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Dichotomous provenance and age of diamictites in the Early Palaeozoic Peru-Bolivia foreland basin of Gondwana

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Introduction

The record of the Ordovician-Silurian transition within the southern Peru-Bolivia Palaeozoic basin of the Central Andes is characterized by a diamictite-bearing unit which overlies several different Ordovician units, and underlies mid Silurian shales. This unit is traditionally used as a stratigraphic marker within the thick and otherwise monotonous Lower Palaeozoic siliciclastic sequences. The diamictites are commonly interbedded with sandstones and shales, and are known as San Gabán Formation in Peru, Cancañiri Formation in Bolivia, and Zapla Formation in northern Argentina, and extends over an area exceeding 400 km wide and 1600 km long (Figure 1). This correlative diamictite unit is here referred to as SGCZ for simplicity. Apart from the SGCZ, a thin limestone-bearing unit (Sacta Member) is found in the Cochabamba area of central Bolivia, either *in situ* and interbedded within shales and sandstones, or resedimented as slabs within diamictites. This unit is here considered as a lower member of the Kirusillas Shale Formation, in contrast with other authors who consider it a correlative of the Cancañiri Formation. The variable character of the underlying contact (transitional or unconformable), and the recycled fossils found within all these diamictite deposits, have led to strong discussions about their age (Suárez-Soruco, 1995; Bosso, 1999; and references therein). The objective of this work is to propose the existence of at least two distinct Early Silurian diamictite units, each of them with a characteristic age, source area (provenance) and palaeogeographic distribution (Figure 1).

Sedimentary environments and provenance

A regional review of the lithostratigraphy and sedimentology of the SGCZ suggests the need to redefine stratigraphic (time and space) relationships previously proposed. Lithofacies analysis allows to reinterpret sedimentary processes and environments involved during its deposition. The diamictites of the western axial depocenter zone (WADZ) present turbidite and shale interbeds with marine palynomorphs, indicating a deep marine environment. Mud flows, debris flows, slumps and large slided slabs are frequent in the WADZ. They provide evidence for sediment instability, failure and resedimentation, and explain some of the Ordovician fauna previously described, which is recycled from underlying units. Glacially-faceted and striated clasts, and large granitoid boulders, are found within the resedimented materials in the axial zone. They provide evidence for glaciation of the western source area, and are interpreted as recycled from former glacigenic deposits. The precise age of glaciation in this part of Gondwana cannot be confirmed due to a lack of well-dated true tillites, but was prior to the late Llandovery (Díaz-Martínez and Grahn, submitted). Both the upper and the lower contacts of the SGCZ may be gradational or sharp, evidencing that the unit resulted from a series of large gravity flow events, with different thickness, geometry and provenance at different sites. In the WADZ, not only softer clasts (shale, siltstone and sandstone) are clearly faceted and striated, but also harder ones (quartzite, quartz and granitoid), indicating (a) that they were derived from a glaciated area and (b) that they are not due to internal shear of the sediment gravity flow during transport. Tectonic deformation and the resulting relief are respectively identified as the origin for sediment instability and for local glaciation along the active margin of western Gondwana during the Late Ordovician and Early Silurian (Sempere, 1995; Díaz-Martínez, 1997, 1998).

