Volume 42, September 2012
ISSN 0191-8141
ELSEVIER

JOURNAL OF
STRUCTURAL
GEOLOGY

Journal of Structural Geology 42 (2012) 279–282

Contents lists available at SciVerse ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Comment on: “Fault inversion vs. new thrust generation: A case study in the Malargüe fold-and-thrust belt, Andes of Argentina” by J. F. Mescua, and L. B. Giambiagi, Journal of Structural Geology 35 (2012) 51–63

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ARTICLE INFO

Article history:
Received 25 April 2012
Accepted 31 May 2012
Available online 15 June 2012

Keywords:
Andean thrust systems
Fault inversion
Malargüe fold and thrust belt
Main Andes of Argentina

1. Introduction

The work of Mescua and Giambiagi (2012) addressing a case study in the Malargüe fold-and-thrust belt in the Argentinian Andes raises a controversy over two structural models: inversion vs. new thrust generation. The authors examine the potential inversion of Mesozoic normal faults using numerical modeling and discuss contrasting geological arguments in the literature dealing with mechanisms of basement involvement in deformation, analyzing some structural cases “suspected of being inverted normal faults”.

Since Mescua and Giambiagi (2012) attribute the alleged source of the controversy to us (Dimieri, 1997; Turienzo, 2010), we would like to clarify our point of view and to explain our different approach to the subject.

2. The controversy

In the Main Andes (see Fig. 1 of Mescua and Giambiagi, 2012) many geological work has been carried out since the beginning of the 20th century. Notably, the works of Gerth (1931) and Groeber (1947) lay the foundations for further geological and structural studies. These works were based on extensive surveys of the Main Andes, producing some fine regional mapping and were followed by some important structural work by numerous geologists (Ramos, 1988; Kozlowski et al., 1993; Manceda and Figueroa, 1995; Ramos et al., 1996; Cristallini and Ramos, 2000; Giambiagi and Ramos, 2002; Giambiagi et al., 2003a; among others). A common feature characterizing all these works is the structural framework depicted in maps and cross-sections: the ubiquitous presence of thrusts and related folds. We consider that the importance of thrust systems in the building of the Andean orogen during Tertiary times have been extensively documented in the Malargüe region and all over the Main Andes.

Some authors have used different tectonic models in attempting to explain the manner in which these Andean thrust systems are resolved within the basement. Our model holds simply that the thrust systems affecting the cover continue into the basement, reaching a main detachment generated during the Andean orogeny. In this manner we can explain satisfactorily the shortening of basement and cover in the Malargüe FTB (Dimieri, 1997; Turienzo, 2010; Turienzo et al., 2012).

The model of inverted normal faults in this region was suggested by the work of Manceda and Figueroa (1995), this same line of thought being followed by other authors (Giambiagi et al., 2003b, 2009) who proposed that the basement underwent deformation through inversion of Mesozoic normal faults that reach the cover, giving birth to the Andean thrust systems already documented in the Malargüe FTB. In this region, normal faults affecting the basement are not exposed, but are interpreted or inferred mainly through analysis of lineaments and seismic lines (Giambiagi et al.,

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0191-8141/$ – see front matter
http://dx.doi.org/10.1016/j.jsg.2012.05.014

2008; Bechis et al., 2010). In the case of thrusts, however, these are documented on basement exposures in the Malargüe TFB (Dimieri and Nullo, 1993; Dimieri, 1997; Cardozo et al., 2005). We consider that the model of inverted normal faults being responsible for the Andean mountain building is a working hypothesis that needs to be properly documented.

3. Balancing and shortening

We wish to clarify some aspects concerning the assumptions made by Mescua and Giambiagi (2012) in their balanced cross-sections. They conclude that the technique of balancing cross-sections is not useful in attempting to resolve the deep structure of the Malargüe FTB because it does not yield a unique solution. Though this is certainly true, the technique nevertheless constitutes a very useful tool for determining which tectonic model applied to the basement is unlikely to provide a solution and what assumptions were made in the construction of a geological cross-section.

