A QUANTITATIVE APPROACH TO THE LOADING RATE OF SEISMOGENIC SOURCES IN ITALY

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Introduction. To investigate the transfer of elastic energy between a regional stress field and a set of localized faults we project the stress rate tensor inferred from the Italian GNSS velocity field onto fault planes selected from the Database of Individual Seismogenic Sources (DISS 3.2.0). For given Lamé constants and friction coefficient we compute the loading rate on each fault in terms of the Coulomb Failure Function (CFF) rate. By varying the strike, dip and rake angles around the nominal values listed in the DISS, we also estimate optimally oriented fault planes, i.e. planes oriented for maximal CFF rate.

Out of 86 Individual Seismogenic Sources (ISSs), all well covered by GNSS data, 78 to 81 (depending on the assumed friction coefficient) load energy at a rate of 0-4 kPa/yr. The sources with larger CFF rate (4 to 6 ± 1 kPa/yr) are all deep (>10 km) faults located in the central Apennine and are all characterized by a significant strike-slip component. We also find that the loading rate of 75% of the examined sources is less than 1 kPa/yr lower than that of optimally oriented faults. We also analyzed the two Mw 6.0-6.5 earthquakes that struck the central Apennine in 2016. The strike of their causative faults based on seismological and tectonic data and the geodetically inferred strike differ by < 30°. Some sources exhibit a strike oblique to the direction of maximum strain rate, suggesting that in some instances the present-day stress acts on inherited faults. The choice of the friction coefficient only marginally affects this result.

Computing the loading rate. The knowledge of current deformation rates at the Earth's surface represents a significant boundary condition for modeling seismogenic processes in most of the Italian region where the typical hypocentral depth is in the order of 5 to 20 km. A few recent papers have proposed the combination of geophysical and geodetic data to infer properties of the crust-mantle coupling (e.g. Palano, 2015) or to constrain finite element models where the deformation is driven by large-scale forces (e.g. Carafa *et al.*, 2015). Such regional models provide fundamental insight for investigating large-scale geodynamic processes but are too coarse to be used for determining the relative state of stress of adjacent faults.

