General title for both talks

Triggering of Earthquakes in Fault Zones - A Contribution to Time-Dependent Hazard Asssement

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Basic Idea

- Standard seismic hazard assessment

  - random distribution of seismicity in space and time

  - earthquake location and magnitude

  - location of active zones

→ long-term probability of seismic hazard

while

- Modelling of stress fields in space and time

  includes

  - plate tectonic stress changes

  - focal mechanisms, location, rupture extend of earthquakes

  - elastic and inelastic properties of the Earth's crust …

→ time-dependent stress fields, leading to

→ time-dependent probability of seismic hazard

Modelling steps

> Estimation of an initial, rather homogeneous, stress field

- Stress release by the 1st earthquake
- Postseismic inelastic stress changes

\+ Stress increase by plate motion

- Stress release by the 2nd earthquake
- Postseismic inelastic stress changes

\+ Stress increase by plate motion

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•
•

The dislocation theory for stratified, elastic/inelastic gravitational media → to determine *shear* and *Coulomb stress*

Cf.

R. Wang, F. Lorenzo-Martín, F. Roth (2006),

PSGRN/PSCMP - a new code for calculating co- and post-seismic deformation, geoid and gravity changes based on the viscoelastic-gravitational dislocation theory,

Computers and Geosciences, vol. 32, no. 4, p. 527-541,

doi: 10.1016/j.cageo.2005.08.006

Determination of the input parameters

The seismic moment

as input to the calculations

$$M_o = \mu \; \bar{u} \; L \; W$$

- W — width of the fault plane
- L — length " " " "
- $\bar{u}$ — aver. dislocation on " " "
- μ — shear modulus at source depth

from

data:

$\bar{u}$

L

assumptions:

μ = 29 GPa

W = 20 km

or

empirical relation

$$\log M_o = .97 \cdot \underline{\underline{M_s}} + 19.5$$

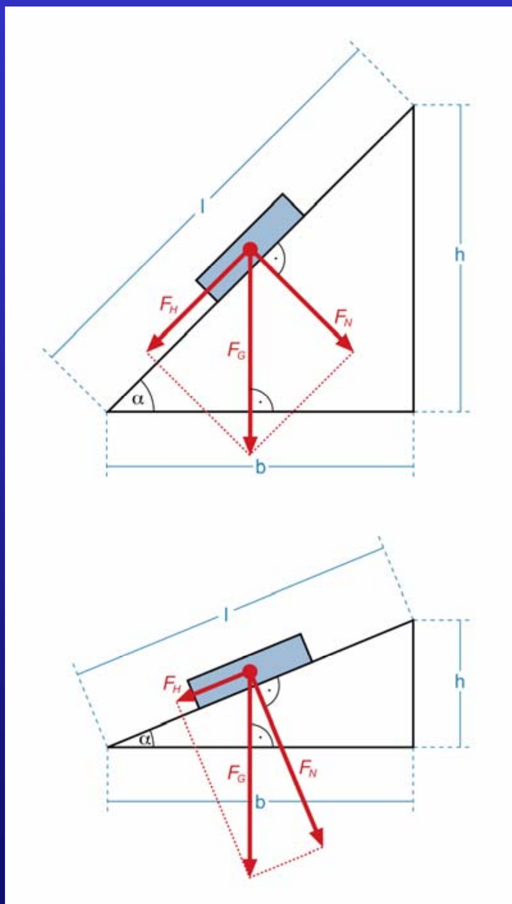
empirical relation

$$\underline{\underline{M_s}} = .58\, I_o + 1.5$$

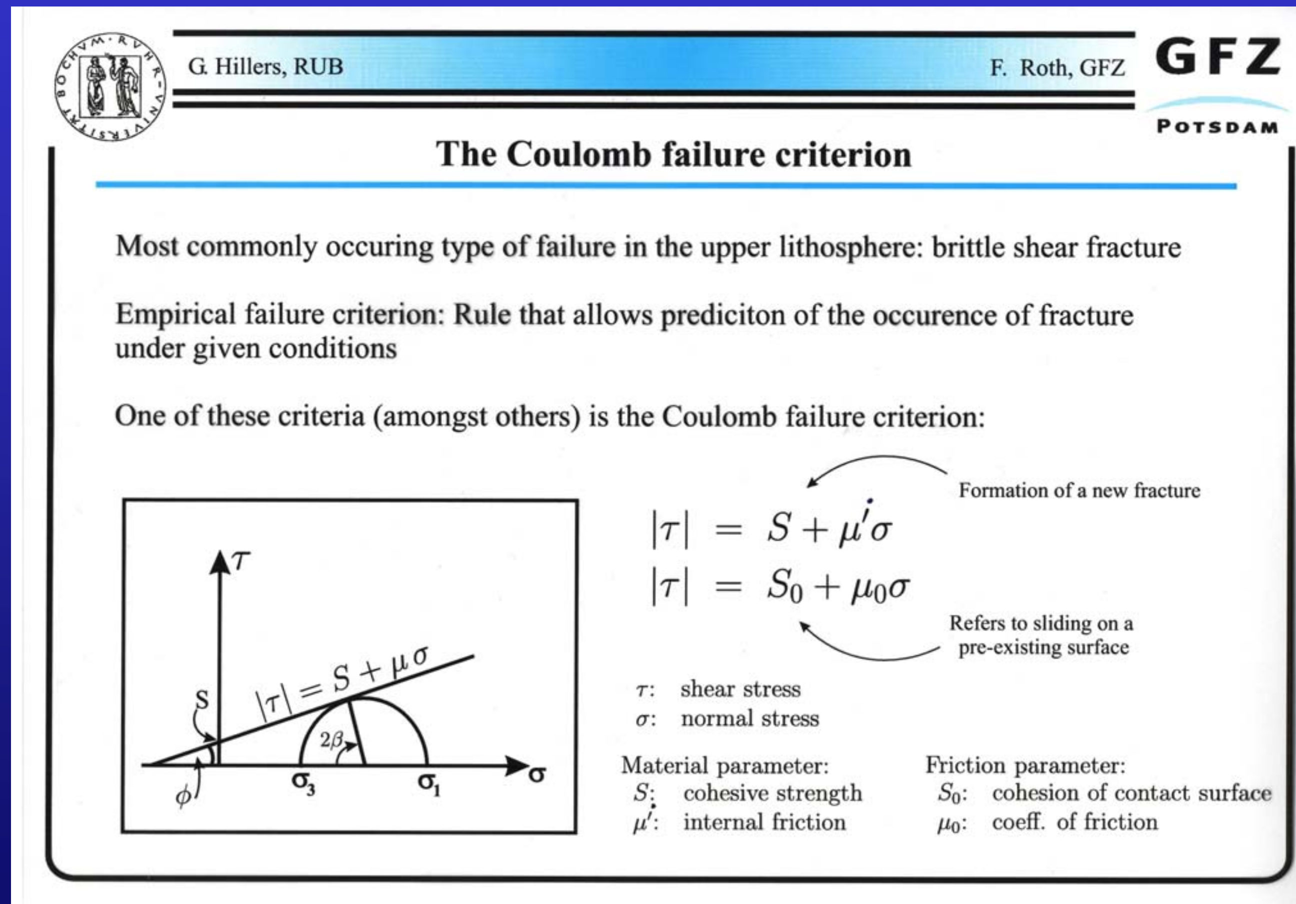
I_o — intensity

Stress components

Friction on a ramp



Coulomb stress



G. Hillers, RUB

F. Roth, GFZ

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The Coulomb failure criterion

Most commonly occuring type of failure in the upper lithosphere: brittle shear fracture

Empirical failure criterion: Rule that allows prediciton of the occurence of fracture under given conditions

One of these criteria (amongst others) is the Coulomb failure criterion:

$$|\tau| = S + \mu' \sigma$$

Formation of a new fracture

$$|\tau| = S_0 + \mu_0 \sigma$$

Refers to sliding on a pre-existing surface

τ: shear stress
σ: normal stress

Material parameter:
S: cohesive strength
μ': internal friction

Friction parameter:
S_0: cohesion of contact surface
μ_0: coeff. of friction

Coulomb stress (I)

G. Hillers, RUB — F. Roth, GFZ — GFZ POTSDAM

The Coulomb failure criterion applied to stress modeling

Reformulation of the Coulomb failure criterion due to stress modeling:

Failure occurs on a plane when the Coulomb stress becomes positive

$$\sigma_C = \tau_\beta - \mu(\sigma_\beta - p)$$

- β orientation of failure plane due to σ_1 axis
- μ coefficient of friction $\Rightarrow \beta = f(\mu)$
- τ_β shear stress on that plane
- σ_β normal stress on that plane
- p pore fluid pressure

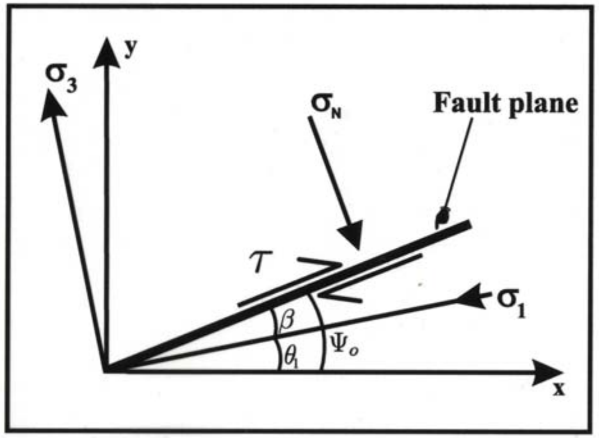
Simplify

$$\sigma_C = \tau - \mu'(\sigma_N)$$

Total stress field: $\sigma^T_{ij} = \sigma^R_{ij} + \Delta\sigma^E_{ij}$

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{2\sigma^T_{xy}}{\sigma^T_{xx} - \sigma^T_{yy}}\right); \qquad \Psi = \theta \pm \beta$$

