SEDIMENTOLOGICAL ANALYSIS OF THE ORDOVICIAN AND DEVONIAN BASINS IN SOUTHERN PERU AND NORTHERN BOLIVIA

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INTRODUCTION

We present data from a study of the evolution of the Early Paleozoic Peru-Bolivia Trough, its facies development and the provenance of sediments deposited during Ordovician and Devonian time. We measured and sampled sections in the Ordovician successions in the Cordillera Oriental of southern Peru (Ollantaytambo, Verónica, San José, Sandia and Calapuja Formations) and northern Bolivia (Coroico, Amutara and Cancañiri Formations), and in the Upper Silurian to Devonian Lampa Formation on the Altiplano, and the Devonian Cabanillas Group on the Altiplano and the Peruvian Coastal Cordillera (Arequipa Massif). Our data contribute to a better understanding of the plate tectonic evolution of the Western Gondwana margin during early Paleozoic times.

ORDOVICIAN FORMATIONS IN SOUTHERN PERU AND NORTHERN BOLIVIA

STRATIGRAPHY

The oldest exposed Paleozoic units in Cordillera Oriental and Altiplano of southern Peru are the volcanigenic Ollantaytambo Formation (Marocco, 1978) and Umachiri beds (Flores and Rodríguez, 1999). The Early to Middle Ordovician age of both formations is indicated by a sparse graptolite fauna (Egeler and De Booy, 1961; Cerrón and Chacaltana, 2002). Whereas the Umachiri beds are unconformably overlain by the Cenozoic Tinajani Formation, the Ollantaytambo Formation is partly truncated by the Middle Ordovician Verónica Formation, which in turn grades into the fine-grained sandstones and predominant black shales of the Middle Ordovician San José Formation (Carlotto et al. 1996). In the locality of Sandia, Laubacher (1978) estimated this formation to be approximately 3500m thick, which seems exaggerated in view of the strong tectonic deformation of the rocks. In particular the black shales of the San José Formation in the Sandia region show alternations of pyrite-rich and pyrite-poor levels, the latter of which contain graptolites. These graptolites place the respective beds in the Darriwillian stage of the Middle Ordovician (J. Maletz, Buffalo, NY, pers. com.). This correlates the formation stratigraphically with the Coroico Formation in northern Bolivia (Suarez Soruco, 1992).

Towards the Late Ordovician, the Sandia Formation and the correlated Amutara Formation in northern Peru record a change to coarser average grain-sizes. We did not find any bodyfossils;- ichnofossils including several examples of *Cruziana* are abundant in some layers. Laubacher (1978) and Martinez (1998) estimated the Sandia Formation to have a thickness of approximately 3500m, which may be exaggerated in view of the tectonic deformation affecting the rocks. The Amutara Formation is estimated to be 3300m thick (Fernández & Thomson, 1995).

The Calapuja Formation in the Cordillera Occidental near Juliaca spans the Late Ordovician (Laubacher, 1978). The formation is c. 3000m thick. In the lower part, 200m of pelites and fine sandstones contain abundant brachiopods, some in concretions. Up-section very fine sandstones contain approximately ten intervals of coarser grained cross-bedded sandstones.

Finally, the Cancañiri Formation represents either the Hirnantian stage of the Late Ordovician (Suárez Soruco, 1992) or extends into the lowermost Silurian (Díaz Martínez, 1997). The formation consists of massive diamictites with thick sandstone intercalations in the middle part. Its deposition is commonly correlated with glacial processes connected to the end-Ordovician glaciation.

SEDIMENTOLOGY AND GEOCHEMISTRY

The most notable unit within the c. 1000m thick Ollantaytambo Formation is an approx. 100m thick succession of lapilli tuffs that originated by hydroclastic fragmentation. These volcanigenic rocks are of calc-alkaline basaltic to andesitic composition. The tuffs are overlain by fine-grained volcaniclastic sandstones and shales which grade into epiclastic turbidites (Bahlburg et al., in press). The Umachiri beds consist of monomict lapilli tuffs with varying lapilli abundance and size that originally formed by hydroclastic fragmentation, and volcaniclastic sandstones. The tuffs have a uniform basaltic andesite composition, and tholeiitic affinity. Chondrite-normalized element patterns of both volcanigenic units show a moderate enrichment of the LREE, and a weak negative Eu anomaly. Pronounced negative Nb and Ta anomalies are indicative of a magma evolution in an arc environment (Bahlburg et al., in press). The sandstone succession of the upper part of the Ollantaytambo Formation consists of turbidites (Bahlburg et al., in press).

