DISCUSSION

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Comment on 'Geochronology (Ar-Ar, K-Ar and He-exposure ages) of Cenozoic magmatic rocks from northern Chile (18-22°S): implications for magmatism and tectonic evolution of the central Andes' of Wörner *et al.* (2000)

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Wörner *et al.* (2000) presented new and important geochronologic data on the Cenozoic magmatic rocks of northern Chile, and proposed magmatic and tectonic interpretations for them. Here we comment on one of their interpretations about the Miocene tectonic evolution of the Precordillera of Arica (Pampa Oxaya, *ca.* 18º30'S), a region referred by them as 'Oxaya Block'. According to their geochronological data and geomorphological observations, the area, which mainly consists of Lower Miocene ignimbrites of the Oxaya Formation, is interpreted as a large gravitationally collapsed rotational block. They interpret the collapse to have been produced by gravitational instability due to steepening of the western Andean slope during uplift of the Altiplano in an overall compressive regime.

PROBLEMS WITH THE GRAVITATIONAL COLLAPSE MODEL

We argue that the Pampa Oxaya can not be considered as a gravitationally collapsed blockbecause of (in order of importance):

Geometry and morphology

In the field, there is no evidence for a basal detachment, lateral boundaries, or even for an amphitheatre of a possible collapse structure. Characteristically, source areas of collapsed blocks present a concave down-slope geometry (*e.g.*, Siebert, 1984; Philip and Ritz, 1999). According to figure 5 of Wörner *et al.*, that is not the case for the proposed amphitheatre of the Oxaya Block which shows a slightly convex down-slope shape. Furthermore, they suggest that the Ausipar Fault represents the main basal detachment at the front of the supposed collapse, which is shown with a concave-upward shape, and breaking up to the surface (Fig. 5). However, where the Ausipar Fault crops out well (Lluta Valley), it is a concave-downward fault, which dips 40-50°E in the floor of the valley and shallows to a subhorizontal thrust up to a tip line at higher levels on the valley walls (García *et al.*, 1999). Above this tip line the Oxaya Formation is only folded (Figs. 1 and 2). On the other hand, the Ausipar Fault is not connected to lateral boundaries proposed for the Oxaya Block (Fig. 5 of Wörner *et al.*, 2000), and the topography and stratigraphy are the same on both sides of these inferred lateral boundaries.

Internal structure

The surface morphology of the Pampa Oxaya is very regular. The Oxaya ignimbrites are coherent; they do not show a chaotic or disturbed structure with 'hummock' blocks and fragmented matrix, typical of gravitational slides and due to fragmentation during transport (Siebert, 1984; Ui *et al.*, 1986). In particular, such fragmentation structures are not observed at all at the distal areas of the supposed collapse where they would be expected to be best developed.

Slope

The authors argue that the rocks at Pampa Oxaya collapsed where the Andean flank 'is by far the steepest'. However, the slope between the front (Ausipar Fault) and source (Chapiquiña-Belén ridge) of the hypothetical collapse is similar to the one observed farther north and directly south of Pampa Oxaya (from *ca.* 2,000 m to 4,500-5,000 m altitude of 50 km horizontal distance). In addition, the giant escarpment in the source area, as shown in the cross section of figure 5, is mainly an artifact due to its vertical exaggeration (4:1).

Volume

The volume of the Oxaya Block is about 500 km^3 (estimated from Fig. 5 of Wörner *et al.*, 2000). The largest gravitational collapses known in the world, in a continental environment, have maximum volumes of 50-100 km^3 (Ibetsberger, 1996; Dade and Huppert, 1998; Philip and Ritz, 1999), which are 5 to 10 times smaller than the volume estimated for the Oxaya Block.

