Earthquake hazard and seismic monitoring efforts in the Istanbul-Marmara region

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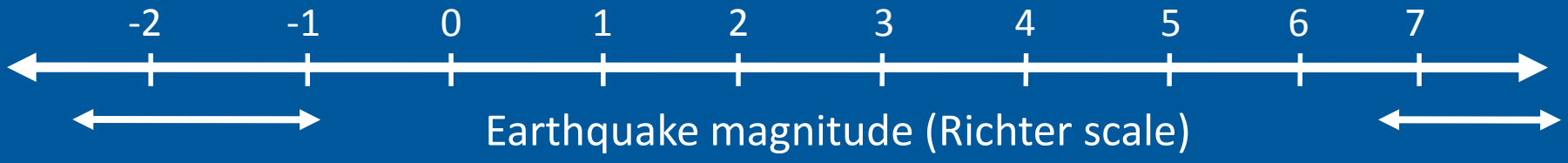
Outline

Earthquakes in Laboratory, Geo-Reservoirs and Along Tectonic Plate Boundaries → all the same?

What we know (and don‘t know) about the overdue Marmara earthquake and its maximum expected magnitude.

The GFZ Plate Boundary Observatory in the Istanbul-Marmara region: Monitoring the small ones to learn more about the ‚big one‘.

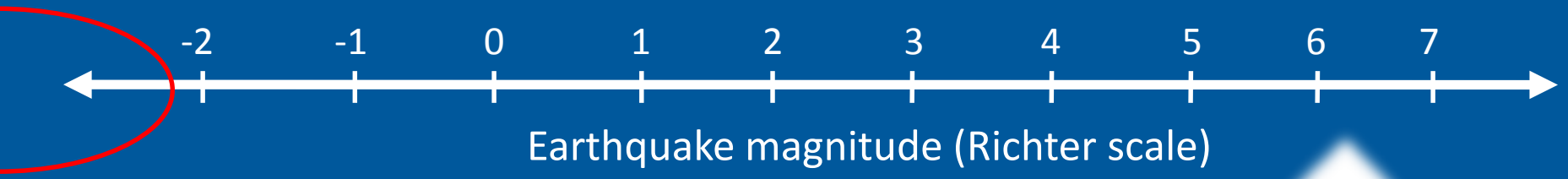
Earthquake Processes: From Laboratory to Field Scale



Magnitude	< -1
Rupture Plane	m²
Coseismic slip	mm

Magnitude	>7
Rupture Plane	>10³ km²
Coseismic slip	m

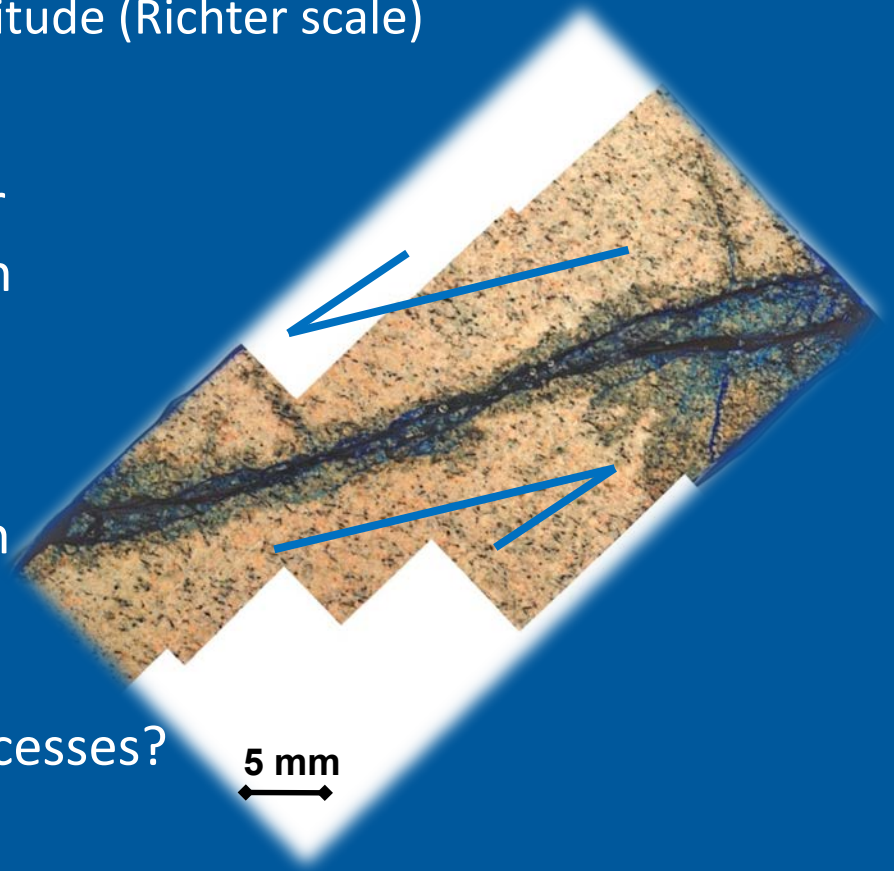
Earthquakes in the Laboratory



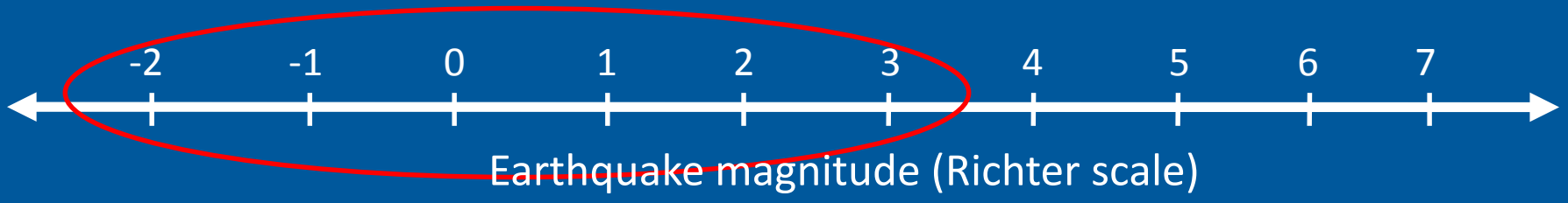
→ Rock deformation experiments under controlled boundary conditions and with acoustic monitoring.

→ What are key parameters for the nucleation, propagation and termination of rupture processes?

→ What are the governing physical processes?



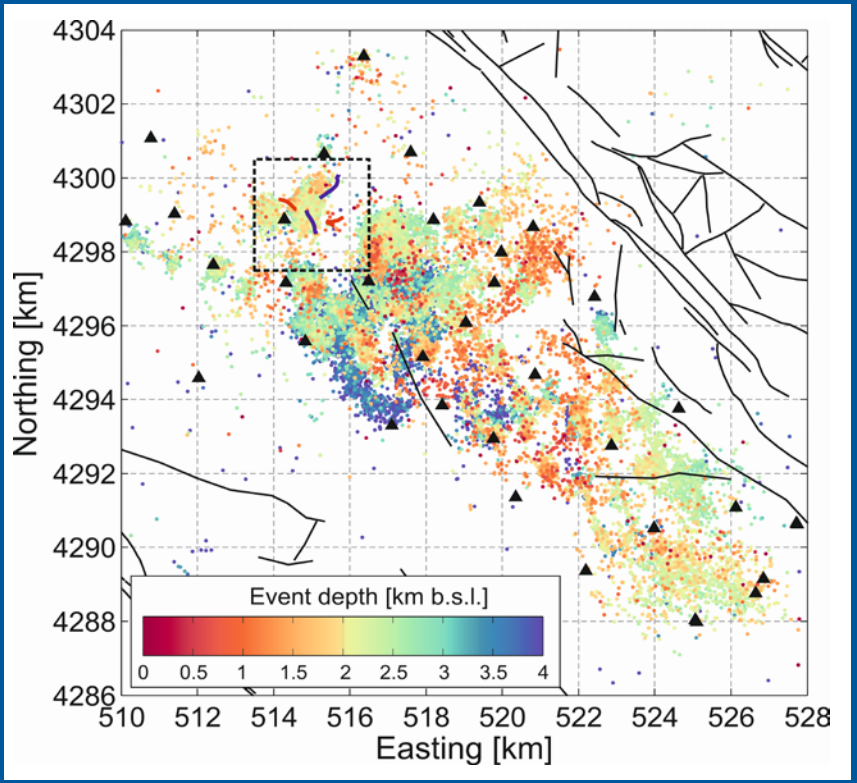
Earthquakes in Geo-Reservoirs



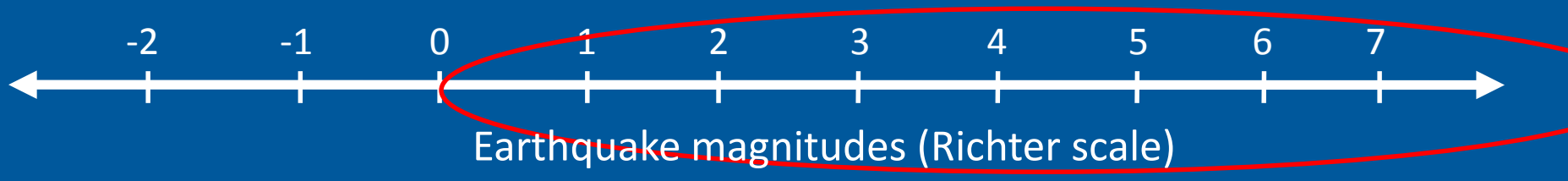
→ Research on the nature and causes of induced seismicity related to hydraulic treatments

→ How can geo-reservoirs be seismo-mechanically controlled during and after exploration, production and storage?

