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Extensional rate budgeting: constraints from geological and seismological data in central Italy

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Abstract: We present quantitative estimates of the stretching rate in central Italy from active faults and earthquake data. Using slip rates, we estimated the horizontal component of the deformation for each fault. Then, using the historical catalogue, we estimated the average displacement for each earthquake and obtained the stretching rates for the last 1000 years of seismicity. Errors in the estimation of slip rates have also been considered. Geological and seismological stretching rate curves show a similar pattern; significant local divergences could be attributed to seismic gaps. We consider the geological database of normal active faults and the historical earthquake catalogue in central Italy complete enough and useful for seismic hazard purpose.

Keywords: central Italy, extensional tectonics, slip rates, geological deformation, seismic deformation, geodetic deformation.

Geodesy, geology and seismicity offer different, complementary views of the active tectonics of a region and can provide important information about the seismic behaviour of the region. In this work, we compare in a systematic way the available data on the geodetic, seismologic and geological deformation rates in the central Apennines of Italy; the results are compared with the deformation rates indicated by geodetic data.

The central Apennines of Italy are affected by active normal faulting (Barchi *et al.*, 2000; Galadini and Galli, 2000; Boncio *et al.*, 2004 and references therein). Normal faults have NNW-SSE average strike, dip mainly toward WSW and display dip-slip to normal-oblique kinematics. Ongoing extension driven by nearly horizontal NE-trending deviatoric tension is confirmed by fault slip data on active faults as well as by earthquake focal mechanisms (Frepoli and Amato, 1997, 2000; Boncio and Lavecchia, 2000).

The knowledge of the geodetic, seismologic and geological expression of active tectonics has largely improved during the last decades. Geodetic strain and extensional rates have been computed by several authors (e.g. Hunstad *et al.*, 2003; Serpelloni *et al.*, 2005). Hunstand *et al.* (2003) determined the geodetic strain for the period 1875-2001, through GPS reoccupation of the first triangulation network of Italy, installed from 1860. In the central Apennines they calculated NE-directed horizontal extensional rates, averaged throughout the Apennine area, ranging from 2.5 to 3.5 mm a^{-1}. Serpelloni *et al.* (2005) combined local, regional and global networks into a common reference frame for the period 1991-2002, estimating a NE-directed extensional rate of about 2.5 mm a^{-1} across the Apennines.

Measurements of geological slip rates along the normal faults were collected by Roberts and Michetti (2004, and references therein), using topographic displacement archived from the last glacial maximum (i.e. during the last ~18 ka). We integrated this dataset with other specific works on the displacement of normal faults (Barchi *et al.*, 2000; Galadini *et al.*, 2000;

