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[Stress evolution and slip deficit on the North Anatolian Fault (Turkey) in the Marmara Sea: insights from paleoseismicity, seismicity and geodetic data]

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ORIGINAL PAPER

The slip deficit on the North Anatolian Fault (Turkey) in the Marmara Sea: insights from paleoseismicity, seismicity and geodetic data

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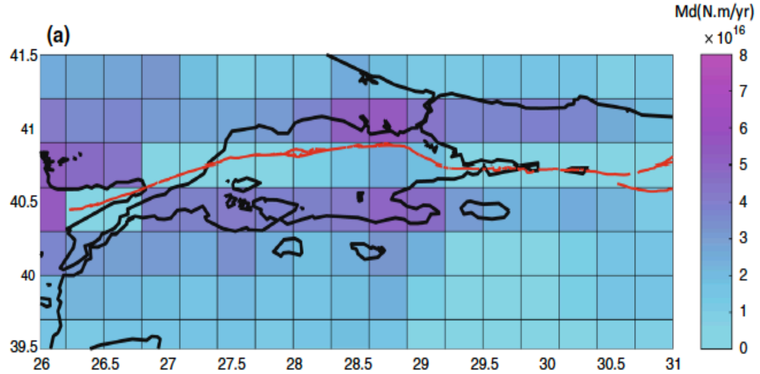
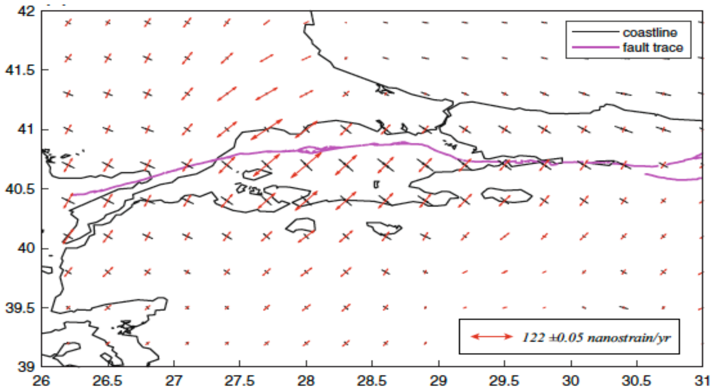
Abstract

The North Anatolian Fault experienced large earthquakes with 250–400 years recurrence time. In the Marmara Sea region, the 1999 (Mw = 7.4) and the 1912 (Mw = 7.4) earthquake ruptures bound the Central Marmara Sea fault segment. Using historical-instrumental seismicity catalogue and paleoseismic results (≃ 2000-year database), the mapped fault segments, fault kinematic and GPS data, we compute the paleoseismic-seismic moment rate and geodetic moment rate. A clear discrepancy appears between the moment rates and implies a significant delay in the seismic slip along the fault in the Marmara Sea. The rich database allows us to identify and model the size of the seismic gap and related fault segment and estimate the moment rate deficit. Our modelling suggest that the locked Central Marmara Sea fault segment (even including a creeping section) bears a moment rate deficit $\dot{M}_d = 6.4 \times 10^{17}$ N.m./year that corresponds to Mw ≃ 7.4 for a future earthquake with an average ≃ 3.25 m coseismic slip. Taking into account the uncertainty in the strain accumulation along the 130-km-long Central fault segment, our estimate of the seismic slip deficit being ≃ 10 mm/year implies that the size of the future earthquake ranges between Mw = 7.4 and 7.5.

