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Late Carboniferous To Middle Permian Copacabana Formation In Bolivia: Cyclic Carbonate-Clastic Successions In A Back-Arc Setting

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The questions addressed in this paper pertain to depositional style, timing and controls of facies succession in Bolivian Permo-Carboniferous sub-basins. Noteworthy for the Laurentian stratigrapher is the presence there of "West Texas" faunas and cyclic depositional patterns of lithofacies similar to time-equivalent strata in North America. Figures 1 & 2 summarize Late Paleozoic geology and regional unconformities in the central Andes. Figure 1 highlights possible commonality with Sloss' North American Absaroka sequence, yet figure 2 and statements below submit that partly cyclothemic sedimentation was influenced by local to regional accommodation in active basins. Therefore, pericratonic depositional patterns in Bolivia suggest a mix of extrabasinal and regional tectonic controls. We provide for the first time detailed biostratigraphic and lithostratigraphic descriptions of multiple sections within a framework of SW Gondwanan geohistory. Our observations incorporate sequence stratigraphic concepts and draw attention to multiple ash beds that could provide further tests and calibration for the existing conodont, fusulinid, and small foram schemes.

Late Carboniferous and Permian marine and transitional rocks of the central Andes were deposited in Gondwanan back-arc seaways above glacially influenced Late Devonian and Early Carboniferous siliciclastic units. Regional geologic relationships and differential accommodation of carbonate-clastic homoclinal ramp successions suggest deposition along a transtensional plate margin below unconformities associated with incipient rifting (figs. 1 & 2, iii, iv & v). Many of these deposits were later karsted and removed from Triassic/Jurassic rift shoulders. Within the regional framework of the Cuevo tectonic supersequence (Titicaca Group), we focus on the heterogeneous shallow-water deposits of the carbonate-dominated Copacabana & clastic-dominated Yaurichambi formations. We use field data from 30 localities in the fold and thrust belt of the Altiplano and Eastern Cordillera. New biostratigraphic data and earlier published work are combined in order to differentiate time-transgressive facies patterns. The principal datable unit in the central Andes (Copacabana Formation) occurs with multiple disconformities in Bolivian sub-basins that were peripheral to the Cordilleran master basin(s) in Peru. As seas transgressed into the region from the northwest, complexities including pre-, syn- and post-depositional tectonics inhibit study of clear "shelf-to-basin" profiles. However, Permo-Carboniferous icehouse-type eustatic excursions may be deduced from sediment stacking patterns.

Over 400m of Bashkirian to Cisuralian strata at Lake Titicaca thin and young-upwards towards the E and SE (generally considered up-depositional dip). SE of Cochabamba, mainly thin Artinskian carbonates overly thick aeolian sandstones (shown only in fig. 1). Figure 2 shows that individual sub-basins subsided diachronously and does not show the depositional featheredge of Copacabana carbonates. As in the northern Bolivian subandes (Mobil exploration wells), the Titicaca sub-basin accommodated thick Bashkirian to Moscovian deposits (Atokan especially). Pennsylvanian deposits are brachiopod-dominated, storm-influenced, muddy, open marine carbonates with cool to warm "Bryonoderm" faunal associations and chert. These beds are interbedded with thin black shales with *Orbiculoidea* sp. and Crurithyrid-rich, burrowed wackestones indicative of restricted conditions. At the decimeter scale these rocks are overlain by tidal to aeolian-influenced cross-bedded sandstone and burrowed foreshore clastics with bivalves. Repeated influx of sand is associated with mobile coastal systems & sabkha (Yaurichambi Fm.). Earliest Pennsylvanian deposits occur in thick (100m) deepening-upward packages (middle & outer ramp limestone over evaporitic lagoon and coastal plain clastics). At the meter to decimeter scale, Copacabana Formation cycles consist of muddy, bioturbated marine carbonates with tempestites that shallow-upward (increase in energy) and are capped by grainstones +/- yellow microcrystalline laminated dolostone with artifacts after evaporates +/- clastics +/- evidence for subaerial exposure. Stacking patterns of complex sabkha-ramp facies mosaics may be explained by progradational autocyclic controls from multiple shorelines, or by high-frequency shingled cycles typical of icehouse ramps.