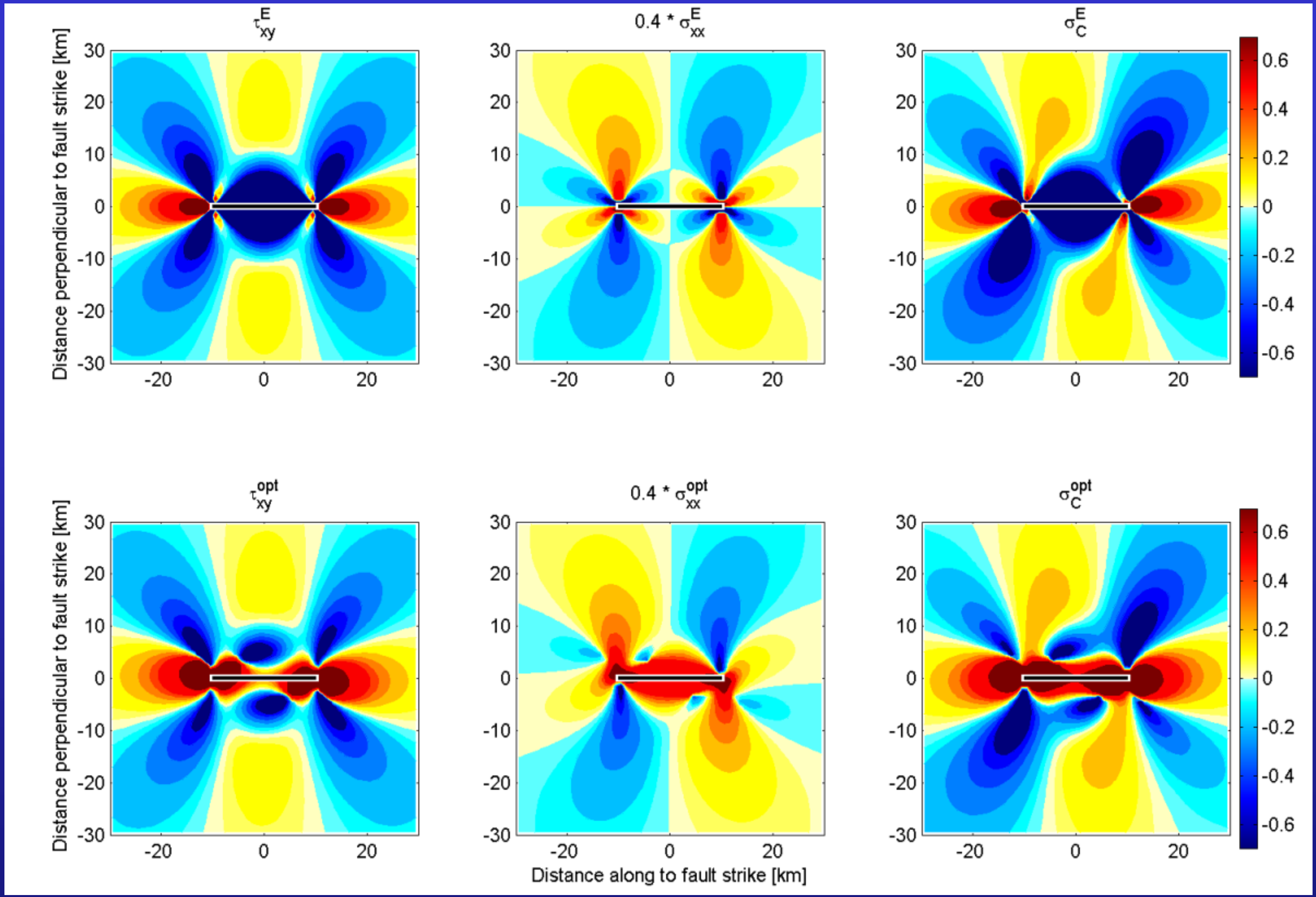
$$\Rightarrow \quad \Delta\tau^{opt}, \ \Delta\sigma^{opt}_N = f\left(\Psi, \Delta\sigma^E_{ij}\right)$$



$\tau > 0$ for the slip sense of the fault

$\sigma > 0$ for compression

Coulomb stress (II)



$$\Delta\sigma_C = \Delta\tau + \mu'\cdot\Delta\sigma_N = \Delta\tau + \mu\cdot(1 - B)\cdot\Delta\sigma_N$$

- τ shear stress (here: positive right-lateral slip)
- σ_N normal stress (here: positive for extension)
- μ' effective coefficient of friction
- μ coefficient of friction
- B Skempton coefficient
- σ_{opt} for regional stress at 30° from horizontal axis (N120°E)

Title for 1st talk on NAF

Elastic and inelastic triggering of earthquakes in the North Anatolian Fault zone

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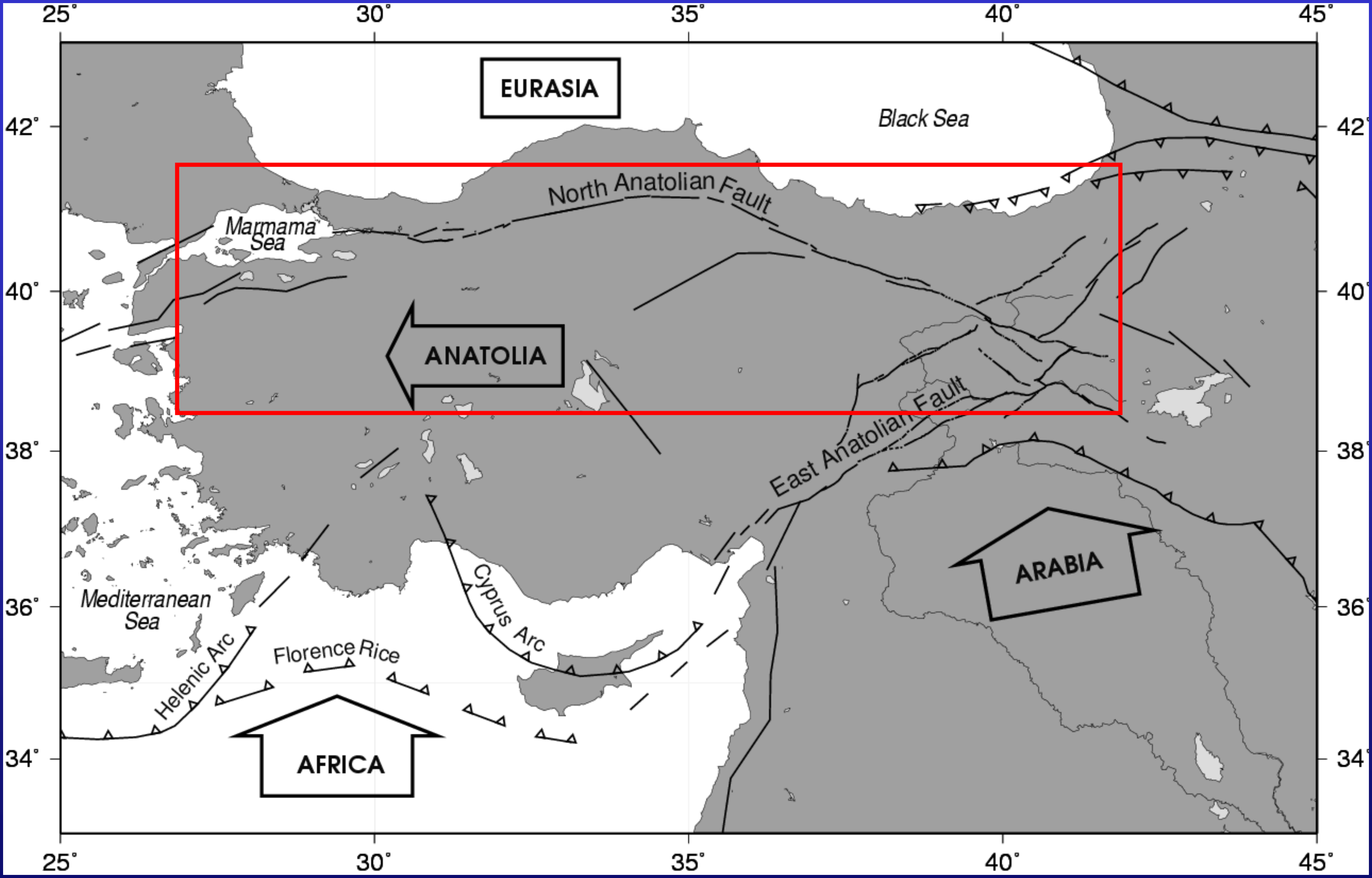
Cf.

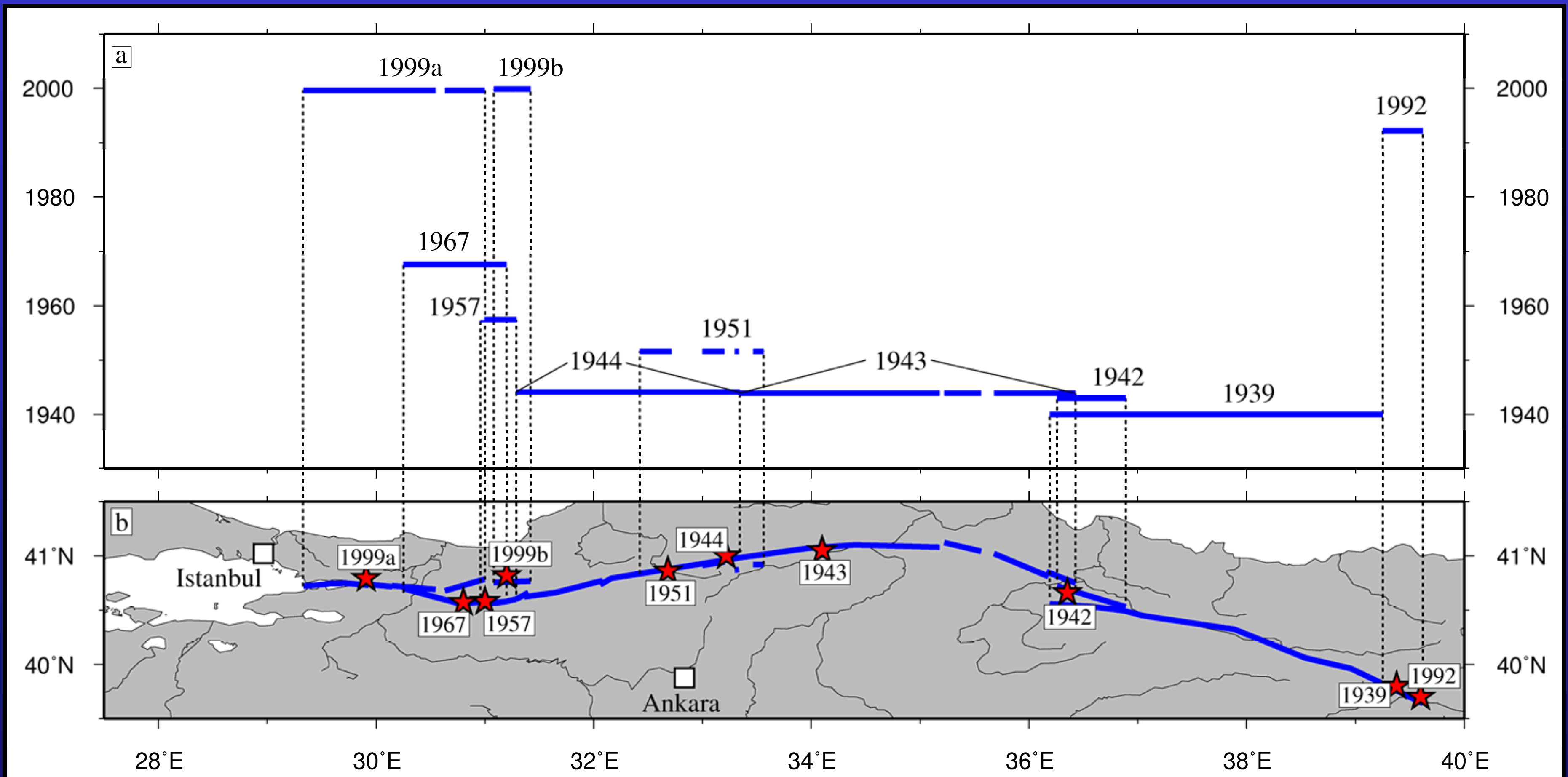
Tectonophysics 424 (3-4), p. 271-289, 2006,

