STRUCTURAL STYLE OF SEISMOGENIC EXTENSION IN CENTRAL ITALY – A 3D INSIGHT FROM L'AQUILA 2009 AND CENTRAL ITALY 2016-17 SEISMIC SEQUENCES

G. Lavecchia, R. de Nardis, F. Ferrarini, D. Cirillo, F. Brozzetti
CRUST-DiSPUTer, Università G. d'Annunzio, Chieti, Italy

Fundamental aspects to be addressed in the understanding of seismogenic fault systems regards, on one side, the recognition of the long-term structural style of the active deformation field at a regional-scale and, on the other, the recognition of the locally active fault system and stress field and the reconstruction of the process of progressive fault development. The latter, in turn, contributes to control the nucleation, development and arrest of earthquakes and seismic sequences.

A 3D approach to reconstruct the active fault geometry and to build a database of detailed, non-planar, seismogenic and potentially active fault segments is an essential tool for seismic hazard evaluations. To reach this goal and to fully constrain the fault geometry, high-quality geological and seismological data are both necessary, together with a deep knowledge of the regional seismotectonics of the area.

An excellent laboratory for such purpose is represented by the sector of the Intra-Apennine extensional belt struck by the L'Aquila 2009 Seismic Sequence (AQSS) and by the 2016-2017 Central Italy Seismic Sequence (CISS) (Fig.1).

Within a lapse of three days (6 to 9 April 2009), AQSS released three events with magnitude decreasing from M_w 6.3 to 5.5, which activated two independent en-echelon west-dipping fault segments (Paganica and southern Gorzano faults) and the underlying common east-dipping detachment (Lavecchia *et al.*, 2012). Coseismic surface fractures for a total length of 13 km were surveyed along the trace of the Paganica fault (Boncio *et al.*, 2010).

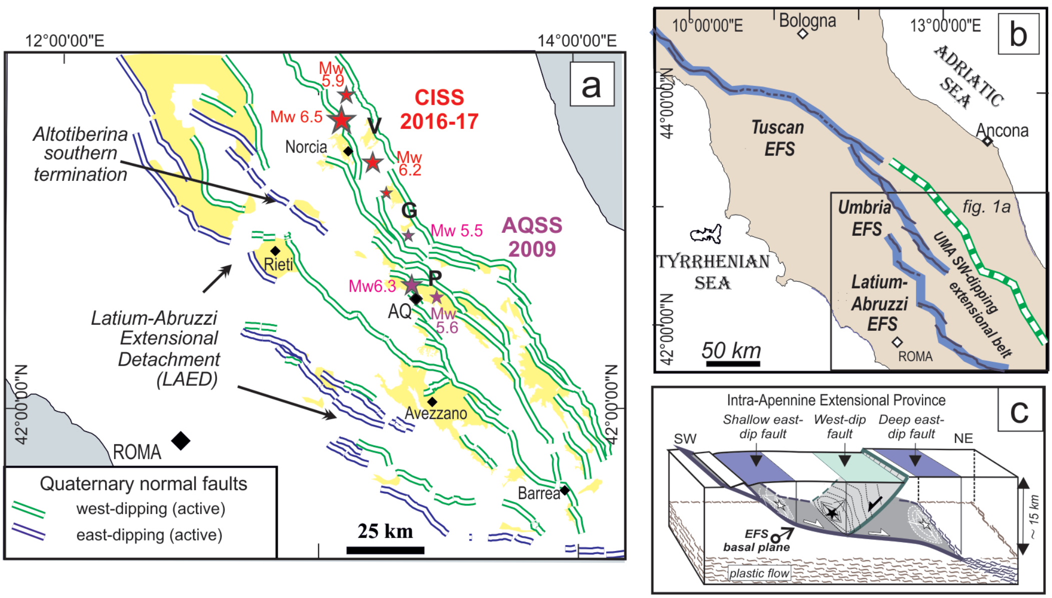

Fig. 1 - From Lavecchia *et al.* (2016): a) location map of the L'Aquila 2009 Seismic Sequence (AQSS) and of the Central Italy Seismic sequence (CISS); V, G and P = Vettore, Gorzano, Paganica master faults; b) schematic view of the East-dipping Extensional Fault System (EFS) and of the outer front of the Umbria-Marche-Abruzzi (UMA) SW-dipping Quaternary extensional belt; c) sketch model of the spatial relationships between the east-dipping extensional detachment and the antithetic SW-dipping high-angle normal faults responsible for most of the energetic intra-Apennine extensional earthquakes.