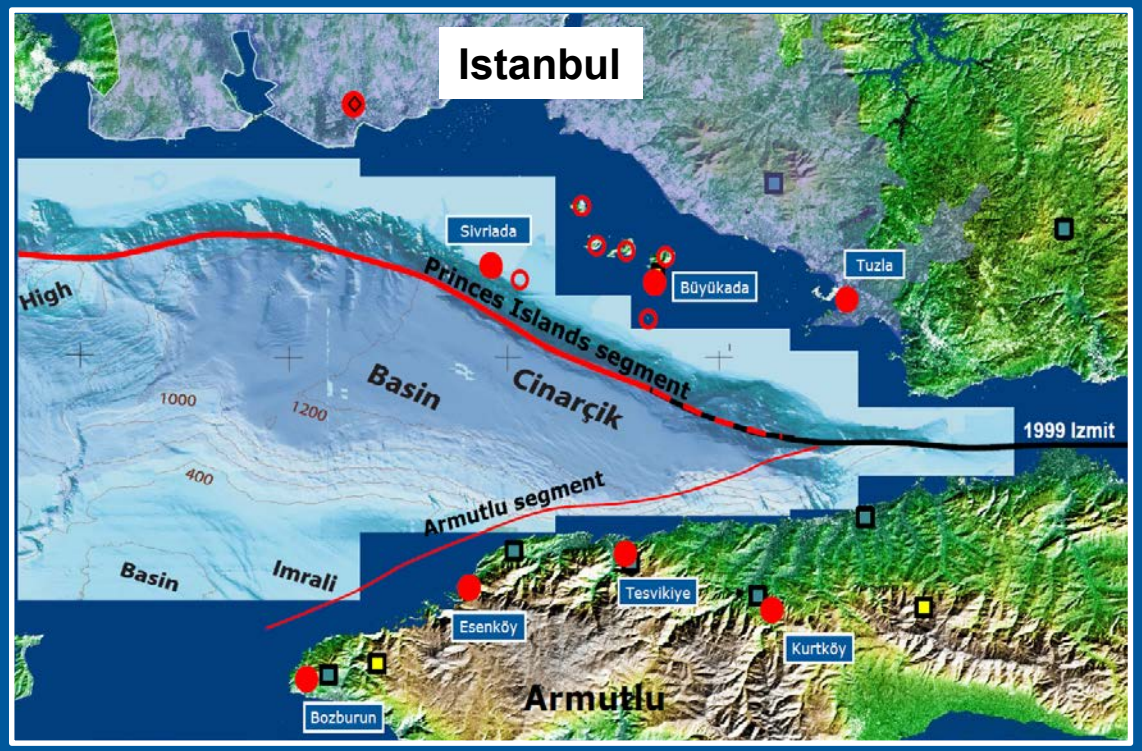
(Martinez-Garzon et al., 2013ff; Kwiatek et al., 2010ff)



Natural Earthquakes



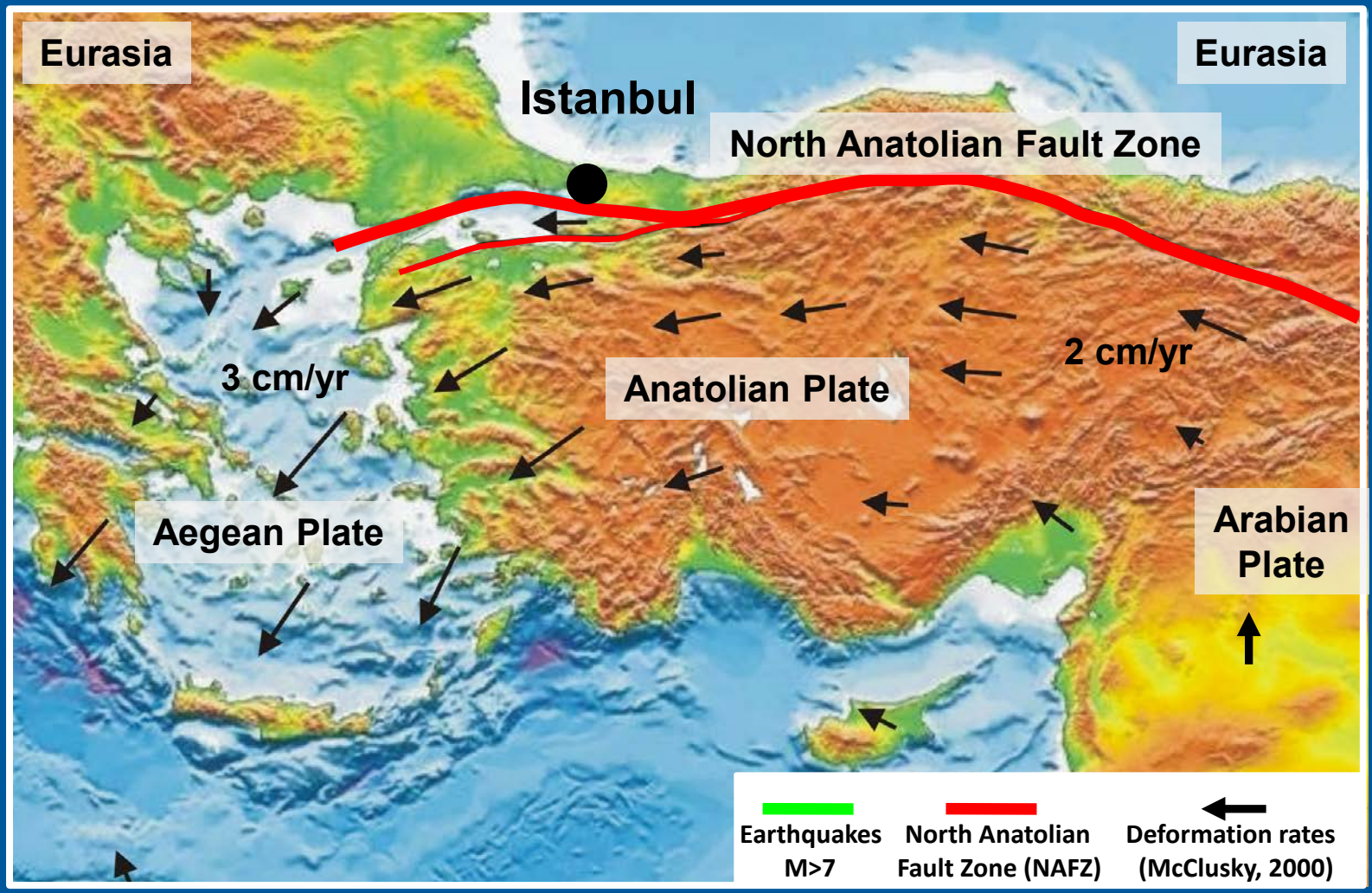
- → Transfer of knowledge to field scale by implementing a geophysical downhole observatory at the overdue Marmara fault offshore Istanbul
- → How do faults work and how can we improve the assessment of seismic hazard and risk?



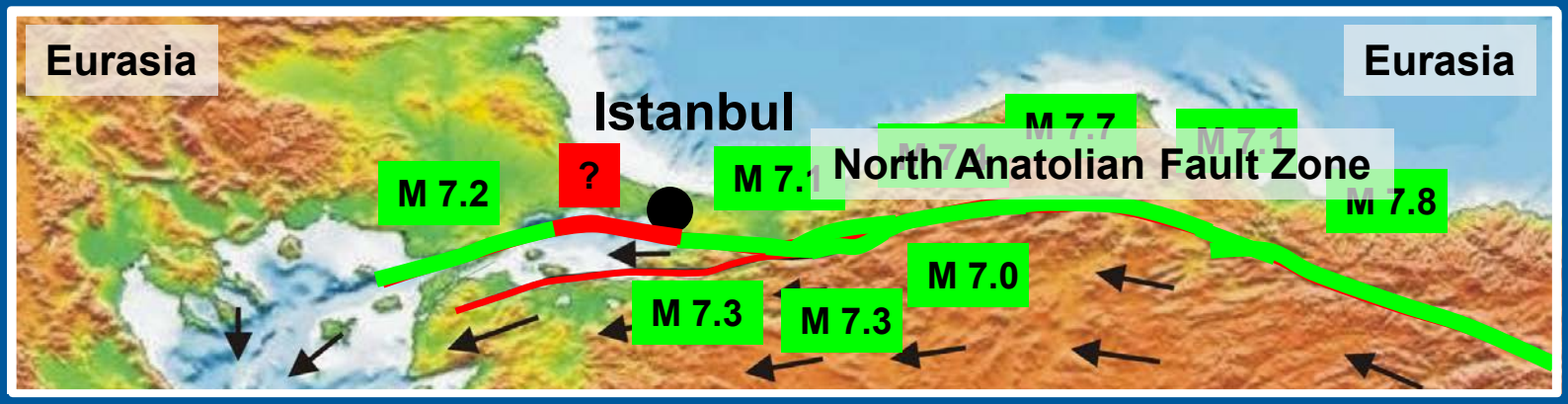
(Bohnhoff et al., 2010ff)

