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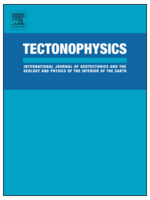

Reply to Comment on "The earthquakes of 29 July 2003, 12 February 2007, and 17 December 2009 in the region of Cape Saint Vincent (SW Iberia) and their relation with the 1755 Lisbon earthquake" by C. Pro, E. Buforn, M. Bezzeghoud and A. Udías

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Cape Saint Vincent
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Source rupture process
Slip distribution

Indeed, the Lisbon earthquake is a very unusual seismic event and an exception to the rule because most great tsunami-generating earthquakes are related to well-defined subduction zones. The epicentral region, focal mechanism and the structures involved at the origin of this earthquake are still a matter of debate, with several models having been proposed (e.g. Baptista et al., 2003; Grandin et al., 2007a,b; Gutscher et al., 2006; Ribeiro et al., 2006; Vilanova et al., 2003; Zitellini et al., 2001).

For example, Vilanova et al (2003) propose that although the mainshock was offshore, the resulting stress changes induced the occurrence of secondary earthquake with rupture of the Lower Tagus Valley fault, located near Lisbon, which caused the large damage of the city. The comment by Fonseca (2014) uses this model to object to the source location and the directivity effects proposed by Pro et al. (2013) to explain the extreme damage caused in Lisbon. But the comment omits three articles that examine in detail the 1755 earthquake, and the rupture directivity and Earth structure effects associated in general to large earthquakes (Bezzeghoud et al., 2011; Grandin et al., 2007a,b). Two of them, cited in Pro et al. (2013), help understand our model and argue the proposed relationship among the earthquake rupture process behavior, ground motion, and tsunami generation.

The comment's main argument is based on the long epicentral distance (about 260 km), explaining that a rupture located offshore San Vicente Cape cannot account for such severe ground shaking at Lisbon. However, Pro et al. (2013) show that a complex rupture along NE–SW trending thrust faults at the Gorringe Bank, the Horseshoe Scarp, and the Marquis de Pombal Fault, with the rupture propagating to the NE (not a simultaneous rupture, as in the comment) could explain the large damage in Lisbon, so no second source near that city would be needed. Moreover, we do not really know how far rupture propagated in the direction of Lisbon. The comment states that the directivity effects are a problematic explanation because the effects have been observed in the near field only, typically up to 20 km away from the fault. But we do not agree this assessment because the effects depend on several factors, such as fault dimension and rupture velocity (Caldeira et al., 2009; Udías et al., 2014). In fact, the directivity effects are proportional to the total rupture length, which must have been very large for this destructive earthquake, for example Stich et al. (2007) suggests a fault length of 230–315 km. In addition, the directivity effects on teleseismic waveforms can be observed when the rupture length is greater than 15–20 km (Pro, 2002). Besides, these effects do not depend on focal mechanisms and it is very important to distinguish between the rupture propagation direction and the fault slip direction, because they are often different (Caldeira et al., 2009). When the rupture front propagates toward the site and the direction of slip on the fault is aligned with the site, forward rupture directivity effects occur. These conditions for generating forward rupture directivity effects are readily met in strike-slip faulting and also certainly for dip slip ruptures where the forward directivity effects are more noticeable in the updip region (Somerville, 2003). But Pro et al. (2013) do not deal with forward directivity, with that particular type of directivity effects.

Grandin et al. (2007b) show that only a few parameters are crucial when simulating ground motion at low frequency range ($f < 0.5$ Hz). The moment magnitude, focal mechanism and source location influence the distribution of intensities in the near field (Caldeira et al., 2009; Udías et al., 2014). For large and great earthquakes ($M > 6.5$), other details of the seismic source can alter dramatically this distribution. Rupture directivity plays a particularly important role in the distribution of intensities, and is conditioned by various parameters, the fault dimensions and rupture velocity as we cited earlier and epicentral location with respect to the fault center and fault strike. In addition, in Grandin et al. (2007b) the authors compare macroseismic observations with synthetic seismic intensity for a set of possible source parameters of the 1969 and 1755 earthquakes. They take into account the major heterogeneities that affect, at various scales, the crustal structure in the region, and that largely condition the distribution of seismic intensities on land, using a realistic velocity model and an appropriate way to study in particular the source parameters of the 1755 earthquake. The velocity model used was proposed and validated by Grandin et al. (2007a). For this purpose, the 1969 earthquake ($M_s = 8.0$) constitutes the most obvious test to calibrate the regression between simulated values of Peak Ground Motion Parameter and Modified Mercalli Intensity: source parameters are reasonably well constrained, and the distribution of macroseismic observations is uniform and of good quality. Using this methodology, the case of the great 1755 earthquake ($M_w = 8.5$–8.7) was examined and the authors concluded that a primary propagating extended source located at Gorringe Bank is the most realistic hypothesis to fit the observed isoseismal pattern.

Bezzeghoud et al. (2011) analyze ground motion modeling using an extended source located near the Horseshoe Scarp to generate synthetic waveforms and compare simulated waveforms, for the Algarve Basin and the Lower Tagus Valley Basin (LTV) (Lisbon area), using a 3-D velocity model down to the Moho discontinuity with a simple 1-D layered model (Grandin et al., 2007a). The authors confirm that the radiated wave field is very sensitive to the velocity model and the rupture directivity. The rupture directivity, strike direction and fault dimensions are

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the critical factors for correctly modeling the azimuthal distribution of maximum amplitude oscillations. From this study, the authors conclude that it is very important, particularly in seismic risk studies, to take into account the rupture directivity and 3-D velocity model. These measures will provide encouraging results for the computation of low-frequency seismograms in the region and can be used to study larger earthquakes, for which the radiated wave field has a pre-dominant low-frequency spectrum. Let us note that this study is based on ground motion simulations of the SW Iberia margin, particularly for LTV Basin, where Lisbon is included.

As shown by Bezzeghoud et al. (2011), the difficulty in explaining the extreme ground motion in Lisbon is relative and depends on the methodology used. We insist and conclude that it is very important, particularly in seismic risk studies for large earthquakes to take into account the rupture directivity and 3-D velocity model. So the ground motion at Lisbon by the 1755 earthquake could correspond to that produce by along complex rupture along NE–SW trending thrust faults starting at the Gorringe Bank area with the rupture propagating to the NE. No secondary earthquake at the LTV is needed. It is also important to realize that the Lisbon earthquake occurred at a very complex plate boundary, where the transition from oceanic to continental structures takes place. This is a very different tectonic situation as that of the recent large earthquakes of Maule (Chile) 2010 and Tohoku-Oki (Japan) 2011, both at subduction zones.

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