Reply to the Comment by M. García and G. Hérail 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' by Wörner *et al.* (2000)

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Process and timing of uplift of the Altiplano of the Central Andes is a first-order geological problem. It has attracted the attention from different disciplines such as geophysics, paleobotany, sedimentology, structural geology and geochemistry (*e.g.*, Isacks, 1988; Gregory-Wodzicki, 2000; Gaupp*et al.*, 1999; Allmendinger et al., 1997, Wörner *et al.*, in press). García and Hérail commented on a paper by Wörner *et al.* (2000a), which is mostly concerned with the presentation and interpretation of geochronological data on volcanic and a few intrusive rocks in northernmost Chile. One, albeit important aspect of the interpretation of the new geochronological data relates to the tectonic evolution of the Western Andean Escarpment near Arica during the Miocene, especially the Pampa de Oxaya (*ca.* 18º30'S), which we interpreted as a large gravitationally rotated block.

AGREEMENTS

We would first like to identify those facts and interpretations where we think we agree with García and Hérail:

1- the Oxaya structure is a highly unusual morphological feature which is observed (at least on land) only in the Arica Bend where, as we have argued, the morphological gradient from coast to the crest of the Western Cordillera is greater than anywhere else in northern Chile. The surface of the Oxaya Block has been rotated towards the east, thus creating the unusual staircase morphology of the western slope of the Andes (Fig. 1b). The angle of the inclined, eastward tiling surface, is low, only about 2 or 3 degrees.

2- the stratigraphic framework of sedimentary, pyroclastic and volcanic rocks comprises:

a- The Azapa Formation which includes the Oxaya Ignimbrites of about 25 to 19 Ma age

b- the younger Huaylas Formation overlies the Oxaya Block. Accomodation space and sedimentary infill was provided in response to the tectonic movements of the Oxaya Block and concomitant uplift of the Western Cordillera.

c- we agree that the Lupica Formation is lithologically different from the Azapa and Oxaya Formations (see figure 1 of García and Hérail's comment). This stratigraphic sequence is also consistent with that of Salas *et al.* (1966) and Seyfried *et al.* (2000). The Lupica Formation underlies the Azapa and Oxaya Formations and thus is older (possibly early Tertiary).

d- displacement and rotation of the Oxaya Block (regardless of its cause) must have occurred in the Late Miocene, *i.e.*, during the time-span between 12 Ma and 10.5 Ma (Wörner *et al.*, 2000).

3- along steep mountain fronts compressional and extensional movements may develop simultaneously indeed (Bailey, 1998).

DISAGREEMENTS

The main point of disagreement with García and Hérail concerns the question whether the rotated Oxaya Block is the result of a ramp-and-thrust structure or was caused by gravitational movements. In this context, we will discuss the remaining contentious points, some of which may turn out to be a mere misunderstanding of our text, figures, and interpretation.

Morphology and internal structure

We do not imply, have not argued, and did not show in our figures that the Oxaya Block is a collapse feature in the sense of a chaotic landslide. In that respect, García and Hérail's arguments with reference to geometry, morphology, scale, volume, and internal structure are mute and comparison to the Lluta collapse or other paleo-landslides (*e.g.*, Philip and Ritz, 1999) do not apply. Therefore, it is not an argument against the gravitational cause for rotation, that *'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.'* (comment by García and Hérail). There are abundant examples for real landslides on the western (and eastern) slope of the Andes (*e.g.*, Lluta Collapse, Naranjo *et al.*, 1993, Seyfried *et al.*, 1995; Hermanns and Strecker, 1999); they come in many sizes and shapes. It is obvious to us that the Oxaya Block is **not** a chaotic landslide and that this structure is larger by more than an order of magnitude than any of the landslides mentioned above.

Steepness of the western slope of the Andes in the Arica Bend area

It is not crucial to the discussion whether the slope of the Western Altiplano directly north and south of the Oxaya Block-may be similarly steep, it certainly is. The high resolution morphological map compiled by the Cornell Andes group, however, does show that N and S of the Oxaya structure-the distance between the Western Cordillera and the coast line does in fact increase (http://www.geo.cornell.edu/geology/cap/CAP_gen/CAP_topo.html). Therefore, the slope from the Western Cordillera to the coast is steeper in the Arica Bend area (Figs. 1b, c).