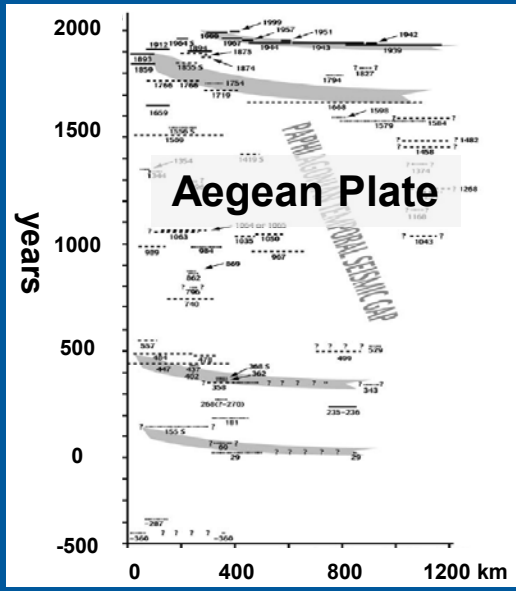
The North Anatolian Fault Zone

The North Anatolian Fault Zone



Tectonic Setting and Recent M>7 earthquakes along the North Anatolian Fault Zone





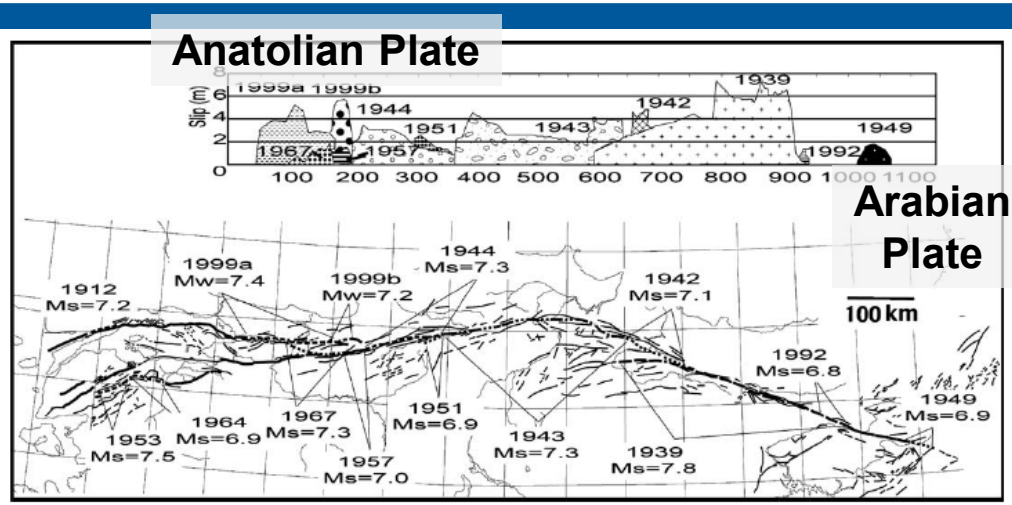
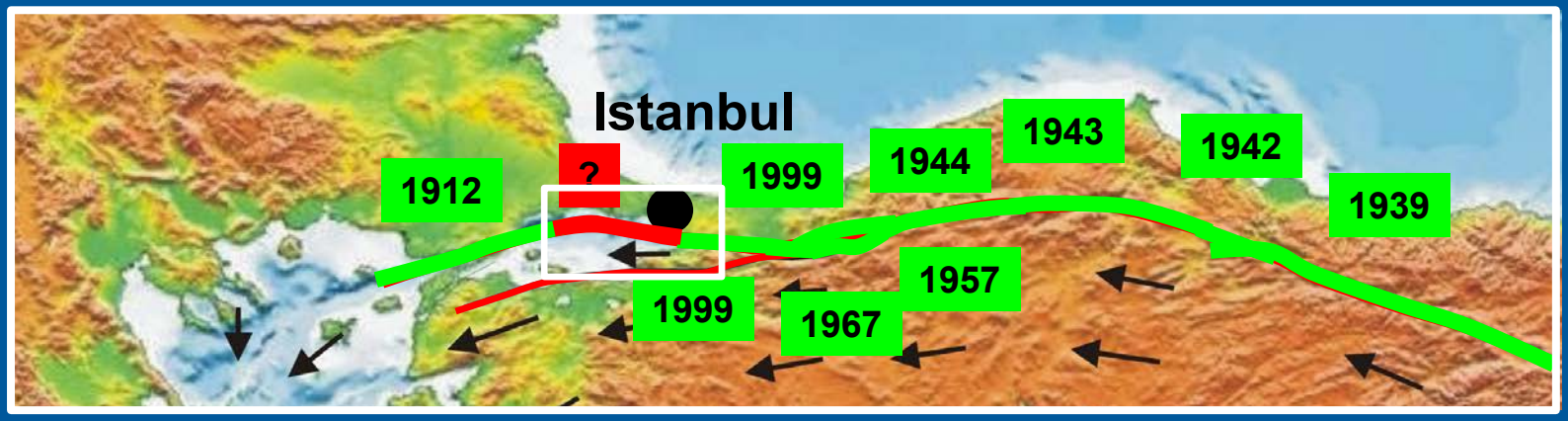


Figure 3 Earthquakes and related fault displacements along the North Anatolian Fault (NAF) since the December 26/27, 1939, Erzincan earthquake. Note the remarkable east-to-west migration of the major shocks, first emphasized by Egeran & Lahn (1944). The figure has been compiled from Şaroğlu et al. (1987, 1992), Eyidoğan et al. (1991), Barka (1996), Barka et al. (2000a), and Akyüz et al. (2000).

(Sengör et al., 2005)

The 20th Century Earthquake Series



Facts & Figures for the Istanbul-Marmara Region:

- Multiple M>7 earthquakes within last 2000 yrs., recurrence period ~200-250 yrs.
- Probability for a M7+ earthquake is 35-70% in 30 yrs. (Parsons, 2004).
- Slip-deficit since last major event in 1766 is >5m (IF FAULT IS FULLY LOCKED).
- Historical documented Tsunamis exceeded wave heights of 6m.
- Istanbul: Population increased from 1 to >13 million since 1950.
- Marmara region generates ~40% of the Turkish GNP.

How can we estimate the maximum magnitude of the next Marmara earthquake?

Several prominent regional-scale continental transform fault zones are located in close proximity to mega-cities of 10+ million inhabitants (e.g. North Anatolian Fault Zone, San Andreas Fault).

The seismic hazard from these faults is closely related to the maximum expected earthquake size. This, however, is poorly constrained by instrumental seismic data given a recurrence interval for large events of typically >>100yrs.

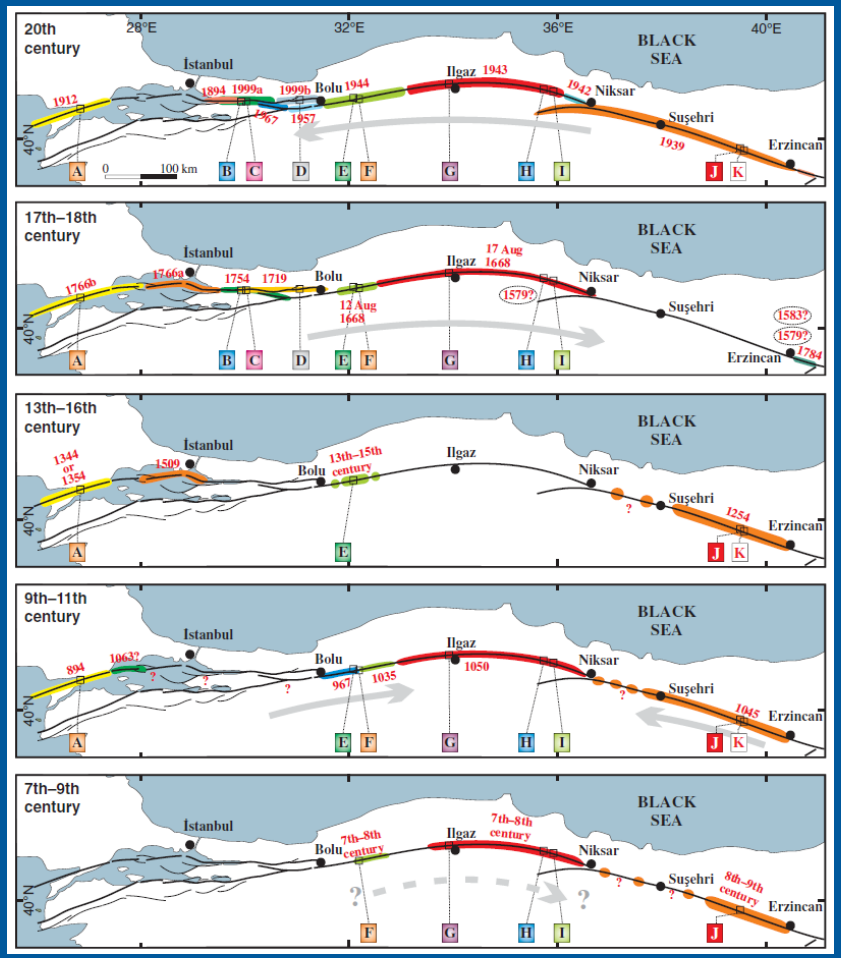
The North Anatolian Fault Zone in Turkey is the only strike-slip fault zone worldwide that both, has a historic earthquake catalogue extending over several millenia and that is well-characterized from instrumental data.