Transitional Pennsylvanian to Permian strata are comparatively thin. Stacked incised channels on the Copacabana Peninsula are filled with sands and current-stable fusulinids. Paleosols and silcretes occur laterally suggesting disconformities and lowstand (figs. 1 & 2, disconformities "ii"). Dominantly sandy lithofacies include nodule-bearing dolomudstone and silicified carbonates. To a degree, this pattern is repeated with silicified Artinskian sections and karst sinkholes below the Chutani Fm. (figs. 1 & 2, unconformity "iii"). Ubiquitous Sakmarian to Artinskian deposits contain bryozoans and corals of increasing diversity, fusulinids, and calcareous algae of warmer "chlorozoan" association. Ooids, however, are rare. Abundant Artinskian skeletal grainstones include locally thick cross-bedded, pelmatozoan-dominated beds that represent high-energy environments. Blue-green air-fall ash beds are present at all sections and times (fig. 2) and suggest episodic compromise in parts of the carbonate factory. These ashes were best preserved in quiet waters, but were also bioturbated or occur in reworked association with larger volcanic grains of subarkosic to sublithic sandstones. Other facies types (e.g., gravel-sized deposits, very thick black shales and rare algal bioherms) are reported <u>only</u> from Peruvian depocenters that accommodated 2000 + m of marine and partly lacustrine sediment.

Foraminiferal biostratigraphy is based on the following First Occurrence Zones (Pinard & Mamet, 1998). The Bashkirian is recognized on *Millerella-Globivalvulina*, the Moscovian on *Bradyinelloides-Polytaxis-Pseudobradyina-Syzrania*, and the Kasimovian-Ghzelian on *Hemigordius-Protonodosarina-Nodosinelloides*. The Asselian-Sakmarian has *Geinitzina-Neohemigordius-Nodosinelloides-Polarisella-Syzranella*, and finally the Artinskian has *Frontinodosaria-Robuloides*. Additional fusulinid biostratigraphy by V. Davydov also confirms and develops previous biostratigraphic efforts (Bolivian & Japanese work & in-house palynology). New conodont information processed by P. Heckel has helped to adjust previous age calls and improve correlation within the Titicaca sub-basin. So far, limited biostratigraphic resolution and outcrops hinder development of a detailed sequence stratigraphy.

Inter-regional interpretations including information from Peru suggest the following large-scale tectonic, eustatic and climatic conditions for sediment accumulation. 1) After the paleotopography of the Mississippian-Pennsylvanian boundary was back-filled, Permo-Carboniferous deposition occurred in a temperate to sub-tropical plate margin-parallel system of troughs and highs. 2) Initial restricted Pennsylvanian sub-basins were cool/deep enough such that large brachiopods and spiny echinoids flourished, but warm/shallow enough that early fusulines (*Millerella-Seminovella*), *Profusulina,* corals and non-endemic foraminiferal communities were established. 3) Individual basins were filled and buried by latest Pennsylvanian-Permian transgressions. *Triticites*-bearing Virgilian rocks are however poorly constrained. Warm equatorial currents flowed into the region from the north and various lines of evidence suggest that seaways were partly open to the cool Panthalassic Ocean. 4) Sakmarian shale to carbonate shoal cycles include abundant warm-water biota and record overall rising relative sea level change. Higher-order facies stacking appears to cease following the Sakmarian suggesting reduced influence of glacio-eustasy. 5) By Artinskian time thick grainstone shoals and thin clastic wedges filled accommodation space and suggest establishment of the maximum Absarokan highstand. Concurrently, accommodation shifted to the Cochabamba area (fig. 2) with thick deposition of basinal shale and limestone cycles without conspicuous sandstone beds. This unanticipated pattern suggests tectonic reorganization previous to establishment of Upper Permian and Triassic rift environments. 6) Restricted marine to fluvial/aeolian environments, complex diachronous unconformities, volcanism and loss of productive invertebrate habitat followed in the deteriorating Latest Paleozoic world. As South America warmed and moved to a lower latitude (with concomitant cooling in arctic Canada), the Titicaca Group experienced local tectonic controls but also recorded first-order trends common to the Americas and Pangea.