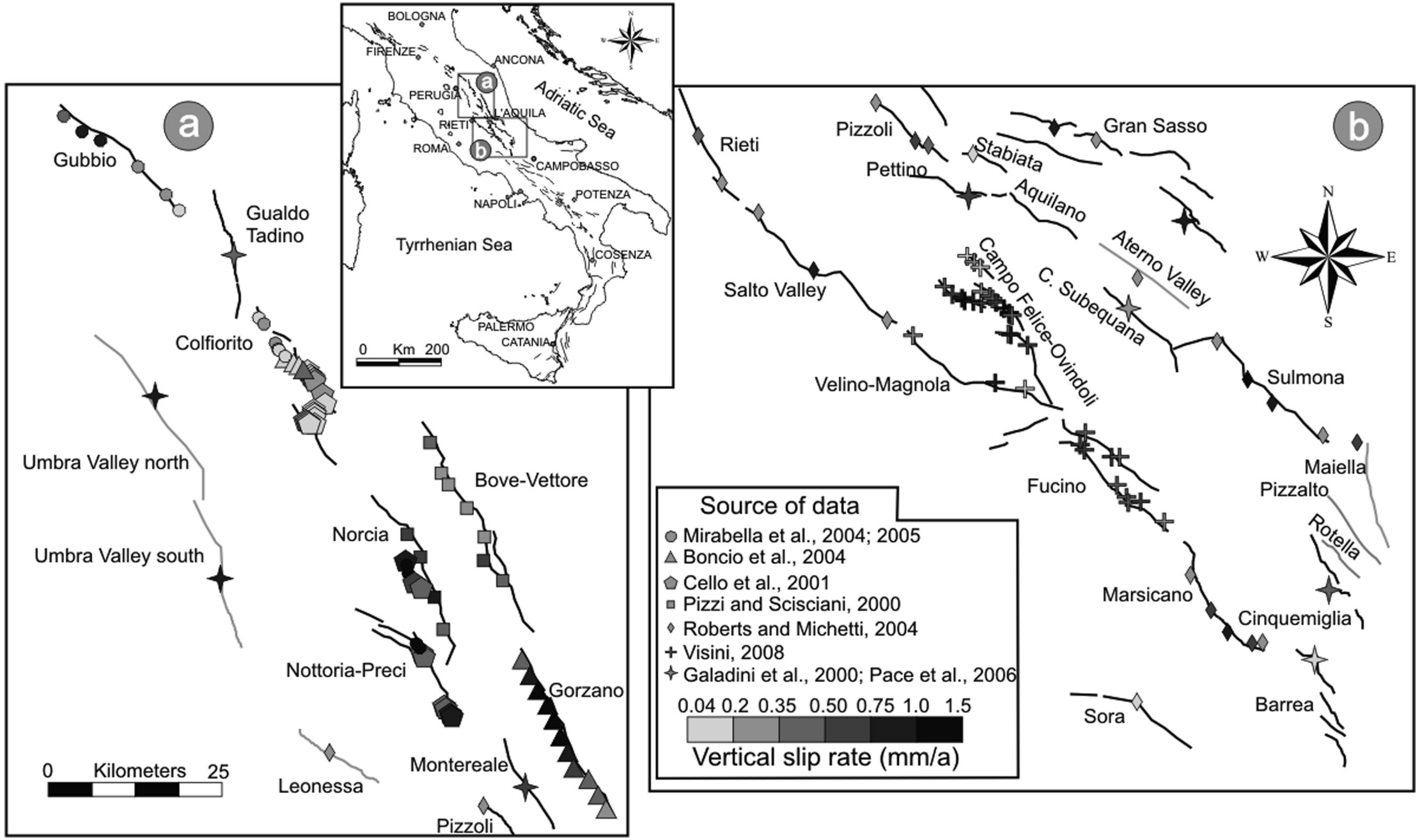

Figure 1. Upper inset: location map for the study area with major active normal faults; a) and b): maps of central Italy showing major active normal faults (accepted fault = solid black line; debated fault = solid grey line) with indication of the localities where vertical slip rates are measured.