Historical NAFZ Earthquakes in a Nutshell

Largest events all in the east:
- Erzincan 1939 → M≥7.9
- Earthquake of 1668 M~7.9

Marmara earthquakes all M≤7.4 :
123 (M7), 740 (M7.1), 869(M7), 989 (M7.2), 1063 (M7.4), 1343 (M7.0), 1556 (M7.2), 1509 (M7.2-7.4), 1766 (M7.4)

(Ambraseys & Finkel, 1991)



(Kozaci et al., 2011)

A Historical Earthquake Catalogue for the NAFZ

Made use of exceptional good historical records (Istanbul cultural hub since 650BC) in connection with paleoseismic results from trenching studies.

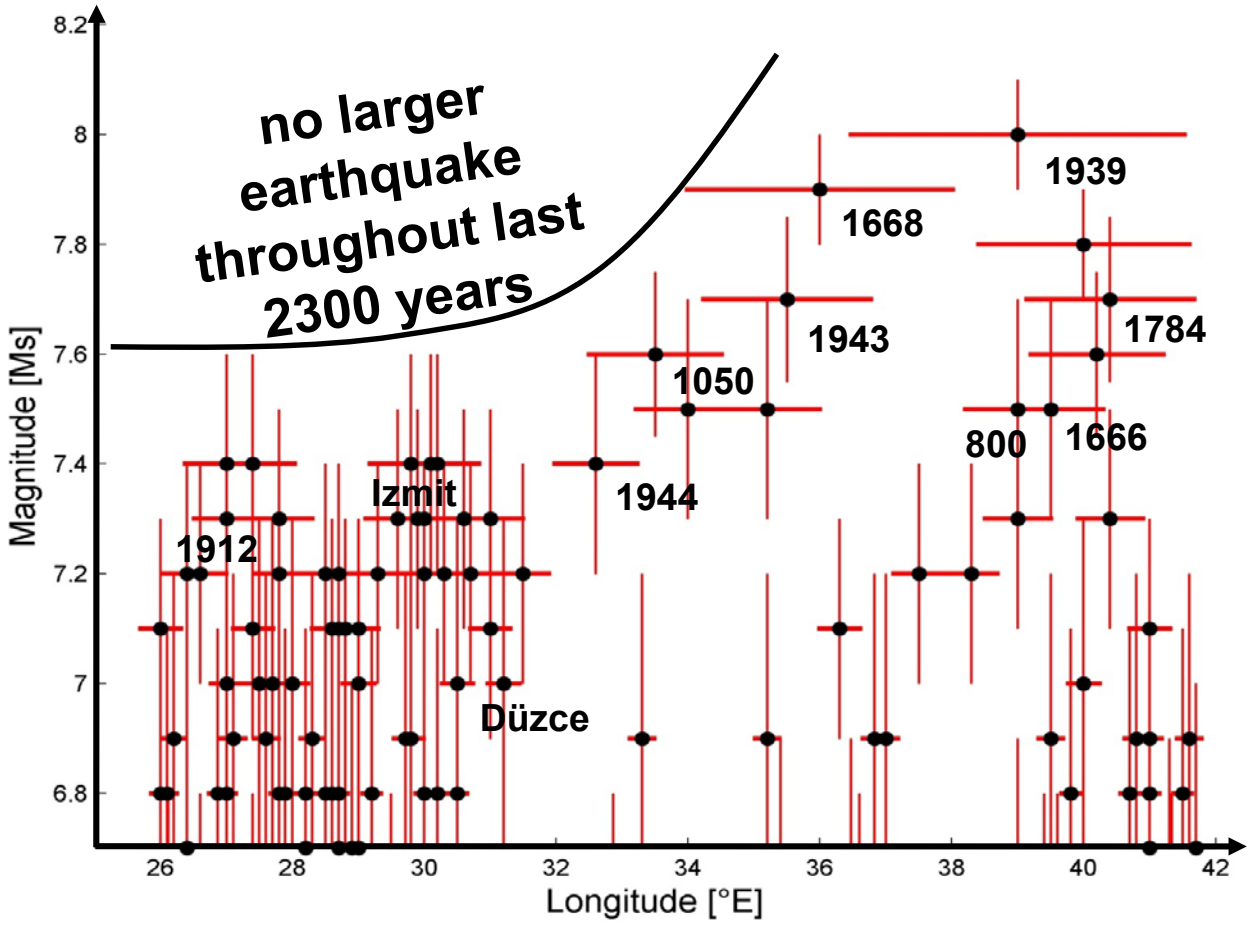
Main literature sources: Ambraseys and co-workers, Grünthal & Wahlström (2012).

All magnitudes were converted to M_s using the relation from Scordilis (2006): $6.2 \leq M_s \leq 8.2$ of $M_w = 0.99(\pm 0.02) * M_s + 0.08(\pm 0.13)$ simplified to $M_s \approx M_w - 0.1$.

→ A unique record of historical earthquakes along the NAFZ for the past 2300 yrs. covering multiple earthquake cycles ($t_{rec\ max}$ at NAFZ = 685 yrs. from trenching).

→ The newly compiled earthquake catalog consists of 203 earthquakes with magnitudes up to M_s=7.8-8.0 and is complete down to M_s=7.3 .

