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## Recurrence time of large earthquakes at the western Alps-Mediterranean sea junction : from geological observations and modelling of the seismicity rate

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**Abstract:** The junction between the Western Alps and the Ligurian basin in the Mediterranean Sea is one of the intraplate areas of Western Europe where strong earthquakes occur. The last of these earthquakes occurred in 1887 activating the Ligurian thrust, the major structure which has controlled most of the deformation in the area for about 5 Ma. The available data (GNSS, geological, seismological) allow us to hypothesize the recurrence time of  $M_w$  6.8 earthquake, equivalent to the 1887 earthquake, and lead to a range of 6500-3000 years.

**Key words:** recurrence time, active fault, seismicity rate, Alps, Mediterranean sea.

### INTRODUCTION

The junction between the Western Alps and the Mediterranean Sea is one of the most seismic area in the westernmost Europe. This intraplate area suffered several damaging earthquakes in the last centuries and particularly the February 23, 1887 ( $M_w$  6.8) which struck the towns along the Italian and French Riviera, killing at least 600 people, injuring several thousand and destroying many buildings.

While the recurrence time of strong earthquakes is one of the critical parameters to be determined, in intraplate and low deformation rate areas qualitative estimates of the order of several thousand to several hundred thousand years are sometimes proposed but usually without precise data to refine the range. In this paper we attempt to discuss the recurrence times of 1887-ligurian-type earthquakes : (i) by estimating slip-rates based on GNSS and geological data and (ii) by determining the earthquake rates from earthquakes catalog.

### SEISMOTECTONIC SETTING

In the western Mediterranean, the junction between the western Alps and the Ligurian Basin corresponds to an area of moderate seismicity which belongs to the Western European intraplate domain (Larroque et al., 2011 ; 2021). The seismicity is mainly located in a zone of long-term cumulated deformation and seismotectonic analyses show mainly reverse faulting, along the so-called Ligurian thrust, extending for about 90 km-long at the foot of the continental margin from Nice to Savona (Fig. 1A,B). From the reappraisal of the 1887 Ligurian earthquake, taking into account macroseismicity, active tectonics and tsunami modelling, we propose that this emblematic earthquake resulted from the activation of the Ligurian thrust (Fig. 1C) Larroque et al., 2012 ; Ioualalen et al., 2014).

### RECURRENCE PERIOD ESTIMATIONS FROM GNSS AND GEOLOGICAL DATA

Our approach is based on 2 hypotheses : (i) we consider that the convergence between the European mainland and the Corsica-Sardinia-block is accommodated by the

Ligurian thrust (Fig. 1A,C). This hypothesis is supported on the long-term (~5 Myr), by the location of cumulated deformations, and on the short-term, by the distribution of the instrumental seismicity, both of which mainly along the Ligurian thrust (Fig. 1B,D). (ii) We consider also a characteristic slip for the targeted earthquake. Taking into account the scaling laws (Wells & Coppersmith, 1994; Leonard, 2010) we set a range of co-seismic slip between 1 m and 1.3 m for an earthquake of  $M_w$  6.8 (Ioualalen et al., 2014).

Several geodetic and geological dataset are available to constrain the slip-rate on the Ligurian thrust through different time scales :

(1) The horizontal velocity estimated between permanent GPS stations in Corsica (AJAC) and on the mainland (NICE) is a shortening of 0.4 mm/yr maximum (Nocquet, 2012 ; Masson et al., 2019). Thus we consider a range of 0.2-0.4 mm/yr of present-day slip-rate on the Ligurian thrust to be realistic. The recurrence times (RT) for co-seismic slip of 100 and 130 cm on the 20° northward-dipping Ligurian thrust (Fig. 1C) for a shortening of 0.2 and 0.4 mm/yr are in the range of 5000-6500 yr and 2500-3250 yr, respectively (Table 1).

CoSS		1 m	1.3 m
Vh			
0.2 mm/yr	RT~ (yr)	5000	6500
0.4 mm/yr	RT~ (yr)	2500	3250

Table 1. CoSS : Co-seismic slip, Vh : horizontal velocity, RT : recurrence time for  $M_w$  6.8 earthquake.