Keywords North Anatolian Fault · Paleoseismicity · Earthquake catalogue · Geodesy · Slip deficit





Comparison of two types of data:

Earthquake catalogue
(Instrumental and historical)

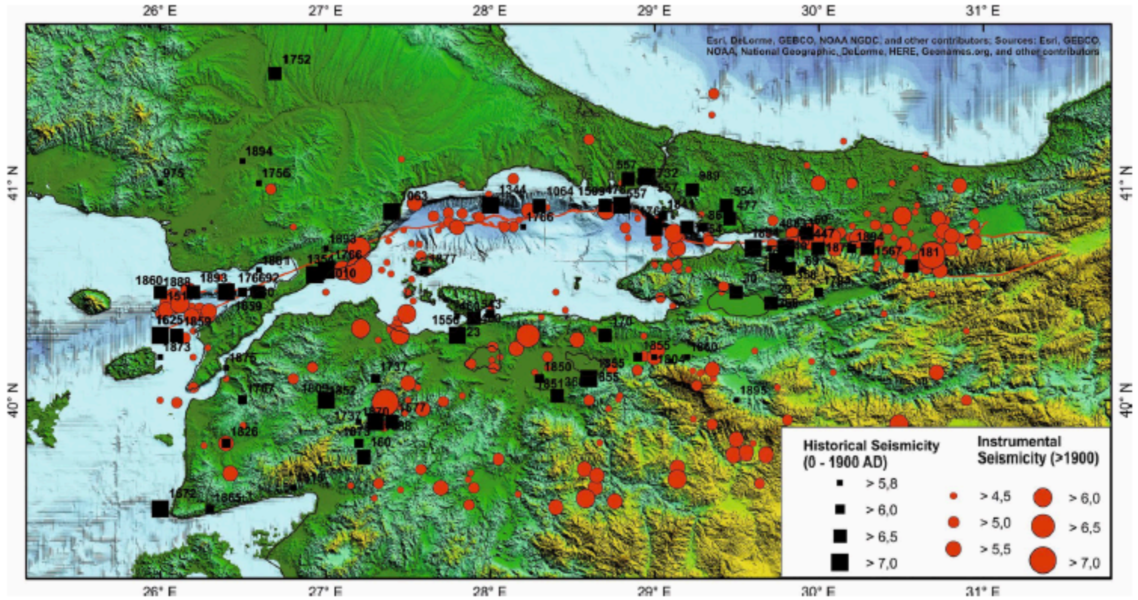
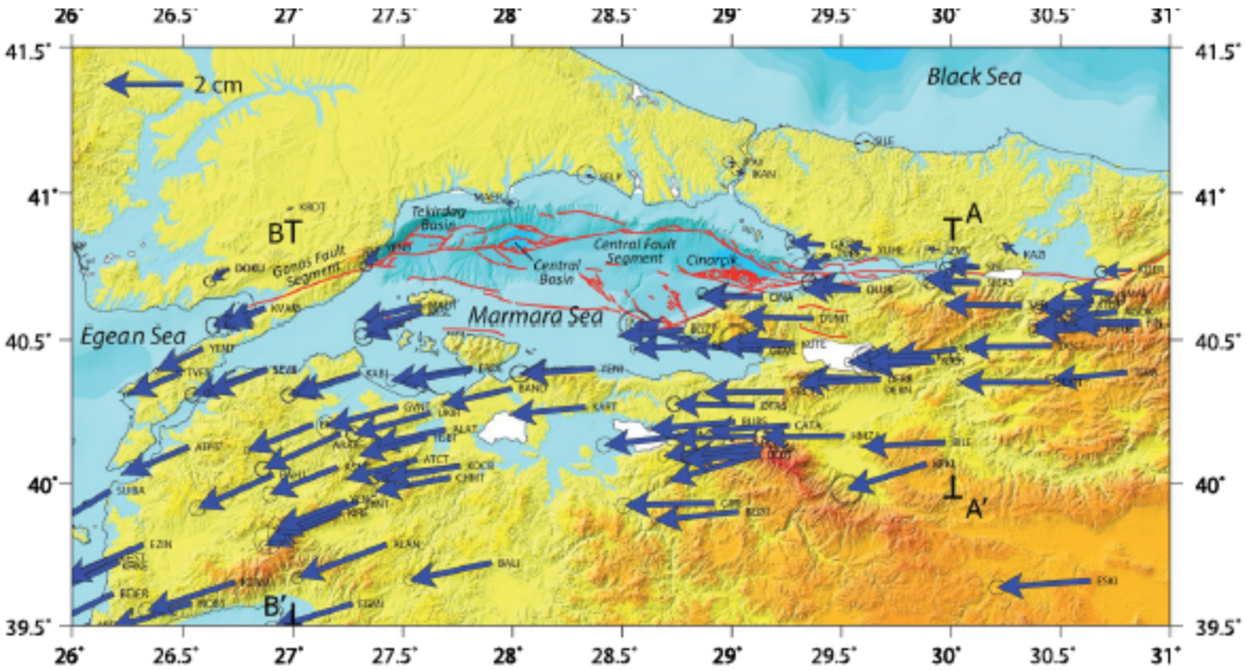
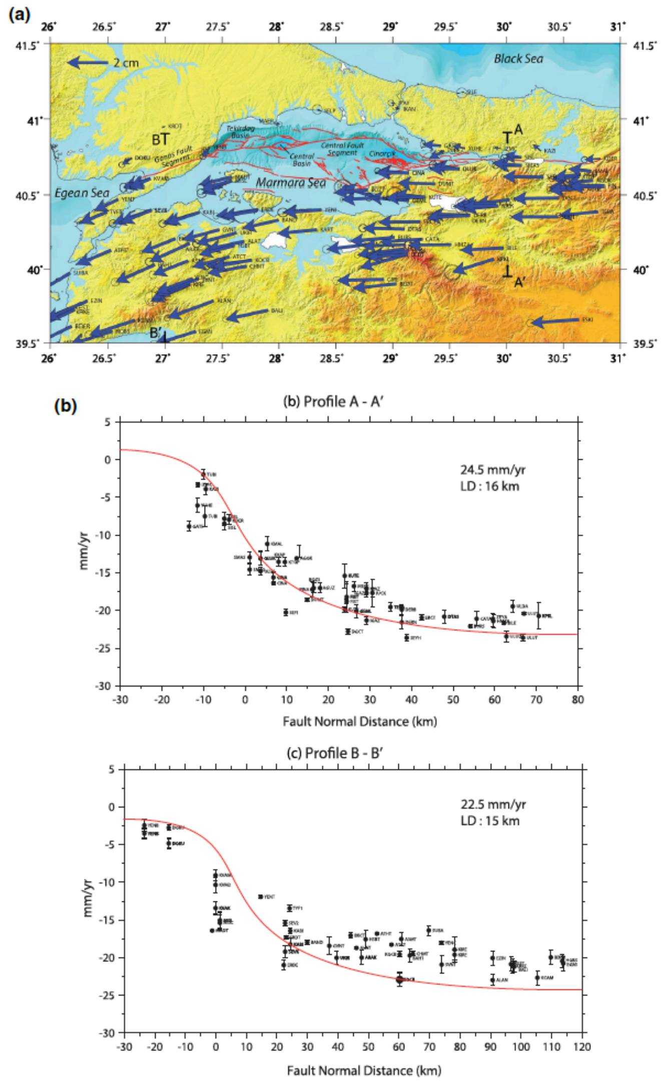


