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Solid Earth
Discussions

Interactive comment on "A reversed hierarchy of active normal faults: the 6 April 2009, M_w 6.3, L'Aquila earthquake (Italy)" *by* L. Bonini et al.

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We thank Anonymous Reviewer#1 for his/her comments, which forced us to reconsider weak or potentially unclear aspects of our work. Following are our responses to the issues that have been raised.

Comment a): I think that manuscripts that propose new ideas and/or concepts that are far away from the main research stream are fundamental for scientific advancement, however the presented manuscript: 1) is not based on solid data that support the blind fault hypothesis of the causative fault of the L'Aquila earthquake; 2) does not take into account and/or mention all the previous works that disagree with a blind fault model.

Response a): The blind fault hypothesis is not a novelty of this paper. Several previous

studies, especially those based on the inversion of geodetic and seismological data, modeled a coseismic source with the top depth raging from 0.5 km to 3 km (see table 5 in Vannoli et al. 2012 for a synthesis of the source parameter proposed to date). We synthesized these models in our manuscript as follow:

"The L'Aquila earthquake was generated by nearly a meter of slip over a planar, 16 km-long, 45–50 SW-dipping normal fault (for a summary see DISS Working Group, 2010; Vannoli et al., 2012). The 6 April mainshock was the culmination of a long foreshock/aftershock sequence recorded by permanent and temporary INGV seismometers (Chiaraluce et al., 2011). Due to the high quality of available data, the whole sequence has been the object of several investigations, resulting in over 100 papers published to date. Instrumental data, including high-resolution aftershock locations, GPS observations and DInSAR measurements based on Envisat and COSMOSkyMed data, revealed coseismic slip between 9–10 to 2–3 km depth, resulting in bowlshaped, gently-asymmetric surface subsidence up to 15–20 cm (Atzori et al., 2009; D'Agostino et al., 2012; Fig. 1)."

If Reviewer#1 considers our synthesis insufficient, we may add to the next version a more accurate description about the models published to date. We also feel that the term "blind" could appear too strong, suggesting that no surface evidence of faulting can be found in these cases. On the contrary, we believe the earthquake caused a great deal of deformation, but this has to be investigated by interpreting the ground deformation over the entire region overlying the fault along with secondary faults and fractures and with the reactivation of pre-existing faults. In our opinion this earthquake is important because it shed light on the relations between coseismic slip at depth and surface breaking, the investigation of which comprise the main goal of our paper.

Comment b1): Three independent research lines suggest that L'Aquila earthquake did not occur on a blind fault. This is supported by 1) field geology (e.g. Boncio et al., GRL, 2010; Vittori et al., BSSA 2011; Gori et al., 2012, Italian Journal of Geosciences; Lavecchia et al., 2012 Italian Journal of Geosciences); . . .

Response b1), on evidence from field geology studies and the Paganica fault. As we wrote in our manuscript, various widely divergent models have been already proposed in the literature (see Vittori et al., 2011, and Vannoli et al., 2012 for a review). Nevertheless, to clarify this point we may add a brief discussion about the coseismic surface rupture length (SRL), pointing out that the proposed estimates are rather incoherent as they range from a minimum of 2.6 km (Vittori et al., 2011) to a maximum of 19 km (Galli et al., 2010; Quaternary Sci. Rev.). More importantly, there exists general consensus on the maximum coseismic surface throw being in the order of a few cm (also based on our direct observations), that is to say, less than 1/20 of the maximum slip detected on the fault at depth (about 1.0 m). For a typical Italian surface-breaking fault such as those reponsible for the 1915 Avezzano and 1908 Irpinia earthquakes this ratio is between 1/2 and 1/1.5. Comment b2): Three independent research lines suggest that L'Aquila earthquake did not occur on a blind fault. This is supported by . . . 2) co-seismic slip models from DInSAR (Atzori et al., GRL, 2009), GPS (Cheloni et al., 2010, GJI), joint inversion of strong motion and GPS data (Cirella et al., GRL, 2009); . . .

Response b2), on evidence from coseismic slip models We do not agree with this comment because, as previously mentioned, coseismic slip models from DInSAR, GPS and joint inversion of strong motion and GPS data all proposed the following depth for the upper tip of the seismogenic fault: - Atzori et al., 2009, GRL, min. depth 1.9 km (±0.2 km) (DInSAR and GPS data inversion) - Cheloni et al., 2010, GJI, min. depth 0.6 km (GPS data inversion) - Cirella et al., 2009, GRL, min. depth 0.5 km (Strong motion and GPS data inversion)

More importantly, they consistently show that slip in the uppermost 2-3 km of the fault plane is a small fraction of slip at depth. For the inversion of GPS data this may be the result of limited resolution, but as far as DInSAR data are concerned the lack of slip at shallow depth is indeed a real feature.