(2) Several geological markers of different ages attest to continuous uplift of the French-Italian coastline and of the northern Ligurian margin from Pliocene to present-day. Since the coastline and the margin are located on the hanging-wall of the fault (Fig. 1A,C), we use these cumulative offsets in order to estimate the slip-rate along the Ligurian thrust at different time intervals and then compute the corresponding RT :

- From underwater mapping, Collina-Girard (2002) identified a sequence of sub-aerial erosion notches dated around 10 kyr and located all along the submarine cliffs from Marseille to Monaco. These erosion notches are

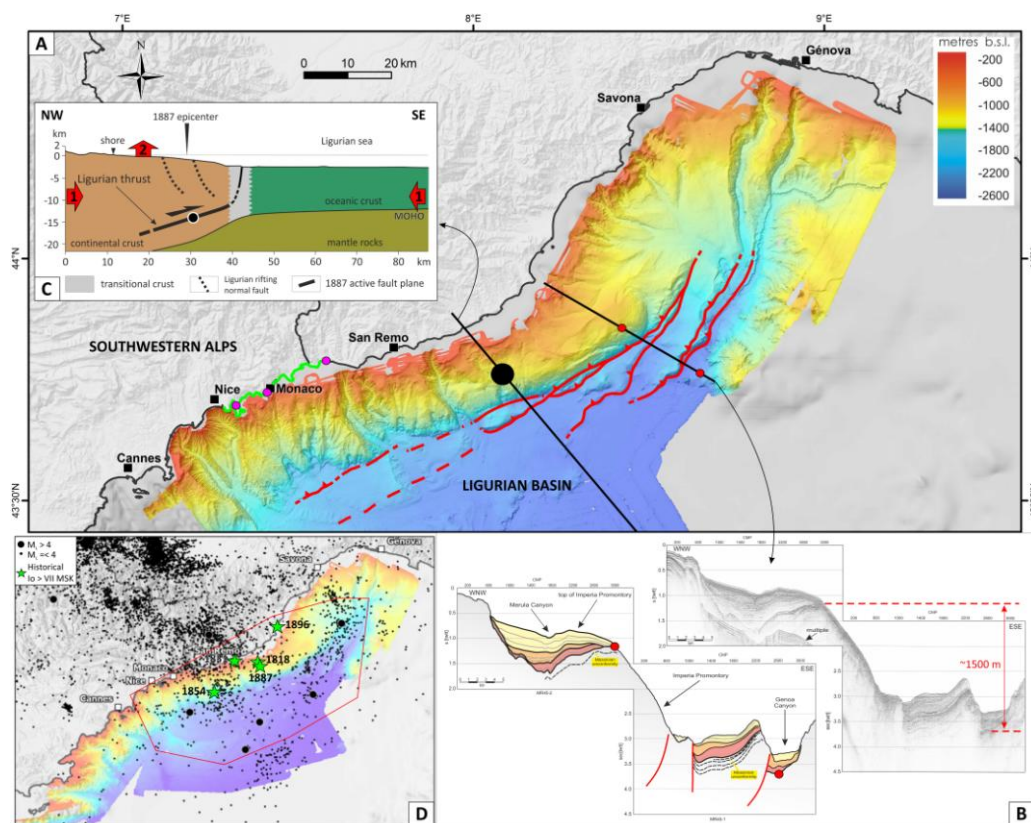


Figure 1. (A) Structural sketch of the western Alps-Ligurian basin junction : red lines are the Ligurian reverse faults system rooted at depth to the Ligurian thrust and extended from Nice to Savona, the black dot is the epicenter of the Ligurian 1887 earthquake. The green line corresponds to the coastal zone where well-marked Holocene erosion notches are raised about 2 m with respect to the area further west (Collina-Girard, 2002); the pink dots localise the uplifted Pleistocene marine terraces (Dubar et al., 2008); the red dots indicate the position of the Pliocene-Quaternary boundary surface showed on (B). (B) MCS profil MR-45 showing the offset of the Pliocene-Quaternary boundary surface on either side of the Ligurian faults system (red dots on A). (C) Seismotectonic sketch : the 1887 Ligurian earthquake (black dot) activated the northward low-dip Ligurian thrust (bold line). At shallow depth, the Ligurian faults system is located at the transitional oceanic/continental crust. 1: shortening between NICE and AJAC GPSc stations, 2: uplift of the hanging wall (modified from Larroque et al., 2012). (D) Instrumental and historical seismicity map from  $M_L \geq 1.5$  and  $I_0 \geq VII$  MSK (CEA-LDG catalog, 1962-2018 and SisFrance), the red parallelogram corresponds to the background extraction from the SERA catalog (Danciu et al., 2021) in order to determine the Gutenberg-Richter distribution.