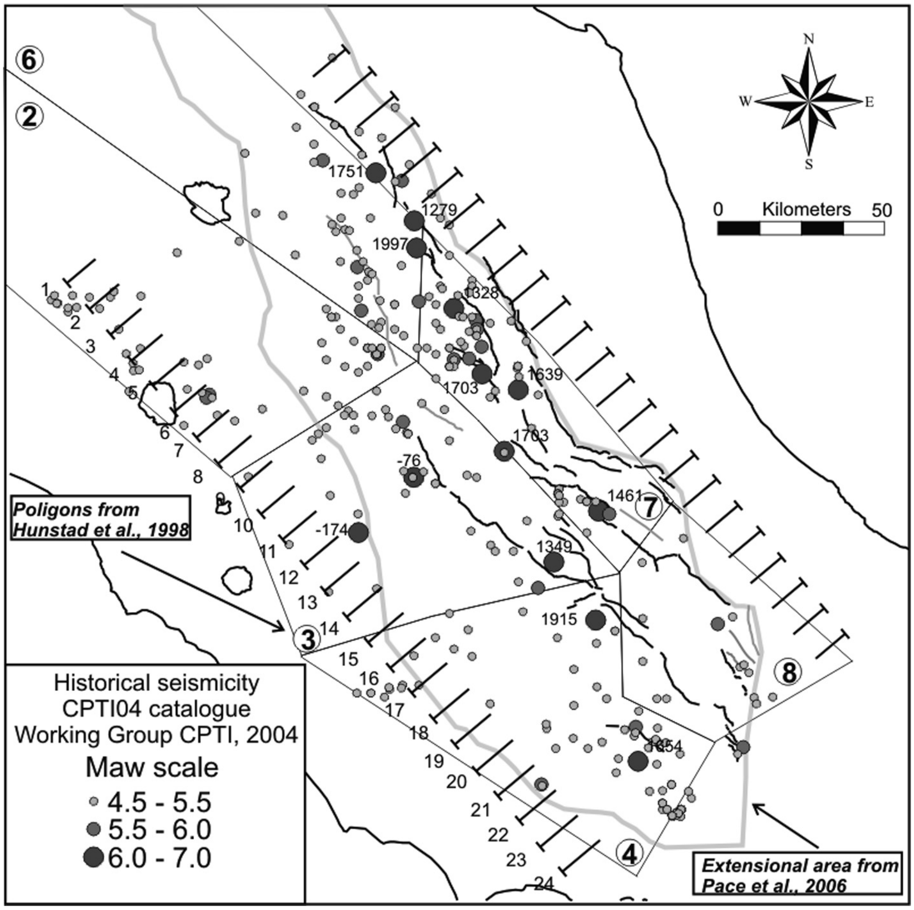

Figure 2. Map of central Italy (accepted fault = solid black line; debated fault = solid grey line) with epicentres of the historical events. Traces of sections (numbers 1 to 24) and number of polygons as in Hunstad *et al.* (2003) (encircled numbers) are also reported.

Pizzi and Scisciani, 2000; Cello *et al.*, 2001; Mirabella *et al.*, 2004, 2005; Visini, 2008). Because our knowledge of different faults is not always the same (see Boncio *et al.*, 2004), the different weight of the less constrained faults on the geological rates is discussed.

The seismicity contribution to the extensional rate was calculated by using the 217 B.C. - 2002 A.D. CPTI04 (Working Group CPTI, 2004) historical catalogue and the reported equivalent moment magnitudes (with relative errors).

Method

Geological deformation

Slip rates in central Italy were principally inferred from detailed topographic profile across the scarp, assuming that the displacement cumulated from the last glacial maximum (~18 ka ago). The errors which may occur in the estimation of the post 18 ka slip rates are discussed in Roberts and Michetti (2004), who fixed the maximum error at ±0.2 mm a^{-1}, including uncertainties in the estimation of fault scarp measurement and time of activity. When recent slip rates were not available, we used the total displacement measured on geological cross sections and the associated slip rate averaged over the entire fault activity. Particularly for the Norcia and Bove-Vettore faults, Pizzi and Scisciani (2000) suggest the commencement of fault activity at 1.1 Ma; for the structures of Gubbio, Colfiorito, Nottoria and Gorzano, the Quaternary displacement is assumed to have developed mostly during the last 700 ka (Cello *et al.*, 2001; Boncio *et al.*, 2004; Mirabella *et al.*, 2004, 2005). We verified that ±0.2 mm a^{-1} is a reasonable estimation of the error for these faults also. As an example for a fault with a displacement of 1.5 km and an age of 1.1 Ma, assuming a range of 1.3 to 1.7 km of displacement and 0.9 to 1.3 Ma of activity, the slip rate error is 0.2 mm a^{-1}. All the slip rate data collected are reported in figure 1. Because we are interested in the horizontal component of the deformation velocity, we varied the average dip of the normal faults through the entire seismogenic layer, from 40° to 60°, and we calculated the associated uncertainty. For each fault we computed the slip rate and its horizontal component, defined as the extensional rate. Then we summed the extensional rates along 24 transects crossing all the active faults in the direction N40°E, and spaced 10 km, in order to compute the stretching rates and their variations along the mean strike of the region (Fig. 2). The faults of figures 1 and 2 do not have the same quality in terms of amount and type of data on the Late Quaternary activity. Following the classification proposed in Galadini *et al.* (2000) and Boncio *et al.* (2004), we separated the best known active faults (solid lines) from the debated and doubtful structures (dashed lines). In figure 3 we considered the likely activity of these debated faults. The solid line is the stretching rate computed by using only the best known active faults; the dashed line is computed by adding the debated faults.