doi: 10.1016/j.tecto.2006.03.046

Tectonic setting

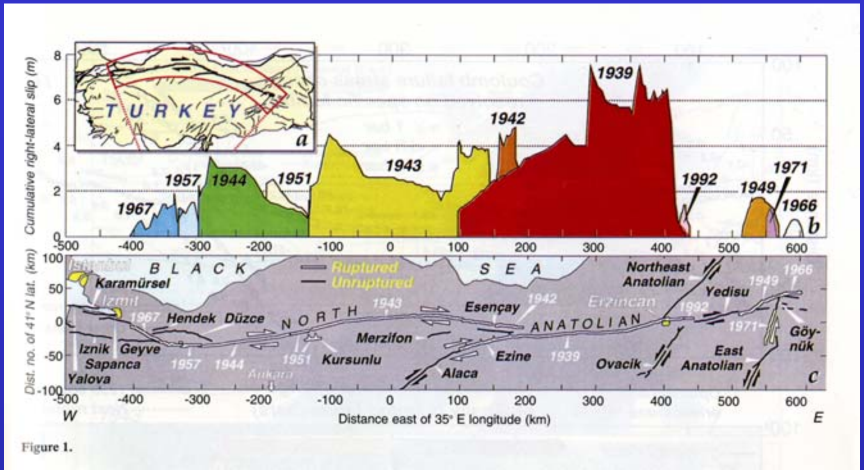


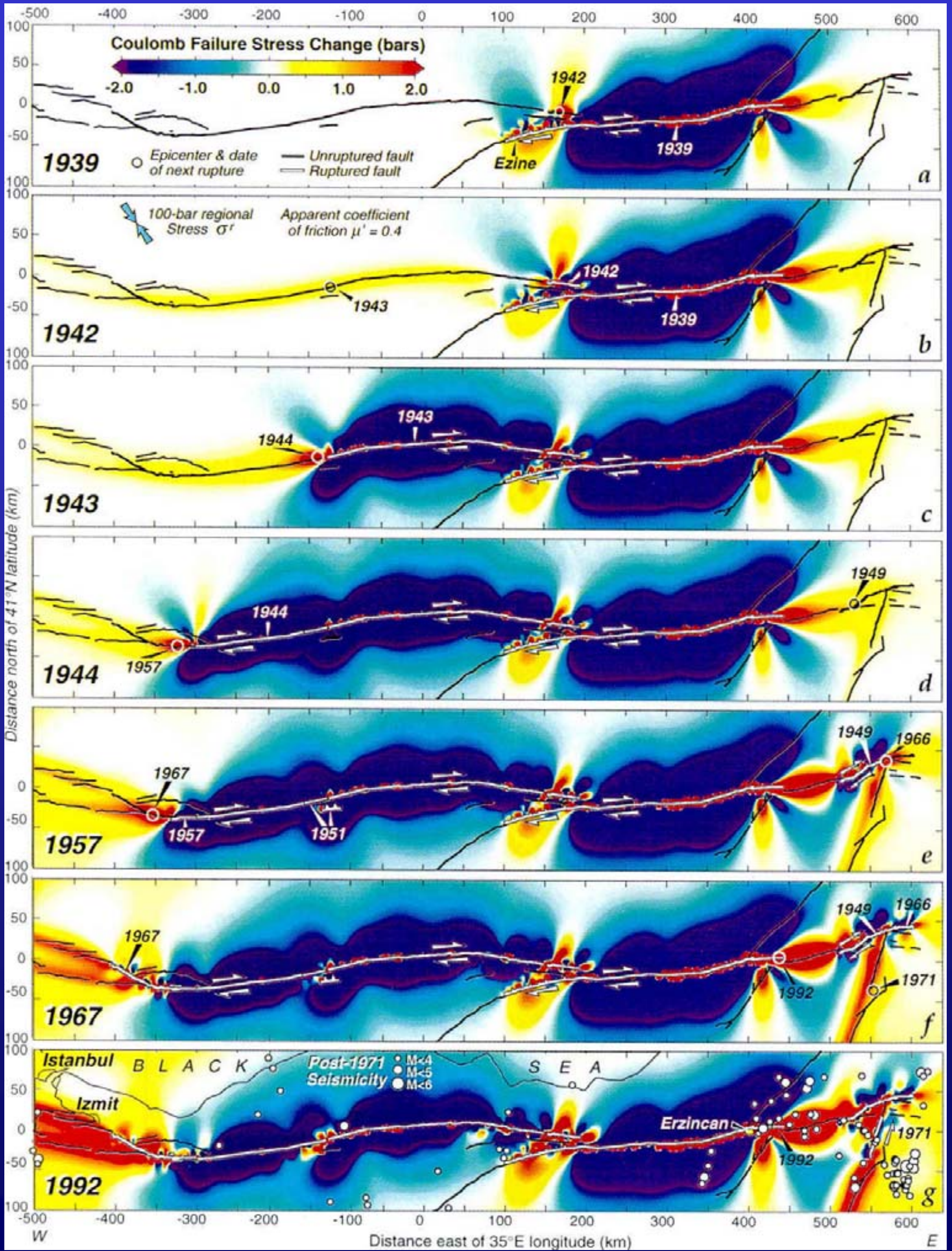
Earthquake migration along the NAF



10 magnitude $M_S > 6.5$ earthquakes

A previous elastic approach

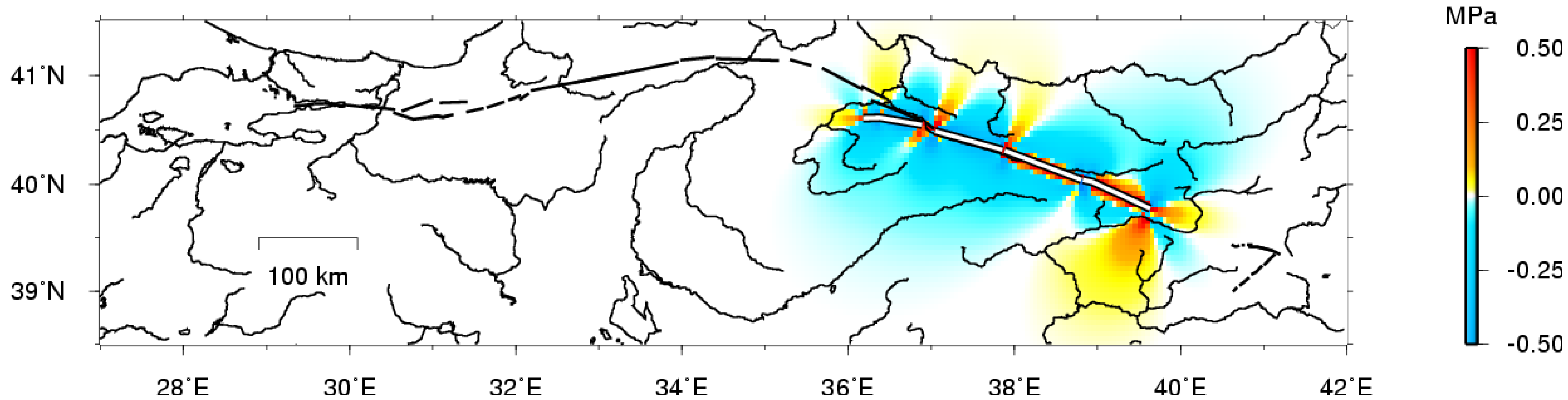




Cumulative elastic stress changes caused by large earthquakes and steady deep slip on the North Anatolian fault since 1939

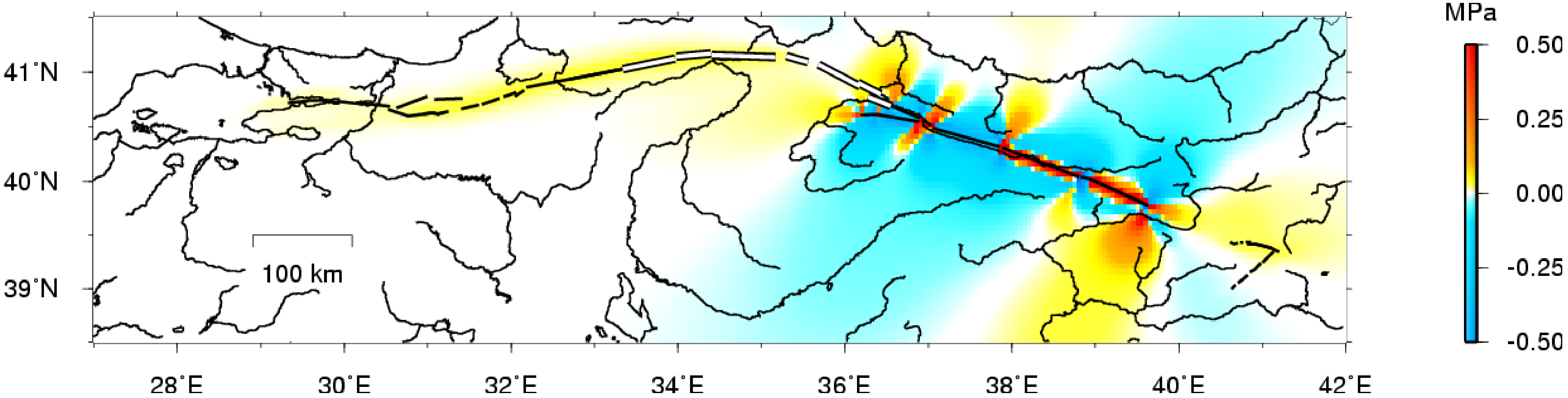
Source: Stein et al., 1997, Geoph. J. Int