A Historical Earthquake Catalogue for the NAFZ

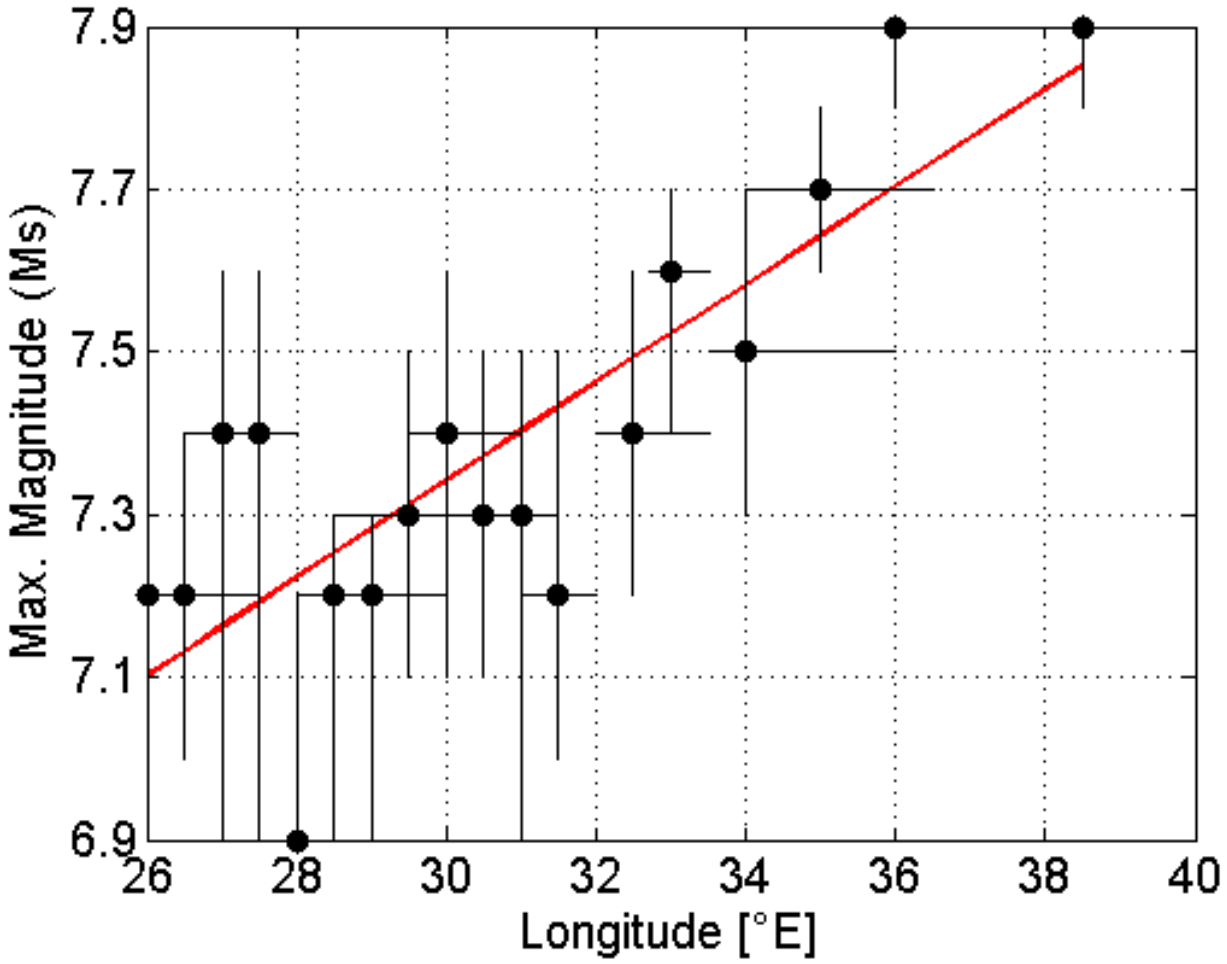


vertical red bars= assumed errors:
M7.0: ±0.3
M7.5: ±0.2
M7.7: ±0.15
M8.0: ±0.1

horizontal red bars = rupture lengths

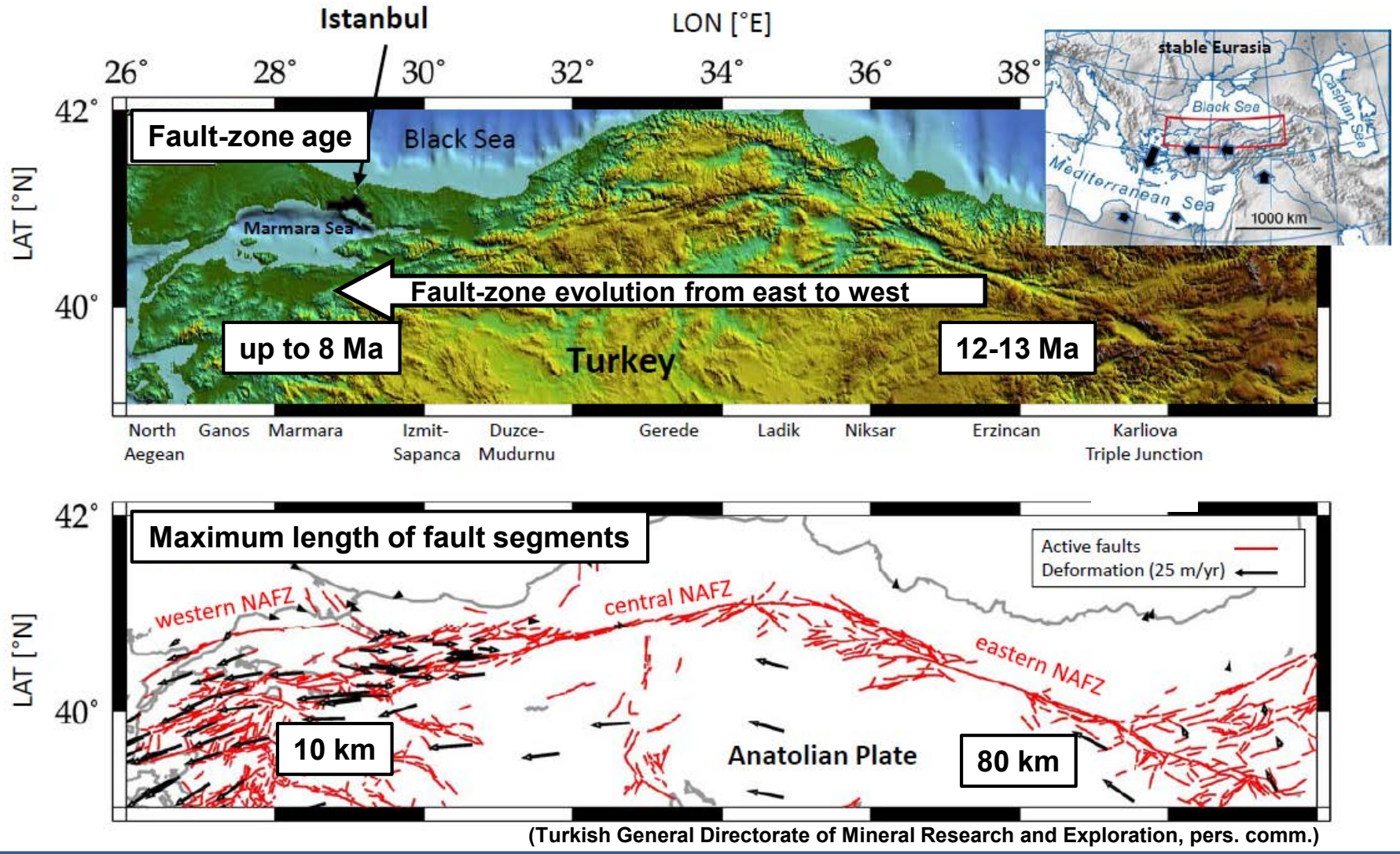
(Bohnhoff et al., Tectonophysics, 2016)

Maximum Observed Magnitudes Along the NAFZ



(Bohnhoff et al., Tectonophysics, 2016)

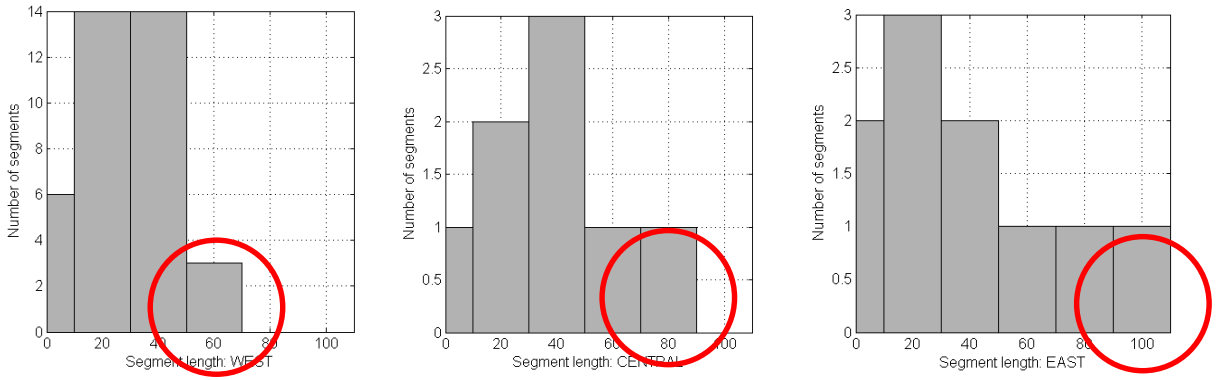
Additional Characteristics of the NAFZ



(Turkish General Directorate of Mineral Research and Exploration, pers. comm.)

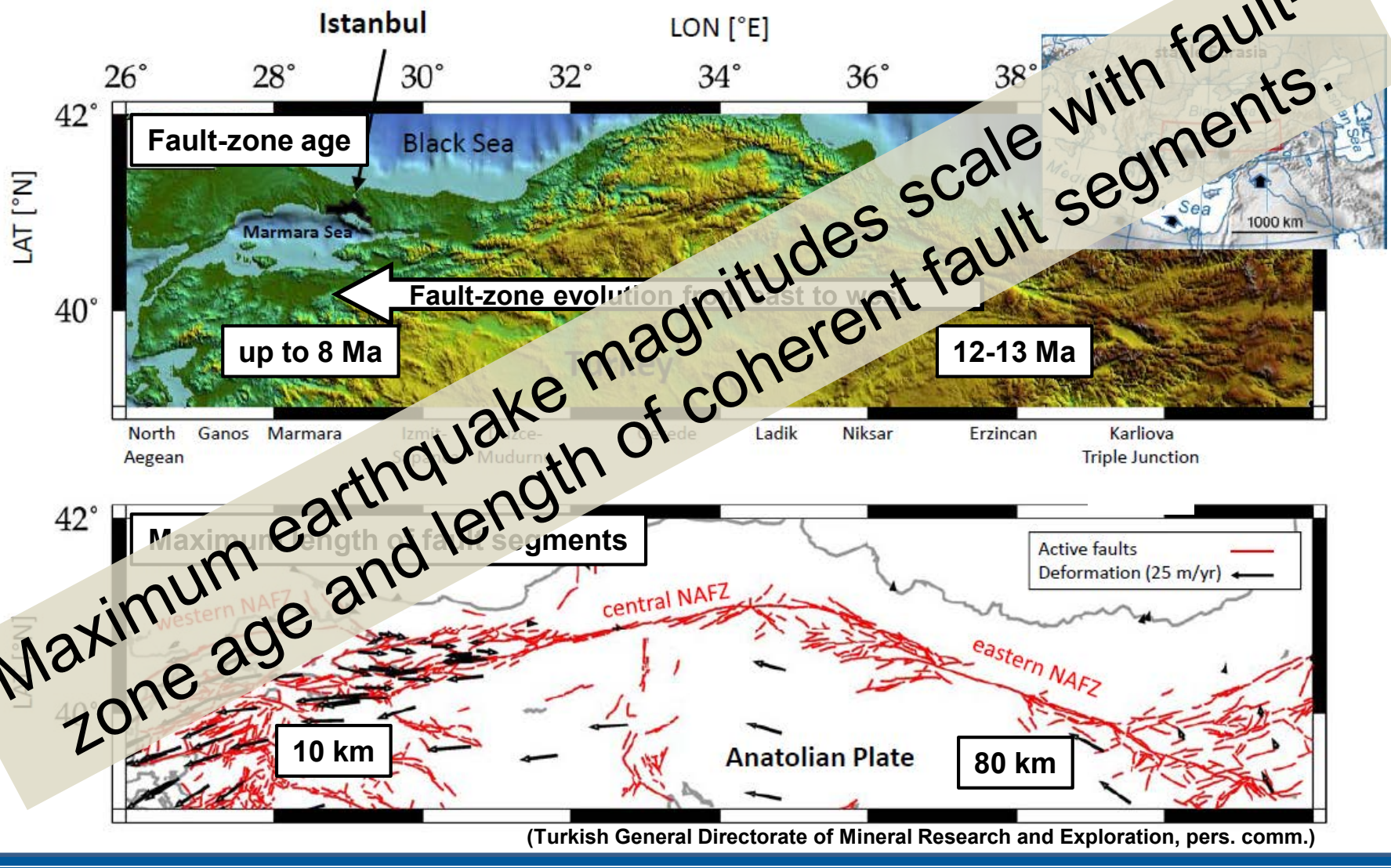
Additional Characteristics of the NAFZ

Length of mapped coherent fault segments



(after Barka, 1992)