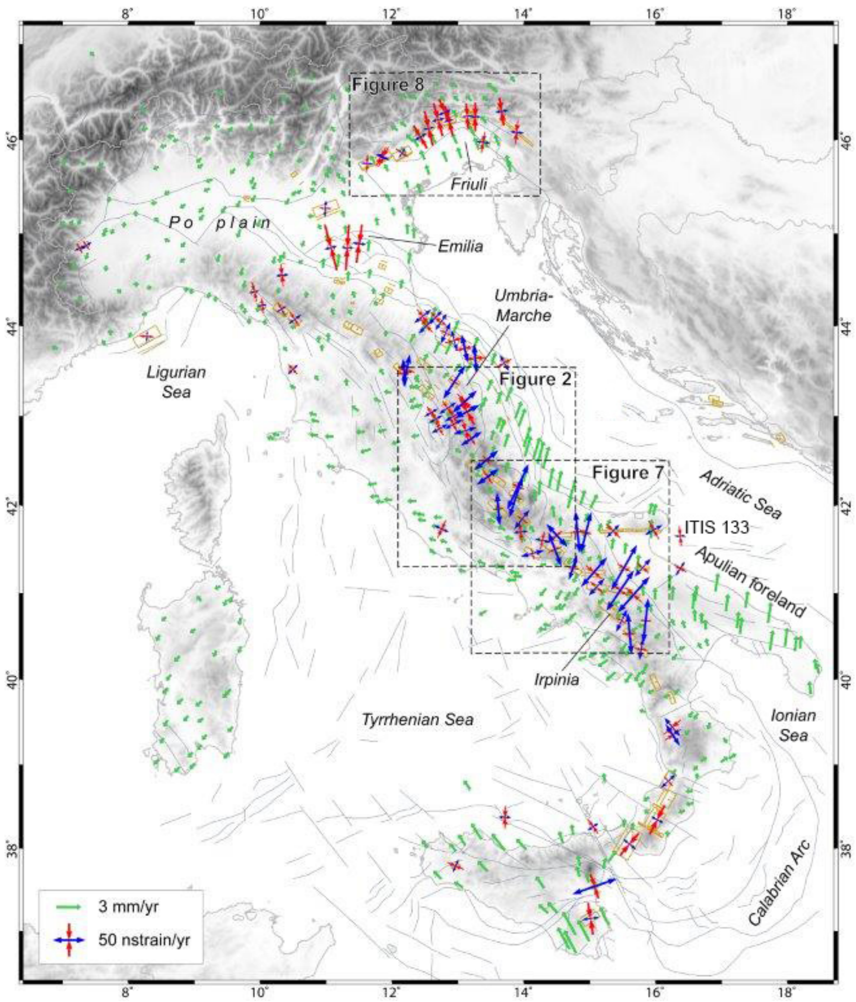

Fig. 1 - Eigenvectors of the strain rate tensor inferred from GPS velocities (green arrows) are interpolated to the center of those 86 ISSs (brown rectangles) sufficiently covered by GPS data. Extension is in blue and compression in red. Major tectonic lineaments are in orange.

Over the past two decades several papers (e.g. King and Cocco, 2000; Console *et al*., 2008; Caporali *et al*., 2016, among others) have investigated the Coulomb Failure Function (CFF) or Coulomb stress change in specific examples of earthquake sequences which are supposed to be both spatially and temporally related. In this approach the stress field generated by an earthquake of known fault plane solution is mapped onto a nearby "receiver" fault. This approach reveals whether this fault has been loaded or unloaded by the occurrence of the parent earthquake.

In this paper we focus on the stress field which is measured on a regional scale by geodetic methods as a source of load on the faults. In particular, GPS geodesy provides a 2D strain rate that can be converted into an elastic plane stress rate (Fig. 1). This can be assumed to approximate the horizontal stress rate field throughout a 15-20 km-thick brittle seismogenic layer. Validation with independent stress data is possible thanks to the new improved stress map of Italy (Montone and Mariucci, 2016). Owing to the dense distribution of geodetic GNSS sites, this stress rate tensor can now be calculated for the centroid of several of the seismogenic sources of the DISS database. The normal and tangential stress rates relative to the fault plane can be computed, and finally the Coulomb Failure Function (CFF) as the difference between the tangential stress rate and the normal stress rate multiplied by an assumed friction coefficient. The obtained CFF represents a measure of the loading/unloading rate on the fault plane. Hence this analysis can eventually indicate the rate at which each fault is loading or unloading elastic energy. As a possible inference, regions where the current strains explain well the known seismicity can be identified, and areas that are historically quiescent but where stress is consistently building up can be singled out. In such areas the lack of seismicity may result from a limited earthquake coupling – i.e. ongoing strains are consumed aseismically - or from the incompleteness of the earthquake record.

Fig. 2 shows the statistical distributions of the CFF in the case of fixed friction of 0.5. We have also tested the option of an optimal friction, i.e. computed on the basis of the angles provided by the DISS for each ISS. the majority of the faults we have examined are positively coupled to the regional field at a relatively modest rate in the 0 : 4 kPa/yr range, with a few notable exceptions in central Italy The notable exceptions are ITIS052 (San Giuliano di Puglia), ITIS053 (Ripabottoni), for which we find a loading rate of 5 kPa/yr, and ITIS094 (Tocco da Casauria) with more than 6 kPa/yr for the variable friction case. Assuming a constant friction only ITIS094 clearly emerges with 5 kPa/yr. Assuming a friction coefficient optimized on the dip and rake of a fault generally increases the CFF by about 1 kPa/yr for some faults that already had a high CFF.