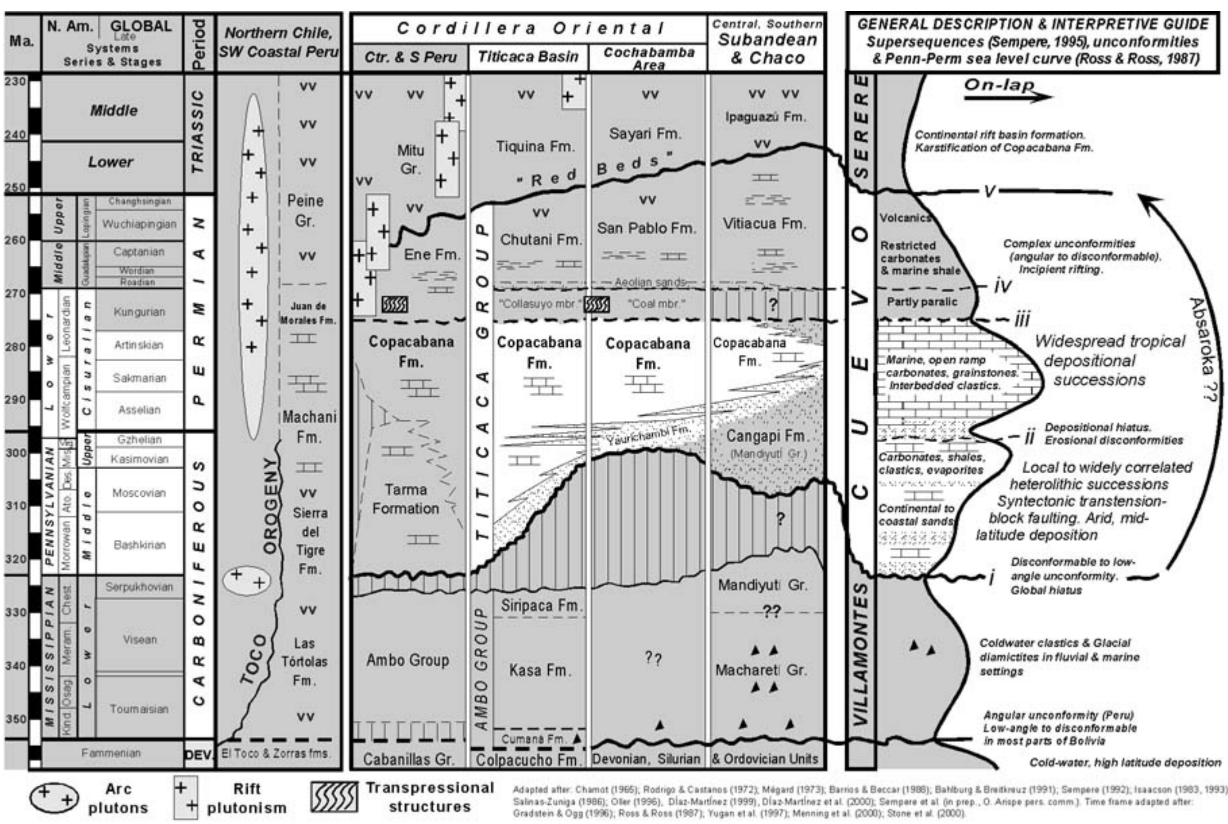

Figure 1. Deposition of the Titicaca Group is synonomous with the tectonic "Cuevo" supersequence. Our focus is on the Copacabana Formation of Bolivia as understood within the framework of Late Paleozoic plate margin tectonics & changing regional/global climates.