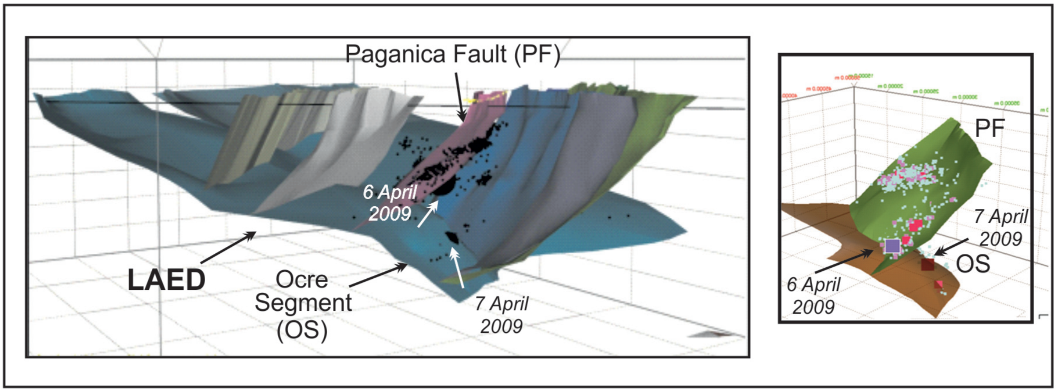

Fig. 2 - 3D fault model of L'Aquila 2009 Seismic Sequence, from Lavecchia *et al*. (2017) (on the right) and from Castaldo *et al*. (submitted to JGR) (on the left); the hypocentral data set is from Chiaraluce *et al*. (2011).

Within a lapse of about five months (24 August 2016 to 18 January 2017), the CISS released four major neighboring events, with magnitude M_w between 5.5 and 6.5, along a WSW-dipping normal fault system extending for a length of about 70 km (Chiaraluce *et al*., 2017). The system consists in two en echelon master faults, Vettore Mt. and Gorzano Mt., articulated in segments and sections, and possibly connected at a depth of about 8 km (Lavecchia *et al*., 2017). An impressive co-seismic ground rupture with an along-strike extent of 37 km and a maximum vertical offset of 2m was generated along the Vettore fault (Open Emergeo Working Group, 2017).

The long-term geology and kinematics of the AQSS and the CISS epicentral areas are well known in the literature, mainly due to the spectacular exposures of both Quaternary active normal faults and pre-existing Late Miocene-Early Pliocene fold-and-thrust structures (Lavecchia,1985; Boncio *et al*., 2004). As well, good-quality seismological data are available; they consists of both hypocentral relocation of aftershock sequences registered soon after the main events (Chiaraluce *et al*., 2011 and 2016), and of minor sequences and background seismicity. A complete dataset of focal mechanisms is also available, together with a large amount of interferometric and geodetic data. Based on morphotectonic, geological, interferometric and seismological input data, we have reconstructed the non-planar, interconnected pattern of first-order and subsidiary faults, directly and indirectly associated with the AQSS and CISS (Figs. 2 and 3).

