GEOMETRICAL AND STRUCTURAL CONTROLS ON RUPTURE ZONE FABRIC: FIELD SURVEYS OF THE 2016 EARTHQUAKES IN SIBILLINI MOUNTAINS (CENTRAL ITALY)

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A detailed field mapping of spatial geometries of the coseismic surface ruptures of active faults is the basis for the identification of seismogenic structures and represent an important step toward assessing the recurrence intervals and magnitude of earthquakes. Structural relations such fracture length and distributions, fault offsets, shear zone width, links between geometries along the fault strands provide insight into mechanics of earthquake rupture. Moreover surface ruptures display key structural relationships that are the essential tools for extrapolating and constraining the depth of the fault plane from a kinematic point of view. Kinematic fault analysis integrated with geophysical data, allowing to constrain any seismotectonic model. Integration of geological and seismological data remains one of the main objectives when identifying active faults and assessing their potential hazard. While large data sets of instrumental seismological data are easy to gather, especially with modern digital seismic stations, field geological data remain very costly in terms of human and economic resources, especially in remote areas. However, evolving technologies have allowed remotely sensed data to be used to obtain a lot of equivalent information.

A significant sequence of earthquakes occurred in the Sibillini Mountains in Central Italy from August to October 2016. On August 24, Mw 6.1 earthquake struck the area between the town of Amatrice (Rieti Province) and Arquata del Tronto (Ascoli Piceno Province). Several ground ruptures along different strands of SW dipping extensional faults occurred over a distance of more than 20 km, throughout the morphologically complex landscape of the Sibillini Mountain chain and the Laga massif. The October 26 Mw 6.0 earthquake was centred in the Visso area (Macerata Province), approximately 30 km northwest of the previous event. On October 30, an Mw 6.5 event occurred near Norcia (Perugia Province), in an area located between the epicentres of the former earthquakes. This event reactivated existing ground ruptures and produced further rupturing over a larger area.

A highly detailed map of the coseismic surface ruptures was created by integrating a direct and a classical structural field survey with low altitude aerial photos and remote sensing data interpretation. An important challenge in the field survey was related to the easy and rapid erosional degradation of fault scarps especially in a mountain range where storms are frequents and the snow cover can reach few meters. The exposed coeseismic rupture surfaces begins degradation immediately after the earthquake, and, within a period as short as a few weeks, many important structural relationships of the surface rupture may have become completely erased and cannot be documented at any scale. Rupture mapping based on low-flying flights of quadricopters and ground based reconnaissance and photos was performed for several weeks after the main event of August 24. This make possible to records few thousands aerial and terrestrial images of the faults scarps useful to compare with larger ruptures of the main event of October 30. The improvements in digital technology, allowed small groups of geologists working in the short window of time following the late quarter 2016 earthquakes to document structural relationships in unprecedented detail over large regions. The digital images has been processed using Structure from Motion algorithms obtaining 3D clouds of more than $3*10^7$ points for each area. These point clouds, permitted to generate a fully rendered 3D geological model making the extraction of the fractures geometries possible. Comparison of the multi-temporal point clouds permitted to define the kinematics of the fault strands. Digital surface models and orthophotos mosaics, allowed to detect displacements of several centimetres where the faults and fractures can be easily traced. The attitude of these discontinuities, expressed by offset, dip direction and dip, was measured using a combination of GIS tools, integrated and verified with the digital field survey checks, and subsequently processed via the traditional geometrical spatial methods using structural statistical tools. The along-strike displacement versus distance of the fault planes and ground ruptures was analysed along several cross sections orthogonal to the fault strikes. One of the main challenges of mapping this particular rupture was to identify and locate the primary rupture paths through a complex network of faults outcrop in the Sibillini and Laga Mountains. Detailed structural relationships of the surface ruptures, are systematically mapped at scales finer than 1:500, and documented the distribution of all fractures with >2 cm of vertical offset, which totalled more than 5,000 individual scarps. The surface ruptures generally crossing many of the already known normal faults. They have a continuous extent of more than 25 km and consist of open cracks and vertical dislocations or warps (2 m maximum throw) orientated NW-SE. The cross sections highlight slip accommodation through linkage, which shows to be a common fault growth mechanism.

A very good structural detail of the fault scarp arrays map is observable especially where primary rupture became distributed across multiple faults in the stepover region of the Mt. Vettore and Pian Grande di Castelluccio. Complex sections of the ruptures are located in the Mt. Vettore - Mt. Porche - Mt. Bove sectors especially because locate in the steep mountainous slopes with high relief. These ruptures typically occurs as multiple overlapping scarps that can be divided into kinematic sets that occur throughout the width of the pre-existing fault zones.

The distribution and internal configuration of shearing in the rupture zone and the map-view width is one of the most important and easiest to systematically document parameters together with the way in which fracture sets are arranged relative to each other. The main factors that define the different aspects of rupture zone fabric include: a) the length and architecture of the rupture zone; b) rupture zone thickness; c) kinematics and magnitude of the coseismic slip within the rupture; d) geometric arrangement and relationship of different fracture sets, patterns of splaying, and their degree of interconnectivity. Moreover the rheology of the ruptures materials (rock, soil, debris), overburned thickness of the rupture zone width and magnitude of tectonic loading, play an important role in the rupture zone fabric.

These coseismic structures are an exceptional example of the complex geological evolution of a region, where at least three tectonic phases are overprinted. The last active extensional phase affecting central Italy, highlighted by the recent seismic activity and the development of coeseismic surface ruptures, permits us to bear witness to the geological evolution of the region.