Fig. 1 Instrumental (circle) and historical (box) seismicity, and North Anatolian Fault zone (red line) in the Marmara Sea region. The instrumental seismicity data (1900–2014) are from Kandilli Observatory and Earthquake Research Institute and the International Seismological Center, and historical earthquakes are from Ambraseys (2002), Atakan and Sorensen (2002)

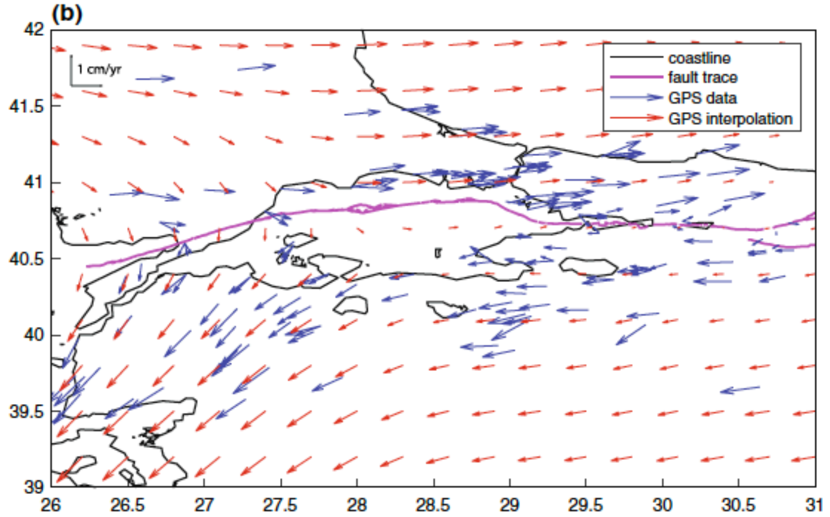
Geodetic data (GPS velocities)