Cumulative viscoelastic stress changes by large earthquakes and steady deep slip



State immediatelly after the 1939 event

Cumulative viscoelastic stress changes by large earthquakes and steady deep slip

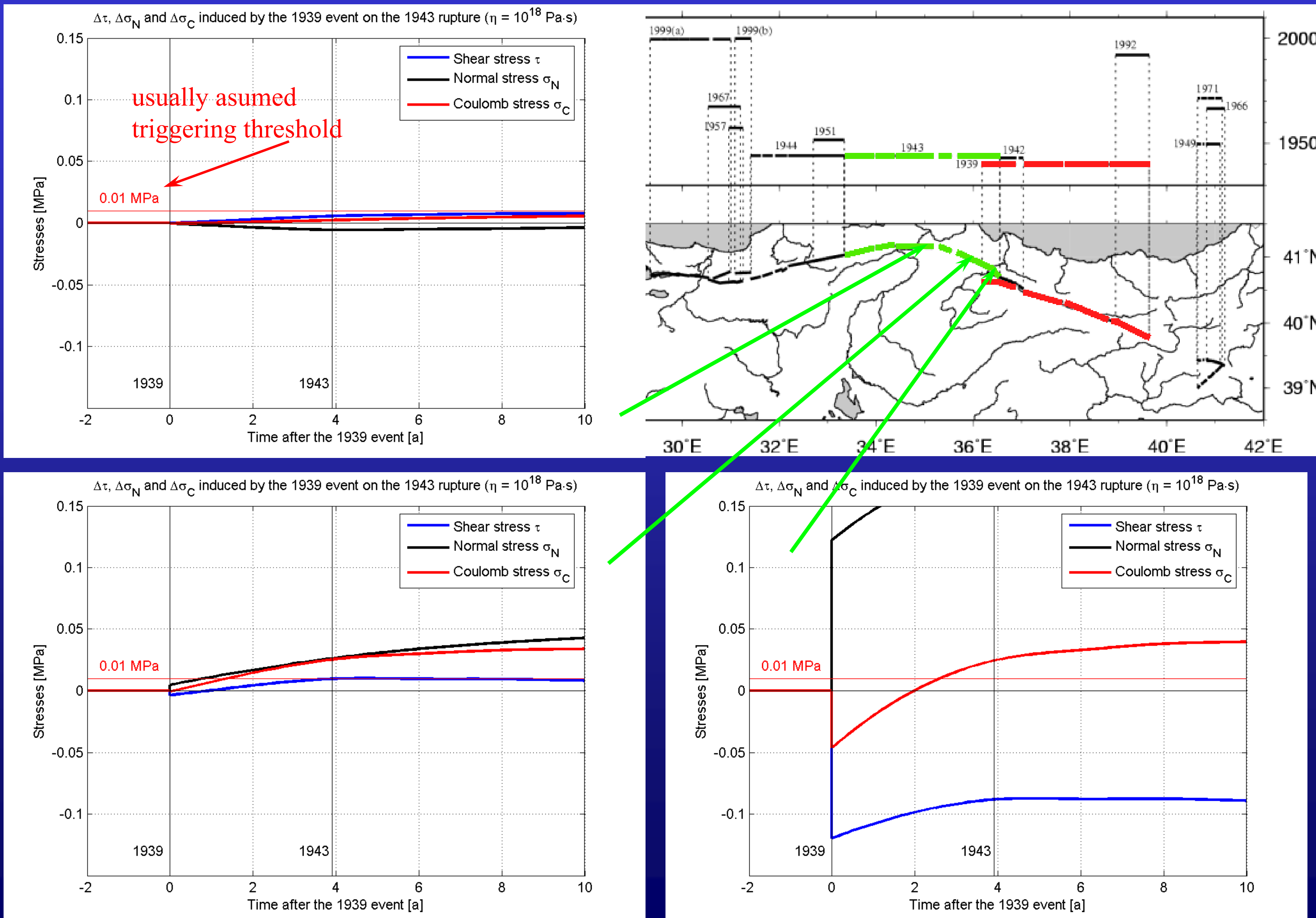


time

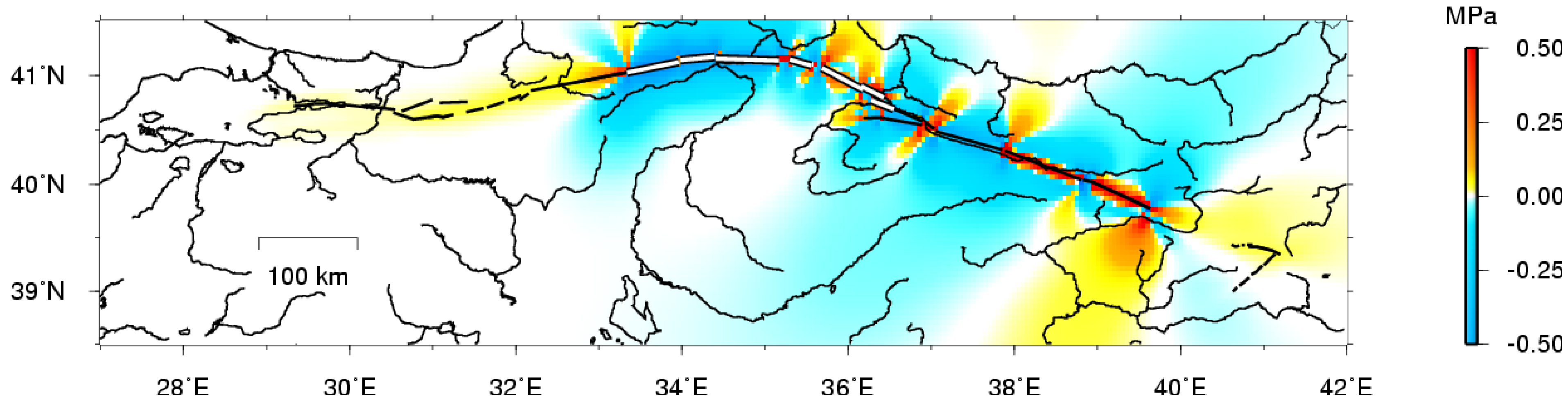
1939 1942 1943 1944 1949 1951 1957 1966 1967 1971 1992 1999a 1999b

State immediatelly before the 1943 event

Effect of the 1939 event on the 1943 rupture

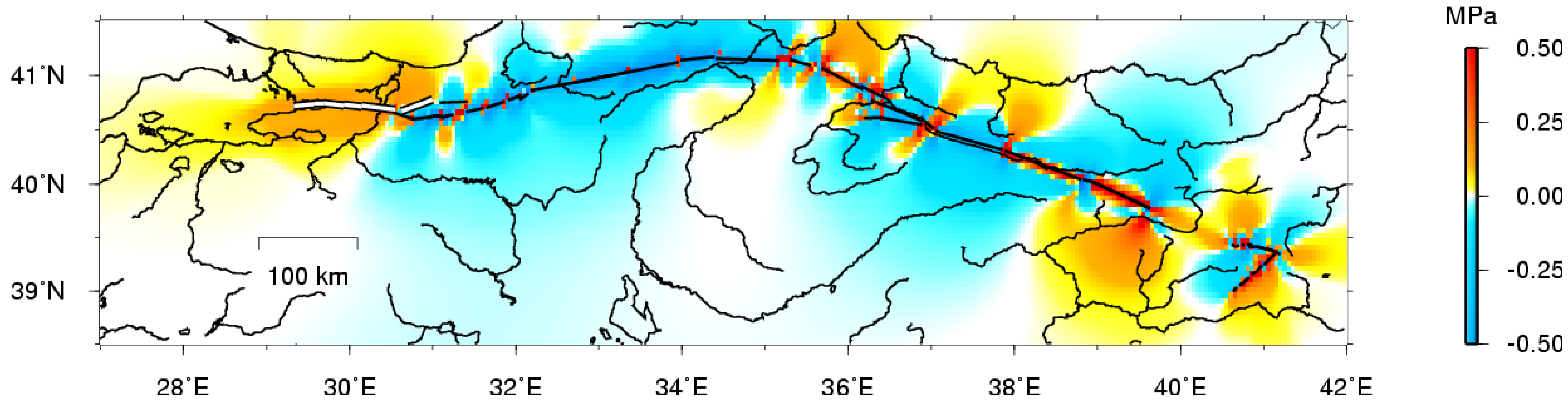


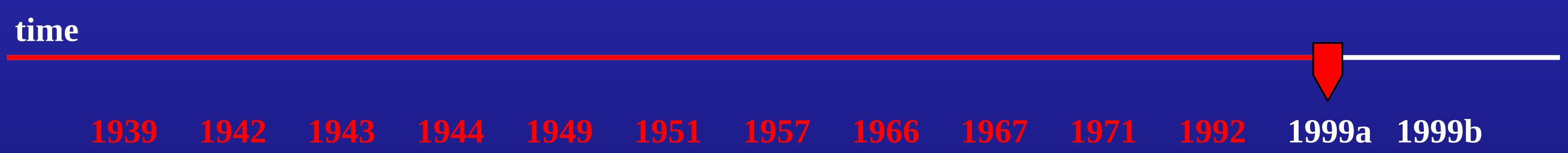
Cumulative viscoelastic stress changes by large earthquakes and steady deep slip



State immediatelly after the 1943 event

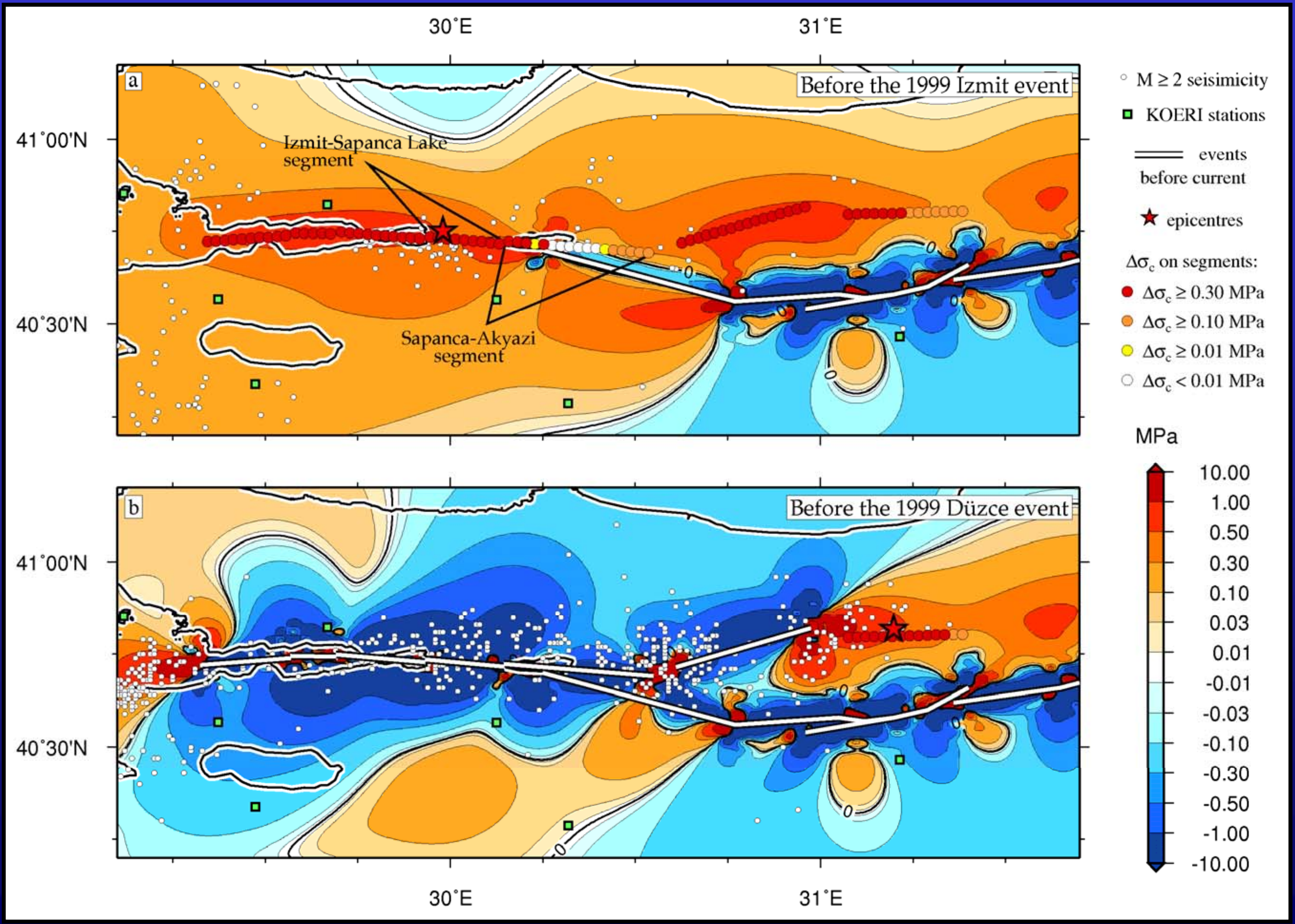
Cumulative viscoelastic stress changes by large earthquakes and steady deep slip