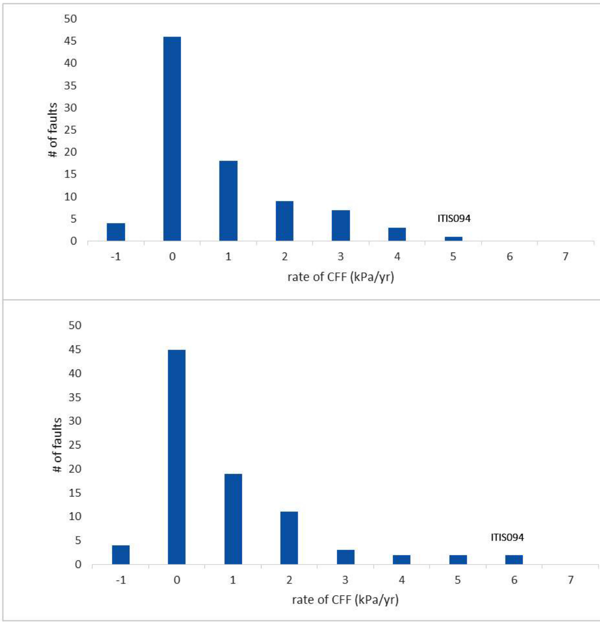

Fig. 2 - Statistical distribution of the ISS's according to the rate of CFF, for a fixed friction.

The Sources ITIS052 and ITIS053 are both associated with the 2002 San Giuliano di Puglia earthquakes of Mw 5.7 and 5.8 at a depth of 16-20 km, according to DISS. They show a pure strike slip mechanism. Di Luccio *et al.* (2005) estimate that the minimum stress (i.e. the extensional stress) is elongated in the N-S direction, which very well agrees with the geodetic estimates of the strain rate eigenvectors in Fig. 1.

The Source ITIS094 (Tocco da Casauria) is associated with the 5-30 December 1456 earthquakes, the largest destructive event, occurred in the Italian peninsula and among of the strongest of the entire seismic history of Italy. Fracassi and Valensise (2007) propose that the 1456 sequence is composed of various sub-events but that only three main events are responsible for the major damage, between 5 and 30 December 1456. According to these authors the seismogenic style falls between the mainly extensional Apennines axis and the mainly right-lateral strike-slip kinematics occurring in the Apulian foreland.

Alignment of the strike to the orientation of the geodetic stress rate field. In areas of high structural complexity the strike angles of the fault plane solutions may differ from the corresponding angles estimated from field survey. The strike of the seismic fault or source may also be offset relative to the direction of the largest eigenvector of the stress or strain rate tensor, for normal and reverse faults. In such cases the seismic slip occurs on inherited faults, or faults which have been reactivated with a different stress regime. An example is given by the structures in Friuli, as discussed by Viganò *et al.* (2008,) and Restivo *et al.* (2016).