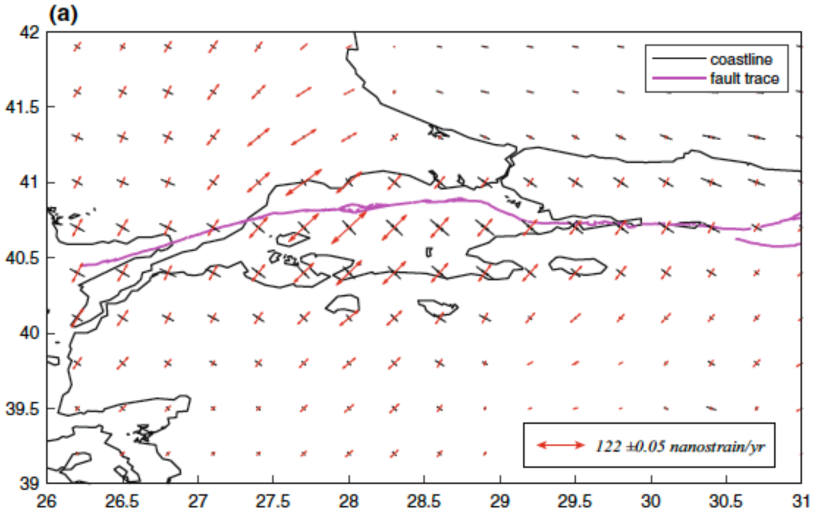
Geodetic data:



Interpolation on a regular grid



Surface strain rate determination



Seismic data: computed seismic moment rate over 2000 years

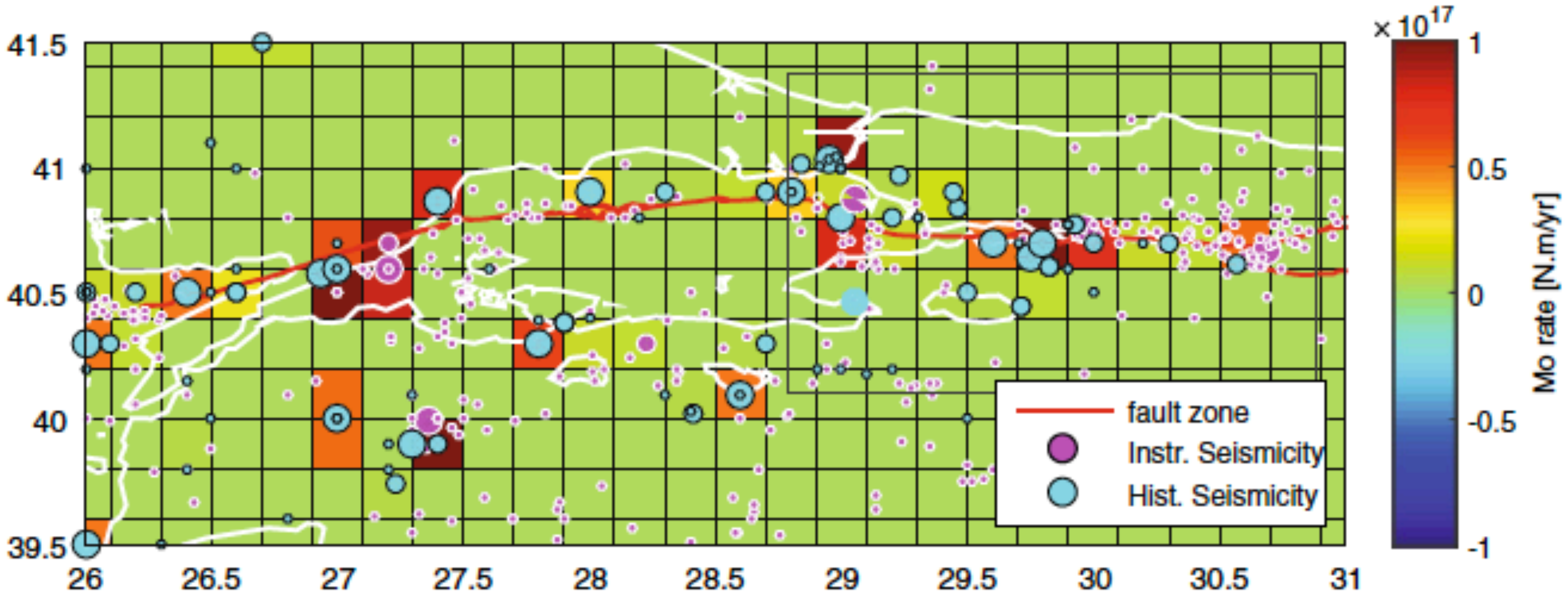


Fig. 3 Seismic moment rate obtain from ≃ 2000 year-long seismicity catalogue using Mw ≥ 6.5 (see also Fig. 1 and Table 1). A seismic moment rate gap appears along the Central region of the North Anatolian Fault in the Marmara Sea

Comparison, method from Savage and Simpson (1997):
Geodetic Moment Rate:

$$M_o = 2\mu HA \begin{bmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & -\Delta \end{bmatrix} \quad \text{with } \Delta = \varepsilon_1 + \varepsilon_2,$$

$$\dot{M}_{o(T)} = \dot{M}_{o(SS)} + \dot{M}_{o(DS)} = 2\mu\text{HA} \times \max\left(|\varepsilon_1|,\ |\varepsilon_2|,\ |\varepsilon_1 + \varepsilon_2|\right). \tag{5}$$

H: brittle lithosphere thickness,
A: cell area,
μ: shear modulus

(a) If $|\varepsilon_1| + |\varepsilon_1 + \varepsilon_2|$ is the minimum, then the geodetic scalar moment rate in strike-slip mechanism is

$$\dot{M}_{o(gSS)} = 2\mu HA|\varepsilon_1|, \tag{6}$$

and the geodetic scalar moment rate in dip-slip mechanism is

$$\dot{M}_{o(gDS)} = 2\mu HA|\varepsilon_1 + \varepsilon_2|, \tag{7}$$

(b) If $|\varepsilon_2| + |\varepsilon_1 + \varepsilon_2|$ is the minimum, then the geodetic scalar moment rate in strike-slip mechanism is