Shape and steepness of the 'Belén Escarpment'

The significance of the steep escarpment between the Oxaya structure and the crest of the Western Cordillera is in fact crucial for our interpretation. In relative terms, the Belén-Escarpment is in fact very steep. Outcrops of Oxaya Ignimbrites to the north and south of the Oxaya Block have not been differentially eroded in significant amounts. Retreating erosion, however, has smoothed the Belén Escarpment. Originally, steepness was not only larger in absolute terms but also relatively to the gently tilted Oxaya surface. We maintain our statement that the Belén Escarpment, which exposes some of Chile's oldest dated rocks (*e.g.*, Wörner *et al.*, 2000b), represents an unusually steep portion of the Western Andean slope in northern Chile. It probably was even steeper prior to retreating erosion, and it should have genetic connection to the origin of the Oxaya Block, which it overtowers.

Lateral and frontal boundaries of the Oxaya Block

We show in figure 1 that the lateral boundaries of the Oxaya Block are in fact transitions rather than boundaries. The overal shape and movement of the block, as seen in the 3-D satellite image is that of a large sag with accomodation zones to the surrounding regions. Therefore, we do not expect sharp sinistral (in the south) and dextral (in the north) offset boundaries, as demanded by García and Hérail.

INTERPRETATIONS OF THE OXAYA BLOCK

There are two fundamentally different models to explain the rotation of this giant block: García and Hérail's interpretation calls for a tectonic ramp structure bounded by two west-vergent thrusts (García *et al.*, 1999, and Comment by García and Hérail). Alternatively, the Oxaya Block is an antithetically rotated, giant gravitational block resulting from oversteepening of the western Andean slope in the Arica Bend area (Wörner *et al.*, 2000).

The sheer size of the Oxaya Block may turn out to be the main problem in accepting it as a large gravitational structure. However, large, gravitationally driven cover nappes are common wherever parts of the Earth's crust has been isostatically uplifted (*e.g.*, Austroalpine and Penninic cover nappes upon and Helvetic cover nappes within the external zone of the Alps).