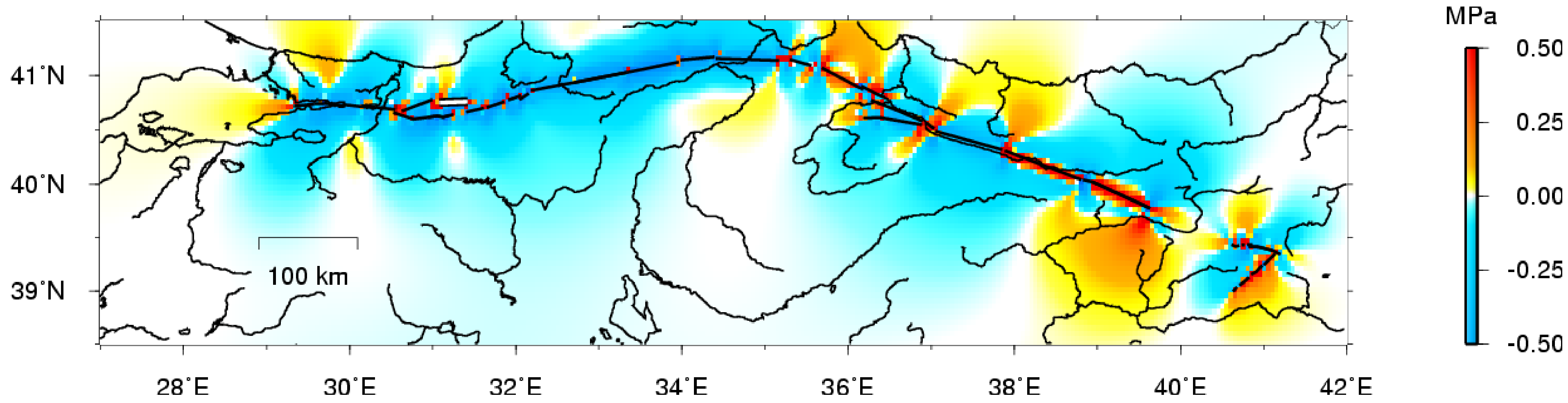


State immediatelly before the 1999, Izmit, event

State before the 1999 Izmit event, zoomed-in at rupture plane



Cumulative viscoelastic stress changes by large earthquakes and steady deep slip

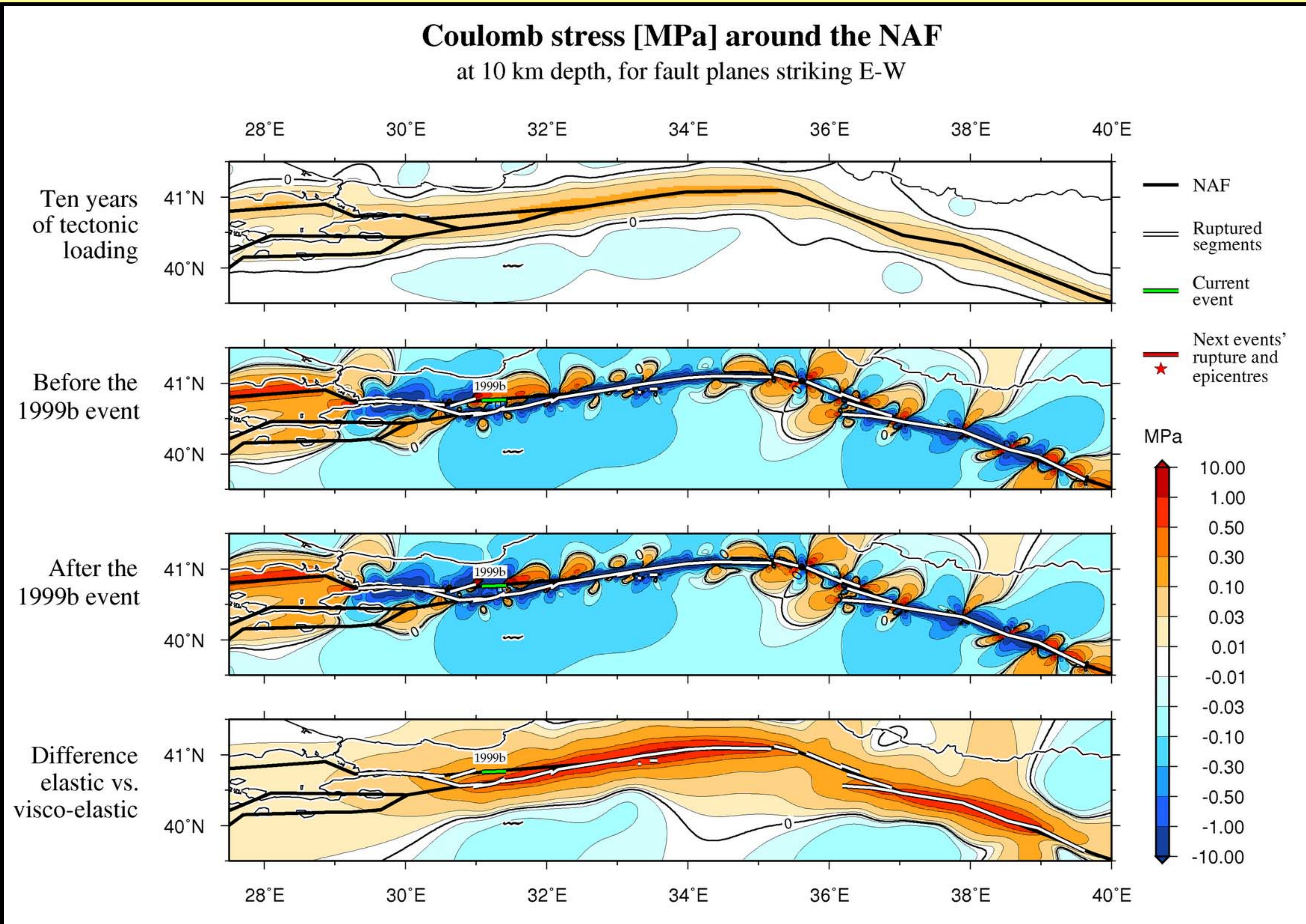


time

1939 1942 1943 1944 1949 1951 1957 1966 1967 1971 1992 1999a 1999b

State immediatelly after the 1999, Düzce, event

North Anatolian Fault zone, Turkey; sequence in time



Evolution of the Coulomb stress field since 1939

10 years of tectonic loading

1939⁺

1943⁻

1943⁺

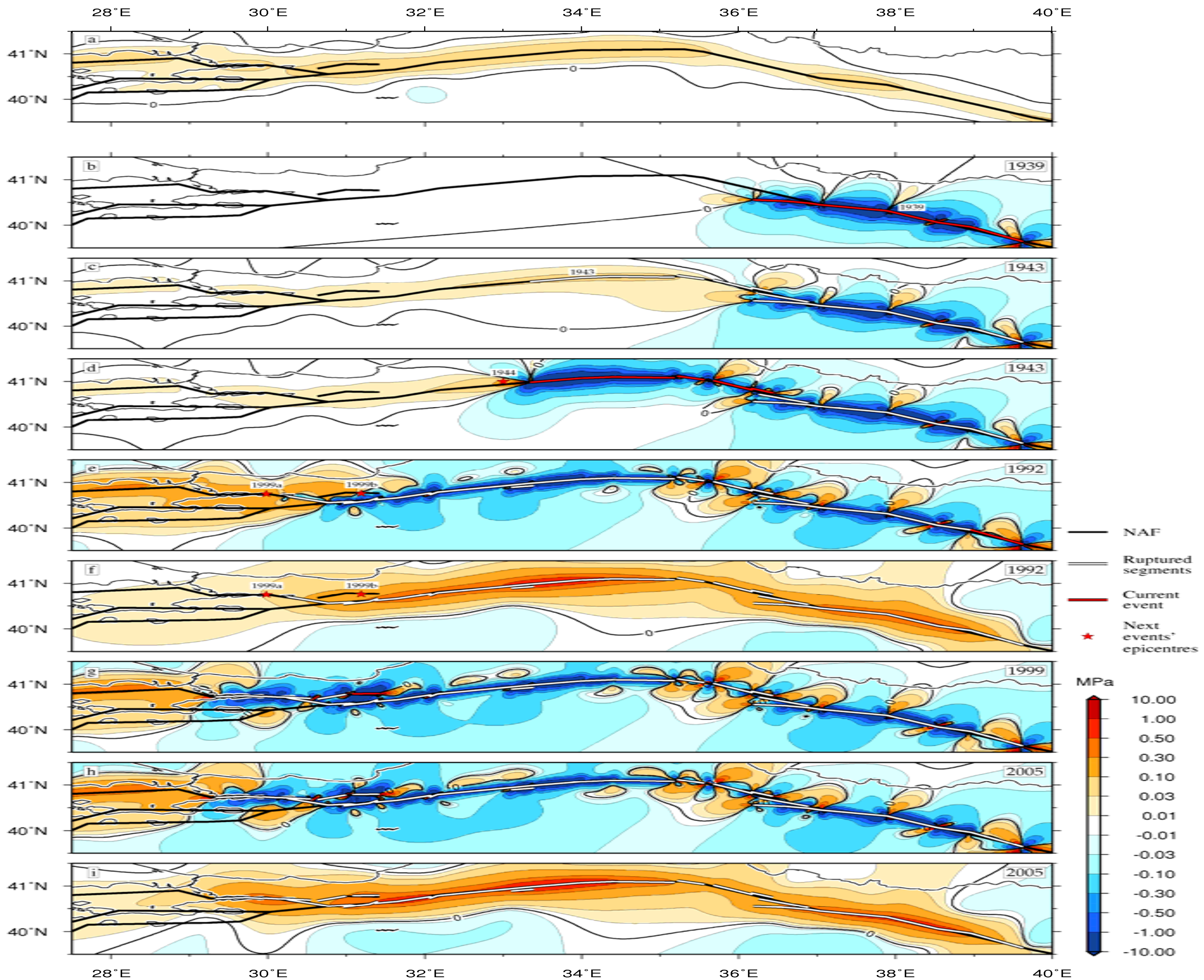
1992⁺

viscoel. relax. from 1939 to 1992

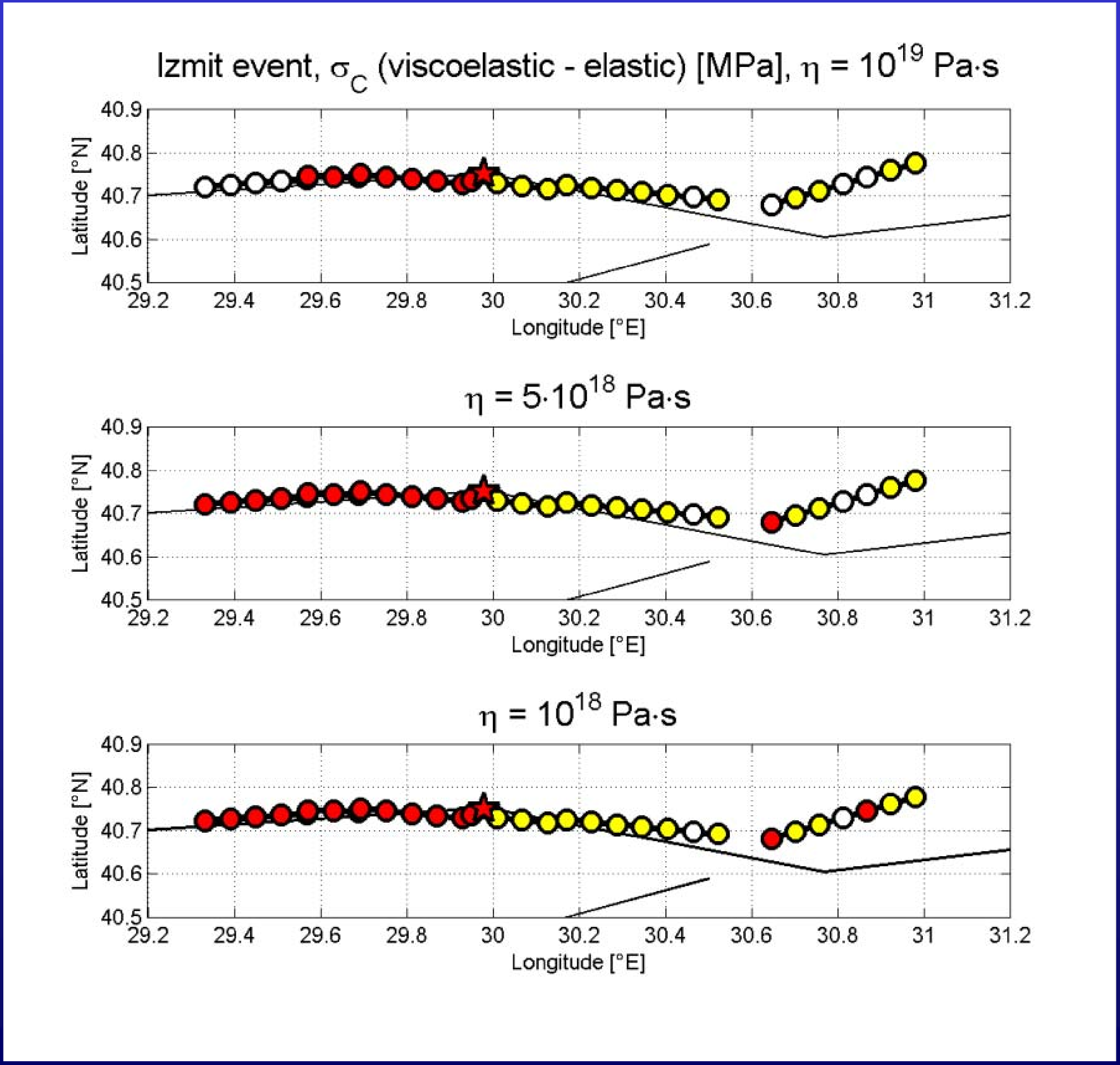
1999⁺

2005

viscoel. relax. from 1939 to 2005



Elastic and viscoelastic stresses on the 1999 Izmit rupture surface



Percentage of fault rupture with $\sigma_C \geq 0.01$ MPa immediately before the event with tectonic loading: *overview*

event	elastic	visco-elastic (viscosity values in Pa·s)			
		$5 \cdot 10^{17}$	10^{18}	$5 \cdot 10^{18}$	10^{19}
1942	14	29	21	18	14
1943	93	96	95	93	93
1944	95	100	100	95	95
1951	0	0	0	0	0
1957	100	100	100	100	100
1967	75	78	78	75	75
1992	100	100	100	100	100
1999a	85	93	91	88	88
1999b	100	100	100	100	100