interpreted as submerged shorelines developed when sea level rise period. A major observation is that east of the Var River ( $\sim 7^{\circ}15'E$ ) this sequence of notches is offset upwards by 2 m (Fig. 1A). We interpret this offset as a tectonic uplift of the hanging-wall related to the activation of the Ligurian thrust which ends  $\sim 7^{\circ}15E$ . Taking into account the  $20^{\circ}$  northward-dip and the uplift of the hanging-wall related to a  $M_w$  6.8 earthquake (0.34 m and 0.44 m for a co-seismic slip of 1 m and 1.3 m, respectively), for a cumulative uplift of 2 m over a period of 10 kyr, we obtain RTs in the range of 1666 yr and 2500 yr, respectively (Table 2).

- On the shore between Nice and San Remo (Fig 1A), several evidences of Pleistocene marine terraces developed during the high-stand sea level of the last interglacial period (MIS5.5, 130 kyr) are currently uplifted 20 m above the present-day sea level (Dubar et al., 2008). Because during the MIS5.5 period the sea level was  $\sim 5$  m above the present-day one (Lambeck et al., 2004), the actual tectonic uplift of the hanging-wall would be 15 m since 130 kyr. Thus, the RTs for a cumulative uplift of 15 m for a period of 130 kyr are 2955 yr and 3824 yr for 1 m and 1.3 m of co-seismic slip, respectively (Table 2).

- On the northern Ligurian margin, Larroque et al. (2011) highlighted a 1500 m-uplift of the hanging wall based on the offset of the Pliocene-Quaternary boundary surface on either side of the Ligurian thrust (Fig. 1B). The RTs for a cumulative uplift of 1500 m over a period of 5.33 Myr are 1208 yr and 1563 yr for 1 m and 1.3 m of co-seismic slip, respectively (Table 2).

CoSS	1 m	1.3 m
uplift / event	$\sim 0.34$ m	$\sim 0.44$ m
<b>RTs (yr) over 10 kyr</b>	<b>1666</b>	<b>2500</b>
<b>RTs (yr) over 130 kyr</b>	<b>2955</b>	<b>3824</b>
<b>RTs (yr) over 5.33 Myr</b>	<b>1208</b>	<b>1563</b>

Table 2. CoSS : Co-seismic slip, RTs : recurrence times for  $M_w$  6.8 earthquake on the Ligurian thrust for different periods of time and different types of data : offset of Holocene erosion notches (10 kyr, Collina-Girard, 2002), uplift of Pleistocene marine terraces (130 kyr, Dubar et al., 2008) and offset of the Pliocene-Quaternary boundary surface (Larroque et al., 2011).

#### EARTHQUAKE RATES DEDUCED FROM THE SERA CATALOG

We extracted seismicity from the SERA catalog (Danciu et al., 2021) for a background covering 30 km around the



Ligurian Thrust (Fig. 1D). Completeness periods were estimated based on an adaptation of the Albarello et al. (2002) approach for earthquakes occurred in the Western Alps region. Using the Weichert method (1980), the slope of the Gutenberg-Richter distribution was also estimated at the regional scale and found to be quite low, close to a value of 0.7 (b-value of 1 is also tested for comparison). We infer that the Ligurian thrust can be considered seismogenic along its entire 90 km-long over a width of roughly 30 km with a slip-rate of 0.2 or 0.4 mm/yr. Different earthquake recurrence models based on geological parameters have been proposed in the literature. The “Exponential” model formulation (Youngs & Coppersmith, 1985) considered here is as follows :

