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Kinematic variations across Eastern Cordillera at 24°S (Central Andes): Tectonic and magmatic implications — Reply

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Abstract

We discuss in detail all the comments made by Petrinovic et al., showing that these are not pertinent to the aim of our study, or based on incomplete information of fault kinematics, or unsupported. Despite our limited amount of data, not any of the raised arguments can be seriously taken into account to alter the proposed scenario. Therefore, we demonstrate that our paper is neither "*largely speculative*" nor "*contains major flaws*".

In particular, the limited evidence of pre-Miocene deformation on a part of a proto-Eastern Cordillera does not affect our interpretation. In fact, our aim was not to reconstruct the tectonic history of Eastern Cordillera, identifying any pre-Miocene episode. Rather, it was to define the kinematics of the largest structures affecting its recent evolution. Therefore, the interesting structures described by Petrinovic et al., also kinematically poorly constrained, cannot give useful insights, simply because the aim and time frame of our study are different.

Keywords: Fault kinematics; Magmatism; Eastern Cordillera

1. Discussion

We thank the authors of the Comment on "*Kinematic variations across Eastern Cordillera at 24°S (Central Andes): tectonic and magmatic implications*", to give us a further opportunity to better discuss our data and hypotheses on the structure of this portion of the Central Andes. The first part of this Reply consists of a detailed response to each comment raised by Petrinovic et al. in order to try to clarify any doubt and to have a more effective and pertinent discussion. The second part, less specialized, will consist of a summary, focused on general considerations.

1.1. Points raised in the Comment

The Comment of Petrinovic et al. is based on several points, listed below, in the same order as they appear to the reader.

1. The model proposed in Acocella et al. (2007) is based on a limited data set.
2. The structure of northern Calchaqui Valley (site 62 of Acocella et al., 2007) is characterized by two opposite-verging reverse or thrust faults; therefore Petrinovic et al. cannot understand how and where the strike-slip motion of Acocella et al. (2007) has been obtained.
3. A major dip-slip component of the Calchaqui Fault during middle Miocene is documented (by Haschke et al., 2005).
4. Measure site 22 of Acocella et al. (2007) is on the reverse Muñano Fault (described in Donato and Vergani, 1988).
5. The computation of the amount of horizontal displacement by Acocella et al. (2007) seems an oversimplification.

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6. "Acocella et al. (2007) assume an Oligocene age for the sediments in the interior of Toro Valley and a late Miocene, or younger, age for the faults juxtaposing the basement on the sediment".
7. Acocella et al. (2007) show a conceptual error by constraining their Andean strain model only from the late Miocene onward. To support this hypothesis, Petrinovic et al. cite eight studies, which, in their opinion, highlight the presence of pre-Miocene tectonics.
8. Magmatism and its relation with the strain field. Three studies are cited by Petrinovic et al. to suggest that magma is currently not present below Eastern Cordillera.
9. Acocella et al. (2007) relate, from a genetical point of view, the Las Burras magmatism to the Altiplano-Puna Magmatic Body (APMB).
10. Neither Matteini et al. (2005a) nor Acocella et al. (2007) present any data to demonstrate the tectono-magmatic relationships at Las Burras pluton.
11. The emplacement of the 14 Ma Las Burras pluton is incorrectly included to prove the alleged relation between late Miocene–Quaternary faulting and magmatism.
12. The study of Acocella et al. (2007) is largely speculative and contains major flaws.

Here we report our detailed replies to the raised comments, numbered as above.

1) We agree with Petrinovic et al. on the fact that our data set is limited, as we already clearly stressed in Acocella et al. (2007), at the beginning of the discussion section. This is the reason why we also wrote, in the same section, that: "*Further investigations may confirm the possible importance of this mechanism in the frame of the tectonic evolution of the eastern Central Andes*".

