PALEOZOIC TO JURASSIC EVOLUTION OF BOLIVIA

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RESUMEN: El registro Cámbrico superior a Jurásico de Bolivia, principalmente marino, ilustra la evolución del Gondwana sudoccidental desde la finalización de la fragmentación de la Protopangea hasta la dislocación de la Pangea. Una crisis compresional durante el Ordovícico medio inició el funcionamiento activo del margen, marcado por una fuerte subsidencia del Ashgill al Mississipiano. Depósitos someros a continentales, menos espesos, caracterizan la época de la Pangea (Pennsylvaniano-Jurásico).

KEY WORDS: Gondwanaland, Bolivia, Paleozoic, Mesozoic, sedimentary record, geotectonics

INTRODUCTION AND REGIONAL SETTING

The late Cambrian to Jurassic record of Bolivia illustrates the evolution of the southwestern margin of Gondwanaland from the definitive break-up of the late Proterozoic Protopangea to the dislocation of Pangea.

Present state of knowledge of the Bolivian Phanerozoic stratigraphy distinguishes eight main periods (Sempere, in press). The stratigraphic units dealt with in this paper belong to the Tacsara (late Cambrian - middle? Caradoc, ≈80 Myr or more), Chuquisaca (late Caradoc? - middle Famennian, ≈85 Myr), Villamontes (late Famennian - Mississipian, ≈40 Myr), Cuevo (Pennsylvanian - early Triassic, ≈85 Myr), and Serere (middle Triassic - middle? Jurassic, ≈95 Myr) supersequences. Boundaries between these supersequences are generally sharp. The late Cambrian to Permian record is mostly of marine origin, whereas the Triassic-Jurassic record is exclusively continental. The Silurian to Jurassic record of Bolivia resembles the coeval record of the Paraná basin (Sempere, 1990, in press).

From late Ordovician to Mesozoic times, Bolivia laid in the southern part of the subsident Bolivia-Peru basin, which ran parallel to the southwestern margin of Gondwanaland and remained bounded southwards by the Sierras Pampeanas area in Argentina. The marine transgressions thus reached Bolivia from the northwest during this interval.

The known basement of the "Phanerozoic" series in Andean Bolivia generally consists of late Proterozoic-early Cambrian rocks, but crops out only in a few spots. In most of the Cordillera Oriental and Subandean belt, the basal décollements of the Andean thrusts are located in shales of Ordovician, Silurian or Devonian age, and, in each case, no older strata are exposed. Some ancient structural elements have largely controlled both Phanerozoic sedimentation and deformations in southwestern Bolivia (Sempere et al., 1991).

LATE CAMBRIAN TO MIDDLE ORDOVICIAN (TACSARA SUPERSEQUENCE)

When Protopangea dislocated in latest Proterozoic and Cambrian time (Bond et al., 1984), North America drifted from South America northwestwards, and the western margin of Gondwanaland (also southeastern margin of the Iapetus ocean) evolved as a passive margin submitted to a large-scale dextral shear. These tensional conditions initiated the Puna aulacogen in middle to late Cambrian time, and favored the installation of a wide marine epicontinental basin along the proto-Andean domain, which was the locus of thick sedimentation (Sempere, 1992, in press).

An important geodynamic upheaval occurred in middle Ordovician time and the Gondwanaland-southern Iapetus margin became active. A magmatic arc appeared, separating a fore-arc from the wide marine back-arc basin, inside which most part of Andean Bolivia is presently located. Closure and deformation of the Puna aulacogen propagated from the west, starting near the Arenig-Llanvirn boundary (according to data displayed by Bahlburg, 1990), and produced the Ocloyic belt of the Argentine-Chilean Puna and southwestern Bolivia. The rest of the previous depositional area evolved as the marine foreland basin of this deformation, which apparently continued well into Caradoc time. The development of the Ocloyic deformation was apparently coeval with the Taconic deformation of the northern Andes and of the symmetrical margin of eastern North America. Development of roughly synchronous major compressional deformations on both sides of the southern Iapetus ocean suggests that a major global plate reorganization occurred in middle Ordovician time (Sempere, 1992, in press).

