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The role of gravitational collapse in controlling the evolution of crestal fault systems (Espírito Santo Basin, SE Brazil) – Reply

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1. Introduction

This reply concerns Jackson et al. discussion, which queries the interpretation of fault propagation styles provided in Ze and Alves (2016). Our emphasis will be on the way Ze and Alves (2016) compiled throw-distance (T-D) and throw-depth (T-Z) plots after recognising a series of *large* faults that comply with the 'isolated' fault growth described in Walsh et al. (2003) and the newer Jackson and Rotevatn (2013). In our work, T-D and T-Z plots were used to highlight the presence of small-scale segments in larger, 'isolated' faults (see Fig. 3 and the start of Section 6 in Page 87, for instance), a character indicating predominant 'fault-linkage' growth models in the study area (Kim and Sanderson, 2005). However, we partly disregarded this latter growth style to support our interpretations on the mapping of the 'trace length in map view' or 'the longest horizontal dimension' of imaged faults (Cartwright et al., 1995; Schultz and Fossen, 2002; Kim and Sanderson, 2005), a scale of analysis a) greater than assumed in Jackson et al. discussion, b) larger than the component segments of discrete faults, c) deemed appropriate for the sizes and geometries of salt structures investigated in SE Brazil. Jackson et al. discussion lead us to invoke an important paradigm concerning the use of T-D and T-Z data in fault analyses; the scale(s) in which one undertakes and interprets fault throw (or displacement) data is variable and depends on data resolution and pre-defined structural criteria (e.g. Walsh and Watterson, 1991; Walsh et al., 2003; Kim and Sanderson, 2005).

2. Local fault geometries and throw distributions

In Ze and Alves (2016) interpreted faults are either associated with single, isolated, fault planes (e.g. Faults 1C, 1D, 2H) on time-structure maps or, instead, reflect segmented structures that experienced distinct degrees of reactivation (e.g. Faults 2A/BF2 and 2C). Reactivated faults show, as a result, sections with characteristic 'double-C' T-Z profiles (see Section 6 in Ze and Alves, 2016, and also Baudon and Cartwright, 2008). Ze and Alves (2016) indicate that fault length varies between ~410 m and 1750 m, with border faults ranging from 1250 m to 1750 m, i.e. values 2-3 times larger than the smaller segments highlighted in T-D plots. When plotting their T-D curves side-by-side, along their strikes, faults do not add up to a cumulative T-D distribution similar to Walsh et al. (2003) definition of a 'coherent' fault array. Instead, segments identified in T-D plots and vertical seismic profiles suggest a predominance of an incipient stage of growth *sensu* the 'fault-linkage' model of Kim and Sanderson (2005), but this characteristic is not confirmed for all 84 faults analysed, some of which grew as discrete structures (Figs. 9-12 in Ze and Alves, 2016). Therefore, Groups 1 to 4 faults comprise the discrete (mappable) structures, showing distinct orientations and throw propagation histories, that Ze and Alves (2016) identified above a salt ridge to later postulate about their propagation history (see Figs. 15 to 19).

We realise, based on Walsh and Watterson (1991), Walsh et al. (2003), Kim and Sanderson (2005) and Fossen and Rotevatn (2016), that published definitions of 'isolated' vs. 'coherent' fault growth modes are based on geometrical and kinematic information so that one distinguishes faults formed under the two models on vertical seismic profiles, and not only through the compilation of isochron maps, or via estimations of *Expansion Indexes* (EI) (see Jackson et al., in press). Geometric coherence, for instance, was defined by Walsh and Watterson (1991) as the existence of regular and systematic displacement patterns in a family of faults. Kinematic coherence reflects the existence of synchronous slip rates and slip distributions that are arranged such that *geometric coherence* is maintained (see also Peacock et al., 2000). Based on these concepts, we must stress that T-Z data for our Group 1 to 4 faults show they first nucleated in strata with multiple ages and thicknesses and, while including a number of structures offsetting the ‘top salt’ horizon, other faults only intersect strata close to, or above horizons H2 and H3, showing growth strata of distinct ages and geometries (Figs. 1, 3 and 4 in Ze and Alves, 2016). As Walsh et al. (2003) rightly stated (...) *failure to recognise that segments are components of a larger fault will inevitably lead to an over reliance of models on the growth of faults by linkage of isolated segments*. This caveat is precisely the reason why Ze and Alves (2016) classified (and identified) the larger faults in separate groups (Groups 1 to 4). We suggest seismic and structural interpreters to follow a similar approach to Ze and Alves (2016): to divide faults in distinct groups at the start of their analyses for the reason that their geometries, heights, T-Z and T-D patterns, are strikingly different.