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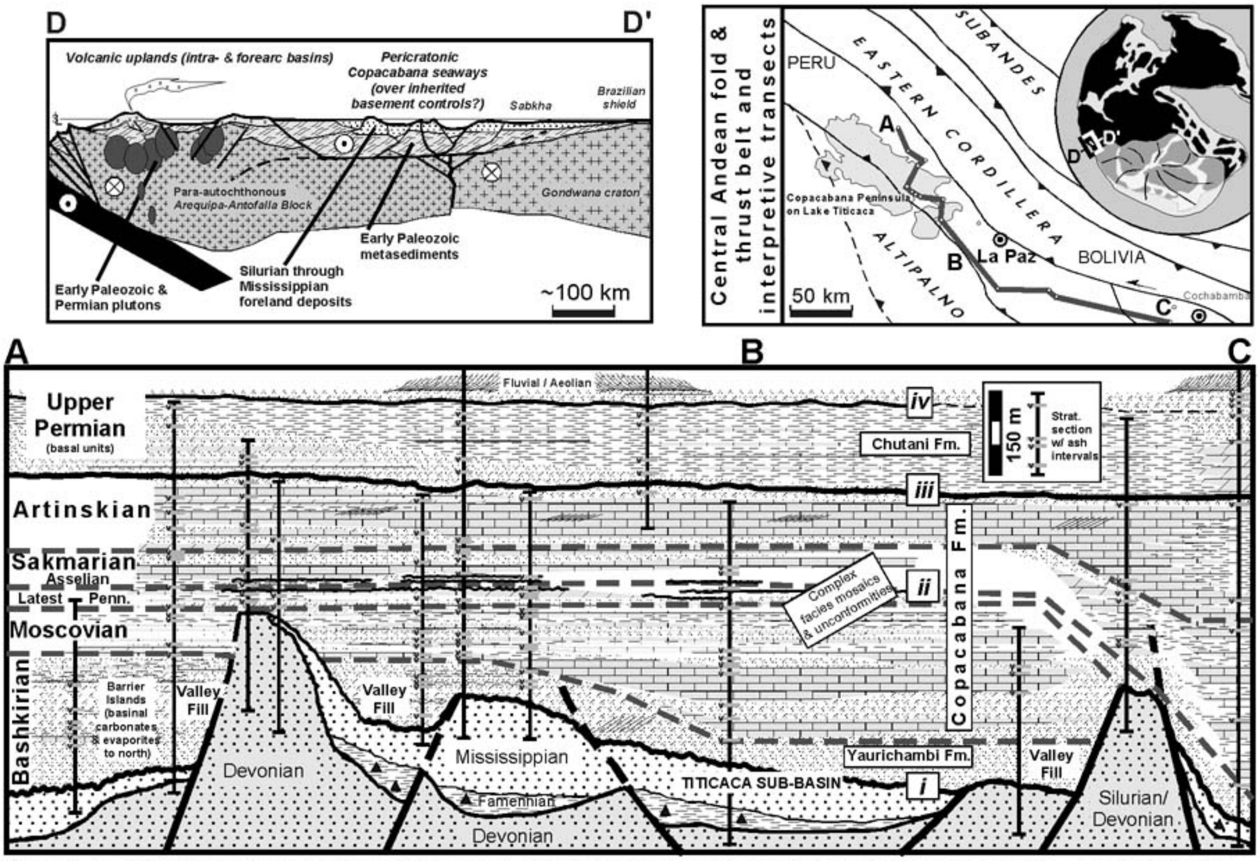

Figure 2. Locality & tectonic setting (above). Tansect A-B-C (below): schematic correlation of the Copacabana Fm. showing Permian-flooded Pennsylvanian paleohighs. Hung from widespread Artinskian carbonates with abundant *Eoparafusulina*. General lithofacies, time-lines, major unconformities (see Fig. 1) & ash intervals are sketched. Titicaca & Cochabamba sub-basins at "B"&"C" respectively.