In southwestern Bolivia (Tarija area), the sequence begins with shallow-marine clastics, which grade to open-marine, thick graptolite shales intercalated with subordinate turbidites and slumps (late Cambrian-Llanvirn). These strata are affected in this area by the Ocloyic deformation, which is post-dated in northernmost Argentina by beds of Ashgill and Llandovery age (Isaacson et al., 1976; Benedetto et al., 1992). The Ocloyic deformation shows an decrease in intensity from west to east and southwest to northeast. It is unknown north of lat 20°S, where a thick (≈ 4000 m) shallowing-upward siliciclastic sequence of Llanvirn to Caradoc age, conformably overlain by the Chuquisaca supersequence, was deposited during the development of the Ocloyic deformation in the south. These thick and monotonous shallow-marine sandstone-siltstone intercalations are therefore interpreted as the fill of the marine foreland basin related to this deformation (Sempere, 1989, 1992, in press).

LATE ORDOVICIAN TO MIDDLE FAMENNIAN (CHUQUISACA SUPERSEQUENCE)

This interval consists of two stratigraphic sets (late Caradoc?-early? Llandovery, and late Llandovery-middle Famennian). The first set begins with black shales (Tokochi Fm; Sempere et al., 1991) which overlie shallow-marine Caradoc strata and were deposited in a relatively deep, anoxic environment during a maximum flooding episode. They are overlain by resedimented glacial-marine diamictites (Cancañiri Fm, Ashgill), which are in turn sharply overlain by the thinning-upward Llallagua Fm (thickly-bedded turbidites) and/or by the late Llandovery to Ludlow age Uncía/Kirusillas Fm (dark shales, with minor turbidites). The first 3 units reach their maximum thickness in the eastern UCU domain, whereas they rapidly thin out to the southeast and east. Some rare limestone beds are known at Ashgill (Toro et al., 1992) and early Wenlock levels (Merino, 1991). Deposition of the late Caradoc? to early? Llandovery strata occurred in a basin controlled by active normal faulting, but facies succession was induced by a major glacio-eustatic sea-level low (Ashgill ice age) which developed between two maximum flooding episodes (Tokochi and Uncía/Kirusillas Fms). The mostly resedimented Cancañiri and Llallagua Fms are interpreted to represent lower and upper lowstand deposits, respectively.

The late Llandovery-middle Famennian set includes several units in the Bolivian Andes, Subandean belt and Chaco-Beni plains. This interval was a time of onlap toward the northeast, and of deposition of major source rocks in Bolivia. The units are generally thick and form three main shallowing-upward megasequences, beginning with thick dark shales and ending with sandstone-dominated units, respectively of late Llandovery-Lochkovian, Pragian-early Givetian, and late Givetian-middle Famennian ages (Racheboeuf et al., 1992). Decrease and geographic homogeneization of subsidence in ≈Llandovery time are interpreted to mark a change in tectonic regime (also reflected by the northeasterly onlap): whereas the late Caradoc?-early? Llandovery set was deposited through activity of a wide tectonic trough in the UCU domain, the late Llandovery-middle Famennian set was deposited in a large, subsident, marine "foreland" basin related to sinistral transpressional activity of the Gondwanaland margin (Sempere, 1992, in press).

LATE FAMENNIAN-MISSISSIPIAN (VILLAMONTES SUPERSEQUENCE)

The conflictive stratigraphy of the Villamontes (≈Ambo Group; ≈Machareti + Mandiyuti groups) and Cuevo (≈Tarma and/or Copacabana groups) supersequences is currently undergoing major revisions, through integration of new biostratigraphic data and analysis of stratigraphic and seismic sections. In much contrast with the underlying series, facies vary rapidly at all scales, and correlations are difficult. Tectonic, eustatic and climatic controls on sedimentation are taken into account to favor first-order correlation tools such as major climatic changes and eustatic events. Resedimented deposits, where predominant, are interpreted to mark local tectonic activity and lead to define active slopes and highs.