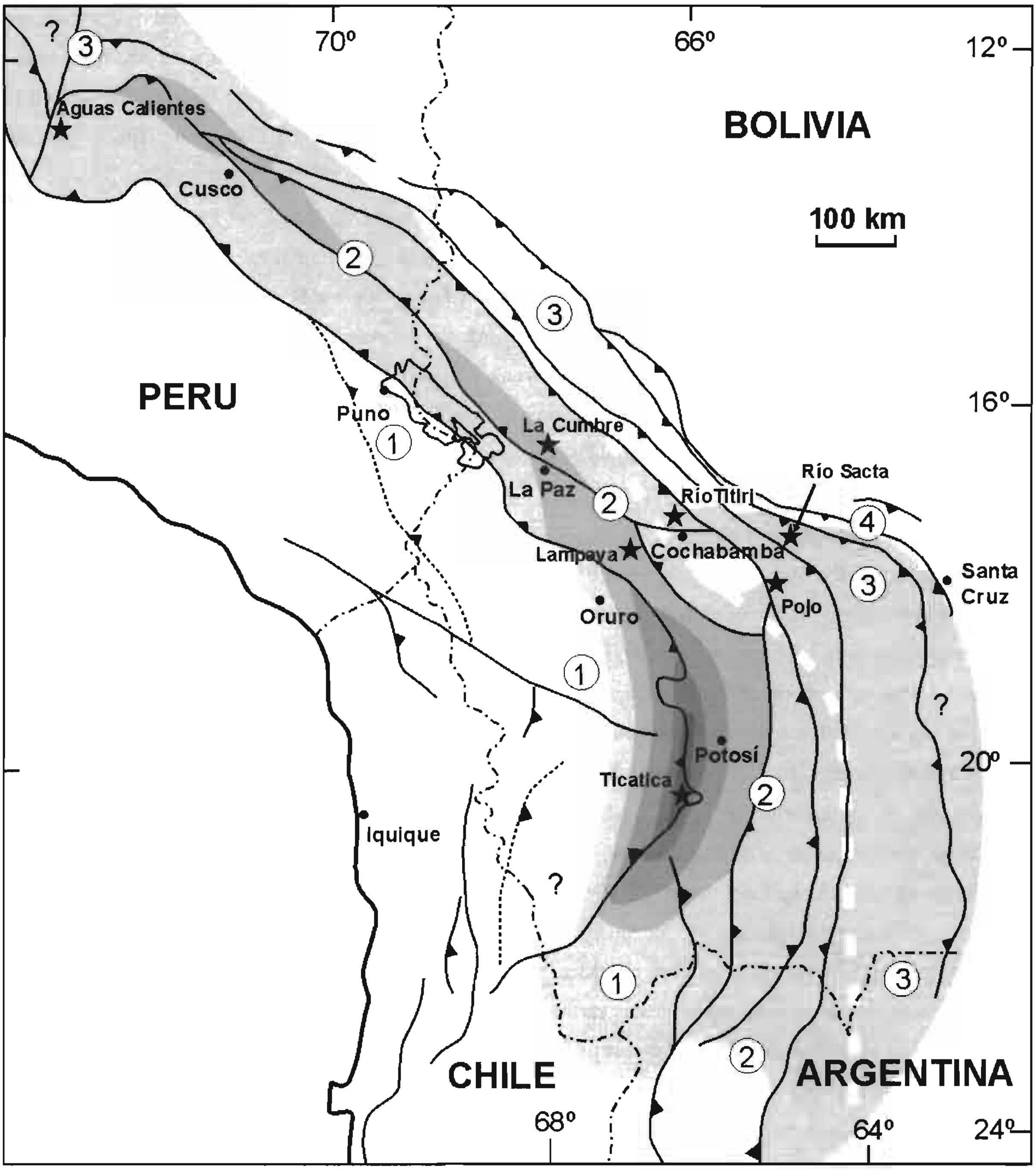

Figure 1: Distribution of the Early Silurian diamictites of the San Gabán Formation (Perú), Cancañiri Formation (Bolivia) and Zapla Formation (Argentina) between 12 and 24°S. Based on Sempere (1995), Suárez-Soruco (1995), González et al. (1996) and Díaz-Martínez (1998). Shades indicate isopachs for 0, 200, 600, 1000 and 1400 m. Numbers indicate main tectonostratigraphic domains within a simplified tectonic map of the Central Andes after Sempere et al. (1988) and Sempere (1995): 1, Altiplano and Puna; 2, Eastern Cordillera; 3, Subandean; 4, Chapare and Boomerang Hills. Stars indicate location of stratigraphic sections mentioned in the text. White dashed line indicates boundary zone between (a) western axial depocenter (foredeep) zone with western-sourced Cancañiri Diamictite Formation (?late Ashgill-Llandovery) and (b) eastern stable margin of foreland basin with eastern-sourced basal diamictites of the Kirusillas Formation (late Llandovery-early Wenlock) including the Sacta Limestone Member.

