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An *in situ* shelly fauna from the lower Paleozoic Zapla diamictite of northwestern Argentina: Implications for the age of glacial events across Gondwana

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ABSTRACT

A shelly fauna from the upper part of the Zapla glacial diamictite includes the lingulate brachiopod *Orbiculoidea radiata* Troedsson, the rhynchonelliforms *Dalmanella* cf. *testudinaria* (Dalman) and *Paromalomena* sp., the bivalve *Modiolopsis*? sp., and the trilobite *Dalmanitina subandina* Monaldi and Boso. Both taphonomic and paleoecologic data indicate a lack of transport reflecting the original community. The assemblage is closely comparable to the widespread latest Ordovician *Hirnantia-Dalmanitina* fauna. The Hirnantian age of the Zapla diamictite is further corroborated by the record of the northern Gondwana chitinozoans *Spinachitina* cf. *oulebsiri* Paris and *Desmochitina minor typica* Eisenack. The graptolites and chitinozoans from the overlying Lipeón Formation indicate that the postglacial transgression took place in the earliest Llandovery (*Parakidograptus acuminatus* Biozone). According to the tectonosedimentary evidence, the Early Silurian age of the Cancañiri and San Gabán diamictites of north–central Bolivia and south Peru based on their palynological record is more likely the age of posglacial gravity flows and not that of the glaciation. We support the hypothesis that the weakly lithified glacigenic deposits of Hirnantian age were reworked and redistributed by high-energy marine processes during the postglacial transgression and then transported to the adjacent deep-marine trough. Iron-rich horizons have been recognized in many basins of southern South America reflecting eustatic and paleoclimatic fluctuations. Most of them formed during the early stages of the postglacial transgression at the Ordovician/Silurian transition and are associated with low sedimentation rates and condensed intervals. The mild maritime postglacial climate, the increasing atmospheric CO_2, and possibly the presence of incipient vegetated areas led to extensive weathering of glacigenic sediments supplying iron into the marine system to form ferruginous deposits. The sea level fall related to the peak of glaciation is recorded by both paleovalley incision and a sharp subaerial to subglacial unconformity. The transgressive systems tract starts with fluvio-estuarine deposits within incised valleys followed by widespread deposition of subtidal to open marine organic-rich shales onlapping regionally the basement rocks. The recognition of key stratigraphic markers (e.g. sequence boundary, flooding surface, ferruginous beds), alongside reliable micro and macropaleontological evidence allow a more accurate correlation between the Central Andean Basin of Peru, Bolivia and NW Argentina, the W Puna region, the Paraguayan and Brazilian sectors of the Paraná Basin, the Precordillera Basin of W Argentina, and the Cape Basin of South Africa.

1. Introduction

In the Central Andes, a lower Paleozoic diamictite extends over more than 300,000 km^2 through southern Peru, Bolivia and northwestern Argentina. This stratigraphic unit has been referred

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to in Peru as the San Gabán Formation, in Bolivia as Cancañiri Formation, and in Argentina as Zapla Formation (the names Mecoyita and Caspalá have also been used for other localities). The thickness of the diamictite unit varies from *ca.* 1500 m in the depocenter located west of Potosí in the Cordillera Oriental (Eastern Cordillera) of Bolivia, to a few tens of meters towards the basin margins (Suárez Soruco, 1995; Díaz-Martínez and Grahn, 2007). Throughout the Central Andean Basin the diamictite rests upon a regional erosional surface truncating different Lower to Upper Ordovician (Sandbian/Katian) siliciclastic marine units. Its glacial origin was first postulated by Schlagintweit (1943) who introduced the name 'Horizonte Glacial de Zapla' (Zapla Glacial Horizon) for the diamictite that immediately underlies conspicuous iron-rich levels in the Sierra de Zapla (Zapla Range) of northwestern Argentina. Since then, the Zapla Formation and correlative units of Bolivia and Peru have been considered by most authors as glacimarine in origin (Berry and Boucot, 1972; Crowell et al., 1981; Buggisch and Astini, 1993; Astini, 2003), though evidence of synsedimentary deformation structures led to interpret the diamictite as glacigenic sediments redeposited in deeper waters (Rodrigo et al., 1977; Sempere, 1995; Díaz-Martínez and Grahn, 2007). The diamictite succession of southern Bolivia (e.g. Tarija region) has been interpreted as true tillites deposited during successive advances of temperate grounded glaciers in a glacioterrestrial environment (Schönian et al., 1999; Schönian and Egenhoff, 2007). By contrary, Boso (1996) rejected the glacial origin of the Zapla diamictite arguing that sedimentary structures point to large-scale sediment gravity flows in a tectonically unstable basin. This hypothesis, however, does not account for the abundance of faceted and striated clasts within the diamictite. Nevertheless, it should be noted that the occurrence of large-scale, tectonically induced events (Díaz Martínez et al., 1996, 2001; Egenhoff and Lucassen, 2003) is not incompatible with glaciated areas in the region.

