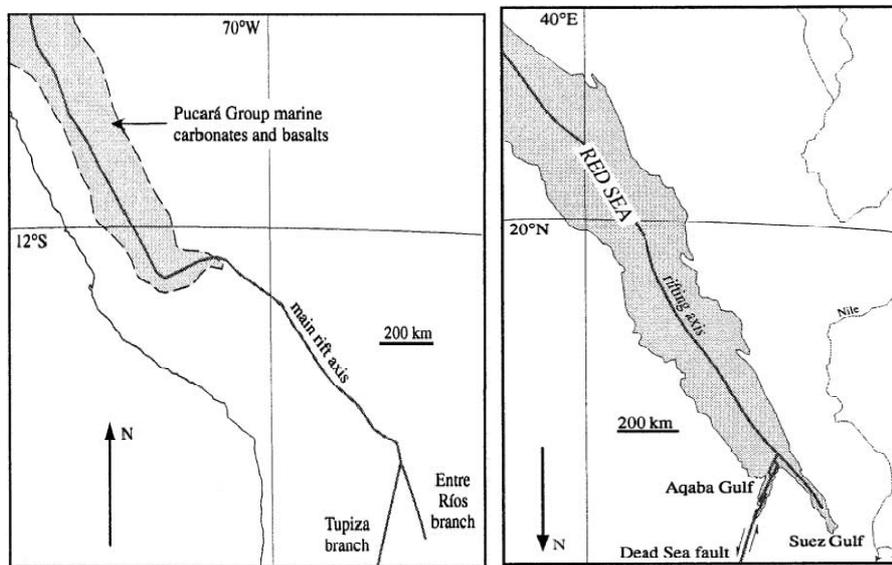

Fig. 2. Comparison between the map view geometries of the Red Sea rift system and of the Central Andean Late Permian– Middle Jurassic rift system (now inverted and shortened). Branching of the rift axis is observed in both cases. (From Sempere et al., 2002).

Controls of the late Paleozoic sedimentation

Allocyclic controls, such as tectonism, magmatism, sea-level changes, and climate, exerted considerable control over the sedimentological and paleogeographic evolution of Late Paleozoic basins (Dalmayrac et al., 1980; Bahlburg and Breitkreuz, 1991; Gohrbandt, 1992; Sempere, 1993).

From the Early Pennsylvanian to the Early Cisuralian, tectonic activity decreased considerably in arc-related basins, and a period of tectonic quiescence seems to have dominated in retroarc basins (Limarino, 2006). As of the latest Carboniferous, volcanism began to expand along the west ernmost areas, forming very thick volcanic–volcaniclastic successions like those reported from the Peine

Group (Bahlburg and Breitkreuz, 1991), Collahuasi Formation, and Punta del Agua Formation. The origin of this volcanism is a key question that should be addressed, but modern geochemical studies seem to relate it to the formation of a new active, arc-related margin to the east in the retroarc basins, volcanism was less important or inexistent and the transition from glacial to postglacial conditions, coupled with sea-level changes, was the most important control on sedimentation. Limited tectonic movements in the cratonic area during the Sakmarian– Artinskian were described in the Rio Bonito Formation by Holz (2003).

During the Late Cisuralian tectonic activity, represented by the San Rafael tectonic phase, was closely associated with volcanism along the arc-related basins (Llambías, 1999; Gonzalez Bonorino, 1991). This volcanism played a principal role as a control on the extension and nature of sedimentation, producing very important paleogeographic changes. In some cases, sediments were progressively replaced by volcanic flows, but in others, fine-grained marine deposits were dramatically overlain by coarse-grained volcaniclastic sequences formed at the foothills of the volcanic chains or during intereruptive stages. Extensional tectonism seemingly began to be established in both arc-related and retroarc basins near the Late Permian (Fig. 3), favoring local reactivation in sedimentation and extensional magmatism (Kontak, 1985; Llambías, 1999).
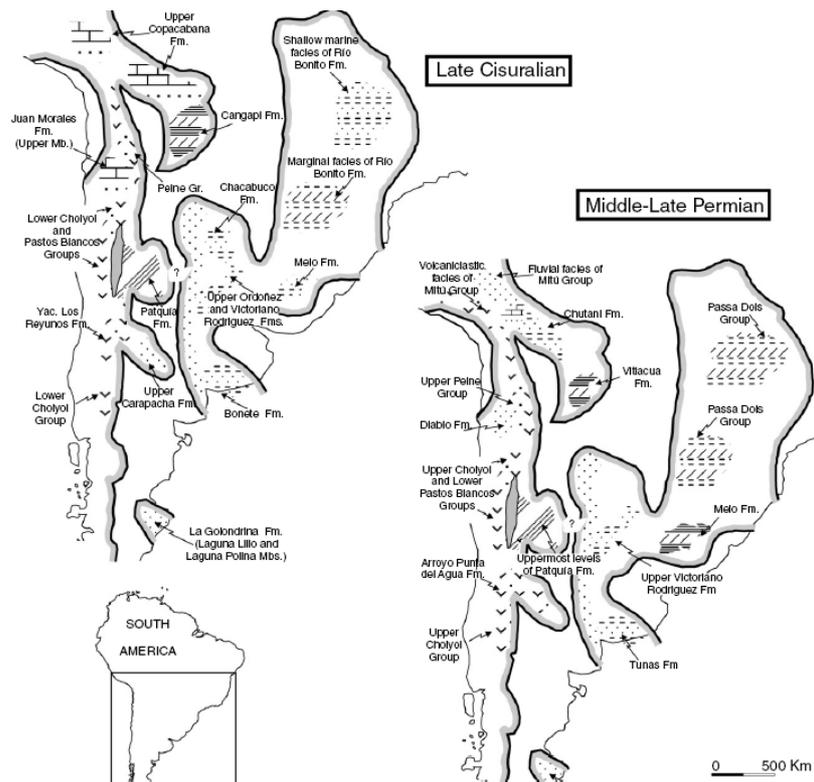