Is this sufficient state that the fault is blind? To be honest, the expression "blind faulting" does not correspond in the literature to a clear definition based on something measurable. We believe that a fault should be considered blind if slip at and near the surface (it does not matter if it is dynamic or essentially passive slip) amounts to a significant fraction of slip at depth. For the 6 April earthquake independent groups have shown that the ratio of surface to deep slip is between 1/10 and 1/20. Simple dislocation modeling shows that this ratio controls the shape of the surface strain field, and particularly the distance between the locus of peak uplift and that of peak subsidence (all the rest being equal).

The inversion of geodetic (GPS, DInSAR) and strong motion data is normally done under the assumption of the fault being perfectly planar. This may not necessarily be 100% true for any earthquake, but the resolution of the data may not always be large enough to resolve minor departures from planarity (see for a discussion Gori et al., IJG, 2012; Lavecchia et al., IJG, 2012). Finally, it should be kept in mind that any variable slip analysis attempts to show where slip concentrates on the fault plane and where it tapers to zero. In order to observe slip tapering correctly the model fault must be kept much larger than the portion of it that actually slipped in the mainshock. It is for this reason that variable slip models inevitably assume that the fault cuts through the surface, even if the resulting slip distribution shows that most of it is confined within a certain depth (the same applies along width and along length of the fault).

Comment b3): Three independent research lines suggest that L'Aquila earthquake did not occur on a blind fault. This is supported by . . . 3) aftershock distribution (Chiaraluce et al., 2011 JGR; 2012 JSG). The absence of aftershocks in the 2-3 km of the crust can be also related to the velocity strengthening behaviour of faults at shallow crustal depth (e.g. Scholz 1998, Nature, Figure 2). For L'Aquila sequence, aftershocks are present up to 1 km depth (Chiaraluce et al., 2012), and the numerous shallow faults depicted by aftershocks alignment can represent fault splays that are typical in the hanging-wall block of normal faults (e.g. Sibson 2000, Journal of Geodynamics).

Response b3), on evidence from the lack of aftershocks in the uppermost 3 km of the crust We may add a discussion on this point, in particular on the nature of the

Paganica fractures and their relation with the aftershock distribution, remarking that no direct data exist linking these surface ruptures and the deeper seismogenic source. For instance, no aftershocks where observed between the surface and 2-3 km depth in the central portion of the area overlying the seismic source (Chiarabba et al., 2009; Chiaraluce et al., 2011; Chiaraluce, 2012). As Reviewer#1 suggested, this could well be explained by the velocity strengthening behavior of faults at shallow crustal depth, but two alternative explanations are equally likely:

1) the normal stress acting in the uppermost part of the fault plane, which controls the effective coefficient of friction on the rupture, may be especially low, thus generating stable sliding (Brace and Byerlee, Science, 1970); or, more simply, 2) there is no fault plane continuity in the uppermost 2-3 km of the crust in the Paganica area.

We wish to stress that the synoptic model of Figure 2 in Scholz (1998) was not meant as a general rule for all seismogenic faults. For instance, Marone and Scholz (1998; Geophys. Res. Lett.) investigated continental faults and concluded that the upper stability transition occurs only for mature fault zones: young faults and those with long recurrence intervals or negligible gouge zones do not exhibit an upper stability transition.

In summary, we do not know the nature of the fault gouge of the Paganica fault because we observed only open breaks in nearby Paganica village. There is simply no surface exposure of the Paganica fault plane which could be used to state whether or not this is a well-developed fault. Nevertheless, also considering the Paganica fault as a secondary feature of the seismogenic source reaching the surface, it is expected that slip along this secondary branch results from velocity strengthening during afterslip, i.e. hours or days after the mainshock (e.g. Perfettini and Ampuero, 2008; JGR). In the L'Aquila case, we know the exact timing of surface breakage as the Paganica-Tempera aqueduct pipe, crossing the Paganica fault not far from the village center, was reported broken in the mainshock. This information is not coherent with afterslip along a secondary branch of the main seismogenic fault, but it is coherent with the bending moment fault model proposed in our manuscript.

