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Discussion on 'The Neoproterozoic glacial record in the Río de la Plata Craton: a critical reappraisal'

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In a recent article, Pazos *et al*. (2008, p. 343) claim that 'the Zanja del Tigre Formation (Uruguay) represents a glacial influenced succession deposited during the Neoproterozoic, correlative with one of the glaciations described in the Kalahari Craton, prior to Kalahari–Río de la Plata assembly in the proto-western Gondwana margin'. However, we question the two lines of evidence that Pazos *et al*. (2008) put forth in their paper to constrain the age of this unit and to support a glacial event.

Age of the Zanja del Tigre Formation. Pazos *et al*. (2008, p. 350, and fig. 4) consider the Zanja del Tigre Formation as part of the Lavalleja Group. This view, however, is incompatible with existing interpretations. According to the latest compilations of the geology of Uruguay (Bossi *et al*. 1998; Bossi & Ferrando 2001), the Zanja del Tigre Formation is part of the Carapé Group, which is stratigraphically below the Lavalleja Group. In fact, the Carapé and the Lavalleja groups have long been considered independent lithostratigraphic units (e.g. Bossi & Navarro 1991), perhaps even belonging to different 'terranes' or 'blocks' (Gaucher *et al*. 2004).

A recent geochronological study (not available to Pazos *et al*. 2008, at the time of writing) based on detrital zircons (U–Pb sensitive high-resolution ion microprobe (SHRIMP) data) from the Lavalleja Group and Zanja del Tigre Formation supports the assertion that these units are separate (Basei *et al*. 2008). The detrital zircons obtained from a metasandstone of the Zanja del Tigre Formation display ages older than 1.8 Ga, and Meso- or Neoproterozoic zircons are absent. For the Lavalleja Group, a broad range of detrital zircon ages, between 3.4 and 0.6 Ga, was obtained. The agreement between the youngest detrital zircon age obtained in the Basei *et al*. (2008) study and the 590 $\pm$ 2 Ma (U–Pb SHRIMP) crystallization age of an interbedded basalt (Mallmann *et al*. 2007) is noteworthy, and certainly indicates a depositional age of *c*. 590 Ma for at least the uppermost Lavalleja Group. This led Basei *et al*. (2008) to speculate that the Zanja del Tigre Formation might be part of the basement of the Lavalleja Group, as previously suggested based on field relationships (see above).

Glacial evidence in the Zanja del Tigre Formation. The identification of a thin diamictite horizon in the Zanja del Tigre Formation (Pazos *et al*. 2008) is questionable. Specifically, the authors invoke glacial influence during the deposition of the diamictite based on the following arguments: 'the metamorphosed and deformed limestones of this unit include a stratigraphically thin (2 m) interval containing outsized clasts (Pazos *et al*. 2005) that vary from pebbles to blocks and include gabbros, quartzites (fig. 8e) and granites (fig. 8f). They are isolated, disrupting the lamination in different form to that resulting from tectonic deformation (rotational deformation). Some are very similar to the examples illustrated by Condon *et al*. (2002) in the compilation of dropstones intervals from Neoproterozoic successions around the world.' In fact, Pazos *et al*. (2008) used the presence of only two very well-rounded clasts of 1.5 and 3 cm diameter in a carbonate matrix (their fig. 8e and 8f) as supporting evidence of a glacially influenced deposit. Pazos *et al*. (2008, p. 357) then interpreted this interval as containing dropstones that might be regarded as distal glacially influenced deposits or the result of a Heinrich-type event (Heinrich 1988).