For instance, Mescua and Giambiagi (2012) state that the shortening obtained for the Malargüe FTB with their balanced cross-section at the Atuel River transect is similar to that of Turienzo (2010), despite the different models applied. In their balanced cross-section Mescua and Giambiagi (2012, their Fig. 5) assume that the basement of the Malargüe FTB is internally strained. By analyzing these strained blocks of basement it is possible to estimate the contribution of this internal deformation to the total shortening. Fig. 1 shows the shape of these strained basement blocks (after Giambiagi et al., 2008). Comparison of the deformed and undeformed states shows that block A has changed its shape: it has been horizontally shortened by about 26% (ab – a'b' in Fig. 1), and elongated by about 15% from the main detachment to the basement-cover boundary measured parallel to the basement ramps (cd – c'd' in Fig. 1). The same happens with the horizontal straining of block B (29%, ef – e'f' in Fig. 1). However, unlike block A, block B hardly underwent any elongation at all (gh – g'h' in Fig. 1). Clearly this block straining, which we do not consider to be an appropriate assumption, is required in order to establish the inversion of normal faults as the process responsible for the intense deformed cover in this region. We consider that deformation of basement blocks in the upper crust (the first 10 km according to Mescua and Giambiagi, 2012) was only attained by fragile processes producing sets of fractures and other structures already documented by Turienzo et al. (2006) and Turienzo et al. (2012). We therefore think that Mescua and Giambiagi's figures of shortening cannot be directly compared with our estimates (Turienzo, 2010).

Another assumption in Mescua and Giambiagi's balanced cross-section is that the basement within the footwall block of the La Manga fault on the eastern border of the Atuel depocenter is intensely deformed (Fig. 1). If in the undeformed state we plot a point (*m*) on the footwall block at the basement-cover boundary, and another point (*n*) vertically reaching the main detachment projection, then we can see that the same points in the deformed state (*m*' and *n*') have a separation that implies a basement vertical shortening of about 57%, which is by all means very unlikely. Hence we are of the opinion that the Mescua and Giambiagi model fails to adequately balance the deformation of the basement.

One aspect that called our attention is that the tectonic model of Mescua and Giambiagi (2012, their Fig. 5) implies the inversion of the whole system making up the Atuel depocenter (Giambiagi et al., 2008). In this scenario we do not quite understand why the inversion is accomplished mainly by the La Manga fault, the easternmost fault of the model, which produces most of the displacement (about 8 km). The inverted displacement inferred in the Alumbre and El Freno faults is very small (together about 1 km) compared with that of the La Manga fault. In a model of tectonic inversion we would expect a more equal distribution of inverted displacement among the main faults (Alumbre, El Freno, La Manga); it follows that it is the more westerly fault (Alumbre), which is the nearest to the push side, that would be inverted first, producing a significant displacement. This is supported by experimental results obtained by Yagupsky et al. (2008) who conclude that, in an inversion process, contractional strain is initially accommodated by the reactivation of the pre-existing hemigraben