Nevertheless, despite this limited data set, our goal was to try to understand whether this was indicative of any specific pattern, which may provide a plausible working hypothesis for researchers studying this portion of the Central Andes. So we believe that, giving a contribution in this direction, our goal has been reached.

2) Site 62 in Acocella et al. (2007) is located immediately to the north of the area shown in Fig. 1 by Petrinovic et al. The exact location and coordinates are shown in Fig. 1a. The site consists of fault measures taken for ~1 km along the incision of the stream in the centre of the Valley (Fig. 1b). The obtained structural data, reported in Acocella et al. (2007), are consistent with a N–S trending fault zone, parallel to the northern part of

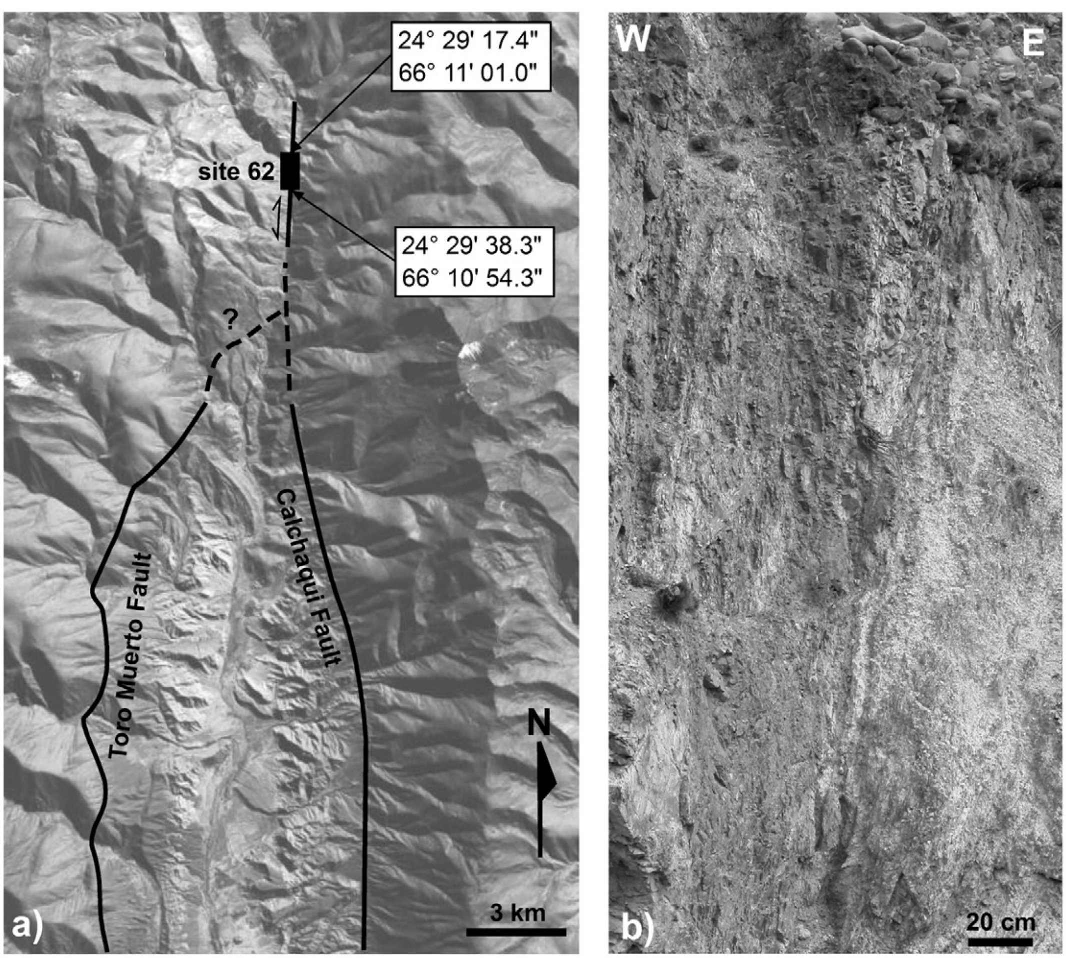

Fig. 1. a) Satellite image and simplified structure of N Calchaqui Valley, western part of Eastern Cordillera of Central Andes. Solid line = major fault; dashed line = inferred fault. Coordinates of measure site 62 in insets. b) Detail of one of the N–S trending subvertical strike-slip splays, associated with cataclastic breccia, of measure site 62.