The Villamontes-Cuevo contact marks a noteworthy paleoclimatic change in northwestern Bolivia, from cool or temperate and rainy, to relatively warm and arid conditions. This climatic change, marked in other parts of Bolivia, is consistent with what is known of the coeval South pole southeastwards migration (Veevers and Powell, 1987). It provides a correlation horizon, as a first approximation because it is likely to have been slightly diachronous. On the basis of conodont biostratigraphy, its age would lie within the Serpukhovian or approximately coincide with the Mississipian-Pennsylvanian boundary (D. Merino, in prep.). Furthermore, the major global regression-transgression event which occurred in Serpukhovian and earliest Pennsylvanian time (Saunders and Ramsbottom, 1986; Veevers and Powell, 1987) is apparently recorded by the upper Villamontes and lower Cuevo facies. A paleosol may occur at this contact.

The mainly marine Villamontes supersequence overlies Devonian strata with a sharp or rapidly transitional contact. Mudstones are black to grey, with some purple shade in the south. Plant fossils are locally common. In the northern Subandean belt, facies include thick mud-dominated slumps, sandstone olistoliths, shallow-marine black laminated shales, sandstones and coal, whereas in the related Lake Titicaca area they display a basal glacial-marine horizon, dark shales, cross-bedded sandstones, diamictites, and coal.

In the Chaco basin and adjacent Subandean belt, the Villamontes supersequence roughly equates with the Macharetí and Mandiyutí subgroups. Basal facies commonly document a brutal increase in paleodepth. Macharetí and Mandiyutí facies are dominated by clast-bearing resedimented deposits, proceed from the Chaco high, and include rarely stratified "diamictites", debris flows, muddy to sandy mass flows and slumps, stratified olistoliths, cross-bedded sandstones, thick and thin regularly-bedded turbidites, regularly-bedded fine-grained sandstones and mudstones, and rarer laminated mudstones. Convincing glacial-marine features are only observed in the Macharetí, although reworked glacial clasts exist in the Mandiyutí. Many resedimented facies were deposited in submarine channels and valleys, which locally display vertical coalescence. Amplitude of scouring at their base apparently increases upsection. The Macharetí shows marked lithologic contrasts between mud-dominated and sand-dominated facies, whereas the Mandiyutí is predominantly sandy and shows near-shore to continental facies in its uppermost part, which indicates a major and rapid shallowing of depositional environments and is interpreted to represent the Serpukhovian global-scale regression (Veevers and Powell, 1987) in Bolivia. Mudstones in the Macharetí are dark grey to purplish, locally with plant debris, whereas they are bright brownish red in the uppermost Macharetí and the whole Mandiyutí, indicating a roughly coeval climatic change (see above).

Some Mississipian strata post-date uplifts of late Devonian or earliest Mississipian age, and Pennsylvanian to early Permian limestones locally onlap upon paleoreliefs formed in late Devonian and/or Mississipian time. Although these limestones may overlie strata as old as Ordovician in age, no angular unconformities are known, which stands against a "Hercynian" major deformation. Furthermore, the "Hercynian" metamorphism and deformation of Bard et al. (1974) has been proved to be of late Triassic age (Farrar et al., 1990) and is only of local importance. But, because of the late Devonian to early Mississipian deformations known in Peru, of the coeval inferred uplifts in several parts of Bolivia, and other evidences for synsedimentary tectonic instablility, it seems clear that the late Devonian and especially the Mississipian were times of high epeirogenic activity in the Bolivia-Peru basin. The Mississipian sedimentation may thus be considered as the culmination of the Silurian-Devonian evolution (see Sempere, in press).