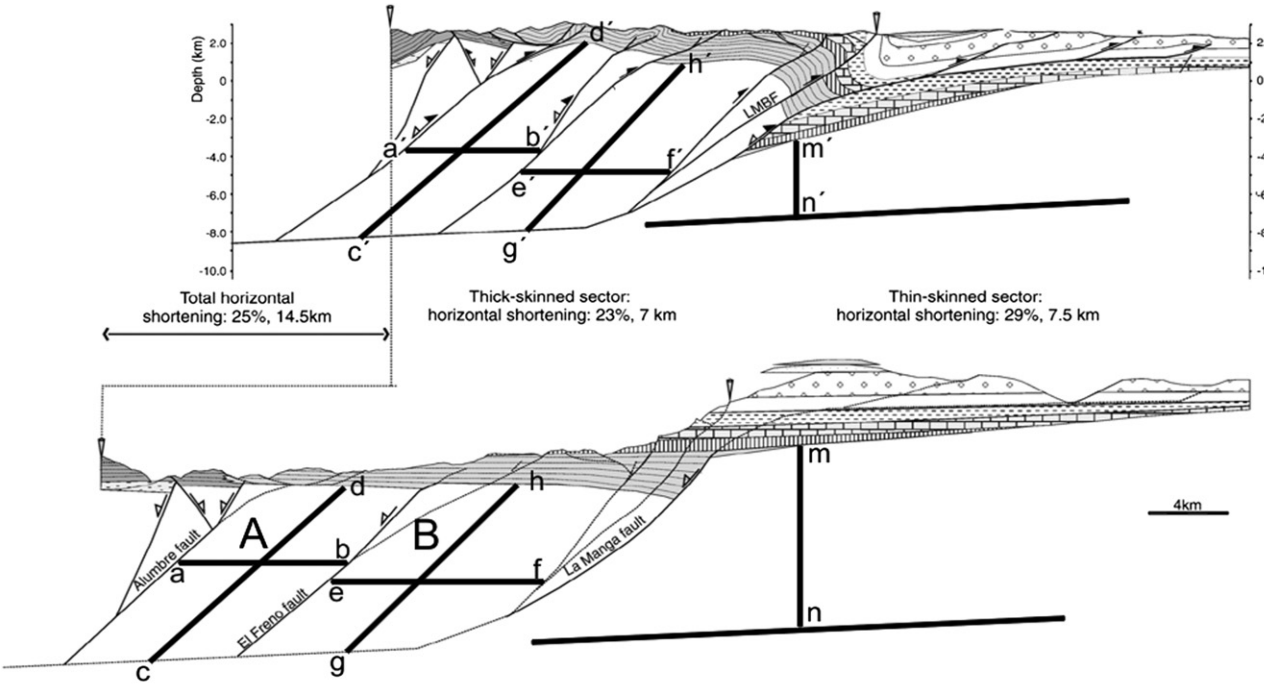

Fig. 1. Balanced cross-section in the area of the Atuel depocenter, from Giambiagi et al. (2008). Thick black lines (ab, cd, ef, gh, mn, a'b', c'd', e'f', g'h', m'n') were added in order to highlight the deformation of the basement blocks (see explanation in text).

segment closest to the deformation front while at some critical distance the deformation front departs from the hemigraben control.

4. The case study: examples of suspected inverted faults

We wish to comment on some aspects of the case study introduced by Mescua and Giambiagi (2012). We will not repeat here the geological characteristics of the Malargüe FTB, which was adequately covered in their work. We would like to focus instead on the magnitude of the stratigraphic units belonging to the Neuquén basin (see Fig. 1 of Mescua and Giambiagi, 2012) that comprise the Malargüe FTB. This basin was initiated with sediments deposited unconformably over basement rocks in isolated depressions during the Late Triassic to Early Jurassic. These sequences, mostly continental deposits with minor thicknesses, are considered synrift deposits that form part of a rift system according to Legarreta and Gulisano (1989); Legarreta and Uliana (1991); Manceda and Figueroa (1995); among others. Above these rocks there is a stratigraphic pile several kilometers thick of Middle Jurassic to Lower Cretaceous platform sequences, Upper Cretaceous to Paleogene continental and marine strata, and Neogene-Quaternary synorogenic continental strata and volcanic rocks. We do not sustain that the development of this Late Triassic to Early Jurassic extensional system in the Malargüe region is a key feature in the building of the Main Andes through inversion tectonic processes, since it is composed of few restricted depocenters whose average stratigraphic thicknesses are of about few hundred meters and seldom exceed a kilometer (Manceda and Figueroa, 1995). In their study of the Yeguas Muertas depocenter, Giambiagi et al. (2003b) accordingly state that "*although the role of pre-existing extensional basin faults in controlling the structural style of the Andes is important, it cannot account for the high levels of shortening within this belt*".

Furthermore, the geometry of the extensional faults systems responsible for these Late Triassic–Early Jurassic depocenters has not yet been well documented. These depocenters are considered hemigrabens (Manceda and Figueroa, 1995). In this matter we think that the assertion of Giambiagi et al. (2003b) concerning the Yeguas Muertas depocenter gives us a clear-cut picture of the problem: "*Although little can be known about the Late Triassic–Early Jurassic rift system because no subsurface data exist and exposures are few, rift stratigraphy, specially thickness variations in strata of this age and their structural relationships, provides evidence for normal faulting*".

In the case of the Atuel hemigraben (Manceda and Figueroa, 1995), most of the architectural design was also inferred largely by means of stratigraphic criteria (Giambiagi et al., 2008; Bechis et al., 2010). In this depocenter these authors proposed their geometrical model based mainly on the stratigraphic studies of Lanés (2005). These studies were intensely debated by some authors (Spalletti et al., 2005, 2007) proposing different facies associations and stratigraphic schemes. The stratigraphy of the Atuel depocenter is thus still unresolved and requires further study; models of fault tectonics founded on these stratigraphic studies can therefore be considered at best hypothetical.

One aspect to be looked at more closely is the orientation of the west dipping master fault (La Manga) located on the eastern border of the Atuel hemigraben (Mescua and Giambiagi, 2012, their Fig. 5). According to Lanés (2005); Spalletti et al. (2005); Giambiagi et al. (2008) and Bechis et al. (2010), the oldest synrift units and the thickest stratigraphic pile are located on the western border. In this scenario we would expect an east-dipping master fault located close to the oldest and thickest units in the western border of the Atuel hemigraben, which is the opposite-facing geometry to that proposed by Mescua and Giambiagi (2012).