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the N–S trending Calchaqui Valley, and therefore possibly controlling its development. The narrow fault zone within the valley axis consists of several closely-spaced subvertical splays, with predominant strike-slip component, associated with intense cataclastic breccia within the Puncoviscana Formation (Fig. 1b).

We believe that this fault zone may belong to the high-angle Calchaqui Fault described by Petrinovic et al. In fact, the fault zone lies exactly along the northern continuation of the Calchaqui Fault, whose activity reaches Quaternary (see comment of Petrinovic et al.). We believe that the apparent disagreement between the strike-slip (Acocella et al., 2007) and reverse (Petrinovic et al.) kinematics results from the fact that different types of data are considered. In the one case (Acocella et al., 2007), several slip data on the fault planes are provided. In the other (Petrinovic et al.), stratigraphic relationships and geological sections show a compressional component of vertical displacement. However, this latter type of data provides only 2D information and no clues on any amount of horizontal slip across the fault, which, in principle, may even predominate. For example, the Solà Fault, in the nearby Toro Basin, because of its acknowledged compressional component of vertical displacement, is commonly regarded as a thrust. Nevertheless, slip measurements on the fault planes show that this is a high-angle fault zone characterized by a significant strike-slip component, giving the fault an overall transpressive motion (Acocella et al., 2007).

Therefore, to define the kinematics of a fault, it is essential to consider the orientation of its slickenlines (possibly at several outcrops), which gives the pitch and thus the real 3D sense of motion. Any other tool, including stratigraphic relationships and geological or seismic sections, gives incomplete 2D information and therefore cannot be considered reliable in assessing the kinematics of a fault. For this reason, defining the kinematics of the Calchaqui and Toro Muerto faults in Calchaqui Valley, without any slip data, as tempted by Petrinovic et al., is incorrect and misleading.

3) The study of Haschke et al. (2005) is cited by Petrinovic et al. to infer that the Calchaqui Fault has a major dip-slip component. While a dip-slip component may be certainly present, this is not indicated as “major” by Haschke et al. (2005), who mention a “local dip-slip component” instead. Again, as stressed in point 2), only the complete 3D motion of a fault provides sufficient information on its kinematics.

4) We confirm that site 22 of Acocella et al. (2007) is on the Muñano Fault. However, there is no evidence that this fault has a predominant reverse motion. Once again, the fact that the fault has a reverse component of vertical displacement is not sufficient to say that it is reverse or a thrust, unless it is proved that any strike-slip component is negligible. So, as our slip data show that the Muñano Fault has a predominant strike-slip motion, we have demonstrated that this is not the case.

5) The computation of the horizontal displacement across Eastern Cordillera is certainly a simplification, but it is the best approximation obtained so far. As any quantification of the horizontal displacement in Eastern Cordillera has not ever been made, our contribute is a first approach in this direction. We expect that it will not be the last.

6) Acocella et al. (2007) assume a Cretaceous to Oligocene and an Oligocene age for the sediments immediately below (i.e. in the footwall of) the two thrusts at the E and W sides of Toro Valley respectively, as shown in their Fig. 3. Even though there is not current consensus on the beginning of sedimentation, these ages are taken from previous studies in the area, involving sedimentary and tectonic models (Jordan and Alonso, 1987). Conversely, the sediments in the interior of Toro Valley have a Miocene age, as discussed in detail in Mazzuoli et al. (in press). We do not envisage any inconsistency between these ages and our structural data, as well as with the proposed tectonic model. As regards the fact that we assume “*a late Miocene, or younger, age for the faults juxtaposing the basement on the sediment*”, we cannot understand what the authors are referring to, as we have never considered, in our work, the deformation in the basement. This is an unclear sentence from Petrinovic et al.