Fig. 3. Suggested paleogeographic evolution of southern South America during the Early, Middle, and Late Permian. (From Limarino et al., 2006)

Pre-rift strata and deformation

The commonly >500 m thick Pennsylvanian-Early Permian (Tarma-) Copaca-
bana Group was deposited prior to rifting, and forms a guide unit as it was fre-
quently preserved in the Mitu Grabens. It is of shallow-marine origin and consists
of fossiliferous limestones and subordinate sandstones, black shales, and cherty
limestones. To the southeast, in the Chaco Subandean belt and lowlands of Boli-
via, the Copacabana carbonate platform grades into sandstones of aeolian and
fluvial origin (Cangapi Formation; Sempere, 1995).

The Vitacua and Chutani formations, Bolivia, and Ene Formation, Peru,
represent the restricted-marine deposits coeval of early rifting. The Vitacua For-
mation of southern Bolivia consist of black shales, siliceous carbonates (mainly
limestones and dolomites with common chert), dark red mudstones, and subordi-
nate sandstones, which form an overall shallowing-upward succession. Marine
black shales are characteristic of the lower Vitacua Formation, whereas restricted-
marine chert-rich carbonates are especially common in the upper part of the unit
(Sempere et al., 1992). The Vitacua Formation overlies the fluvio-eolian sand-
stones of the Cangapi Formation with a rapid transition (marking a transgression),
and is sharply overlain by mudstone-dominated, gypsum-bearing, continental red
strata of the Ipaguazú Formation. In Peru, the Ene Formation displays facies simi-
lar to those in the Vitacua and Chutani formations. In particular, the lower part of
the Ene Formation predominantly consists of organic-rich black shales of late
Permian age. At two localities near the Mitu rift axis (Fig. 1), these black shales
conformably overlie the Copacabana Group and grade upward into siliceous car-
bonates and/or shallow-marine to fluvial or eolian sandstones; this continuous
succession is in turn conformably overlain by altered volcanic rocks and red strata
(including mudstones, sandstones and gypsum) that represent the local facies of
the Mitu Group (Carlotto et al., 2000). The Ene Formation is widespread in the
Subandean belt and lowlands of Peru, i.e. east of the Mitu rift system (Mathalone
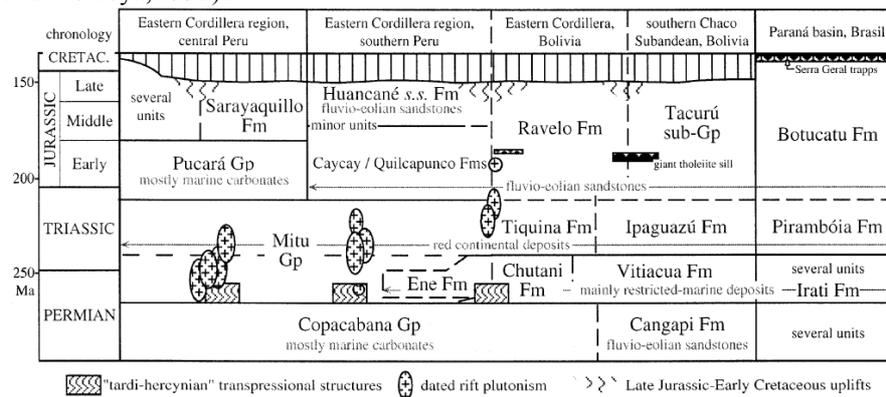and Montoya, 1995).