We had the opportunity to visit the outcrop described by Pazos *et al*. (2008) and, despite considerable attempts to confirm their interpretations, we found no evidence of glacial features or even sedimentary lamination. The outcrop is located in a limestone quarry and the quality of the exposure is fairly good, yet both the lower and upper contacts are poorly visible. A detailed analysis of the quarry has shown an outstanding variety of tectonic structures (Fig. 1). Highly deformed mylonitic limestones and schists with boudinaged dykes and veins that cross-cut the original metasediments are the most common features in the quarry. The limestones contain a single distinct mylonitic foliation accompanied by the occurrence of sheath folds and abundant kinematic indicators. The composition of the dykes and veins parallels that of the 'outsized clasts' reported by Pazos *et al*. (2008, p. 355) and corresponds to granite, gabbro, calcium carbonate and quartz. Both are folded, boudinaged and sometimes rotated, occasionally showing structures that might resemble dropstones. However, their tectonic origin of these 'clasts' is evidenced in the field by the intrusive nature of the bodies that progressively deformed in the proximity of the shear zones. Furthermore, re-analysis of the images shown by Pazos *et al*. (2008, figs. 8e and f) reveals the presence of grain-tail complexes aligned with the foliation, which clearly suggests a strong shearing component.

In summary, the radiometric data do not support a Neoproterozoic age for the outcrop described by Pazos *et al*. (2008) and the geological interpretation of the 'glacially influenced diamictite' is inconsistent with field observations.

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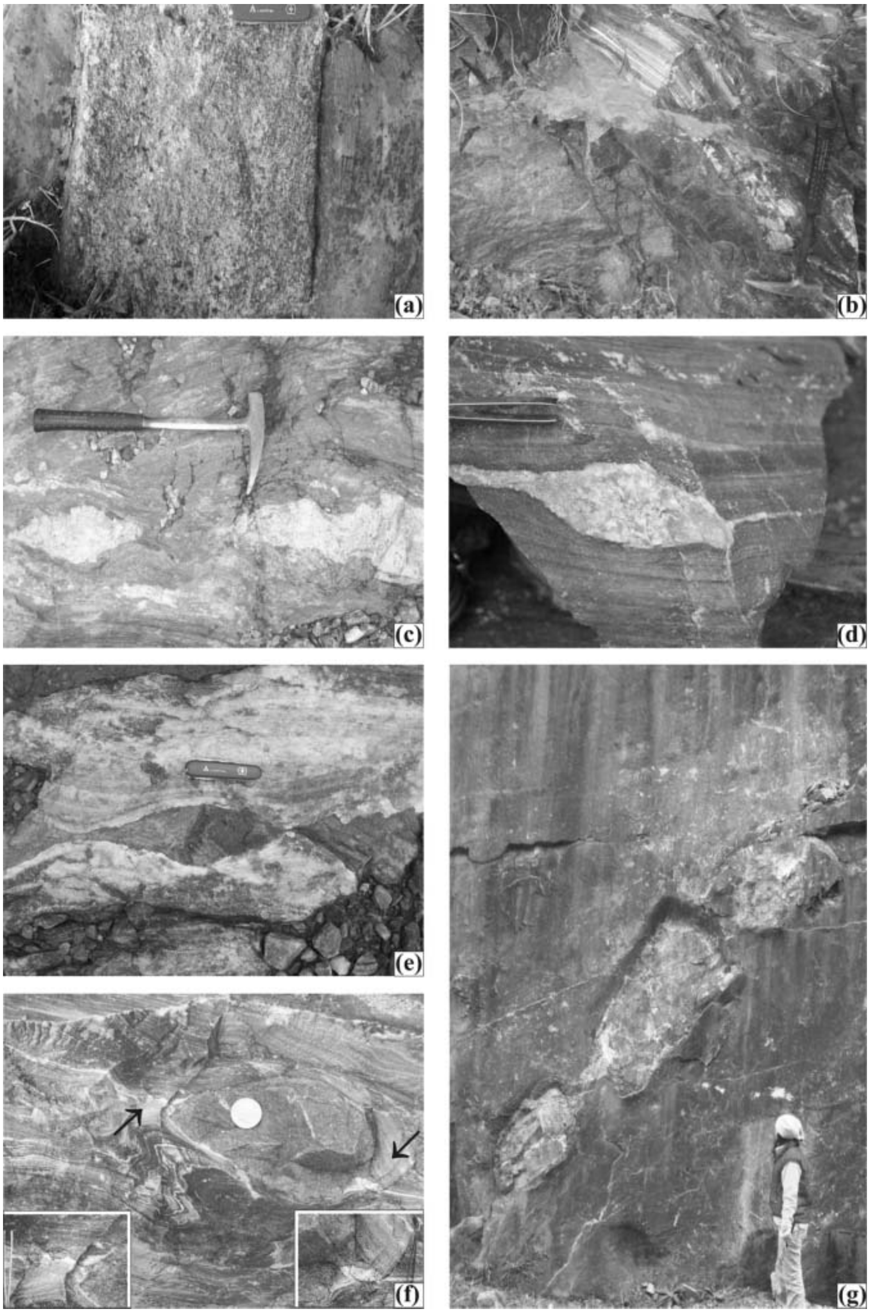

