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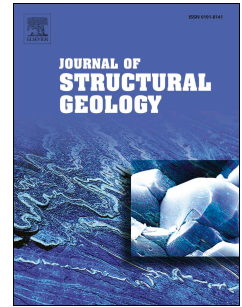
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The role of gravitational collapse in controlling the evolution of crestral fault systems**(Espírito Santo Basin, SE Brazil) – Reply**

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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).

27 2. Local fault geometries and throw distributions

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

43 We realise, based on Walsh and Watterson (1991), Walsh et al. (2003), Kim and Sanderson
44 (2005) and Fossen and Rotevatn (2016), that published definitions of 'isolated' vs. 'coherent' fault
45 growth modes are based on geometrical and kinematic information so that one distinguishes faults
46 formed under the two models on vertical seismic profiles, and not only through the compilation of
47 isochron maps, or via estimations of *Expansion Indexes* (EI) (see Jackson et al., in press).
48 Geometric coherence, for instance, was defined by Walsh and Watterson (1991) as the existence of
49 regular and systematic displacement patterns in a family of faults. Kinematic coherence reflects the
50 existence of synchronous slip rates and slip distributions that are arranged such that *geometric*
51 *coherence* is maintained (see also Peacock et al., 2000). Based on these concepts, we must stress
52 that T-Z data for our Group 1 to 4 faults show they first nucleated in strata with multiple ages and

53 thicknesses and, while including a number of structures offsetting the ‘top salt’ horizon, other faults
54 only intersect strata close to, or above horizons H2 and H3, showing growth strata of distinct ages
55 and geometries (Figs. 1, 3 and 4 in Ze and Alves, 2016). As Walsh et al. (2003) rightly stated (...)
56 *failure to recognise that segments are components of a larger fault will inevitably lead to an over*
57 *reliance of models on the growth of faults by linkage of isolated segments.* This caveat is precisely
58 the reason why Ze and Alves (2016) classified (and identified) the larger faults in separate groups
59 (Groups 1 to 4). We suggest seismic and structural interpreters to follow a similar approach to Ze
60 and Alves (2016): to divide faults in distinct groups at the start of their analyses for the reason that
61 their geometries, heights, T-Z and T-D patterns, are strikingly different.

62

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

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

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

85 86 **4. Compilation of EI and isochron maps from synkinematic sequences**

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

103

104 **5. Vertical resolution as a function of data sampling**

105 We invite the readers of this reply, to revert to *sub-section 6.4* (Page 89) in Ze and Alves (2016),
106 explaining why can one observe Group 4 faults with offsets of 8 ms and less. The value of 8-10 m
107 suggested early in the paper for *near seafloor strata* is, to all effects and purposes, a very
108 conservative estimate used in virtually every research paper dealing with the interpretation of
109 seismic data. It is based on the dominant frequency of the acquired seismic data and, specifically for
110 the study area, was estimated taking into account the low frequency of seismic reflections observed
111 in sediment drifts accumulated below the modern sea floor (e.g. Alves et al., 2012; Gamboa et al.,
112 2015). Upon careful analysis, one can use (as we did) the wiggle display on a seismic workstation
113 to verify that trace (or wiggle) spacing, and the *de facto* vertical seismic resolution at the depth of
114 our analysis, is at least 4 ms for the high-frequency strata below Horizon H5, in which the majority
115 crestal faults are observed (Fig. 4, Page 84 in Ze and Alves, 2016). Fault offsets below 4 ms were
116 often resolved in the interpreted seismic volume when approaching the faults' lateral tips, hence
117 seismic vertical resolution is surely beyond 1/4 of the characteristic wavelength (i.e. still a higher
118 resolution than 8-10 m), or dominant frequency, invoked in most research papers and by Jackson et
119 al. in their discussion (Chopra et al., 2006; Chopra et al., 2016; De Angelo and Hardage, 2016;
120 Rafaelsen et al., 2006). We advise seismic and structural interpreters to measure definite,
121 unequivocal fault offsets. In our study area, only the four (4) faults in Group 4 present average
122 offsets around 4-8 ms two-way time. All other faults show offsets of 20 ms or more, in average,
123 reaching more than 80 ms over the crest. These are values 5 to 20 times larger than the sampling
124 interval of our seismic volume, i.e. significant values when considering that we are imaging
125 shallow-buried structures (< 0.75 s below the sea floor).