Percentage of fault rupture with $\sigma_C \geq 0.01$ MPa immediately before the event with tectonic loading: *effect of viscosity, maxima in red*

event	**elastic**	**visco-elastic (viscosity values in Pa·s)**			
		$5 \cdot 10^{17}$	**10^{18}**	**$5 \cdot 10^{18}$**	**10^{19}**
1942	14	29	21	18	14
1943	93	96	95	93	93
1944	95	100	100	95	95
1951	0	0	0	0	0
1957	100	100	100	100	100
1967	75	78	78	75	75
1992	100	100	100	100	100
1999a	85	93	91	88	88
1999b	100	100	100	100	100

Percentage of fault rupture with $\sigma_C \geq 0.01$ MPa immediately before the event without tectonic loading: *overview*

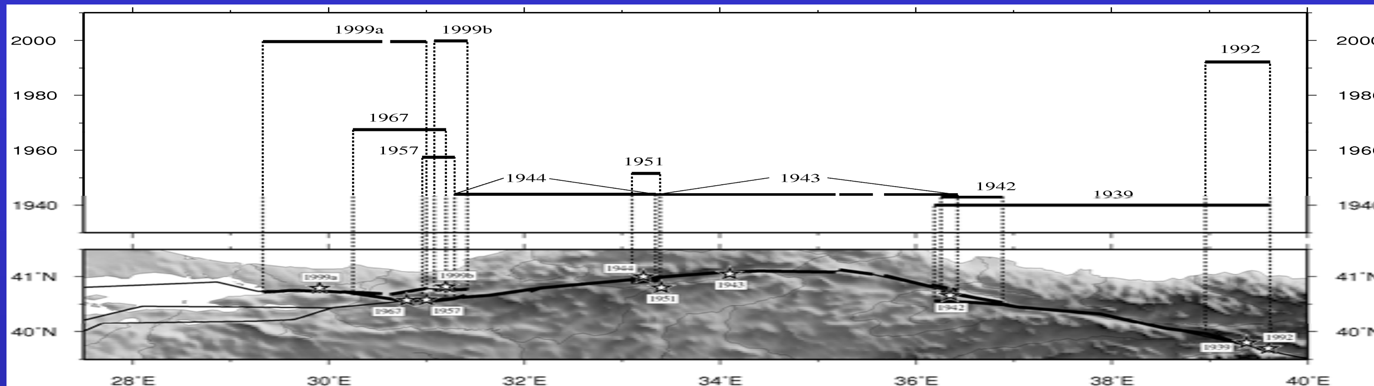
event	elastic	visco-elastic (viscosity values in Pa·s)			
		$5 \cdot 10^{17}$	10^{18}	$5 \cdot 10^{18}$	10^{19}
1942	11	21	21	14	11
1943	20	59	44	21	21
1944	52	67	57	54	53
1951	0	0	0	0	0
1957	100	100	100	100	100
1967	70	75	73	73	73
1992	94	100	100	94	94
1999a	49	81	81	81	81
1999b	7	29	29	21	21

Percentage of fault rupture with $\sigma_C \geq 0.01$ MPa immediately before the event with (and without) tectonic loading: *comparison*

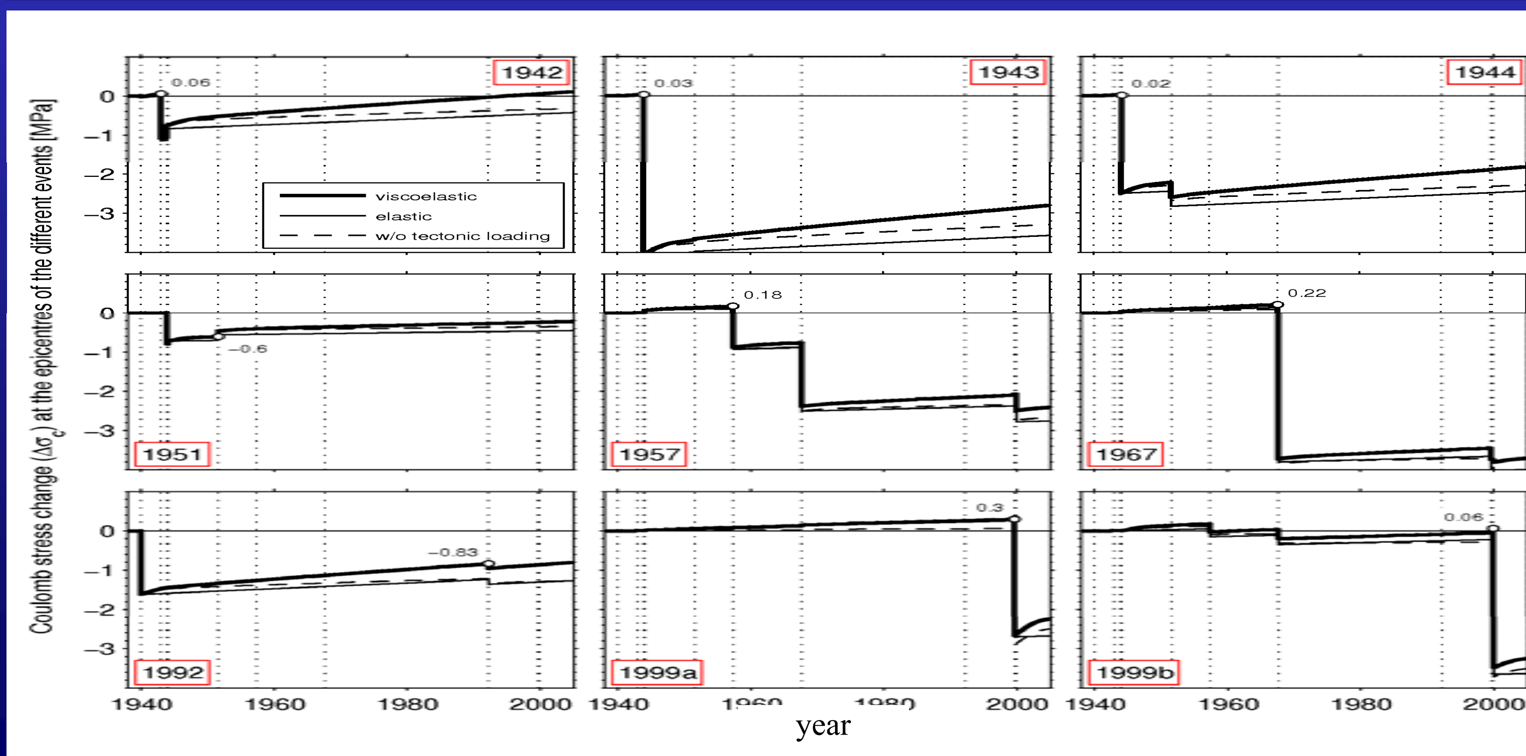
event	**elastic**	**visco-elastic (viscosity values in Pa·s)**				stress triggering dominated by
		$5 \cdot 10^{17}$	**10^{18}**	**$5 \cdot 10^{18}$**	**10^{19}**	
1942	14 (11)	29 (21)	21	18 (14)	14 (11)	preceding eq.
1943	93 (20)	96 (59)	95 (44)	93 (21)	93 (21)	plate tectonics
1944	95 (52)	100 (67)	100 (57)	95 (54)	95 (53)	50% pl + 50% eq
1951	0	0	0	0	0	---
1957	100	100	100	100	100	eq
1967	75 (70)	78 (75)	78 (73)	75 (73)	75 (73)	eq
1992	100 (94)	100	100	100 (94)	100 (94)	eq
1999a	85 (49)	93 (81)	91 (81)	88 (81)	88 (81)	eq
1999b	100 (7)	100 (29)	100 (29)	100 (21)	100 (21)	pl

Only one number indicates: no difference

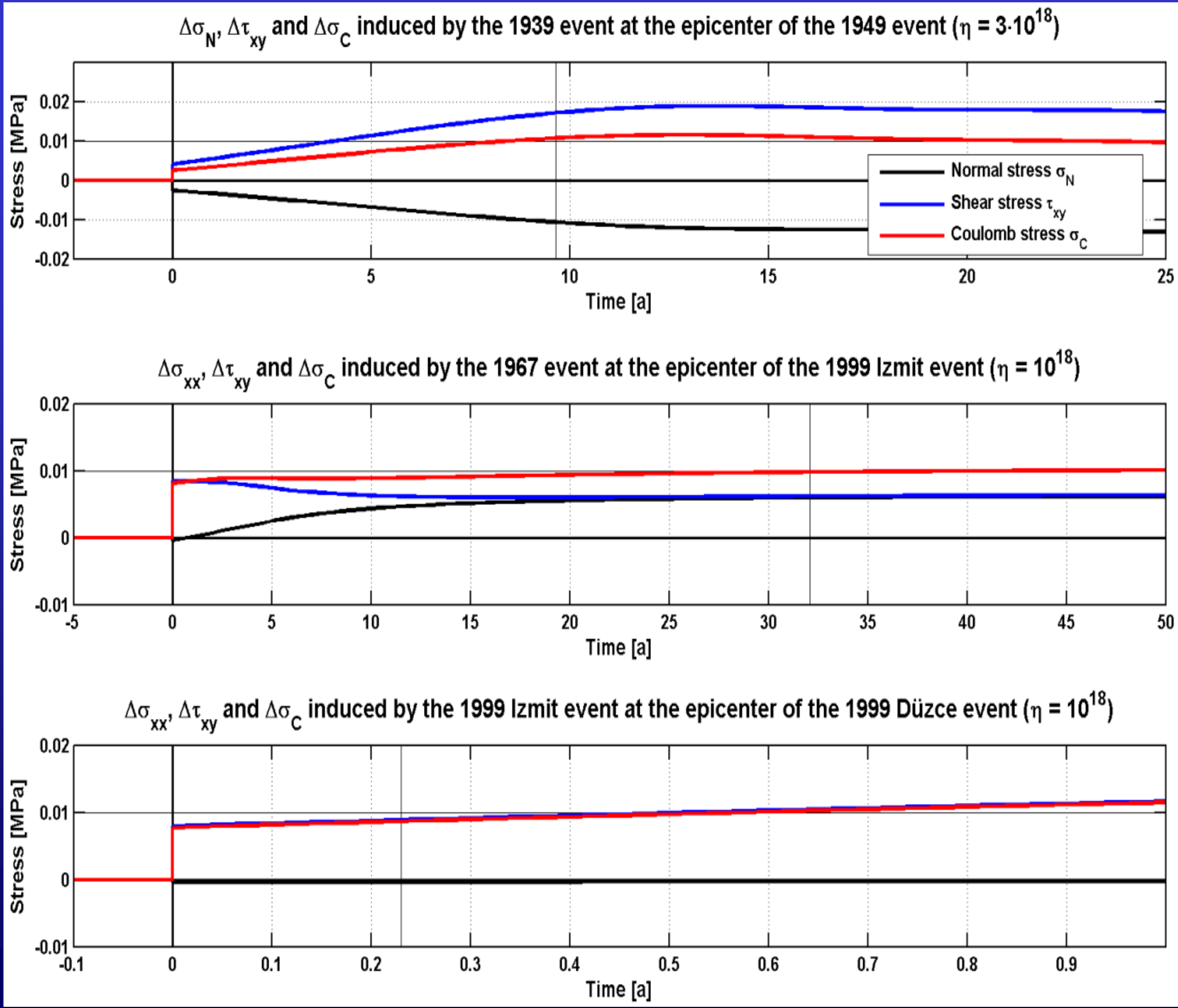
Space-time migration of events along the NAF