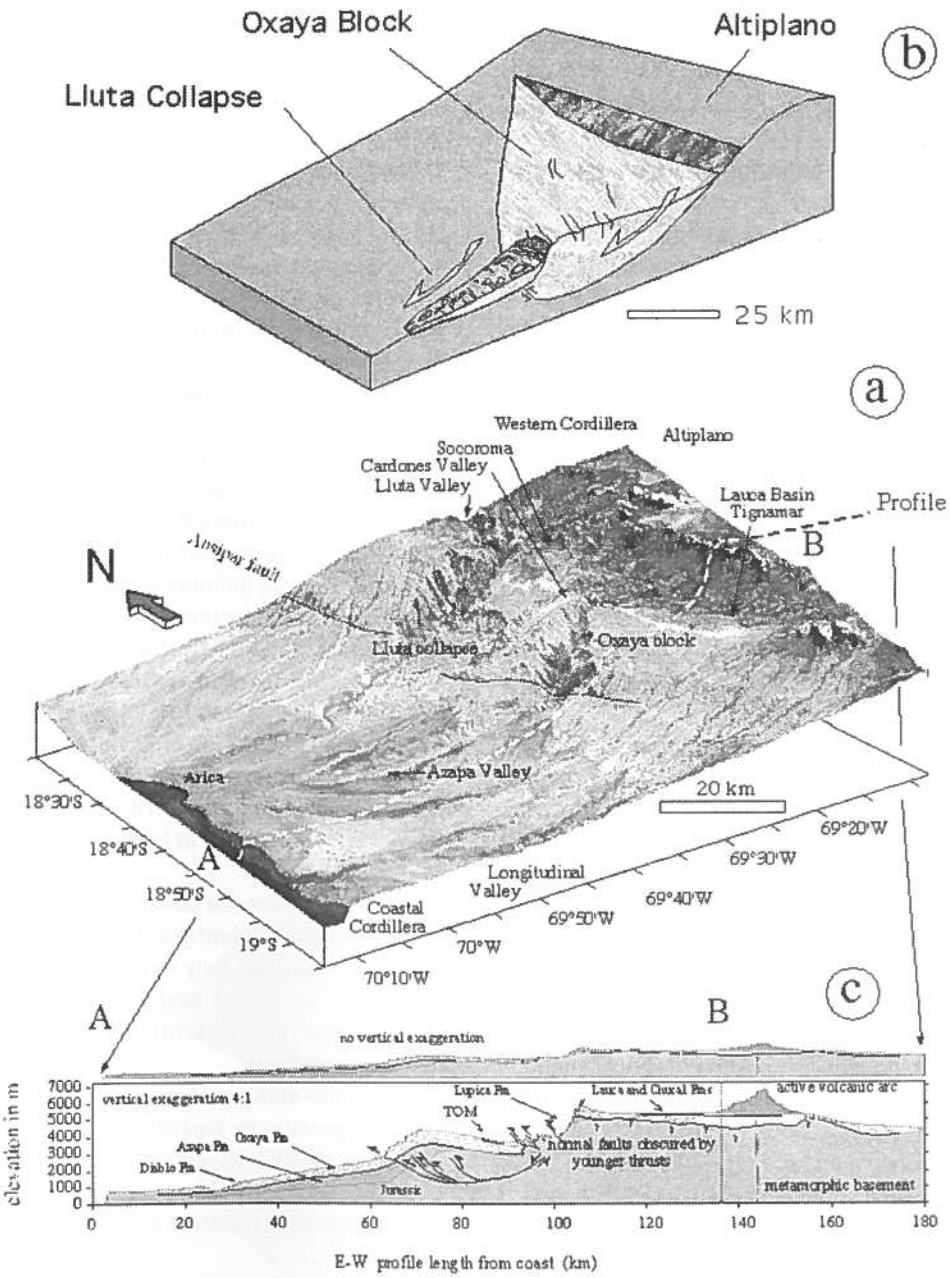

FIG. 1. a- 3-D satellite image showing the structure and morphology of the Oxaya Block and the steep Belén-Escarpment. Note that the lateral boundaries are very smooth and the north and south tips of the structure are actually at a higher elevation than the central parts. The simplified morphological model; b- depicts the block rotation and the Lluta collapse at the steepened front; c- west-east cross section through the Oxaya Block along the topographical profile taken from the 1:250.000 topographical map. The profile shows the steep Belén-Escarpment.

In the following we justify why we do consider the ramp-thrust interpretation to be in conflict with some observations. Secondly, we present data that strongly favour our concept of gravitationally driven tectonics.

Problems with the ramp-and-thrust model

One problem to explain such structure by a stack of ramp thrusts is the fact, that this process would produce much steeper limbs than are actually observed (R. Allmendinger, oral communication, 2000). Rocks of similar competence, which deformed in a ramp-and-thrust fashion (*e.g.,* Kley, 1996) indeed have limbs significantly steeper than observed here.

Another problem is the presumed short duration of the rotation (10.6 -12 Ma) which is more consistent with a gravitational **event** rather than continuous tectonic movements related to the uplift of the Altiplano. Rapid displacement and rotation are further constrained by radiometric ages provided by Wörner *et al.* (2000) and the observation of a reversed drainage system on the Oxaya Block (Uhlig, 2000; Wörner *et al.*, in press)).

Both Muñoz and Charrier (1996) and the Comment by García and Hérail imply that the reverse faults in question mainly caused the uplift of the western Altiplano. We see two problems with this interpretation:

1- the amount of uplift (1500 m) is not explained by the observed vertical throw along the faults (see below) and,

2- the morpho-tectonic structure of the Oxaya Block is restricted to the Arica bend area whereas uplift and a gently dipping western margin of the Altiplano is observed for many hundreds of kilometres alongstrike the western Andean slope. With reference to the slope of the Oxaya surface on both sides (north and south) of the Oxaya Block, the uplifted frontal part of the structure is geometrically balanced by the downward movement of the block. Thus, there is no net uplift related to the structure. While we do not dismiss westward thrusting along the western Andean margin, we observe that regional uplift is not confined to the existence of a ramp-and-thrust structure and that to the north an south of the Oxaya Block, the Western Cordillera is just as high.

Problems with our interpretation of a giant gravitational sag

A problem with our interpretation of the Oxaya Block as a gravitational structure was in fact accentuated by the Comment by García and Hérail in pointing out that where the Ausipar Thrust crops out (Lluta Valley), it is a concave-downward fault, shallowing to a subhorizontal thrust near the surface (García *et al.*, 1999). We do not observe the continuation at depth of the Ausipar Fault as a zone of decollement, but nor do we see the continuation as a blind thrust as postulated in García and Hérail's comment. The main problem with the interpretation of the Ausipar fault as the surface expression of a decollement is the fact, that it has a much smaller displacement than the offset between the crest of the Western Cordillera and the Oxaya Block (1,500 m, see above). This difference in movement between the east- and west-bounding fault zones would argue for internal deformation of the Oxaya Block (Fig. 1c). Moreover, the western limit of the Oxaya Block is close to the Ausipar reverse fault but it may not even be directly related. This is because the reverse offset of the Ausipar fault is larger in the N of the Oxaya Block (as exposed in the Lluta Valley, García *et al.*, 1996) compared to further south in the Azapa Valley.