The age of the diamictite remains controversial due to the reworked nature of most of the fossils and, additionally, by the fact that some fossiliferous beds attributed to the upper part of the Cancañiri Formation (e.g. those yielding the Silurian shelly faunas described by Antelo, 1973) are currently ascribed to the base of the overlying non-glacial Kirusillas Formation (Benedetto and Suárez-Soruco, 1998). Further data from chitinozoans recovered from the Zapla Formation (Grahn and Gutiérrez, 2001) and the Cancañiri Formation (Díaz Martínez and Grahn, 2007; Díaz Martínez et al., 2011) allow reinterpreting the 'Cancañiri glacial event' as essentially Early Silurian. This age has been uncritically accepted in some global-scale Early Paleozoic paleoclimatic discussions (i.e. Brand et al., 2006; Eyles, 2008; Cherns and Wheeley, 2009; Lehnert et al., 2010; Loi et al., 2010). However, an increasing amount of micro and macropaleontological evidence, including the fauna described in the present work, tends to constrain the main glacial advance in the Central Andean Basin essentially to the Hirnantian in accordance with the timing of the glaciation peak in northern Gondwana and other regions of the world.

The aim of this paper is to briefly describe and illustrate the shelly fauna recovered from the glacial diamictite of the Zapla Formation exposed in the Sierra de Santa Bárbara of northwestern Argentina. The interest of this assemblage lies in its undoubtedly autochthonous nature, then providing critical information on the age of the end of the main phase of the glacial event as well as the beginning of the subsequent marine transgression triggered by the ice cap melting. We also propose some explanations to account for the inconsistency in the age of the diamictites of Argentina, Bolivia and Peru. Finally, we attempt a regional correlation of the Upper Ordovician/Lower Silurian successions of southern South America to enlighten the complex dynamic of the end-Ordovician glacial event in the high-latitude western Gondwana.

2. Stratigraphy, taphonomy and paleocology

The fauna was collected from the Zapla Formation exposed along the Arroyo Pedregoso creek (Pedregoso River) in the southern part of the Sierra de Santa Bárbara (Fig. 1). This range, together with the adjacent Sierra de Zapla and other mountain systems, constitutes the Subandean Ranges morphotectonic unit (Rolleri, 1976; Kley and Monaldi, 1999, 2002). In the studied area, the Zapla Formation overlies unconformably the Centinela Formation, of probable Sandbian age, which consists of *Skolithos*-rich quartzsandstones interbedded near the base with greenish siltstones bearing fragments of linguliform brachiopods. The thickness of the Zapla Formation in the Arroyo Pedregoso section is of 78 m (Fig. 2). The lower 15 m consist of dark gray massive diamictites intercalated with a *ca.* 1 m thick bed of coarse-grained quartz-sandstones. This interval is followed by a lenticular sandstone bed reaching a maximum thickness of 5 m, consisting of fine-to very coarse-grained sandstone showing diffuse low-angle cross stratification. Higher in the section the massive diamictites are interbedded with packages up to 25 m thick of lenticular quartz-sandstones displaying hummocky cross stratification. Throughout the unit diamictites contain small quartz grains and boulders up to 20 cm in diameter of quartzite, shale, granitoids, chert, and diamictite reworked from the same unit, and scarce pyrite nodules. The sandstone beds are contorted and often broken appearing as isolated blocks of quartzite, denoting synsedimentary soft deformation linked probably to glacial processes. At the top of the section the diamictites are intercalated with thin beds of dark gray mudstones yielding the fauna described herein (Fig. 2). These levels bear scattered quartz clasts (<5 mm in diameter) that may represent ice-derived dropstones.

The Zapla Formation is conformably overlain by the Lipeón Formation (=Cachipunco Formation), which starts with *ca.* 10 m thick fine-grained micaceous gray sandstones followed by a conspicuous chamoisitic oolitic ironstone bed reaching 1.50 m in thickness. This horizon is overlain by yellowish fine-grained micaceous sandstones with abundant *Zoophycos* followed by a second ferruginous sandstone reaching 3.70 m in thickness. The exposed stratigraphic section culminates with dark gray micaceous shales and sandstones truncated by an inverse fault against Cenozoic rocks.

As stated above, the studied fauna comes from a dark gray mudstone bed near the top of the Zapla Formation. The only trilobite recovered is *Dalmanitina subandina* (Monaldi and Boso, 1987). This species is represented by isolated pigydia, cranidia and free checks corresponding probably to molt remains. Some bivalve specimens (*Modiolopsis*? sp.) are preserved with their valves open but united along the hinge (Fig. 4). Because this genus is edentulous, *post mortem* resistance to disarticulation after the ligament decay should have been very low, and then this is important evidence against hydrodynamic transport or long residence time on the substrate. Although valves transported by non-turbulent sediment gravity flows can occasionally remain conjoined, there is no sedimentological evidence of such processes in the sampled interval.

Brachiopods are the more abundant component of the Zapla community, the small organophosphatic discinoidean *Orbiculoidea radiata* Troedsson being largely dominant (Fig. 3). This species is represented by both dorsal and ventral valves, but the former are more numerous and better preserved than the thinner and flattened ventrals. The presence of juvenile and adult shells in the same bedding plane reveals absence of sorting. Moreover, although valves of *O. radiata* and associated rhynchonelliform brachiopods are disarticulated do not show signs of mechanical damage and their external ornament is finely preserved, indicating absence of