THE PAMPA OXAYA AS FORMED BY FOLDING

The Oxaya Anticline

We agree with Wörner *et al.* (2000) that lithospheric loading cannot explain the eastward tilting of the Pampa Oxaya. However, this tilting is not necessarily produced by gravitational rotation. Alternatively, our field mapping (1:50.000 scale) indicates that the considered segment of the Precordillera presents all the characteristics of an asymmetric major gentle fold: the Oxaya Anticline. This west-vergent compressive tectonic structure was recognised by Salas *et al.* (1966), Muñoz and Charrier (1996), García *et al.* (1999) and Rochat *et al.* (1999). The fold affects the Oxaya Formation, which to the west conformably overlies the Azapa Formation, and to the east unconformably overlies a more deformed Mesozoic sequence and Cretaceous-Paleogene intrusions (Salas *et al.*, 1966) (Fig. 1). Along its strike (N10-25W), the Oxaya Anticline can be followed for 50 km, with a half-length wave of 25 to 30 km and a maximum amplitude of 1,000 m (Fig. 1). In the hinge, buckling of the strongly competent Oxaya ignimbrites has caused normal faulting and 'hinge grabens'. These normal faults are parallel to the fold axis and show a negligible superficial displacement (up to 80 m). To the east, the Oxaya Anticline is cut by a Miocene west-vergent fold-and-thrust system (Muñoz and Charrier, 1996). The gravels of the Huaylas Formation (Salas *et al.*, 1966), overlying the eastern limb of the Oxaya Anticline, were deposited immediately after folding, indicating a Late Miocene age for the structure (García *et al.*, 1999).

The Ausipar Fault

We interpret the Oxaya Anticline as having formed by propagation at depth of the blind Ausipar Fault (Figs. 1 and 2). This thrust does not cut the upper Oxaya Formation, but its projection at the surface is well defined in the field, with a constant N20W strike. The fault projection is parallel to, and has the same extension as, the Oxaya Anticline. As described above, the Ausipar Fault is well exposed in the Lluta valley (Tiñare) (Fig. 2). At the floor of the valley, it juxtaposes the Mesozoic-Paleocene substratum with the lower Oxaya Formation. Higher up it dies into a tip line at ~1,500 m altitude. This geometry defines a fault-propagation fold involving the basement (Narr and Suppe, 1994; Mitra and Mount, 1998). The negligible horizontal shortening (60-80 m), the relatively important vertical displacement (*ca.* 1,000 m), and the shape and magnitude of the uplift surface in section, produced by the folding, implies that the Ausipar Fault projects downward as an east-dipping high-angle reverse fault (Fig. 1).

Comparison with the Lluta Avalanche

Gravitational instability due to uplift of the Oxaya Anticline produced, on its western flank (Lluta valley region), the Lluta Avalanche (Naranjo, 1993; Uhlig, 1999). In contrast to the hypothetical Oxaya Block, this landslide shows a clear concave down-slope amphitheatre, well-defined lateral boundaries, a basal detachment, and highly chaotic and disturbed deposits. Estimates on the volume of the Lluta Avalanche range between 50 km^3 (Uhlig, 1999) and 100 km^3 (Naranjo, 1993).