In order to compare the stretching rate due to normal faulting with the geodetic one, we evaluated the geometric moment M_g for each fault and summed the contribution of the population of faults within the same polygons delimited by Hunstad *et al.*, (2003).

Scholz and Patience, (1990) defined:

$$M_g = \overline{D}LW \qquad (1),$$

where $\overline{D}$ is the mean displacement, L is the along-strike length and W is the down-dip length of the fault.

We used the mean slip rate derived from slip rate measurement previously described, in order to obtain the M_g rate ($\dot{M}_g$). The strain rate $\dot{\varepsilon}$ from the fault, calculated along the N40°E direction, can then be expressed by:

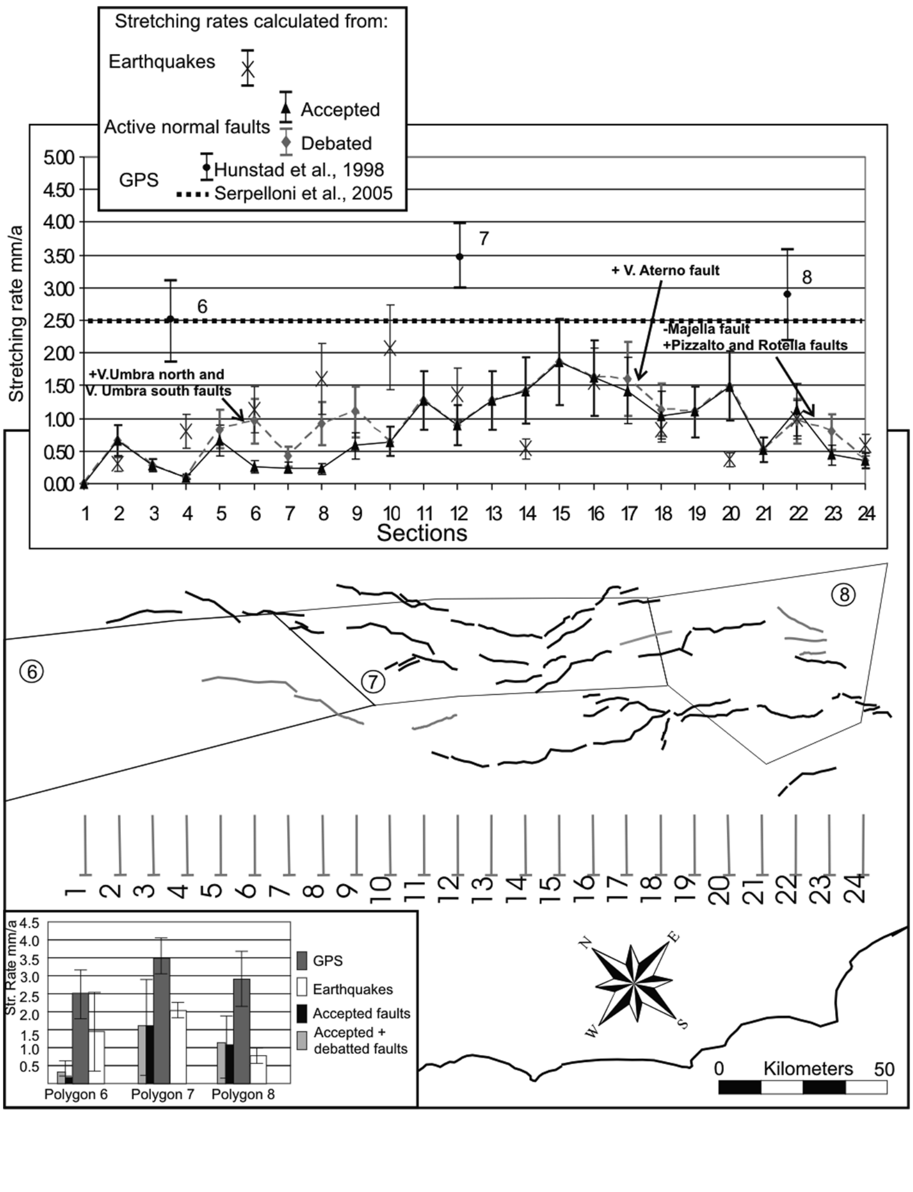

Figure 3. Fault map together with stretching rate profiles for active normal faults in central Italy. Traces of the 24 sections throughout the area for which extensional rate have been summed. In the lower histogram, the stretching rates computed within the polygons (encircled numbers) from faults and earthquakes are compared with the geodetic ones.

$$\dot{\varepsilon} = \frac{1}{2\mu V}\dot{M}_g \quad (2),$$

where V is the volume of the seismogenic deforming region and μ is the rigidity modulus.