Above a pronounced erosional unconformity follow the conglomerates of the Lower Ordovician Verónica Formation. The conglomerates appear structureless and are irregularly bedded with beds reaching thicknesses of up to 10m. The beds represent lenses which have a lateral extent probably exceeding several hundred meters. The conglomerates are mostly clast supported with a sandy matrix and consist almost exclusively of subrounded to well rounded pebbles of clastic sedimentary rocks. The Verónica Formation was most likely deposited by debris flows and is interpreted as an up to 500m thick and c. 10km wide complex of stacked shallow marine channels.

The overlying San José and correlated Coroico formations consist predominantly of black shales with rare intercalations of fine-grained T_{cd} and $T_{b\text{-}c,d}$ turbidites. Their T_c current ripple laminations rather uniformily indicate southwestward paleocurrents. Occasionally we found evidence of reflected paleocurrents indicated by alternating foreset orientations within the same T_c layer.

The late Ordovician represented by the Sandia, Amutara and Calapuja Formations records shallower marine conditions above storm wave base. Storm action is indicated by high energy bedforms like hummocky cross stratification and successive levels of climbing ripples both of which are associated with graded sandstone layers. Sandstone beds containing current cross-bedding indicate paleotransport towards the SW in all three formations. The diamictites of the Cancañiri Formation are only faintly stratified and are interpreted as debris flow deposits (Díaz Martínez, 1997). The intercalated psammite sections of the lower and middle part of the formation show abundant trough cross-bedding which indicates a SW paleocurrent direction similar to the underlying Amutara Formation.

PROVENANCE

Petrographically and geochemically, the sandstones of the Sandia and Ollantaytambo Formations show a range from less recycled to well recycled compositions. The shales and siltstones of the San José Formation, in turn, are chemically much more homogenous with a composition close to that of the upper continental crust (McLennan, 2001). The petrographically and geochemically mature sandstones are richer in Zr than the petrographically less recycled sandstones. Zr/Sc ratios vary between 26.4 and 205.2. This indicates Zr enrichment by zircon concentration connected to sorting and recycling processes (McLennan et al., 1993). When considering the ratios of immobile incompatible to compatible elements, the mature sandstones consist of well recycled detritus which gives the appearance of having originated in a passive margin setting whereas the others preserve characteristics of an arc-type source.

The age of this arc-type signature is not known. It may have been derived from the Ollantaytambo Formation arc regarding the close association of the mafic and intermediate lapilli tuffs of the Ollantaytambo Formation and Umachiri beds with mature sandstones and shales. In view of the partially well recycled detritus this signature can alternatively represent an inherited older crustal signal.

DEVONIAN FORMATIONS

STRATIGRAPHY AND SEDIMENTOLOGY

The c. 350m thick Lampa Formation near Juliaca is uppermost Silurian to Lower Devonian in age as determined by brachiopods (Laubacher, 1978; Suárez Soruco, 1992). The formation consists predominately of base absent T_{bc} to $T_{b\text{-}d}$ siliciclastic turbidites which are replaced in the upper parts of the formation by current cross-bedded sandstones. The succession includes a few slumped horizons of usually less than two meters thickness. Paleocurrents derived from flute marks and ripple cross-laminations indicate a transport direction to the SW.

In the Cordillera Occidental, the Cabanillas Group forms continuous and extensive outcrops. It is c. 1200m thick (Palacios et al., 1993) and rich in brachiopods, trilobites, crinoids, and conularias preserved in concretions. In the lower part, slumped beds are associated with sandstones with hummocky cross stratification and indicate a storm depositional environment. Up-section this influence diminishes and finer-grained current cross-bedded sandstones dominate. They reflect paleocurrents directed to the southeast, the only locality where this current direction has been recorded.

