ANALYSIS OF THE AUGUST - OCTOBER 2016, CENTRAL ITALY, COSEISMIC SURFACE FAULTING SLIP-DISTRIBUTIONS, PARAMETERIZATION AND COMPARISON WITH GLOBAL EARTHQUAKES

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Introduction. We analyze in detail the coseismic surface faulting exposed along a segment of the Mt Vettore-Mt Bove fault system (VBF, central Italy), that activated during the 24 August 2016, Amatrice event (Mw 6.0) and soon after re-activated during the 30 October 2016, Norcia mainshock (Mw 6.5). We systematically recognized the coseismic surface ruptures of the two events, which document an example of rupturing on the same seismogenic structure in close temporal succession. Coseismic surface slip on the same fault planes, during both the 24 August and 30 October events is shown by the “double-slip free faces” well exposed along the southern segment of the VBF, named here Vettoretto-Redentore segment (VRS). Such a feature represents, the outcropping geological expression of the 24 August-30 October foreshock-mainshock pair nucleated on the VRS. Reconstructing the geometrical pattern of such a pair and comparing the spatial distribution of coseismic slip with the deep sources of the two events might help understanding the causes of this double activation and the control played by structural complexities on rupture nucleation and propagation.

We provide the coseismic parameters of the 24 August VRS rupture and of the entire earthquake rupture, which are the surface rupture length (SRL), average displacement (AD) and maximum displacement (MD). Further aims of our work are: i) demonstrate the primary origin of the surveyed surface ruptures; ii) analyze the slip distribution of the 24 August and 30 October events and compare them with the long-term (Pleistocene to present) segmentation pattern and displacement, as obtained from structural geology and fault scarp profiling and, iii) discuss the coseismic parameters (SRL, AD, MD) and slip profiles with those available in the literature for global earthquakes (Mw >6).

Methods and phases of work. After the 24 August earthquake, we performed a detailed fieldwork along the fault scarp of the VRS, aimed at mapping in detail (1:1000) the long-term fault trace and at surveying the associated coseismic ground ruptures. The survey was carried out at a high-resolution, with a sampling rate of at least 1 site/50m, and locally of 3 sites/1m. All the sampling sites with evidence of primary coseismic fracturing were characterized in terms of rupture type, attitude, kinematics, slip vector and displacement (throw, opening and net displacement).

After the 26 October foreshock, and before the 30 October mainshock, the few data collected along the northern VBF attested primary surface faulting SE and NE of Ussita with throw in the range of 8-15 cm.

From 31 October to December 2016 we surveyed in detail the 30 October ruptures, from the southern tip of the VBF to Mt Porche. The ruptures north of Mt Porche were mapped from Spring to Fall 2017. Also the survey of the 30 October ruptures was carried out with a high-resolution sampling procedure. The data collected on the entire VBF have been analyzed in order to constrain the coseismic parameters (SRL, MD, AD). The average net displacement was computed as both arithmetic and integral means, with the latter corresponding to the ratio of the area subtended by the displacement profile to the rupture length. The robustness of our estimates is suggested by the high number of data collected and processed. In fact we surveyed 1747 evidence of coseismic ruptures, 325 fault plane attitudes along the VRS, and over 4000 data along the entire VBF. We subsequently calculated both the geologic (i.e. long-term) and topographic (i.e Late Quaternary) displacement along the VRS of the VBF in order to compare obtained values and their along-strike variation with the coseismic displacement of 2016 earthquake. The geologic displacements were calculated by restoring the offset of the stratigraphic markers.
in a set of 1:25,000 scale geological sections. The topographic displacement was calculated by realizing several topographic profiles across the VRS fault scarp. Elevation data were extracted from a Digital Elevation Model (DEM) built from topographic map at scale 1:5000.

The offset of the far-field topographic slope across the fault scarp was calculated and interpreted as displacement cumulated by several slip events, after the demise of the Last Glacial Maximum (LGM), that is after ~15±3 kyrs ago.