7) This is an important point, which deserves a detailed analysis. First, as already cited in Acocella et al. (2007), there is widespread evidence that Eastern Cordillera developed from Miocene to Present, as clearly reported in several studies (Cladouhos et al., 1994; Marrett et al., 1994; Vandervoort et al., 1995; Drozdzewski and Mon, 1999; Strecker and Marrett, 1999; Marrett and Strecker, 2000; Reynolds et al., 2000; Mon et al., 2005).

On the contrary, of the eight references cited by Petrinovic et al. two regard the evolution of Puna, and not of Eastern Cordillera (Kraemer et al., 1999; DeCelles et al., 2007), two clearly state that Eastern Cordillera developed in the last 20 Ma (Miocene; Coutand et al., 2006) and 22 Ma (Dekeen et al., 2006), one does not give any detailed time indication (Mon et al., 1996). Only the studies of Coutand et al. (2001), Del Papa et al. (2004) and Hongn et al. (2007) cite pre-Miocene tectonic episodes for the beginning of the development of a proto-Eastern Cordillera, limited at its western transition with Puna. Moreover, as the authors of Del Papa et al. (2004) and Hongn et al. (2007) are the same, and, as many of these papers cited by Petrinovic et al. (Coutand et al., 2006; DeCelles et al., 2007; Deeken et al., 2006; Hongn et al., 2007) were not published when we returned our last version of the manuscript to *Tectonophysics*, there was poor evidence (Coutand et al., 2001; Del Papa et al., 2004) that pre-Miocene tectonic episodes affected a proto-Eastern Cordillera. Therefore, considering that eight studies (Cladouhos et al., 1994; Marrett et al., 1994; Vandervoort et al., 1995; Drozdzewski and Mon, 1999; Strecker and Marrett, 1999; Marrett and Strecker, 2000; Reynolds et al., 2000; Mon et al., 2005), against two (Coutand et al., 2001; Del Papa et al., 2004), stress that Eastern Cordillera developed from Miocene to Present, our statement was mostly correct.

It is also necessary to emphasize that there is a more relevant point of our study which was not captured by Petrinovic et al. In fact, these Authors seem to ignore that, even though the existence of any pre-Miocene episode of deformation may be demonstrated in any part of Eastern Cordillera, this cannot

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affect the implications of our study. As already stressed (section 3 of Acocella et al., 2007), our investigation on the most important structures across Eastern Cordillera was based on recognizing large and recent fault systems, responsible for an intense deformation and displacement, whose significant extent was supported by clear morphological evidence. Of course, the latter condition implies that the considered fault systems cannot be significantly old, and certainly not of Eocene age. Our aim was not to reconstruct the whole tectonic history of Eastern Cordillera. Rather, it was to define the kinematics of the largest structures affecting its recent evolution. With this regard, we proposed a possible correlation with the underthrusting of the Brazilian Shield, evident north of 24°S and not older than Miocene (Allmendinger and Gubbels, 1996). In this context, the results of Hongn et al. (2007), as well as the map of Petrinovic et al. (reporting the Eocene Toro Muerto Fault, Fig. 1), give no useful insights, simply because the aim and time frame of our study are different.