3. Scale variance in T-Z and T-D plots

It is therefore important to distinguish (and map) resolvable faults from the moment one begins to analyse them (see sub-section 5.1 in Pages 85 and 86). In Ze and Alves (2016), faults present distinct orientations and curved geometries in most places, a character that continues to the north and south of the study area around distinct salt structures (Figs. 1 and 3 in Ze and Alves, 2016). They are seldom laterally linked, and are also cross-cut by the transverse accommodation zone (TAZ) described in Ze and Alves (2016). This same approach (to distinguish and map the larger resolvable faults) is important and precedes the recognition of fault segments using T-D plots. Fault segment recognition, however, is known to be scale-variant, not depending on absolute throw (or displacement) values, but rather on the distinction of meaningful throw gradients representing segment linkages on T-D (or D_{max}/L) plots, accompanied by their analysis on vertical seismic profiles, structural maps, or at outcrop (Kim and Sanderson, 2005). It is also a known fact that distinct fault segments often present distinct T-D (or D_{max}/L) relationships due to multiple geological, and methodological, reasons when interpreting 3D seismic and outcrop data (Kim and Sanderson, 2005). Thus, one crucial question arising from Jackson et al. comments is at what scale(s) should one distinguish 'isolated' from other fault growth models (e.g. Fig. 7 in Kim and

Sanderson, 2005)? Based on the fault geometries observed in our study area, and on the size(s) of interpreted salt structures, we consider that greater emphasis should be given to the 'isolated' faults in Groups 1 to 4, which clearly dissect the crest of multiple salt ridges and diapirs (Figs. 1 and 3, Ze and Alves, 2016), not to their constituting segments. This choice is primarily based on the fact that clear interruptions in fault trace are observed in between distinct Group 1 to 4 faults, not between their constituting segments.

4. Compilation of EI and isochron maps from synkinematic sequences

The underlying objective of Ze and Alves (2016) paper was, therefore, to try and test how could one ascertain the development of crestal faults above a salt ridge in SE Brazil when it is understood that crests of salt structures form broad areas of uplift, fault reactivation and seafloor erosion without (or with truncated) synkinematic sequences. We agree that EI (*Expansion Index* sensu Thorsen, 1963 in Groshong, 2006) data could have been broadly collected, but the larger faults (namely Groups 1, 2 and 3) are still relatively small, concave-shaped and listric, important characteristics that were later stressed in the discussion prepared by Ze and Alves (2016). The larger faults were also too often reactivated, and offset by opposite-dipping faults (*crossing conjugate faults* in Ferrill et al., 2000), to provide a meaningful set of EI measurements along their full length. These are characteristics providing important evidence as to what the genesis of the interpreted faults might be, and meant that the methods in Alves (2012) could not be applied to our study area. For these reasons, we found appropriate to test the validity of local unconformities as relative markers from which one can obtain information (if only partially) about fault growth and propagation, and to classify crestal faults in distinct groups. These same techniques by Baudon and Cartwright (2008) were successfully applied to areas recording discrete uplift, subsidence and erosion, as often is the case above evolving salt structures.