Time-evolution of the Coulomb stress on the events' epicenters



Time dependency of the Coulomb stress for several pairs of events

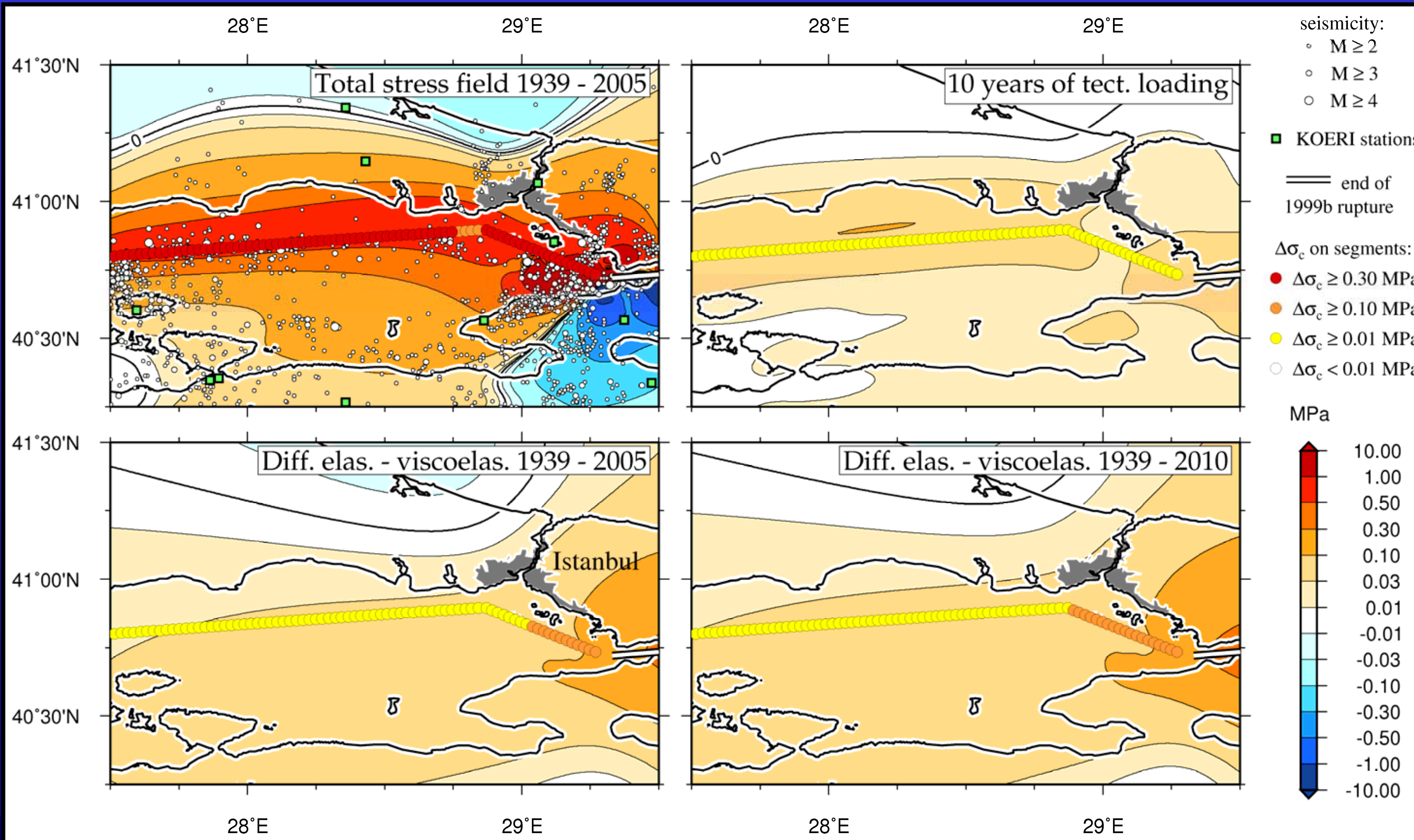


Conclusions

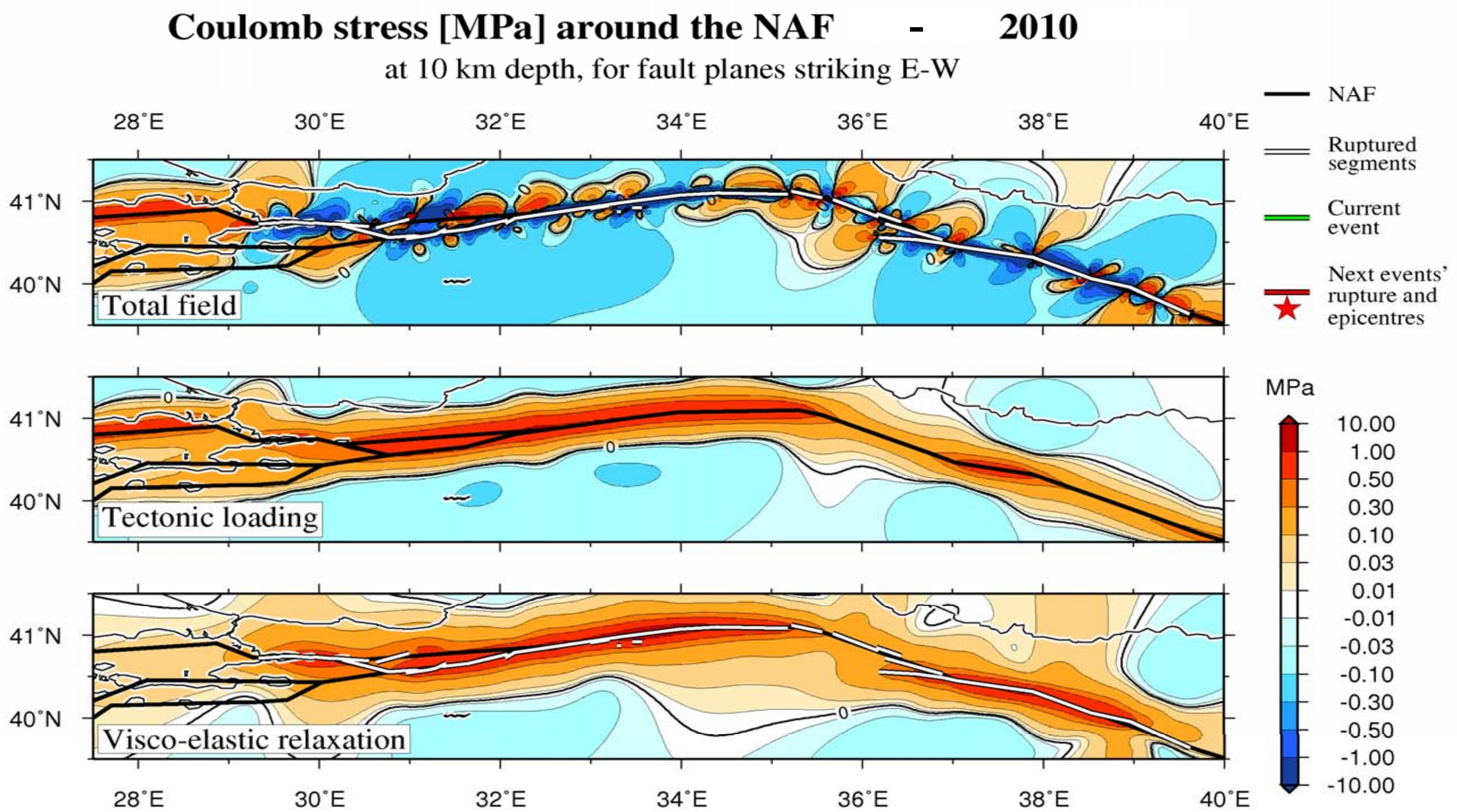
- Coulomb stress failure criterion provides good results for this sequence of events: 8 out of 9 rupture surfaces show Coulomb stress above threshold before the event.
- Including the stress build-up by plate tectonics, the area with $\sigma_C \geq 0.01$ MPa is greater than 20% for 8 of 9 events, >75% for 7 of 9 events.
- Looking only to the stress transfer by the preceding event, the area with $\sigma_c \geq 0.01$ MPa is greater than 20% for 7 of 9 events, >50% for 5 of 9 events.
- In several cases, post-seismic relaxation effects are important and greater in magnitude than the co-seismic ones.
- Taking the effect of visco-elastic relaxation into account improves the result in 5 out of 9 cases and raises the stress by >100% in some cases.
- A viscosity of $1–3\cdot10^{18}$ Pa·s gives the best results. It seems to be at the lower boundary of values usually assumed. This might be an indication that other time-dependent processes might play an important role.