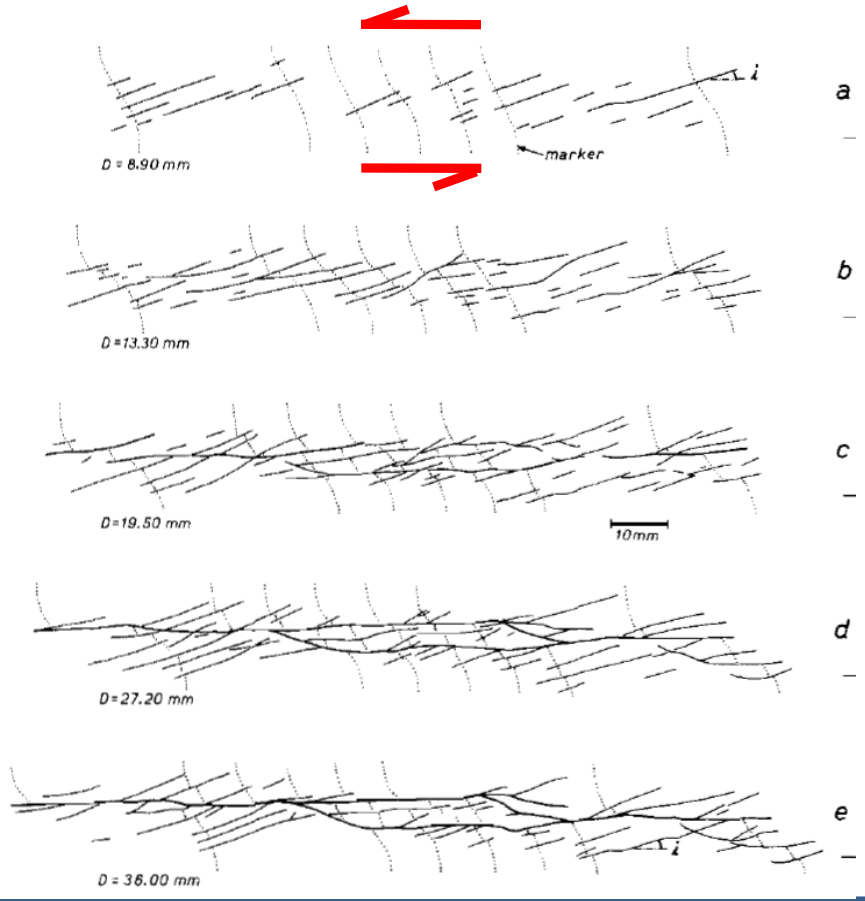
Additional Characteristics of the NAFZ



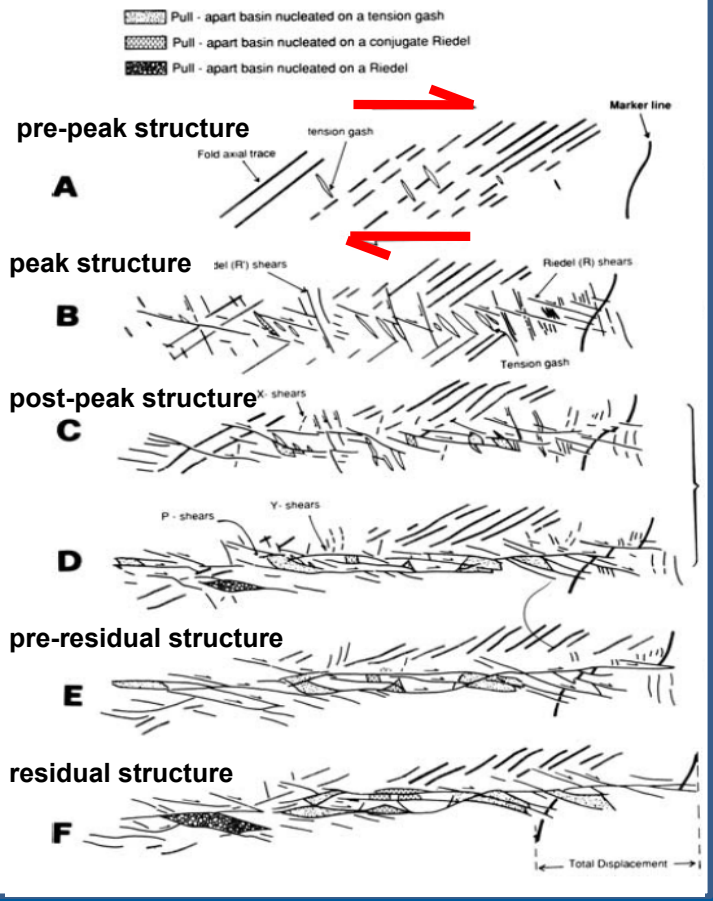
(Turkish General Directorate of Mineral Research and Exploration, pers. comm.)

Evidence for seismological fault-zone evolution

(Tchalenko, 1970 [based on work from Cloos, 1920s])



(Sengör, 1995; Sengör et al., 2005)



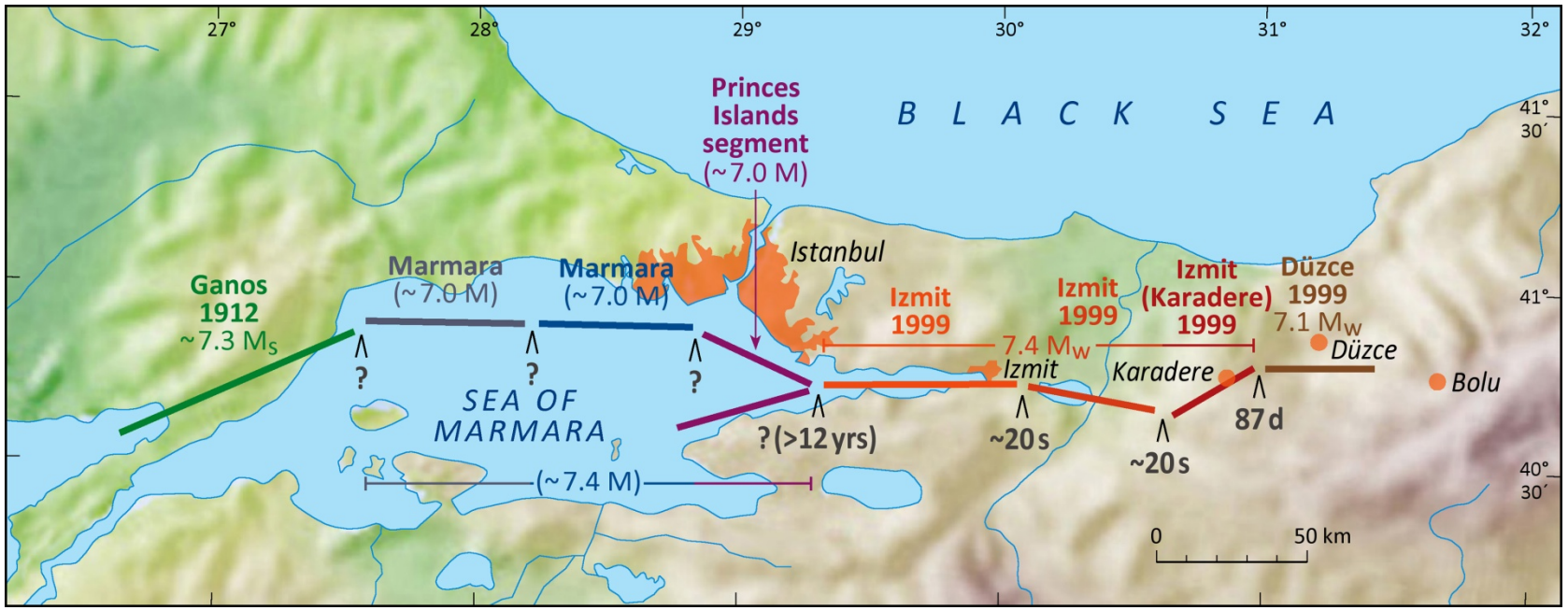
progressing fault-zone evolution with time