5. Vertical resolution as a function of data sampling

We invite the readers of this reply, to revert to *sub-section 6.4* (Page 89) in Ze and Alves (2016), explaining why can one observe Group 4 faults with offsets of 8 ms and less. The value of 8-10 m suggested early in the paper for *near seafloor strata* is, to all effects and purposes, a very conservative estimate used in virtually every research paper dealing with the interpretation of seismic data. It is based on the dominant frequency of the acquired seismic data and, specifically for the study area, was estimated taking into account the low frequency of seismic reflections observed in sediment drifts accumulated below the modern sea floor (e.g. Alves et al., 2012; Gamboa et al., 2015). Upon careful analysis, one can use (as we did) the wiggle display on a seismic workstation to verify that trace (or wiggle) spacing, and the *de facto* vertical seismic resolution at the depth of our analysis, is at least 4 ms for the high-frequency strata below Horizon H5, in which the majority crestal faults are observed (Fig. 4, Page 84 in Ze and Alves, 2016). Fault offsets below 4 ms were often resolved in the interpreted seismic volume when approaching the faults' lateral tips, hence seismic vertical resolution is surely beyond 1/4 of the characteristic wavelength (i.e. still a higher resolution than 8-10 m), or dominant frequency, invoked in most research papers and by Jackson et al. in their discussion (Chopra et al., 2006; Chopra et al., 2016; De Angelo and Hardage, 2016; Rafaelsen et al., 2006). We advise seismic and structural interpreters to measure definite, unequivocal fault offsets. In our study area, only the four (4) faults in Group 4 present average offsets around 4-8 ms two-way time. All other faults show offsets of 20 ms or more, in average, reaching more than 80 ms over the crest. These are values 5 to 20 times larger than the sampling interval of our seismic volume, i.e. significant values when considering that we are imaging shallow-buried structures (< 0.75 s below the sea floor).

6. Propagation styles of crestal faults

Comprehensive information on physical models and seismic-based studies of salt-related faults, from Letouzey et al. (1995), Schuster (1995), Ge et al. (1997), Ge and Jackson (1998) to Rowan et al. (1999), Cotton and Koyi (2000) and more recent work, have shown that areas of gravitational movement of overburden strata above evaporites, when developing in similar geological settings as our study area, will form discrete fault segments, often concave-shaped, that link together in later stages of crestal collapse (see also Vendeville, 1991; Childs et al., 1993; Vendeville et al., 1995; Vendeville, 2005; Morley, 2007; Clausen et al., 2014). Importantly, Fossen and Rotevatn (2016) consider these same geometries as occurring naturally in systems comprising a competent unit (sandstone, limestone, basalt layer) over a softer or viscous unit (shale or salt) or, instead, in clastic sediments sliding on a low-angle décollement of evaporites or overpressured shale on a passive margin. They lead to the development of 'isolated' faults. Based on our own data and the information above, we interpret the great majority of crestal faults in our study area as having been formed in association with recurrent episodes of salt growth, subsidence (crestal collapse) and associated crestal erosion, following an 'isolated' fault growth model (Fig. 17, Page 95). Ze and Alves (2016) also postulate that gravitational collapse is a significant process in their study area, and that border faults (and transverse accommodation zones) are key features controlling this same collapse, separating areas on a salt ridge with distinct fault geometries. The complex fault geometries observed in Ze and Alves (2016) are essentially a result of the gravitational component (variable in space and time) that, ultimately, generated 'isolated' faults separated by a transverse accommodation zone (Figs. 16 to 18, Pages 95 and 96).

7. Conclusions

In conclusion, we accept the fact that Jackson et al. discussion results from an important, often overlooked, paradigm concerning the use of T-D and T-Z plots in fault analyses: the scale(s) in which one collects and interprets fault throw (or displacement) data should be defined early in any structural analysis (Walsh and Watterson, 1991; Kim and Sanderson, 2005). In structural geology the chosen scale(s) of observation, and analysis, depends on the degree of detail one can meaningfully interpret using varied data sets, from seismic data, outcrops and structural maps, to physical laboratorial models and micro-structural experiments. It also depends on how significant (i.e. helpful) the acquired structural data are to the understanding of 'broader' larger-scale structures - in our case, the salt ridges identified in Ze and Alves (2016). A known fact when using T-D and T-Z data is that the interpretation of fault propagation styles is scale-variant, and geometric coherence should occur at smaller scales of observation in even the most 'isolated' of faults (Walsh and Watterson, 1991). We are thus compelled to stress that interpretation errors may occur in many a structural analysis if one systematically overlooks these caveats, particularly in an era of ever-so-quickly improvements in the quality and resolution of 3D seismic data, remote sensing imagery and outcrop-based studies. Based on our own Ze and Alves (2016), we suggest structural interpretations of high-quality seismic data to be based on the recognition of the 'trace length in map view' or 'the longest horizontal dimension' of distinct faults (Cartwright et al., 1995; Schultz and Fossen, 2002; Kim and Sanderson, 2005), with further detail being built upon the recognition of these primary structures.

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