North Anatolian Fault zone, Turkey; states 1999+6 and +11 years

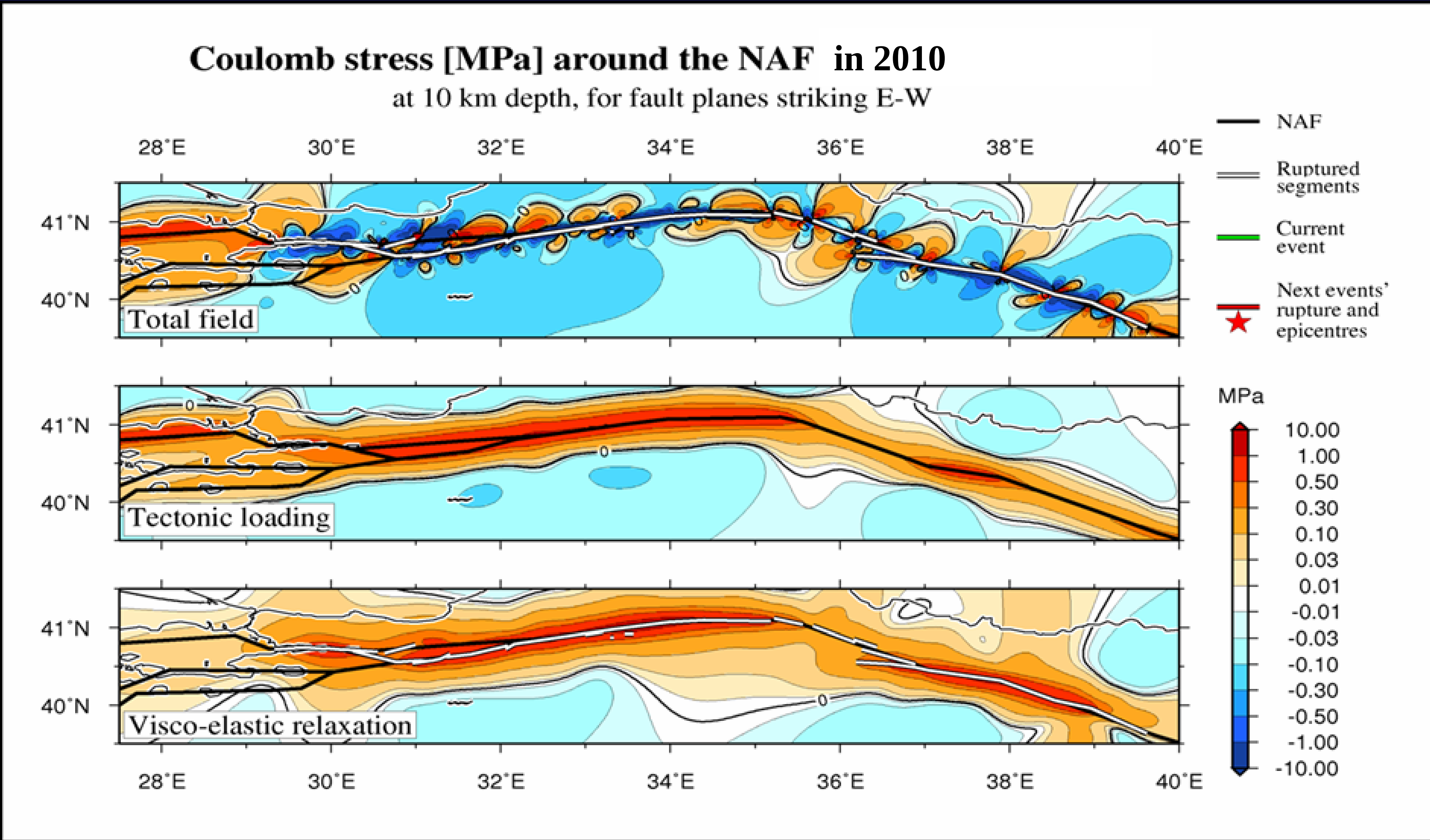
- Situation in the Sea of Marmara



North Anatolian Fault zone, Turkey



North Anatolian Fault zone, Turkey



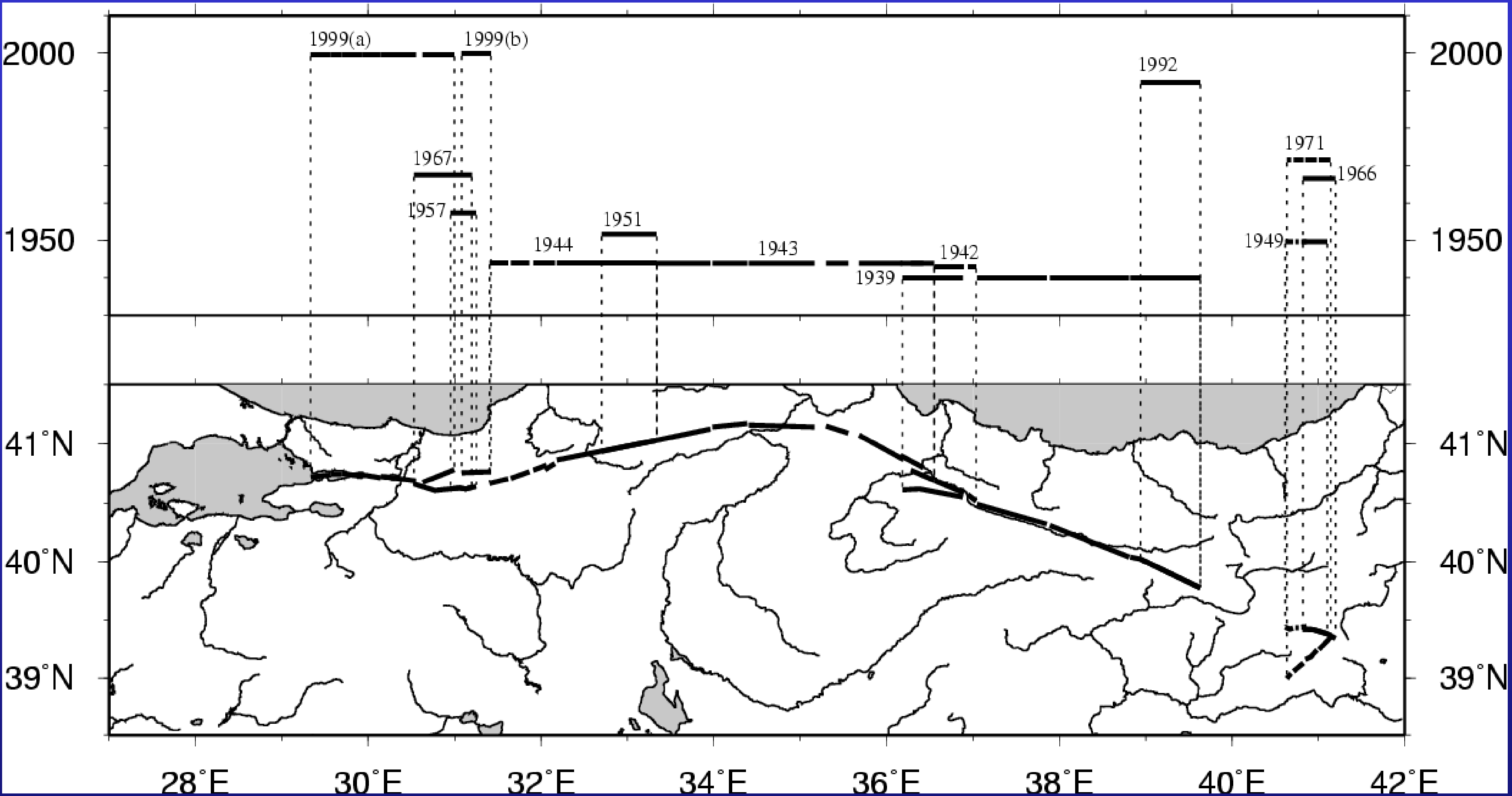
Source parameters of the events considered

Table 1
Parameters of the sequence of earthquakes used

Date	GMT	Lat. (°N)	Lon. (°E)	M_s	M_o (Nm)	References
1939 26 Dec	23:57	39.80	39.38	8.0	$4.11 \cdot 10^{20}$	(3), (4), (6), (8)
1942 20 Dec	14:03	40.66	36.35	7.3	$1.74 \cdot 10^{19}$	(3), (4), (6), (8)
1943 26 Nov	22:20	41.05	33.72	7.6	$2.51 \cdot 10^{20}$	(3), (4), (6), (8)
1944 01 Feb	03:23	41.00	33.22	7.6	$1.48 \cdot 10^{20}$	(3), (4), (6), (8)
1951 13 Aug	18:33	40.86	32.68	6.7	$2.12 \cdot 10^{19}$	(1), (4), (5)
1957 26 May	06:33	40.58	31.00	7.2	$1.35 \cdot 10^{19}$	(3), (4), (6), (8)
1967 22 Jul	16:56	40.57	30.80	7.3	$2.82 \cdot 10^{19}$	(2), (3), (4), (6), (8), (14)
1992 13 Mar	17:19	39.71	39.60	6.9	$1.14 \cdot 10^{19}$	(6), (7), (9), (10)
1999 17 Aug	00:01	40.70	29.91	7.8	$2.15 \cdot 10^{20}$	(12), (13), (14)
1999 12 Nov	16:57	40.818	30.198	7.3	$4.67 \cdot 10^{19}$	(11), (12), (16), (17)

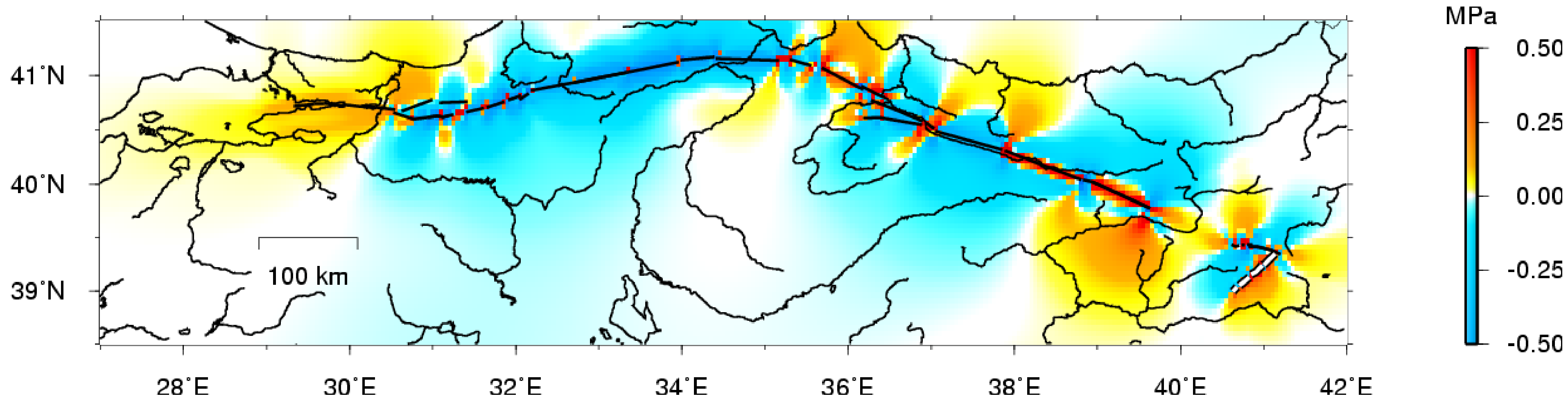
Epicentral coordinates are from Dewey (1976) until 1967, with the exception of the 1943 event, for which Dewey's epicentral coordinates appear to be too far East (Ambraseys, 1970; Alsan et al., 1976; Saroglu et al., 1992). For this event and the more recent ones, we used the coordinates provided by the Earthquake Research Directorate (ERD), Seismological Division, Turkey. M_s values are from the USGS. M_o values correspond to the geometry and slip distribution used in the present work, comparable to those of Stein et al. (1997). The references used are: (1) Pinar, 1953; (2) Ambraseys and Zatopek, 1969; (3) Ambraseys, 1970; (4) Dewey, 1976; (5) Barka and Kadinsky-Cade, 1988; (6) Saroglu et al., 1992; (7) Pinar et al., 1994; (8) Barka, 1996; (9) Nalbant et al., 1996; (10) Grosser et al., 1998; (11) Ayhan et al., 2001; (12) Tibi et al., 2001; (13) Wright et al., 2001; (14) Barka et al., 2002; (15) Muller et al., 2003; (16) Utkucu et al., 2003; and (17) Umutlu et al., 2004.

Earthquakes on the North Anatolian Fault Zone



13 moment magnitude M > 6.5 earthquakes

Cumulative viscoelastic stress changes by large earthquakes and steady deep slip



time

1939 1942 1943 1944 1949 1951 1957 1966 1967 1971 1992 1999a 1999b

State immediatelly after the 1971 event

North Anatolian Fault zone, Turkey; states 6 and 11 years after the Düzce event