Fig. 1. Structural features of the quarry where Pazos *et al*. (2008) described limestones containing dropstone levels interpreted as a result of Heinrich events. (**a**) Undeformed granite dyke with sharp contacts intruding the limestone. (**b**) Gabbro–dolerite sill intruding the limestone parallel to foliation. Although exceptional, the presence of metre-long fragments of undeformed granite and dolerite dykes suggests that strain localization preferentially took place along shear corridors in a regional regime. (**c**) Competent quartz vein boudinaged by ductile shear. (**d**) A boudinaged quartz vein showing long dynamic recrystallized tails parallel to the mylonitic foliation. (**e**) Narrow granite dyke displaying pinch-and-swell structure as a result of continuous necking caused by layer-parallel extension. (**f**) Boudinaged dyke. The granite boudins acted as rigid objects during the shearing, generating long recrystallized tails in response to flow in the host rock. Insets show the partial assimilation of the granite by the limestone as a result of the high strain undergone by these rocks. (**g**) Discrete granite boudins formed after continuous necking of a dyke. Although showing identical mineral composition and texture, the difference in scale compared with photographs (**a**)–(**f**) should be noted. Scale: knife 9 cm; hammer 40 cm; tweezers 3.5 cm.

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Pecoits *et al*. (2010) question the stratigraphic and glacigenic origins of a tiny section of the Zanja del Tigre Formation that constitutes the least well-constrained of all confirmed and suspected glacial deposits in the Río de La Plata craton (Pazos *et al*. 2008, 2010).

Age of the Zanja del Tigre Formation. Pecoits *et al*. assert that in the 'latest compilations of the geology of Uruguay' the Zanja del Tigre Formation is part of the Carapé Group and not the Lavalleja Group. However, this disregards the contemporaneous stratigraphic scheme of Sánchez Bettucci (1998), which includes the Zanja del Tigre Formation in the Lavalleja Group. This is the stratigraphic scheme followed by Pazos *et al*. (2008, 2010), as well as by Mallmann *et al*. (2007) and Basei *et al*. (2008). We further point out that the geochronological results presented by Mallmann *et al*. (2007) and Basei *et al*. (2008) were not available to us at the time of writing. However, we dispute the suggestion that the absence of detrital zircons younger than 1.8 Ga from the Zanja del Tigre Formation necessarily demonstrates a Mesoproterozoic depositional age, significantly older than that of Lavalleja Group (Basei *et al*. 2008). Some units within undisputed Neoproterozoic sedimentary successions elsewhere in Uruguay and Argentina similarly lack Neoproterozoic detrital zircons (Gaucher *et al*. 2008). Detrital zircon data can only be used to place lower limits on sedimentation.

Glacial evidence in the Zanja del Tigre Formation. The second point contested by Pecoits *et al*. concerns the glacial origin of the interval documented in the Zanja del Tigre Formation. There is no disagreement that these rocks have undergone intense deformation in the vicinity of large-scale shear zones during the late Ediacaran (Gray *et al*. 2008; see also Pazos *et al*. 2005, 2008). The illustration of 'only two' clasts (quartzite and granite) is a common and accepted number in any other glacigenic paper. However, even if we accept that shearing affected the succession and the presence of deformation tails as correctly pointed out by Pecoits *et al*., there is no plausible alternative explanation to that of Pazos *et al*. (2008). We entirely reject the suggestion that the well-rounded quartzite and granite fragments are not clasts but the results of boudinage of intrusions.

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