**Structural analysis.** The 24 August to 30 October earthquakes ruptured at the surface almost entirely the VBF. The pattern of coseismic ruptures indicate a common primary (i.e., tectonic) origin testified by the following geological observations:

- most of the ruptures reactivation long-term fault scarps or are arranged in alignments whose direction is independent of the orientation of the topographic surface;
- the set of ruptures which originated along the VRS after both the events, develops with continuity along its geological trace also where it crosses and displaces the Sibillini thrust, with an associate long-term offset of ~300m propagating within the thrust footwall block;
- coseismic slip of both the events shows locally oblique kinematics which are clearly unrelated to the local dip-direction of the slope;
- some kilometer-scale ruptures, due to the 30 October event, affect flat areas or footslope debris characterized by very low slope-gradient, allowing to exclude significant gravitational deformation.

The VRS is the southeasternmost segment of the VBF; it extends along strike for a length of 10.5 km in direction N160° and is characterized by clear and continuous fault scarp. A number of synthetic and antithetic splays affect the hanging wall on the distance of ~ 2 km from the fault trace.

The segment has a hierarchic organization in second-order fault sections (FS) and third order sub-sections identified based on sharp strike-deviations, along-strike terminations and step-over zones, with spacing in the order of hundreds of meters. The VRS has been subdivided into three FS, with lengths in the order of 3-4 km, and into six sub-sections. From north to south, we recognized FSI= Quarto San Lorenzo section, FSII= Redentore section and FSIII= Vettoretto section. All FS show an average surface dip-angle of about 65°. They differ in the long-term slip vector attitudes, which highlight a slight right-lateral component on FSII and a left-lateral component on FSI and FSIII. The calculated long term average slip vector, for the entire VRS is 232/65. The geological displacement reaches a maximum value of 500 m (throw=470 m) across the FSII; the post LGM displacement, ranges from 13 to 29 m along FSI and FSII. The corresponding post-LGM (15±3 kyrs) throw-rate is in the order of 1.45±0.3 mm/y.

The 24 August event ruptured almost completely the fault sections FSII and FSIII for an along-strike length (L) of 5.8 km, in an average N160° direction. The related coseismic throw (CT) shows values in the 0-27 cm range, with four relative maxima progressively decreasing southward. The highest value (27 cm, corresponding to a maximum net displacement MD=28.5 cm) is measured in the central portion of FSII; the other three peaks are observed along FSIII and mark the median parts of corresponding fault sub-sections, in which FSIII is articulated. The mean integral throw of the 24 August rupture is ~ 12 cm (average net displacement, AD = 12.7 cm). The azimuthal distribution of the fractures shows a general good agreement with the fault strike.

The 30 October mainshock ruptured at the surface the VRS for 7.6 km. The ruptures mainly occurred along the main fault trace, but also along subsidiary splays outcropping within a few kilometres from the main fault trace. The CT values, for this event (i.e. subtracting the 24 August slip) varies in the 0-217 cm range, with four relative maxima nearly coincident with the 24 August ones. In the northern part of FSII, the CT rapidly increases, up to ~ 100 cm and, in its middle part, its “Acme Zone” occurs, with the absolute maximum (217 cm, corresponding to a maximum net displacement of 222 cm near Scoglio dell’Aquila). In detail, the “Acme zone” is characterized by two well distinct peaks separated by a narrow drop whose corresponding
minimum is compensated by the slip occurred on a N-S striking synthetic fault which contribute to maintain the westward downthrow definitely above 2 m. Nevertheless, it is noticeable that where CT values >150 m are observed, they seem to be partly counteracted by the significant slip occurred along a N-S striking, 2 km long, antithetic fault on which CT values up to ~ 60 cm, have been measured.