Subsequently, simplifying by using the assumption that the deformation along strike is negligible, we computed the stretching rate. Errors which may occur in this calculation are mainly due to the geometry of the fault and to the value of mean slip rate for each fault. Starting from the slip rates measured (Fig. 1), we calculated mean and standard deviation for each fault and then, varying the angle of fault dip from 40° to 60°, we evaluated the extensional rate within the polygon used by Hunstad *et al.* (2003).

The seismic deformation

In order to compare the seismic and geological budgets of deformation and their variation along the central Apennines normal fault alignment, we derived the slip for each event using the empirical relationships of Wells and Coppersmith (1994) between moment magnitude and average displacement. To obtain slip rates we used historical events that have occurred in the last 1000 years, and summed the events that occurred within a half-space of 10 km from the section. We used the even sections in figure 2, so we were able to compute seismic slip rates with a double spacing in respect of the geological ones. Errors in the estimation of the extensional seismic rate are due to uncertainties in magnitude (error data in CPTI04 catalogue, Working Group CPTI, 2004), angle of dip of fault (in the range 40-60°) and to the standard deviation of the empirical relationship of Wells and Coppersmith (1994).

In order to estimate the velocity tensor within the same polygon of Hunstad *et al.* (1998), we used the formulae by Molnar (1979) and Jackson and McKenzie (1988).

The scalar seismic moment rate $\dot{M}_o$ within the seismogenic volume was calculated using Molnar's (1979) formula:

$$\dot{M}_0 = \frac{A}{1\text{-}B} M_{0\,\max}^{1\text{-}B} \quad (3),$$

where $\dot{M}_0=10^{c\text{-}M_s+d}$, $A=10^{[a+(bd/c)]}$ and $B=b/c;$

a and b are values of the Gutenberg-Richter relation, c and d values are constants of the moment-magnitude relation (Kanamori and Anderson, 1975), and M_{0max} is the scalar moment of the largest observed earthquake in the region.

We considered c and d equal to 1.5 and 16.05, respectively, as defined by Kanamori and Anderson (1975) and we calculated the a and b values and their uncertainties for each polygon, considering the historical dataset complete since the year 1000 ± 100 for Maw ≥ 6.4, since 1600 ± 100 for 5.5 ≤ Maw < 6.5 and since 1900 ± 100 for 4.5 ≤ Maw < 5.0.

The components of the velocity tensor U_{ij} may be calculated using the formula developed in Jackson and McKenzie (1988):

$$U_{ij} = \frac{1}{2\mu l_k l_j}\dot{M}_0 \bar{F}_{ii} \quad (4),$$

with $i = 1, 2, 3$, and $k \neq i, i \neq j, j \neq k;$

$$U_{12} = \frac{1}{2\mu l_1 l_3}\dot{M}_0 \bar{F}_{12} \quad (5),$$

$$U_{i3} = \frac{1}{2\mu l_1 l_2}\dot{M}_0 \bar{F}_{i3} \quad (6),$$

with $i = 1, 2$;
where l_1 and l_2 are along-strike length and along-dip width of the deforming zone and l_3 is the average thickness of the seismogenic layer (10 km, from Hunstad *et al.*, 2003).