Laboratory scale

Field scale

The NAFZ in the Istanbul Region

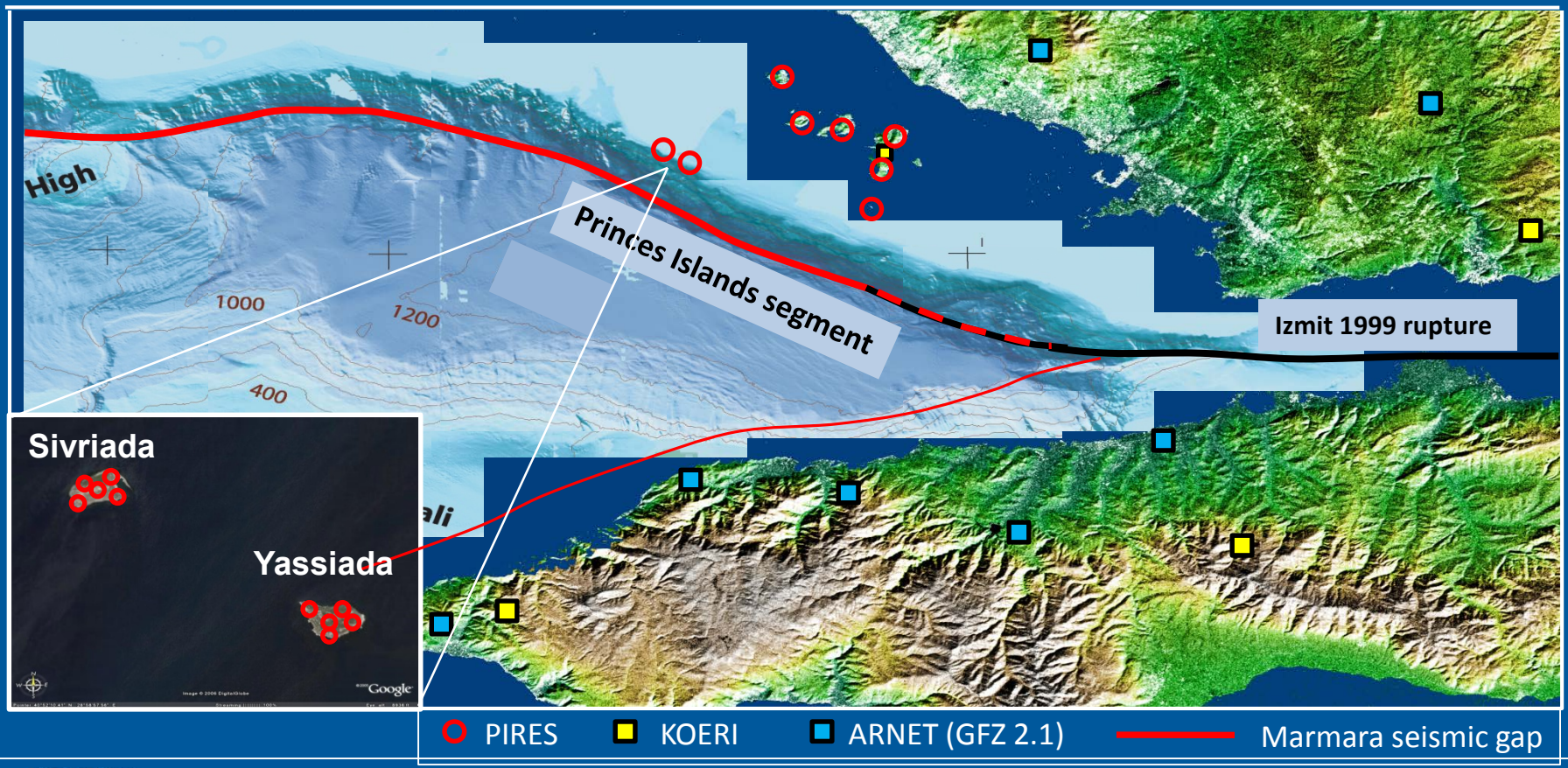
- A major (M>7) earthquake is overdue at the Marmara segment offshore Istanbul.
- The Marmara section can be characterized by three segments along its major northern strand with a potential for an up to M7.4 earthquake.
- The current seismotectonic status of the Marmara section not known in detail.



(Bohnhoff et al., 2013)

Seismic Monitoring of the Princes Islands Segment

- Regional M_c ~2.8 → aim was to densify local network geometry close to fault
- PIRES network with 16 stations on the Princes Islands (real-time monitoring)
- M_c lowered to ~1.8 providing first insights on ongoing processes and fault geometry