In contrast with the WADZ, in the Tunari Cordillera, north of Cochabamba (Figure 1), the diamictites are characterized by relatively small thicknesses (from being absent to a maximum of 20 m), by strong lateral changes within short distances (tens of meters), by an absence of glacially-abraded clasts, and by clast compositions including limestones and lacking granitoids. These features, together with the early Wenlock age of the resedimented limestone slabs found within these diamictites, suggest that they do not correspond to the Cancañiri Formation, but that they are sediment gravity flows located towards the base of the Kirusillas Formation. The thin limestone bed is found *in situ* in the Río Sacta, Chapare and Boomerang Hills (Figure 1), suggesting an eastern provenance for the diamictites.

Sempere (1995) and González et al. (1996) described the latest Ordovician and Early Silurian sequence of the WADZ between La Paz, Oruro, Potosí and Ticatica (Figure 1) consisting of the following: 0 to 350 m of Tokochi Shale Formation, 0 to 1500 m of Cancañiri Diamictite Formation, and 0 to 1900 m Llallagua Sandstone Formation. The resulting siliciclastic wedge for this time interval exceeds a total accumulated thickness of 3.5 km in the WADZ, with deep facies implying a very strong subsidence (foreland foredeep). In contrast, towards the eastern margin of the basin, the diamictites pinch out and develop shallower facies, including the aforementioned Sacta Limestone, on what would be the foreland basin's distal stable margin (Figure 1).

Biostratigraphy and age

The age of the SGCZ diamictites has been difficult to constrain due to an apparent lack of diagnostic fossils and to the incorporation of units with different significance. Only very recently have palynological studies contributed to solve the problem. Antelo (1973) described a fossil association of Llandovery age collected at the Pojo and Lampaya sections of Bolivia (Figure 1) in siltstones here considered to be the part of the basal Kirusillas Formation. The reviews by Branisa et al. (1972), Laubacher et al. (1982) and Suárez-Soruco (1992) suggest that the lower Kirusillas Formation has a late Llandovery-Wenlock age, and was thus synchronous in part with the Llallagua Formation in the WADZ, and the Sacta Limestone Member in the eastern area. Recent chitinozoan biostratigraphy of sections in NW Argentina and north of La Paz indicates a Llandovery age of the main depocenter and axial area of the SGCZ (Grahn and Gutiérrez, 2001; Díaz-Martínez and Grahn, submitted). Previous proposals of a Hirnantian age for the SGCZ were based on endemic trilobite species which still require calibration of their chronostratigraphic significance. One of them (*D. milluniensis*) was found within the Sacta Limestone Member, dated with conodonts as earliest Wenlock (Sheinwoodian), and here considered as part of the basal Kirusillas Formation, instead of part of the Cancañiri Formation. It is obvious that more work is still needed before we consider the chronostratigraphic value of the invertebrate macrofauna of the SGCZ. Grahn and Gutiérrez (2001) mentioned that Silurian units overlying the Zapla Formation (Lipeón and Cachipunco formations) began their deposition in the late Telychian, and therefore include the lowest Wenlock (Sheinwoodian), similarly to what happens in Bolivia with the lower Kirusillas Formation.

Conclusions

The biostratigraphy, age, sedimentary environments and correlations of the Cancañiri Formation are better constrained if the Sacta Member is excluded from its definition and considered part of the lower Kirusillas Formation. The possibility that they represent different resedimentation events was previously suggested by

González et al. (1996, p. 121). Within the new palaeogeographic model proposed, the diamictites of the Cancañiri Formation would be older (Llandovery) and with their source area located to the west and south, and the diamictites of the basal Kirusillas Formation would be younger (early Wenlock) and with their source area located to the east. Figure 1 shows a hypothetical boundary zone between the diamictites of the Cancañiri Formation and the diamictites of the basal Kirusillas formations. This new conceptual and integrated palaeogeographic model solves some of the problems arising from the differing age of the diamictites at some localities. The model also implies that there may be sections near or at the boundary zone displayed in Figure 1 which include both (a) Llandovery glaciomarine diamictites corresponding to the SGCZ and resedimented from glaciated and tectonically-active western relieves (sediment gravity flows which recycle previous glacigenic deposits), and (b) early Wenlock diamictites corresponding to the basal Kirusillas Formation and resedimented from the eastern stable shelf (sediment gravity flows which recycle lithified carbonates and unconsolidated siliciclastic shallow shelf deposits). In the case of sections receiving resedimented material from both sources, only a careful and detailed sedimentology (lithofacies and provenance analysis) and micropalaeontology study will allow to locate the boundary between the two units.

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