The errors which may be involved in the calculation of equation (3) are mainly controlled by errors in M_o, while the directions of the eigenvectors of the deformation, equations (4), (5) and (6), are mainly influenced by errors in the focal mechanism tensor (F = 130/50 with dip-slip kinematics, assuming the extensional rate perpendicular to the average strike of the fault system). The uncertainties in the magnitude of the observed velocities for each source are estimated through errors in using the Monte-Carlo simulation method. As can be seen from equation (3), the errors in M_o are derived from errors in a, b, c, d and M_{Smax}. Assuming random errors in these parameters, with known means and standard deviations, Gaussian deviates can be introduced. Simulating 10,000 catalogues we evaluated the M_o and the corresponding stretching rate expressed in terms of mean and standard deviations.

Results

The stretching rates from fault data show a spatial pattern with a maximum of ~2 mm a^{-1} approximately corresponding to the centre of the fault array, decreasing in both directions along strike (Fig. 3). This result suggests that the active extension in central Italy defines a first order segmentation pattern, while local minima (corresponding to sections n°4, 10, 12, 17, 21) may be due to the second order of segmentation pattern.

Geological stretching rates are consistent with the seismological ones. The distribution of seismic stretching rates shows a spatial pattern similar to the geological one, with a first-order belt-shape curve. From section 4 to 7 a gap between the two data of about 1 mm a^{-1} is evident. However, in this area at least two debated active faults are reported in the literature: the Valle Umbra north and the Valle Umbra south. If we assume for these structures slip rates of ~0.8±0.2 mm a^{-1} (from Pace *et al.*, 2006) the difference is filled, or at least contained, within the errors. Very interesting local minima (section 14 and 20) let us speculate about the possibility of a missing earthquake in these areas. The first minimum corresponds to section n°14 (from Valle del Salto to Vettore fault); the second to section n°20 (from Fucino to Sulmona). Considering that within polygon n°7 (Fig. 2) the rates from geological and seismological data are very close, it is possible to infer that the deficit is due to a missing earthquake of the Valle del Salto fault, where no historical events are recorded. Clearly it is also possible to assume that the Valle del Salto fault is not active, but we ruled out this idea considering the first order segmentation pattern of the geological stretching rate. As regards the minimum located in section 20, it is possible to attribute the deficit to the Sulmona fault, considering that the other fault crossed by the section is the Fucino fault, activated by the 1915 Fucino earthquake (Mw~7).

When the geological and seismological budgets of deformation are compared with the geodetic one (from Hunstad *et al.*, 2003), the first evident discrepancy is the constant difference of at least 1 mm a^{-1}. It is interesting to observe that the decreasing slip rate pattern toward NW and SE terminations is maintained in any case.

However, this difference is significantly reduced considering data from Serpelloni *et al* (2005), who estimated 2.5 mm a^{-1} of extensional rate, a value close to the slip rates computed in this study.

Discussion and conclusions

The large difference of 1 mm a^{-1} highlighted by the ratio between geodetic and geological or seismological stretching rates in polygon 7, as estimated by Hunstad *et al.* (2003), is hard to explain in terms of incompleteness of the data for faults or earthquakes. In fact, in this area, a dense population of normal faults exists. Moreover, the ratio geological/seismological slip rate is ~1. Also, in polygons 6 and 8 (Fig. 2), a good agreement exists between the geological and seismological stretching rates.

The likely occurrence of two earthquakes, possibly on the Sulmona and Valle del Salto faults, will reduce the difference between geological and seismological stretching rate in figure 3, along the sections n°14 and 20.

In order to explore the differences between the geodetic rates and the geological and seismological ones, we did some tests to quantify the "magnitudes" needed to fill up the gap. Assuming a double value for the slip rates along all the faults, the maximum value of stretching rate, along section n°15 will be ~3.5 mm a^{-1}, close to the geodetic value, but we are unable to obtain the geodetic values of 2.5 and 2.9 mm a^{-1} in the northern and southern areas. As regards the seismologic stretching rate, we need to double the number of events along all sections (except sections n°8 and 10, where a factor of 1.5 is enough) or to add in each section at least two earthquakes with Mw~6.6 (or one with Mw >7).

Due to the close correspondence between the geological and seismological stretching rates, we consider such a high under-estimation of the active deformation rates as unreasonable. Finally, for central Italy, we consider the geological fault dataset and the seismic catalogue quite complete, certainly useful for seismic hazard study, without risk of over-estimation in terms of the velocity of deformation.

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