Fig. 4. Synopsis of Permian through Jurassic main stratigraphic, deformational, and magmatic data
discussed in text concerning the Eastern Cordillera of Peru and Bolivia, the Chaco basin of Bolivia,
and the Paraná´ basin of Brazil. (From Sempere et al., 2002).

The black shales that characterize the lower parts of the Vitiacua, Chutani and Ene formations represent a marine transgression of Late Permian age, which is also represented by units in the Paraná basin, Brazil, and the Karoo basin, South Africa (Sempere et al., 1992; Tankard et al., 1995). This widespread transgression is likely to have extended over a very broad region of western Gondwana, but was also coeval with the early stage of the rift-related Mitu magmatism (Fig. 3). In southern Peru, limestones bearing Late Permian fusulinids are locally intercalated within red strata of the Mitu Group (Laubacher, 1978), demonstrating that marine ingressions occurred within some Mitu grabens.

The Vitiacua, Chutani and Ene formations conformably overlie the Copacabana Group, and, given their age, appear as restricted-marine time-equivalents of the older Mitu syn-rift deposits, whereas they predate younger Mitu syn-rift deposits as they are overlain by Mitu or Mitu-equivalent red strata (Fig. 4). Given the approximate Middle Triassic age of the top of these restricted-marine units, the Mitu rifting appears to have been twofold, with a first stage spanning the Late Permian–Early? Triassic interval, and a second stage beginning in the Middle Triassic.

Deformation and rifting

As stressed above, the sedimentary continuity commonly observed in Bolivia and southern Peru between the Pennsylvanian–Early Permian Copacabana Group and overlying Late Permian–Early? Triassic units markedly contrasts with the pre-Mitu, locally intense deformation observed in the Copacabana Group in some areas of the Eastern Cordillera between ~11°S and ~17°30´S. This deformation, traditionally explained by Late Permian ''tardi-hercynian tectonics'' (e.g., Dalmayrac et al., 1980), is in fact restricted to a narrow belt within the Eastern Cordillera (Sempere, 1995); given the contemporaneity of Late Permian deformation and deposition, this belt was probably discontinuous, deformation occurring in specific areas while shale-dominated sedimentation was quietly going on in other areas of the same Eastern Cordillera domain.

Such relationships are strongly suggestive of a transcurrent rift system in which transtensional segments would have been separated by transpressional ''nodes''. Sempere (2002) favors the idea that local transpression caused deformation of pre-Mitu strata at the onset of continental dislocation, before general graben formation and intense magmatism developed. Coeval transtension produced slow downwarping of elongated areas, where the Copacabana Group was preserved and deeper marine shales conformably deposited over it, before accelerating rifting processes enhanced magmatism and formed true grabens.

A similar scenario, albeit later in time, could also explain the occurrence of Late Triassic plutons showing deformation that was contemporaneous with their emplacement. In the Cordillera Real of western Bolivia, the Zongo–Yani pluton yielded Late Triassic U–Pb ages; emplacement of this foliated, peraluminous, two-mica granite was contemporaneous with schistosity and low-pressure meta-

morphism, reflecting a high heat flow (Bard et al., 1974). In nearby Peru, the similar, foliated and peraluminous, two-mica Limacpampa pluton is dated to near the Triassic–Jurassic boundary. South of Abancay, a cataclastic ''quartz-diorite'' yielded a Late Triassic U–Pb age. Sempere (2002) suggest that emplacement and early deformation of these intrusions might have occurred in local transpressional settings at a later, Late Triassic, stage of rifting.

Triassic uplift of plutons is recorded by clasts of Mitu-age granitoids that are commonly found in conglomerates and pyroclastites of the Mitu Group in central Peru (Mégard, 1978), suggesting a twofold development of rifting (Soler, 1991). Such uplifts are likely to have been caused by lithospheric deformation related to rifting.

Rift-related magmatism

Intense magmatism was associated with the Mitu rifting in southern Peru (Noble et al., 1978; Dalmayrac et al., 1980; Carlier et al., 1982; Kontak, 1984; Bonhomme et al., 1985; Kontak et al., 1985, 1990; Clark et al., 1990a; Cenki, 1998). In a major contribution, Kontak et al. (1985) clearly identified that the entire Mitu-age magmatism in southern Peru was rift-related, and recognized that ''the predominantly basic Mitu Group volcanics and the batholithic granodiorites and monzogranites are most probably representative of a continuum with a cause and effect relationship''.