We conclude from the discussion above that

1- Our model of a giant gravitational sag, as depicted in figure 1 was not fully explained in the paper by Wörner et al (2000) and thus several important points were insufficiently documented and/or misinterpreted;

2- the ramp-and-thrust model is incompatible with some observations, and thus

3- the gravitational sag model is still a viable alternative.

We therefore reiterate our ...

Arguments in favour of a gravitational cause for Oxaya Block rotation

The Oxaya Block formed in the Arica bend area where the western Andean slope from coast to the crest of the Western Cordillera is by far the steepest.

The topography in this region produces a strong negative component in Gephart's (1994) antisymmetric residual in the overall Andean topographic symmetry. It is thus characterized by a topographic anomaly. While the present slope could be steeper than at the time when the Oxaya Block formed, we would argue that the particular location at the Arica Bend would have caused a relatively steep slope also in the geological past.

The short duration of movement (less than 2 Ma) for Oxaya Block rotation is consistent with a gravitational event rather than longer-lasting movements along reverse faults of a ramp and thrust structure.

With reference to the slope of the Oxaya surface to the north and south of the Oxaya Block, the uplifted frontal part of the structure is geometrically balanced by the downward movement of the block. Thus, there is no net uplift related to the structure as would be expected if the block were related to a tectonic ramp structure.

The Oxaya Block has its center at the altitude of the Cardones Valley. However, the Ausipar fault has a larger displacement N of the Lluta valley compared to the area south of the Azapa valley. Thus, the Oxaya Block and the displacement of the Ausipar reverse fault are not directly related.

Our interpretation of a large tilted structure in an overall tectonic regime of convergence and regional tilting is also consistent with conclusions derived by Hartley *et al.* (2000) based on their tectonic and sedimentological analysis of the northern Chilean forearc. Isacks (1988); Lamb *et al.* (1997), and Lamb and Hoke (1997) also argued for regional west-ward tilting of the western Andean slope to explain the uplift of the western Altiplano. These models do not preclude but rather imply distributed reverse surface faulting. The mechanical model of Bailey (1998) also predicts gravitationally induced thrusting on oversteepened orogenic slope and ductile flow within the crust when rheologic properties of the crust are favourable. Rheological weakening due to heating by extensive magmatic activity is certainly attained in the Andean arc region.

One more observation in favour of a gravitational sag structure comes from off-shore geophysical investigations: the CINCA (1995) study showed the

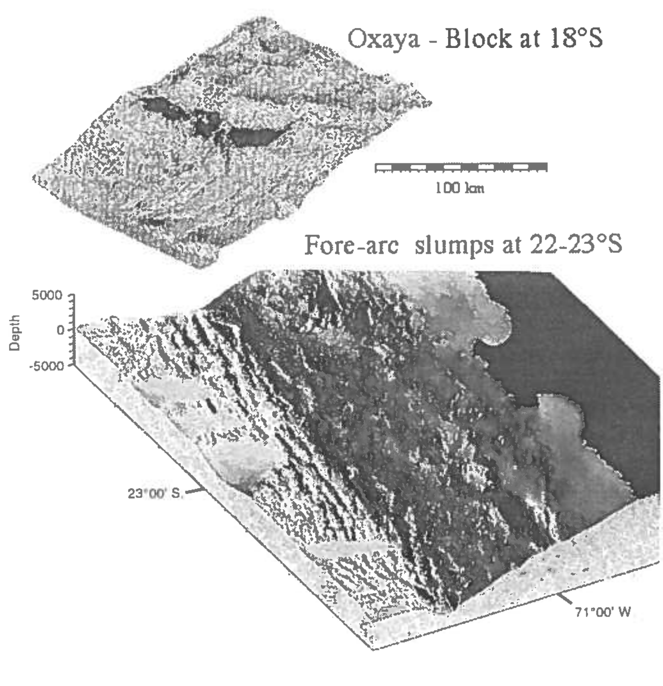

FIG. 2. Comparison of the digital elevation model of the fore-arc region near Antofagasta (modified after CINCA, 1995; see also von Huene *et al.*, 1999). Sizes and shapes of large rotated blocks are similar to the Oxaya Block and the fore-arc 'sags' below sea level. The latter have been identified by von Huene as antithetically rotated blocks due to oversteepening of the fore-arc region.

existence of large north-south oriented sagged blocks in the forearc (>30 km by 15 km in size, Fig. 2). These were interpreted to result from frontal (and basal) tectonic erosion of the outer forearc and subsequent antithetical gravitational rotation (von Huene *et al.*, 1999). In our opinion the Oxaya Block is an on-shore equivalent of these structures.

By weighing the above arguments, we still prefer the interpretation of the Oxaya Block as a large gravitational structure.

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