PENNSYLVANIAN TO EARLY TRIASSIC (CUEVO SUPERSEQUENCE)

Controlled by a low subsidence and subtropical climatic conditions, a shallow carbonate platform extended in western Bolivia (Copacabana Fm), while littoral to continental sands were deposited in southeastern Bolivia (Cangapi Fm). Occurrences of eolian deposits and evaporites in the Pennsylvanian and early Permian may be noted, as well as similarities with the Amazon basin. Tuffaceous beds document contemporaneous explosive magmatism in the west. An extensive restricted-marine carbonate transgression developed in the middle to late Permian (Vitiacua/Chutani Fm; Sempere et al., 1992), as in the Paraná and Karoo basins, and was followed by a general regression.

Deposition of the Cuevo supersequence was coeval with an important compressional or transpressional intracratonic deformation mainly known in the Cordillera Oriental of central and southern Peru. This widespread "Gondwanian"-age deformation is postdated by a post-orogenic calc-alkaline magmatism of early to middle Triassic age, which evolved in the late middle Triassic toward continental tholeiitic compositions indicating regional extension or transtension (see Soler and Sempere, 1993), which in Bolivia initiated the Serere supersequence.

MIDDLE TRIASSIC TO MIDDLE? JURASSIC (SERERE SUPERSEQUENCE)

The stratigraphy of this time interval in Bolivia was recently updated (Oller and Sempere, 1990). An initial rifting process of late middle Triassic age developed in several areas, probably within an extensive and complex extensional to transtensional setting related to the coeval fracturation of Pangea. Numerous small grabens were filled by fluvio-lacustrine red beds and evaporites, while alkaline and tholeiitic magmatisms developed, as in other parts of western South America (see Soler and Sempere, 1993).

Abortion of rifting in Bolivia was probably a consequence of a regional tectonic reorganization at ≈220 Ma, which produced local intracratonic transpressional conditions, as evidenced by the pervasive cataclasis of the Zongo-Yani (Bolivia) and Abancay (southern Peru) Triassic intrusions and the deformation of their enclosing strata (Bard et al., 1974; Dalmayrac et al., 1980; Farrar et al., 1990). Some grabens or transtensional structures were inverted during this event, which probably marked the regional resumption of subduction along the Pacific margin. The subsequent, late Triassic-middle? Jurassic, onlapping sedimentation (mainly fluvial and eolian sands, as in the Paraná basin) was controlled by the thermal subsidence which developed after rifting became inactive (Oller and Sempere, 1990).

This evolution ended with a late Jurassic large-scale rifting event, apparently related to the initiation of the southern Atlantic rift system. Bolivia, which until then had somehow behaved in a cratonic way, was then captured by the Andean-Pacific system.

CONCLUSIONS

The Bolivian Phanerozoic record illustrates the dislocation of the late Proterozoic Protopangea, the initiation and evolution of the western Gondwanaland margin, the aggregation and consolidation of Pangea, its subsequent fracturation and dislocation, and the convergence effects of the motion of South America.

The late Cambrian to Mississipian record (≥ 205 Myr) highlights the regional evolution from the break-up of Protopangea to the assemblage of Pangea. The source rocks of the Bolivian hydrocarbons presently under production were deposited during this period of high subsidence.

The Pennsylvanian to mid-Jurassic record (≈165 Myr) illustrates the epoch of Pangea. Final coalescence, consolidation and subsequent fracturation of Pangea occurred during this time interval. Active subduction probably ceased in the Permian in relation to the coalescence of Pangea (Kay et al., 1989), but resumed in the late Triassic. In the central Andean region, the coeval geological evolution includes a complex set of tectonic, magmatic and sedimentary events.

Much Bolivian oil and gas occurs in Devonian and Carboniferous reservoirs, and is derived from source rocks deposited during epochs of major marine inundation (Ordovician-early Mississipian: thick dark shale units, major subsidence; middle Pennsylvanian-late Permian: thinner shallow-marine carbonates and dark mudstones). Propagation of Andean thrust deformation, and sedimentary and tectonic burying of Paleozoic organic-rich units, have had a major control on hydrocarbon migration and present-day distribution. The geometry of the Paleozoic basin and sedimentary pile closely controls the geometry of Andean deformations.

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