Several types of apparently unrelated mantle-derived magmas, including alkaline basalts and locally thick peralkaline facies, occur among the Mitu volcanic rocks (Kontak et al., 1985). Basic volcanics can form up to 20% of the total Mitu volcanism and consist of tholeiitic or alkaline spilitized basalt flows that are generally intercalated with the Mitu Group sedimentary rocks (Vivier et al., 1976; Kontak, 1984). In contrast with the mantle-derived Mitu volcanic rocks, the Carabaya batholith plutons (southern Peru) derive from crustal melts, and are also similar to plutons known in the Oslo rift (Kontak, 1984; Kontak et al., 1985, 1990). Intrusion of the main plutons occurred in the Late Permian and Triassic. The Carabaya batholith is commonly cut by coeval and younger alkaline, Ti-rich, basic dykes that display characteristics similar to the basalts known in the Mitu Group (Kontak et al., 1985, 1990).

Rift-related magmatism in Bolivia was dominated by basic magmas. The basic magmatism related to the main rift axis displays alkaline compositions (Aldag, 1913; Smulikowski, 1934; Soler and Sempere, 1993; Tawackoli, 1999), whereas the giant sill known in the ''Entre Ríos branch'' of the rift (Sempere et al., 1998) has a tholeiitic composition (Sempere, 1993). All these basic rocks indicate ''intraplate'' mantle-derived magmatism and lithospheric thinning. Present known differences in rock composition does not preclude this hypothesis, as alkaline and tholeiitic magmatisms can coexist during rifting.

Lead–zinc(–silver) ore deposits are commonly associated with ancient rifts, and the stratabound deposits known in the Late Triassic–Liassic Pucará Group of central Peru are no exception (Rosas and Fontboté, 1995). Although they occur in the Paleozoic, the lead–zinc(–silver) ore deposits known in the Eastern Cordillera of Bolivia are distributed along both sides of the main rift axis and thus possibly formed at depth in relation with the rift system (Sempere et al., 1998).

Syn-rift deposits

The Mitu Group consists of a red to purple, locally >2000-m-thick succession of conglomerates, sandstones and mudstones, with local carbonates and evaporites, that accumulated in subsident grabens (Mégard, 1978; Carlotto, 1998). These sedimentary rocks are commonly interbedded with locally dominant volcanic and volcaniclastic rocks, and/or intruded by subvolcanic to plutonic rocks that do not intrude overlying units. Paleoenvironments identified in the Mitu Group include alluvial fans, fluvial depositional systems and (playa-) lakes.

Discussion and Conclusions

The available evidence consistently demonstrates that the present-day Eastern Cordillera of Peru and Bolivia underwent significant lithospheric thinning during the Late Permian-Middle Jurassic interval. Development of this rift system is no extraordinary phenomenon, as coeval similar processes were common in western Gondwana due the contemporaneous dislocation of Pangea. Onset of the rifting seems to have been diachroneous, propagating from north to south. Mitu sin-rift strata were apparently deposited earlier in the north than in the south, where they overlie a Late Permian-Early Triassic partly marine unit that was not deposited in a rift setting.

In the central part of the Andes (South of Peru, Bolivia, north of the Chile and Argentina), the lowermost sections of the Mitu Group (south of Perú) were deposited during the Middle–Late Permian. According to many authors, it is convenient to divide the lower Mitu Group in two major lithological associations: (1) terrigenous sedimentary and (2) volcanic and volcaniclastic. Good examples of the terrigenous sedimentary association occur in the Pisac Formation, a thick (up to 500 m) red bed succession composed of coarsening and thickening upward sequences of interbedded mudstones, breccias, and conglomerates that unconformably cover limestones of the Copacabana Formation. Although the Pisac Formation has been considered deposited in alluvial fans, locally muddy intervals deposited in lacustrine environments were also reported (Carlotto et al., 2004). The volcanic and volcaniclastic association of the Mitu Group comprises mesosilicic, acid, and basaltic lavas, as well as different genetic types of breccias.

To the south, in the Tarija Basin, Middle–Late Permian sediments appear mainly in shallow marine facies of the Vitiacua Formation (Fig. 3). A semiarid climatic condition likely prevailed during the deposition of the Chutani, considered to have been deposited in shallow marine and fluvial (deltaic) environments. In the Navi-

dad–Arizaro Basin, Middle–Late Permian sedimentation was influenced by Permian–Triassic volcanism (Fig. 3). In this way, high-energy fluvial volcaniclastic deposits composed of coarse conglomerates, sandstones, and shales occur in the Diablo (north of Chile) and Machani (south of Perú) formations. Coevally, thick volcaniclastic sequences were included in the upper levels of the Peine Group.

Before and during the carboniferous was developed volcanism along the active continental margin of the central Andes, which was continued by extensional processes in Permian ages yielding pronounced rift volcanism in the Eastern Cordillera. This volcanism is characterized by the coexistent of tholeiitic and alkaline magmatism, which was probably produced by strong radial mantle convection.

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