The 3D reconstruction was performed by adopting the multi-step workflow, outlined in Lavecchia *et al*. (2017):

1st step) compilation of a unified and detailed fault trace database in GIS, with faults kinematics and hierarchy;

2nd step) building of «Fault Ribbons» obtained by projecting the surface traces to depths of 2-3 km depth (with the MOVE Midland Valley extrusion tool);

3rd step) 2D extrapolation to depth of the fault traces by integration of geological and seismological data. Along a large number of closely-spaced and differently oriented cross-sections, the Fault Ribbons are connected with the best-fitting planes across the underlying hypocentral volumes, also taking into account dip-direction and dip-angle of both the outcropping faults and the preferential planes from focal mechanisms;

4th step) 3D fault model building. The fault surfaces, with variations along strike and dip, are obtained with the Midland Valley Move Software by interpolating and/or extrapolating the previously built map-view and section-view representation of the Quaternary faults and of the corresponding seismogenic patches. A weight is assigned to the quality of input constraints and to the accuracy of each fault model.

Obtained results give the opportunity to afford a number of discussion point:

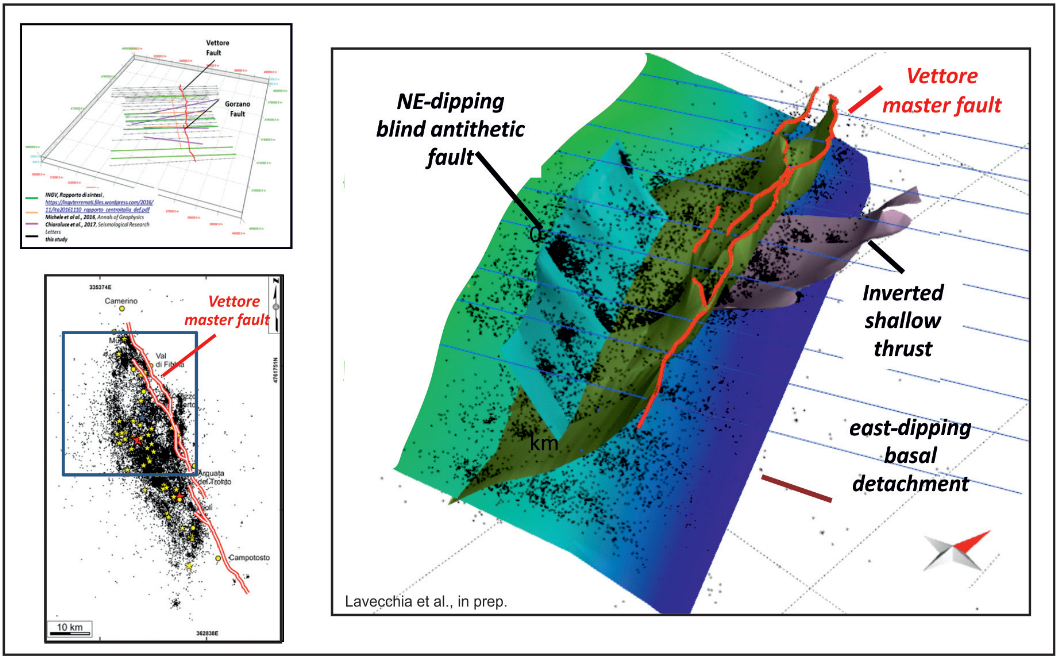

Fig. 3 - 3D fault model building of the northern sector of the CISS (Central Italy Seismic Sequence 2016-2017). The reconstruction is in progress and to be submitted by Lavecchia *et al.* to Tectonics. The hypocentral data set is from Chiaraluce *et al.* (2017).

1 - Deep geometry of the central Italy fault pattern and primary/secondary role of the co-seismic ruptures.
2 - Passive *versus* active role of pre-existing and long inactive fault discontinuities within the hypocentral area and their role in driving primary events or exclusively in localising subsidiary low-magnitude events and back-ground seismicity.
3 - Tectonic control played onto the time-space evolution of a seismic sequence by structural complexities such as sharp bends along strike or dip of an individual fault, interaction and linkage between overstepping fault strands, fault leakages, intersection between parallel or transversal faults, role of tectonic-controlled basal detachments.
4 - Structural style of the active and potentially seismogenic extensional tectonics in central Italy, at the light of the geometric similarity among the CISS and AQSS fault systems, both characterized by WSW-dipping high-angle normal faults detaching onto an east-dipping basal detachment.