8) Regarding the possible relationships between tectonics and magmatism, it is first important to recall that only a possible explanation is given in Acocella et al. (2007). In fact, we stressed that: "*The lack of magmatism to the east of Las Burras-Almagro may be related (a) to the effective lack of magma at depth or (b) to the local structural setting, which hinders the shallow rise and extrusion of magma below the easternmost part of the Eastern Cordillera. Since several evidence highlights the widespread presence of molten zones below the Eastern Cordillera (Fig. 7;*Lamb and Hoke, 1997; Pope and Willett, 1998; Riller et al., 2001; Yuan et al., 2000*), it is possible that the absence of magmatic centres to the east of Las Burras-Almagro may be explained by the observed pure contraction*". While the studies we cited suggest the current existence of magma below Eastern Cordillera, it is interesting to learn that the three studies cited by Petrinovic et al. are not particularly useful in suggesting (not even proving) the opposite. In fact, while Haberland et al. (2003) studies the Bolivian Altiplano, Zandt et al. (2003), consistently with Yuan et al. (2000), suggest that, at ~24°S, the eastern limit of the molten zone at depth currently reaches ~65°30′. This area lies to the NNE of our measure site 50 (Fig. 2 in Acocella et al., 2007), beyond the eastern limit of our investigated area. This confirms that magma may be present below a significant part of Eastern Cordillera. This also suggests that the molten zone at depth may have been larger in the past, especially during the peak of volcanic activity in the Central Andes, between 10 and 4 Ma (De Silva and Gosnold, 2007, and references therein), which coincides with the age of the youngest volcanic products in the Las Burras area (Matteini, 2005a,b; Mazzuoli et al., in press). Therefore, it is likely that, despite the widespread presence of molten zones below most of Eastern Cordillera in the past, the rise and emission of the moderate magmatic volumes may have been controlled by tectonics. Stressed this, we cannot exclude, as pointed out (Acocella et al., 2007), that the lack of significant magmatic centres to the east of Eastern Cordillera also resulted from any local lack of magma at depth.

9) Considering the current molten zone below Central Andes (see point 8) as a relic of APBM does not mean that Las Burras magmas and those associated to APBM have a common genesis or history. In fact, one thing is to consider the current, continuous molten zone below the Central Andes as the remnant of that responsible for the peak of volcanism in the region between 10 and 4 Ma, which may have constituted a storage and/or a feeding zone for both the APBM and Las Burras magmas. Other thing is to suggest that both magmas have similar sources and evolution. In fact, there is no evidence of this last statement in Acocella et al. (2007). A more detailed description of our data and hypotheses on these topics is given in Mazzuoli et al. (in press).

10) This misunderstanding in the apparent lack of a proper citation is probably due to the fact that there has been an error in citing the paper of Matteini et al. (2005a) in our study. In fact, the proper citation should have been Matteini et al. (2005b), mentioned in our study, which clearly answers the issue raised by Petrinovic et al. We thank Petrinovic et al. for noticing the error. For a more comprehensive description of the structural data and interpretation, please see Mazzuoli et al. (in press).

11) We have demonstrated, in the replies of points 8, 9 and 10, that this comment is not supported by any fact.

12) This general point is considered in the next section.

1.2. General and conclusive considerations

We believe that, in the previous section, we have shown in detail that the comments made by Petrinovic et al:

(a) are appropriate (points 1 and 10);
(b) derive from an incomplete knowledge of the kinematic and, more in general, structural features of the fault zones in part of Eastern Cordillera (points 2, 3, 4);
(c) are unsupported or inconsistent (points 5, 6, 8, 9, 11);
(d) are not pertinent with the aim of our study and, partly, incorrect (point 7).

Therefore, we have demonstrated, conversely to what proposed by Petrinovic et al. that our paper is neither "*largely speculative*" nor "*contains major flaws*". In fact, despite the limited amount of collected data, not any of the remaining arguments raised by Petrinovic et al. is robust nor convincing enough to alter the tectonic and magmatic scenario proposed in Acocella et al. (2007).

However, because of the limited collected data, we are aware that our study, even though proposing a possible and innovative tectonic model, is far from having clarified the recent tectonic history of Eastern Cordillera. In fact, we do believe that future structural investigations in the area will be necessary, at least to confirm the feasibility or the limits of our proposed model.

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