Comment c): The analogue model is not constrained by data. The analogue model reproduces a 3 km thick sedimentary sequence. Why the sedimentary rocks are only 3 km thick? In the same region the CROP11 seismic profiles shows that sedimentary rocks are very thick, more than 10 km (Patacca et al., 2008, Tectonics). In addition, the borehole Varoni (drilled by Eni 30 km north of L'Aquila) encountered dolomites at 5700 m. What is the lithology located below the 3 km thick sedimentary sequence where the blind fault is positioned? Why the sedimentary sequence is decoupled from what is located below?

Response c): We agree with Reviewer#1's comment. This is probably due to a mistake in our statement about the stratigraphy of the studied area. Therefore we changed the sentence

"Our technique follows well established rules (e.g. Shellart, 2000; Bonini et al., 2011) aimed at reproducing the brittle behavior of upper crustal carbonate rocks (up to 3 km depth) similar to those that exist in the L'Aquila region."

into:

"Our technique follows well established rules (e.g Schellart, 2000; Bonini et al., 2011). The model aims at reproducing and modeling only the uppermost 3 km of carbonate rocks below the topographic surface, i.e. the rock volume that (based on the blind faulting hypothesis) would be deformed by bending rather than shearing. By doing this we may observe and analyze the brittle structures generated during the bending of the portion of the crust that, in a blind faulting model, lies above the upper tip of the fault."

We agree with Reviewer#1 that sedimentary rocks extend at much deper depth than just 3 km, although we believe that referring to the stratigprahy of the Varoni borehole, located 30 km north of L'Aquila, is inappropriate in view of the highly non-cylindrical setting of the region. The work by Bigi et al. (Terra Nova, 2013) shows that the Varoni

1 well drills a tectonic stack of thrust sheets located below the Gran Sasso thrust sheet, which is the tectonic unit that hosts the Paganica fault. To reconstruct the stratigraphy along the cross-section of our Figure 3C we used the results of S and P-wave analyses, respectively from Bianchi et al. (2010) and Di Stefano et al. (2011). These investigators pointed out a complex distribution of geological units at depth with a very high velocity layer in the north-central portion of the ruptured area (Vs about 4.2 km/s and Vp >6 km/s), which can be explained by the presence of a mafic basement between 3-4 and 10 km depth. In the other zones, Vs and Vp data are coherent with those of the Meso-Cenozoic carbonate cover.

Comment d): Are surface breaks formed by surface bending a common feature of the Apennines or this is a new interpretation proposed in the manuscript? Can the Authors better explain/ document this point? The fact that the major earthquakes of the Apennines occur in the proximity of intermountain basins bounded by normal faults is not consistent with normal faulting produced by surface bending. Can the Authors comment on this?

Response d): We do not have enough data to establish if bending moment faults are a common feature of the Apennines, altough we suspect this might be the case. We believe this mechanism could explain the weak geomorphic expression of the Paganica fault. We can neither confirm nor rule out this mechanism for other cases in Italy and elsewhere. The statement "... major earthquakes of the Apennines occur in the proximity of intermountain basins bounded by normal faults...", however, is not supported by the observations we have: at least not with statistical significance. The well-known 1980, Irpinia earthquake (Mw 6.9), for instance, caused surface breakage along faults that do not bound any intermountain basin. The 1915 Avezzano earthquake (Mw 6.8) caused surface breaks away from the the basin boundaries. The surface breaks associated with the 1857 Val d'Agri earthquake (Mw 7.0) run close to the top of the ridge flanking the main valley. The 1997 Colfiorito earthquake (Mw 6.0) did not generate sizable surface breaks, and the available knowledge on the seismogenic source shows

that it does connect with the known range-bounding faults. The number of positively coseismic surface breaks is indeed rather limited all across Italy. In fact, the ambiguity of coseismic surface signatures following some of these earthquakes, including that of the Paganica fault, is exactly what prompted our work. We all believed that seismogenic normal faults should coincide with range-bounding faults at the surface, but the evidnce for that is simply not there and in most instances things appear much more complex. We also believe there is nothing wrong in changing interpretations when new data shed light on previously unknown processes, as in the case of the 6 April 2009 earthquake.

Comment e): The Authors propose that earthquake was caused by a blind fault, controlled at depth by pre-existing discontinuities. What are these pre-existing discontinuities?

Response e): We faced this question when writing about the alignment of several aftershocks along an interpreted sub-horizontal plane running at about 3 km depth above the central portion of the seismogenic source (see Figs 3, 4). In recent papers (e.g. Chiaraluce et al., 2011; Charaluce, 2012; Valoroso et al., 2013 JGR) this plane has been already interpreted as a thrust fault, inherited from a previous compressional phase which deformed this portion of the Apennines up to the Early Pleistocene.

Interactive comment on Solid Earth Discuss., 5, 117, 2013.