On the Arequipa Massif, the Cabanillas Group deposits are preserved in isolated, discontinuous outcrops. Those outcrops are Aplao, Cocachacra and Estique Pampa (50km north of Tacna). They commonly include a well developed basal conglomerate consisting of cobble to granule-sized clasts of the underlying Proterozoic basement gneisses. The conglomerates grade into fine-grained sandstones and finally into pelites. Within the first 50m of the succession chert lenses and laminae occur. The sandstones are commonly cross-bedded and indicate paleocurrents towards western directions. The first brachiopod occurences were made known by Boucot et al. (1980), which assigned them to the Emsian stage. The thickness of the deposits does not exceed 400m.

CONCLUSIONS ON THE FACIES OF THE ORDOVICIAN AND DEVONIAN FORMATIONS

In the Ordovician basin, deposition starts with the lapilli tuffs of the Ollantaytambo Formation and Umachiri beds. After a marked erosional unconformity the conglomerates of the Verónica Formation represent a complex of stacked shallow marine channels. The erosional unconformity below the Verónica Formation may potentially coincide with a major drop in sea-level near the Early to Middle Ordovician transition (Ross & Ross, 1988), producing a sequence boundary. After deposition of the Verónica Formation, the Ordovician basin then registers a change from black-shale deposits intercalated with turbidites in the Middle Ordovician San José Formation to sandy storm deposits in the Late Ordovician (Spiske, 2005). The black shales of the San José and Coroico formations may have formed during the Middle Ordovician global sea-level rise on the eastern shelf of the Ordovician basin, i.e. at the southwestern margin of the Amazonia craton. In the Late Ordovician the depositional site records a shallowing indicated by frequent storm depositional events. This coincides with a period of high sea-level which was terminated by the global sea-level drop connected to the end-Ordovician glaciation of Gondwana (e.g. Ross & Ross, 1992). This event is in this region represented by the Cancañiri Formation in northern Bolivia (Suárez Soruco, 1992; Díaz Martínez, 1997), the Zapla Formation in northwestern Argentina (Monaldi & Boso, 1987) and the San Gabán Formation in southern Peru (Carlotto et al., 1996; Díaz Martínez et al., 2001).

The low-energy deep-water conditions, i.e. below storm wave base, almost continued throughout the entire Silurian. Starting in the terminal Silurian, a shallowing trend leads to platformal deposition uniformely characterised by storm and shallow marine deposition above storm wave base in the Lower and Middle Devonian. This is testified by the Lampa Formation (Cordillera Occidental) which records turbidite deposition accompanied by slumping. Towards the Cabanillas Group, sedimentary patterns reflect a shallowing to deposition above storm wave base in shallow marine environments inhabited by an abundant benthic fauna.

A noteworthy feature of all studied Ordovician, Silurian and Devonian sections is the scarcity of major erosional surfaces and hiatus. Our data indicate that deposition occurred in a tectonically relatively stable and quiet basin, and that the facies patterns of the basin partly reflect the changing global sea-level. Paleocurrent data almost uniformly indicate derivation of detritus from the NE during the Ordovician and the Devonian.

The lapilli tuffs of the Ollantaytambo Formation and Umachiri beds are the product of arc volcanism (Bahlburg et al., in press). The respective arc may have been located on the Arequipa Massif which records Ordovician plutonism (Loewy et al., 2004) of as yet undetermined geochemical affinity. It is permissable to assume that these plutons represent a northward continuation of the Famatina-Puna arc system in northwestern Argentina and northern Chile. Assuming also a similar polarity of the subduction system, the Ordovician basin was located in a backarc position. Our data substantiate hypotheses of Sempere (1995) and Jaillard et al. (2000) that postulate a change in the plate-tectonic setting towards an active continental margin beginning in the Early to Middle Ordovician. The same setting may apply to the Devonian basin which evolved inboard of the late Silurian-Devonian San Nicolas batholith of probable arc affinity (Mukasa and Henry, 1990; Jaillard et al., 2000).

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