$$\dot{M}_{o(g,\,SS)} = 2\mu HA|\varepsilon_2|, \tag{9}$$

and the geodetic scalar moment rate in dip-slip mechanism is

$$\dot{M}_{o(g,\,DS)} = 2\mu\text{HA}|\varepsilon_1 + \varepsilon_2|, \tag{10}$$

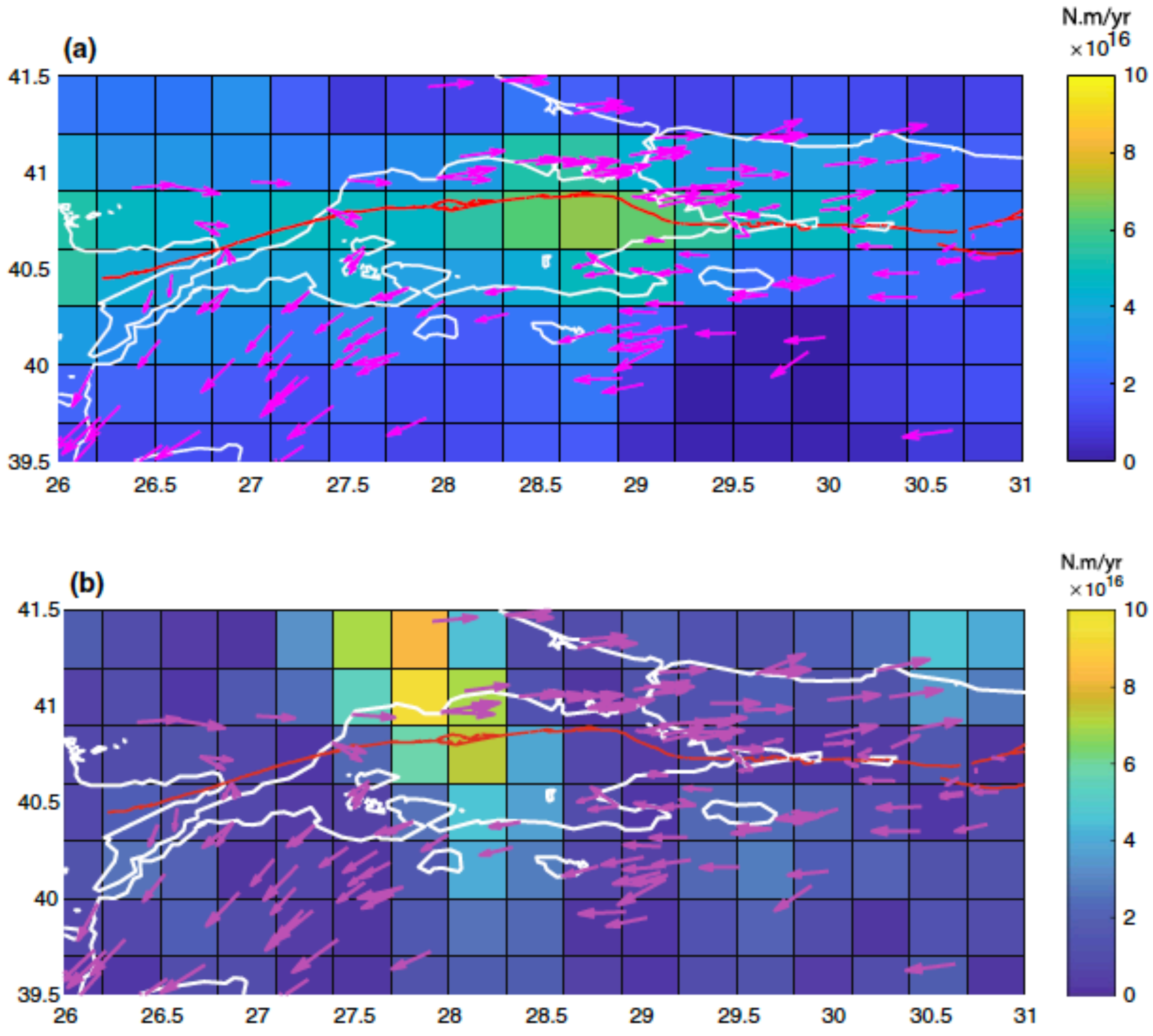
(c) If $|\varepsilon_1| + |\varepsilon_2|$ is the minimum: there is no geodetic scalar moment rate in strike-slip mechanism, i.e.

$$\dot{M}_{o(g,\,SS)} = 0, \tag{12}$$

and the geodetic scalar moment rate in dip-slip mechanisms is

$$\dot{M}_{o(g,\,DS)} = 2\mu HA|\varepsilon_1| + |\varepsilon_2|, \tag{13}$$

Computed Geodetic Moment rate



Strike-slip

Dip-slip

Fig. 4 Geodetic moment rate (in N.m/year) obtained from the GPS data in the Marmara Sea (see also Figs. 2 and 6 a and b for scaling). **a** The high geodetic moment rate is linked to the strike-slip component of active deformation along the central fault segment; **b** according to the dip-slip mechanism, a higher moment rate is located around the Central pull-apart basin. A shift to the North of the geodetic rate may also be partly due to the poor GPS data coverage near the North Anatolian Fault (red line). Pink vectors are inferred from the interpolation of GPS velocities processed to fill the limited GPS data coverage in the Marmara Sea. The interpolation is made according to 0.3° cell distribution