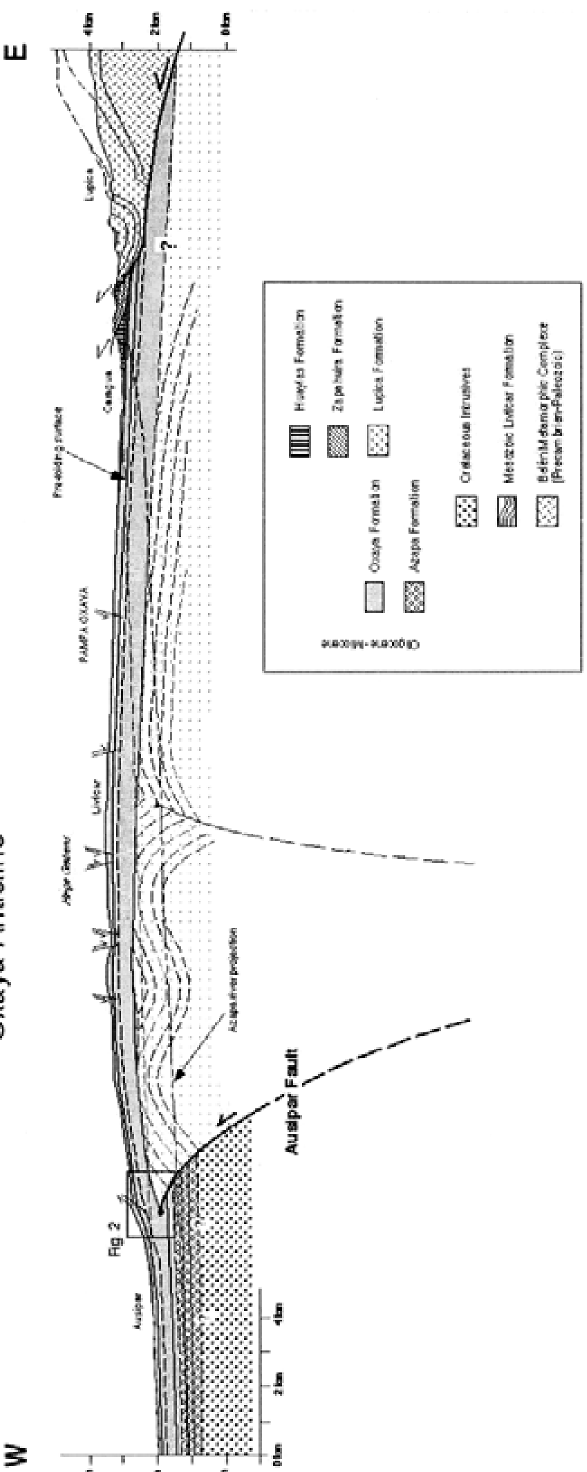

FIG. 1. Cross section of the Oxaya Anticline. No vertical exaggeration. Location is as the cross section of figure 5 in Wörner *et al.* (2000). The box shows the localisation of figure 2 projected into this cross section.

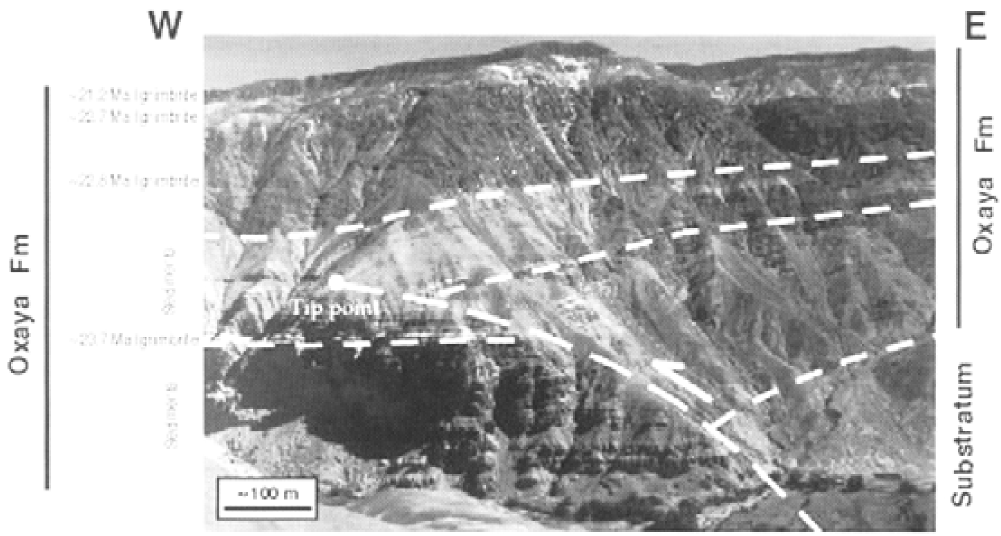

FIG. 2. The Ausipar Fault in the northern side of the Lluta valley (Tiñare). View to the North. The thinning to the east of the Oxaya Formation is apparent due to the perspective of the photography.

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