126

127 **6. Propagation styles of crestal faults**

128 Comprehensive information on physical models and seismic-based studies of salt-related faults,
129 from Letouzey et al. (1995), Schuster (1995), Ge et al. (1997), Ge and Jackson (1998) to Rowan et
130 al. (1999), Cotton and Koyi (2000) and more recent work, have shown that areas of gravitational

131 movement of overburden strata above evaporites, when developing in similar geological settings as
132 our study area, will form discrete fault segments, often concave-shaped, that link together in later
133 stages of crestral collapse (see also Vendeville, 1991; Childs et al., 1993; Vendeville et al., 1995;
134 Vendeville, 2005; Morley, 2007; Clausen et al., 2014). Importantly, Fossen and Rotevatn (2016)
135 consider these same geometries as occurring naturally in systems comprising a competent unit
136 (sandstone, limestone, basalt layer) over a softer or viscous unit (shale or salt) or, instead, in clastic
137 sediments sliding on a low-angle décollement of evaporites or overpressured shale on a passive
138 margin. They lead to the development of 'isolated' faults. Based on our own data and the
139 information above, we interpret the great majority of crestral faults in our study area as having been
140 formed in association with recurrent episodes of salt growth, subsidence (crestral collapse) and
141 associated crestral erosion, following an 'isolated' fault growth model (Fig. 17, Page 95). Ze and
142 Alves (2016) also postulate that gravitational collapse is a significant process in their study area,
143 and that border faults (and transverse accommodation zones) are key features controlling this same
144 collapse, separating areas on a salt ridge with distinct fault geometries. The complex fault
145 geometries observed in Ze and Alves (2016) are essentially a result of the gravitational component
146 (variable in space and time) that, ultimately, generated 'isolated' faults separated by a transverse
147 accommodation zone (Figs. 16 to 18, Pages 95 and 96).

148

149 **7. Conclusions**

150 In conclusion, we accept the fact that Jackson et al. discussion results from an important, often
151 overlooked, paradigm concerning the use of T-D and T-Z plots in fault analyses: the scale(s) in
152 which one collects and interprets fault throw (or displacement) data should be defined early in any
153 structural analysis (Walsh and Watterson, 1991; Kim and Sanderson, 2005). In structural geology
154 the chosen scale(s) of observation, and analysis, depends on the degree of detail one can
155 meaningfully interpret using varied data sets, from seismic data, outcrops and structural maps, to
156 physical laboratorial models and micro-structural experiments. It also depends on how significant

157 (i.e. helpful) the acquired structural data are to the understanding of 'broader' larger-scale structures
158 - in our case, the salt ridges identified in Ze and Alves (2016). A known fact when using T-D and T-
159 Z data is that the interpretation of fault propagation styles is scale-variant, and geometric coherence
160 should occur at smaller scales of observation in even the most 'isolated' of faults (Walsh and
161 Watterson, 1991). We are thus compelled to stress that interpretation errors may occur in many a
162 structural analysis if one systematically overlooks these caveats, particularly in an era of ever-so-
163 quickly improvements in the quality and resolution of 3D seismic data, remote sensing imagery and
164 outcrop-based studies. Based on our own Ze and Alves (2016), we suggest structural interpretations
165 of high-quality seismic data to be based on the recognition of the 'trace length in map view' or 'the
166 longest horizontal dimension' of distinct faults (Cartwright et al., 1995; Schultz and Fossen, 2002;
167 Kim and Sanderson, 2005), with further detail being built upon the recognition of these primary
168 structures.

169

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