$$N (M_w \geq M) = Mfs*(1.5-b) (1 - \exp(-\beta (M_{max} - M)))/b*MomentMax* \exp(-\beta (M_{max} - M)) \quad \text{Eq. 1}$$

where the moment rate of the faults system, Mfs, is given by  $\mu*A*s$  with  $\mu$  the shear modulus, A the area of the faults system, s the slip-rate and b is the b-value,  $\beta=b*\log(10)$ ,  $M_{max}$  is the maximum magnitude being tested, the MomentMax is the corresponding seismic moment given by the Hanks & Kanamori (1979) equation :

$$\text{MomentMax} = 10^{(1.5*M_{max} + 9.05)} \quad \text{Eq. 2}$$

Figure 2 shows the comparison between SERA earthquake catalog and theoretical recurrence models (Youngs & Coppersmith, 1985) for the Ligurian thrust, considering three  $M_{max}$  around the target magnitude,  $M_w$  6.8, and the two slip-rate values considered (0.2 and 0.4 mm/yr).

Recurrence $M_w \geq 6.8$		$M_{max}=6.9$	$M_{max}=7.0$	$M_{max}=7.4$
b-value 0.7	SR 0.2	<b>5365</b>	<b>3485</b>	<b>3237</b>
	SR 0.4	NC	NC	<b>1618</b>
b-value 1	SR 0.2	NC	NC	4046

Table 3. RT estimates of  $M_w \geq 6.8$  coherent with activity rates deduced from the SERA catalog. SR : slip-rate, NC : Parameters not compatible with the SERA catalogue.

Table 3 presents the range of recurrence values for  $M_w \geq 6.8$  for different hypothesis of  $M_{max}$ , slip-rates and b-values that are compatible with the earthquake rates deduced from the catalogue. RTs estimations are comparable to the geological estimates and coherent with SERA earthquake catalogue rates only when considering  $b=0.7$  and  $SR=0.2$ . For  $SR > 0.2$  it is necessary to advocate the possibility  $M_{max} = 7.4$  (equivalent to rupturing the entire faults system).

## DISCUSSION AND CONCLUSION

In intraplate regions the process that triggers earthquakes has been recently questioned (e.g. Calais et al., 2016). Earthquakes in such regions could potentially occur as a result of transient stress/strength perturbations (deglaciation, erosion, fluid circulation...), releasing elastic energy from a pre-stressed crust rather than due to the localized accrual of tectonic stresses. Were this to be the case everywhere in intraplate regions, probabilistic seismic hazard assessments (PSHA) should also be questioned, since they are based on the assumption that

earthquakes have a recurrent nature controlled by far-field tectonic forces. It is therefore paramount to document in which regions classical PSHA approaches can be still considered valid or may need to be revised.

The present-day setting of the western Alps-Mediterranean Sea junction is consistent with the long-term tectonic evolution attested by the uplift of the northern Ligurian margin relative to the basin since 5 Myr (Bigot-Cormier et al., 2011). Therefore, we consider that the Ligurian thrust is a major long-lived tectonic activated structure.

Our results show that whatever the data used and the time interval regarded, the RTs estimated for a  $M_w$  6.8 on the Ligurian thrust are always lower than 6.5 kyr. The major result is that we obtain an upper bound for this intraplate context, which is supported by independent approaches but the values vary in a still quite wide range between 6.5 kyr and 1.2 kyr (Table 1 and 2).

The GNSS and geological data (Table 1 and 2) give fairly consistent RTs around 4000 years depending on the slip-rate and co-seismic slip assumptions. Analysis of the longest period (5.33 Myr) gives the shortest RTs (Table 2) but this result is highly questionable as it is based on a characteristic co-seismic slip which should not be a realistic condition given the likely changes in geodynamic conditions at this time scale. Nevertheless, this result could be an indication of a slowing down of the convergence rate between the Corsica-Sardinia block and the European mainland since 5 Myr.

RTs obtained by comparing theoretical RTs with the ones deduced from the SERA earthquakes catalog indicate a wider range of possible RT depending on the slip-rate hypothesis (Table 3). These results depend strongly on the earthquake catalog, in particular the computed b-value of 0.7 and also on the geometry chosen for the background seismicity used to compute it and supposed to represent the seismic activity surrounding the fault volume.