Computed Deficit: top, with strike-slip compoents. Bottom, dip-slip components

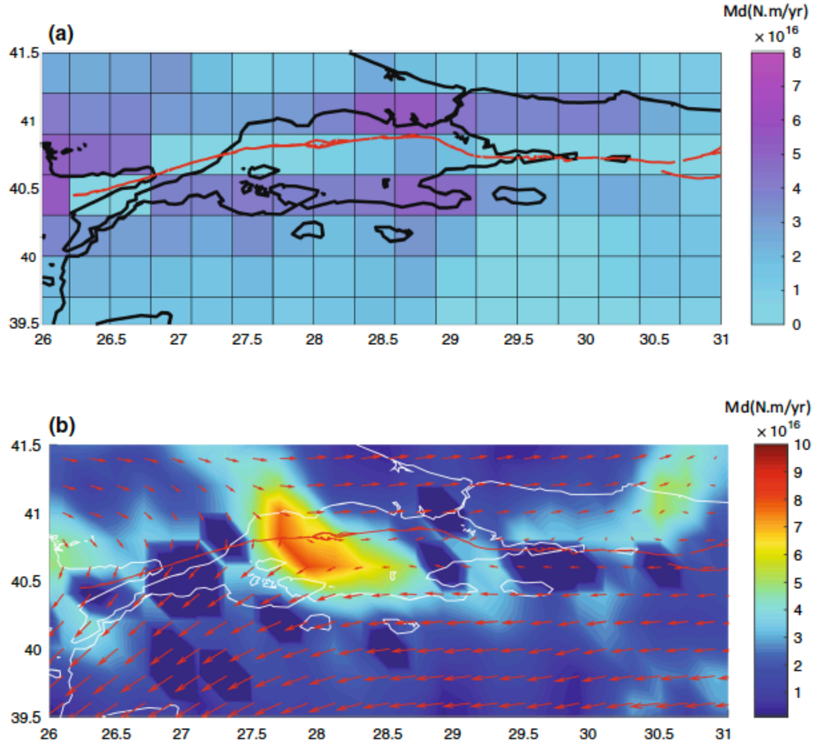


Fig. 5 Moment rate deficit calculated from the difference between seismic and geodetic moment rate along the Marmara fault segments (red line). **a** The high moment rate deficit is associated with the high geodetic rate (see Fig. 4a) and related strike-slip component of active deformation along the central fault segment; **b** The high moment rate is here according to the high geodetic rate and dip-slip mechanism located around the Central pull-apart basin. Red arrows are as in Fig. 4b (see also Fig. 6b for scaling). The moment rate deficit show 6.4×10^{17} N.m/year and 2.5–4 m slip deficit for Ti = 250 to 400 years return period of large earthquakes along the~ 130 km-long central Marmara fault segment (see also Table 2)

Table 2 Parameters of the future large earthquake in the Central Marmara fault segment, for different time intervals (Ti), inferred from our modelling of moment rate deficit $\dot{M}_d$ (see text for explanation)

Ti	$\dot{M}_d$	Mo (N.m)	Mw	L (km)	W (km)	μ (N/m²)	u (m)	$\dot{u}$(mm/yr.)
251	6.41×10^{17}	1.60×10^{20}	7.40	130	15	3.3×10^{10}	2.5	9.96
300	6.41×10^{17}	1.92×10^{20}	7.45	130	15	3.3×10^{10}	2.99	9.96
350	6.41×10^{17}	2.24×10^{20}	7.50	130	15	3.3×10^{10}	3.49	9.96
400	6.41×10^{17}	2.56×10^{20}	7.54	130	15	3.3×10^{10}	3.98	9.96

Marmara seismic gap. Considering the moment deficit rate and related average 2.5–4 m slip deficit since the May 22, 1766 earthquake, the size of the Central Fault segment needs to amount 130 km-length. These results suggest that the expected earthquake is along the Central Fault segment of the Marmara Sea and may reach Mw 7.4 with a return period *Ti* of 250–400 years regardless of the contribution of aseismic creeping.