Enlarging the 30 October ruptures analysis to the entire VBF, and considering the coseismic faulting due to all the M≥5.5 events, the total cumulative surface rupture length (SRL), calculated along the principal fault is 30 km. Unfortunately, we could not solve the uncertainties about the SRL of the 26 and 30 October events separately. Most or the entire surface displacement on the Cupi-Ussita sections is due to 26 October shocks, but it is not clear if and how the 30 October event reactivated these sections. Our field measurements confirm that the 30 October event ruptured entirely the VRS and Bove-Porche segment, at least up to the latitude of Ussita, for a total SRL of ~22 km. This value can be considered the total (minimum) rupture length of the 30 October mainshock. The maximum cumulative displacement (MD), recorded on the Redentore fault section of the VRS, is 240 cm, while the maximum displacement of the 30 October event is 222 cm. The latter was recorded close to, but not exactly on the same point of the cumulative MD. The average cumulative displacement (AD) calculated as both integral and arithmetic means are 36 and 37 cm, respectively.

Discussion and Conclusions. The FSII, Redentore section of the VRS is characterized by a zone of very high maximum displacement (MD) localized in a ~700 m-long trace. Recently Boncio et al. (2018) propose that at least part of MD (~20%) can be due to hanging wall back-tilting. Back-tilting can accommodate volumetric problems in the hanging wall due to up-dip steepening of the fault. Considering that the fault is on limestone bedrock, the steepening should be due to dip variations of the bedrock fault surface. In the same area there is an antithetic hanging wall fault rupture located 400 - to - 650 m from the principal fault. Also antithetic faulting might result from volumetric adjustment in the hanging wall due to fault dip variations at depth.

Interestingly, in the same trace of the Redentore FS the slip vectors, both long-term and coseismic slickenlines deviate of 20-40° from the average (N230°) slip vector, while the fault strike is nearly constant. In summary, the localized anomalously-high maximum displacement can be due to local tectonic factors due to fault irregularity.

We compared the obtained SRL, AD and MD data of the 24 August, 30 October and “cumulative” surface ruptures with global coseismic data from the literature in the form of empirical relationships (Wells and Coppersmith, 1994; Wesnousky, 2008; Pavlides and Caputo, 2004) and normalized displacement profiles. For the cumulative rupture, we used a magnitude M_w = 6.7, obtained by summing the seismic moment of the 24 August-to-30 October M≥5.0 earthquakes. The comparison with empirical relationships shows that the 24 August rupture parameters are well within the values predicted by the empirical regressions. Instead, the parameters for the 30 October and cumulative rupture divert significantly from the empirical regressions for M_w vs rupture parameter. The MD is much higher than the expected values and AD is significantly lower than the expected value. SRL approaches the empirical regressions better than MD and AD, but it is still higher than the expected values. Comparing the obtained displacement profile, normalized by the maximum displacement, D/MD, plotted against the normalized fault length, L/SRL, with a compilation of profiles for normal faulting earthquakes published by Wesnousky (2008), the 2016 profile locates close to the lower boundary of global normal faulting field. This is clearly an effect of the very high 2016 MD.

As aforesaid, the MD value, exceeding the expected, might be due in part to localized tectonic phenomena. The AD value, lower than the expected, might be probably caused by an attenuation of coseismic displacement toward the surface, possibly due to the high segmentation of the fault system.

We conclude that caution is needed in using regressions based on MD and AD because it can not be ruled out that other global earthquakes might be affected by comparable problems.
Similarly, caution is needed in the use of AD and MD, for Seismic hazard analysis, when obtained indirectly from other parameters (fault length, expected magnitude).

Finally the use of displacement values and slip rates for calculating recurrence times of large earthquakes have to be carefully evaluated: in fact, using displacement values measured on a section of the fault where D~AD and slip rate values obtained in a section close to MD, lead to underestimate the recurrence time and vice versa. In other word, when the aforementioned coseismic parameters are to be used for these purposes it is necessary, as much as possible, to determine them at the same point of the fault.

References