Finally, we consider that the transposition of the maximum convergence rate determined by GNSS (Masson et al., 2019) into a slip-rate on the Ligurian thrust is not realistic because diffuse seismicity occurs southward in the basin (Fig. 1D). The preferred value for the slip-rate on the Ligurian thrust is 0.2 mm/yr and leads to a range of RTs of 6500-5000 yr versus 3000 yr for GNSS data, geological data and Gutenberg-Richter-distribution approaches, respectively.

At the end, we must not forget that the 1887 Ligurian earthquake only broke part of the Ligurian thrust (about 35 km-long estimated, Larroque et al., 2012) and that the adjacent parts have not yet broken.

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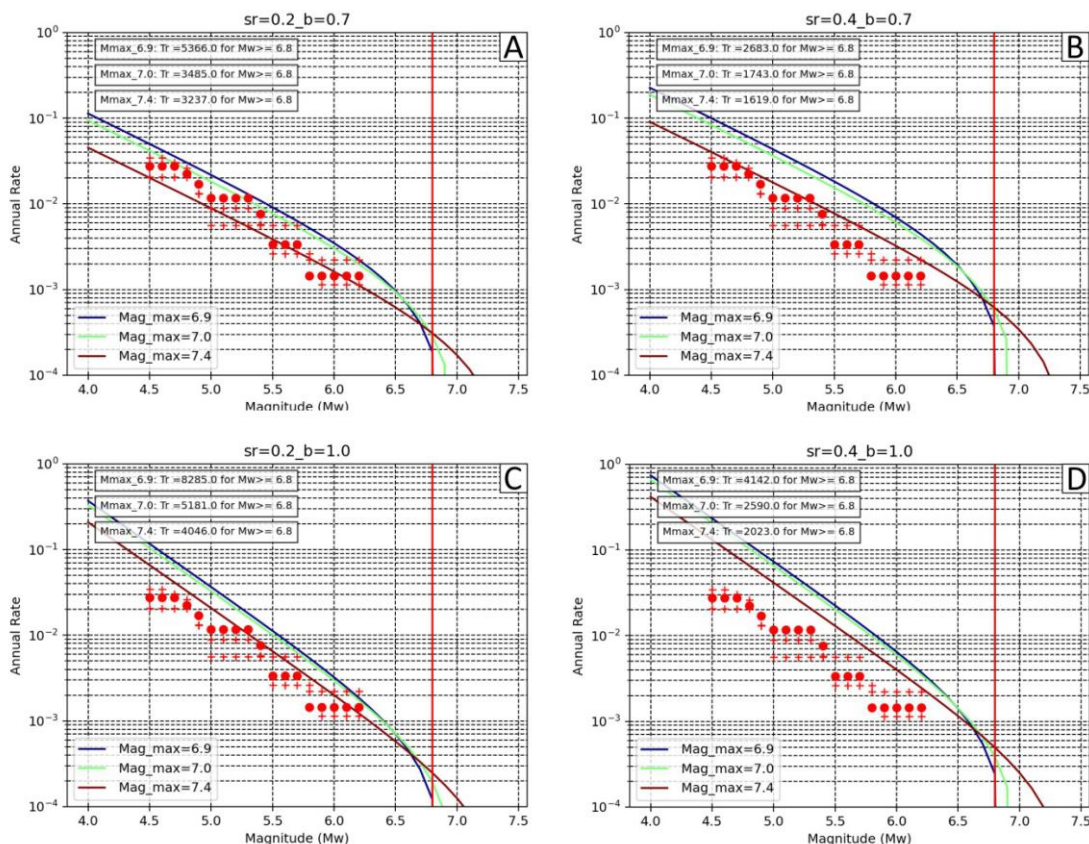


Figure 2. Theoretical earthquakes recurrence models for different Mmax (color curves) versus SERA catalog for the Ligure area (red dots). A, B : b-value=0.7 (suggested for the western alpine region based on the Weichert method) with a slip-rate of 0.2 and 0.4mm/yr respectively. C, D : b-value=1.0 (for comparison). The vertical red bar indicates the target magnitude  $M_w$  6.8.

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