Some of our results concerning the 3D geometries of the AQSS and the CISS are shown in Figs. 2 and 3, where the similarity in scale and size between the two situations appears rather evident. The proposed reconstruction highlights the important role played at regional scale, in Quaternary times, by the east-dipping detachment, which coincides with the southern prosecution of the Altotiberina fault in the Vettore-Gorzano area and with the Latium-Abruzzi Extensional Detachment (LAED) beneath the AQSS (Lavecchia *et al.*, 2017) (Fig.1a). In both cases, the reconstructed geometry shows an along-dip ramp-flat-ramp configuration, which can open to the possibility of significant mid-crust earthquakes eventually released on the moderately steep segments of the basal detachment (40-45° dip).

Such a preliminary hypothesis needs to be further investigated as it might contribute to partially fill the deficit in seismic release (Mulargia, 2013) observed within the intra-Apennine extensional province when only considering the well-known west-dipping high-angle faults.

References

Boncio P., Lavecchia G., Pace B. ; 2004: Defining a model of 3D seismogenic sources for Seismic Hazard Assessment applications: The case of Central Apennines (Italy). Journ. Seismology, 8, 407-425.

Boncio P., Pizzi A., Brozzetti F., Pomposo G., Lavecchia G., Di Naccio D. and Ferrarini F.; 2010: Coseismic ground deformation of the 6 April 2009 L'Aquila earthquake (central Italy M_w6.3). Geophysical Research Letters, 37, L06308, doi:10.1029/2010GL042807.

Chiaraluce L., Di Stefano R., Tinti E., Scognamiglio L., Michele M., Casarotti E., Cattaneo M., De Gori P., Chiarabba C., Monachesi G., Lombardi A., Valoroso L., Latorre D. and Marzorati S.; 2017: The 2016 Central Italy Seismic Sequence: A First Look at the Mainshocks, Aftershocks, and Source Models. Seismological Research Letters, 88, 1-15 (doi: 10.1785/0220160221).

Chiaraluce, L., Valoroso L., Piccinini D., Di Stefano R. and De Gori P.; 2011: The anatomy of the 2009 L'Aquila normal fault system (central Italy) imaged by high resolution foreshock and aftershock locations, J. Geophys. Res. B: Solid Earth, 116 (B12)

Lavecchia G.; 1985. Il sovrascorrimento dei Monti Sibillini: analisi cinematica e strutturale. BOLL. SOC. GEOL. IT., 104, 161-194.

Lavecchia G., Adinolfi G.M., de Nardis R., Ferrarini F., Cirillo D., Brozzetti F., De Matteis R., Festa G. and Zollo A.; 2017: Multidisciplinary inferences on a newly recognized active east-dipping extensional system in Central Italy, Terra Nova, doi: 10.1111/ter.12251.

Lavecchia G., Ferrarini F., Brozzetti F., de Nardis R., Boncio P. and Chiaraluce L.; 2012: From surface geology to aftershock analysis: Constraints on the geometry of the L'Aquila 2009 seismogenic fault system. Italian Journal of Geosciences, 131, 330-347, doi: 10.3301/IJG.2012.24.

Lavecchia, G., Castaldo, R., de Nardis, R., De Novellis, V., Ferrarini, F., Pepe, S., Brozzetti, F., Solaro, G., Cirillo, D., Bonano, M., Boncio, P., Casu, F., De Luca, C., Lanari, R., Manunta, M., Manzo, M., Zinno, I. and Tizzani P.; 2016: Ground deformation and source geometry of the August 24, 2016 Amatrice earthquake (Central Italy) investigated through analytical and numerical modeling of DInSAR measurements and structural-geological data. Geophys. Res. Lett., 43, doi:10.1002/2016GL071723.

Mulargia, F.; 2013: Why the next large earthquake is likely to be a big surprise, Bull. Seismol. Soc. Am., 103, 2946-2952.

Open EMERGEO Working Group; 2017: Surface ruptures following the 30 October 2016 Mw 6.5 Norcia earthquake, central Italy. Journal of Maps, in press.