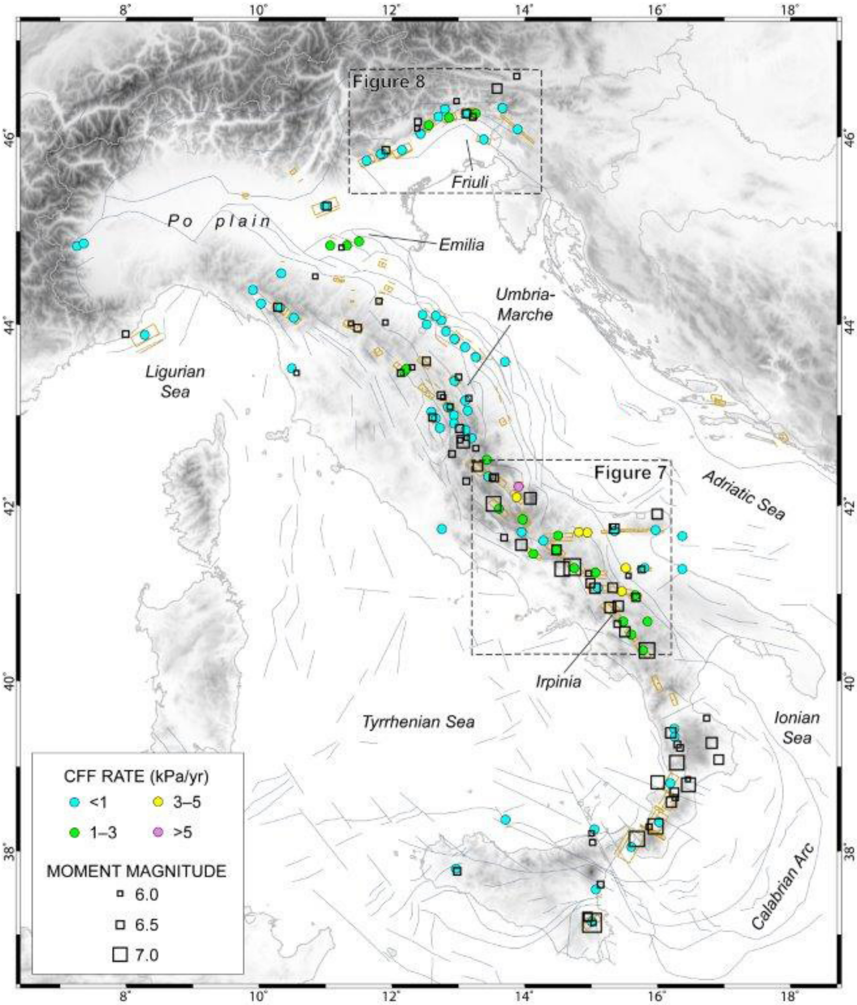

Fig. 3 - Classification of the selected ISS's according to their CFF. The area in central Italy of Aquila and Avezzano appears the one with the maximum loading rate. Squares indicate the epicenters of historical earthquakes, according to the CPTI2015 catalogue (Rovida *et al.*, 2016).

We compared the strike of selected seismogenic faults (normal and reverse) with the direction inferred from the eigenvectors of the strain rate tensor. Gemona is associated with the 1976 Mw=6.5 event, Colfiorito is associated with the 1997 Mw=6.0 event, Paganica with the 2009 Mw=6.3 event, Mirandola and Finale Emilia with the dual 2012 Mw=6.1 events and Amatrice with the 2016 Mw=6.0 event. For this last source we have assumed as principal plane the SW dipping. Considering that the overall uncertainty in the strike angles is of the order of 20-30 degrees, we conclude that the geologically determined angles are consistent with the directions of maximum strain rate, at least for these structures. As shown in Fig. 1, in NE Italy the the alignment is very close only near the tip of the indenter where Gemona (ITIS120) is located. Further west and east the compressional eigenvector clearly rotates less than the strike of the structures.

Conclusion. The coupling between a regional stress rate field implied by GPS data and the fault geometry described in the DISS provide important quantitative information on the loading/unloading of potentially active seismogenic sources. Our analysis provides a first quantitative scale for this mechanical coupling. Sources located in NE Italy, were the Adria microplate is actively indenting the southern Eastern Alps, appear all subject to load. There exist sources for which the loading rate is higher than the average. They are all located in the northern Apennines (Emilia), central Apennines (Umbria Marche and Aquila Avezzano) and southern Apennines (Irpinia). Does a high rate of CFF on a fault necessarily imply a higher probability of activation? If a stress drop of about 3 MPa is taken as reference (Allman and Shearer, 2009) then some 600 years would be needed to a fault loading at a rate of 5 kPa/yr to make up the stress which is on average released seismically. However we know very little about the ability of each fault to release stress aseismically, nor is it clear if and to which extent these sources can translate the applied stress into permanent deformation. A central question is how can one address systematically the relation between the *(a,b)* parameters of the regional Gutenberg Richter, which refer to events of release of energy, and the loading rates/frictional properties, which refer to the process of stress buildup. A number of authors (e.g. Spada *et al.*, 2013, Scholz, 2015; Chen *et al.*, 2016) have recently pointed out that the b-value could be related to the difference between the maximum and minimum principal stresses. Whence the inference that the b value could be time dependent, besides being a function of the stress regime.

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