With respect to the "suspected inverted" Palauco fault, we consider there are more suitable interpretations than that of Mescua and Giambiagi (2012, their Fig. 6). An alternate interpretation is that instead of an inverted fault, there is a backthrust connected to a foreland-directed thrust system affecting the basement and cover rocks; this interpretation is supported by the fact that such structures are common in the Malargüe FTB. For instance, in the Bardas Blancas section (Dimieri, 1997; Cardozo et al., 2005), to the west of the Palauco fault, a backthrust affecting the basement and cover is exposed (Fig. 2). If in the case of the Bardas Blancas section, a nice exposure of uplifted basement and cover rocks, there is no evidence of inversion tectonics or master normal faults (Manceda and Figueroa, 1995; Dimieri, 1997; Cardozo et al., 2005; Giambiagi et al., 2009), then surely it is questionable to interpret inversion tectonics in a neighboring eastern region (Palauco) with an unexposed basement.

The model of inverted normal faults implicitly involves the intimate linking between uplifted basements blocks and the hanging walls of inverted normal faults. After inversion therefore those uplifted hanging wall blocks must carry the thickest stratigraphic pile of synrift rocks. The Malargüe FTB has some nice exposures of the uplifted basement and its cover rocks at the localities of Bardas Blancas and Las Leñas. In these places there is no evidence of inverted normal faults, and the thicknesses of the synrift rocks are very small, so the model of inversion of normal faults can hardly be applied here (Manceda and Figueroa, 1995; Dimieri, 1997; Cardozo et al., 2005; Giambiagi et al., 2009). It seems that the model works only where the basement is unexposed (Atuel and Palauco depocenters), so it must be constructed through the interpretation of seismic lines and lineaments.

Fig. 2. Photo showing thrusting in basement and cover rocks in the area of Bardas Blancas, to the west of Palauco fault.

5. Numerical modeling

We welcome the studies introduced by Mescua and Giambiagi (2012) pertaining to the analysis of the potential inversion of normal faults through numerical modeling of physical parameters in fault surfaces. The aim of their modeling focused on the analysis of the conditions under which a normal fault with a dip of 50–60° can be inverted. Though their results can be valuable, we consider that this dip assumption is inaccurate for normal faults near the surface. According to Walsh and Watterson (2002), dip data from actual normal faults averaged 70° in the upper 3–4 km of the crust, which is a better approximation than the commonly accepted value of 60°. The assumption of dip angles of less than 60° is more appropriate for deeper sections of the fault surfaces.

Another aspect deserving of comment is that Mescua and Giambiagi (2012) conclude that the coefficient of friction on the fault plane must be lowered considerably in order to produce reactivation of normal faults. Since a low coefficient of friction is a necessary condition, they state that this can be met in the Malargüe FTB because the normal faults systems might have generated clay gouges and smears or even phyllonite. On the contrary, close examination of one of the few exposures of a thrust that affects basement and cover in this region (Fig. 2) reveals a tiny discrete fractured zone with no evidence of phyllonite or clay gouges.

Although the results of the numerical modeling may be valuable, we do not consider that the assumptions made by Mescua and Giambiagi (2012) for the physical parameters meet the prevailing conditions in the Malargüe FTB.

6. Concluding remarks

The work of Mescua and Giambiagi (2012) presents a controversial hypothesis of the way Andean thrust systems resolve within the basement in the Malargüe FTB of the Argentinian Andes. They conclude that the Andean thrust systems exposed in the Malargüe FTB were generated by inversion of normal faults that belong to Late Triassic-Early Jurassic extensional depocenters. They further state that these inversion processes should be considered the rule rather than the exception in this region.

We on the contrary think that Andean thrust systems, which are exposed on basement and cover, were the main structures that generated the Malargüe FTB. The inversion of normal faults is still not well documented in the Malargüe FTB. The model proposed by Mescua and Giambiagi (2012) did not properly balance the deformation of the basement. The "suspected" inverted faults form part of a few isolated depocenters that extend only partially below the Malargüe FTB, clearly indicating that the inversion process cannot be responsible for the building of the entire belt. For these reasons we consider that the inversion of main normal faults in the Malargüe FTB, although theoretically feasible and a process that could possibly have occurred, is not significant in the building of the Main Andes, let alone the "rule".

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