PIRES: Installation of Seismic Stations

Dummy for concrete lid

Preparation of station housing

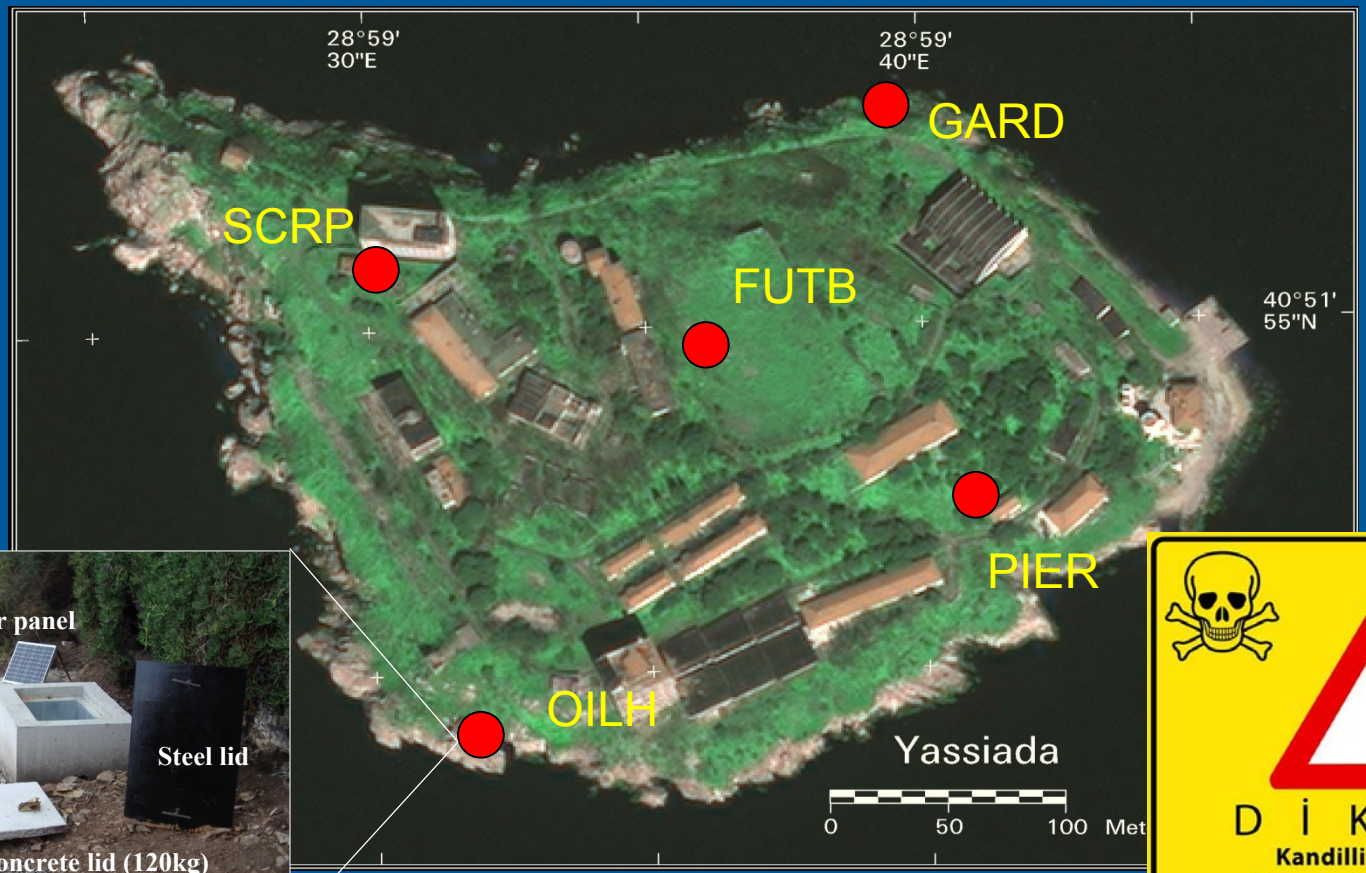
Preparation of station housing

PIRES: Impressions from Yassiada

‘Science is the thing to live for‘

PIRES Subarray on Yassiada: Station Distribution

Aperture 300m; abandonned prison

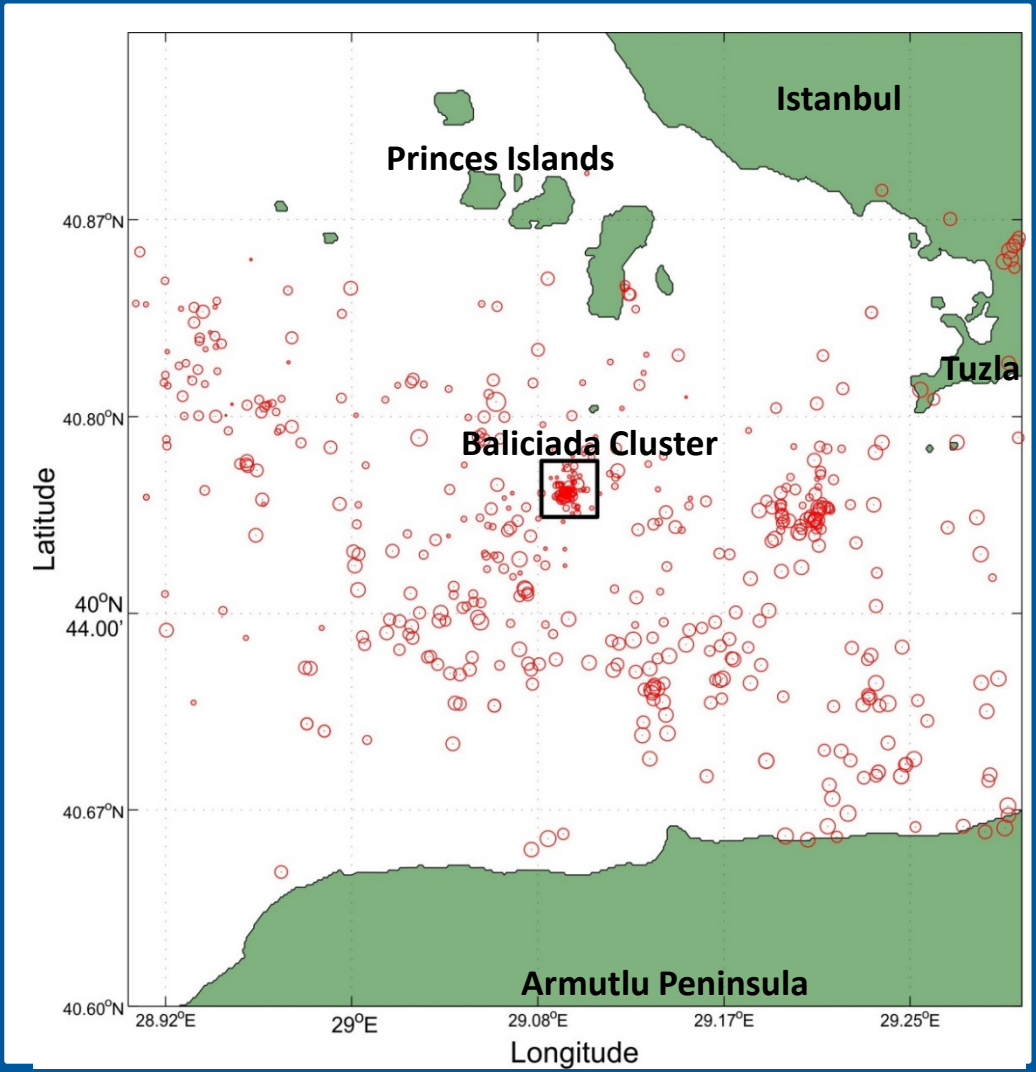


Seismic Surface Station

Station Layout

Warning Sign

Recent Microseismicity Offshore of Istanbul



Seismicity 2006-2009

PIRES network on Princes Islands.

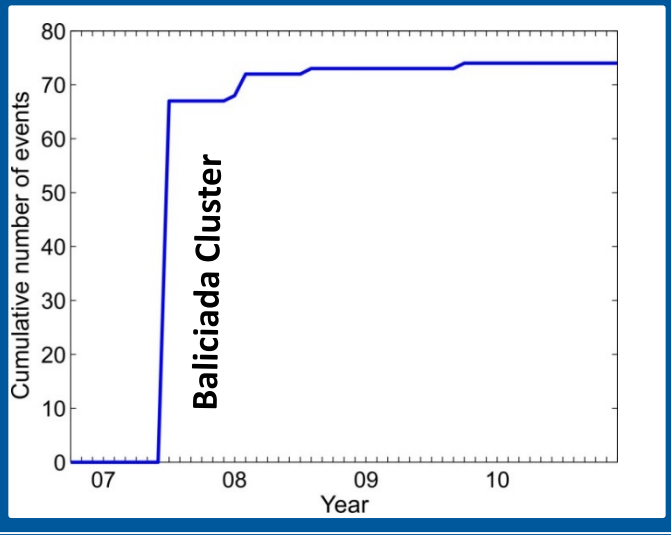
~800 relocated events.

Baliciada cluster:

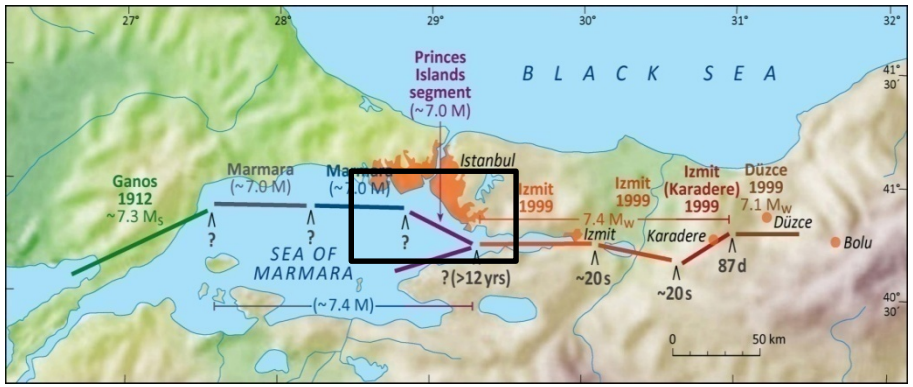
- 100 events in less than 24h.
- Migration of activity from main fault onto splay fault.

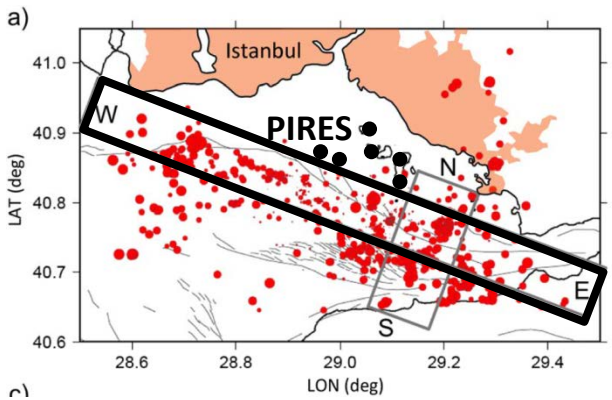
(Bulut et al., BSSA, 2011)

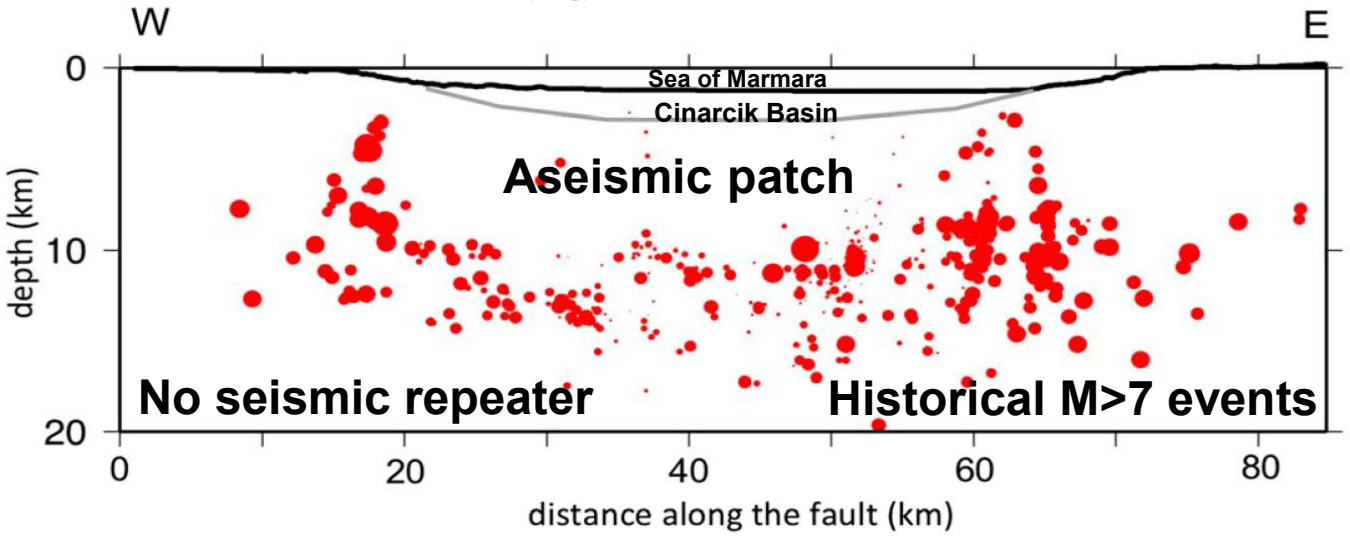
Cumulative number of EQ:



Current setting of the Princes Islands Segment: Locked or creeping?







(Bohnhoff et al., Nat. Commun., 2013)

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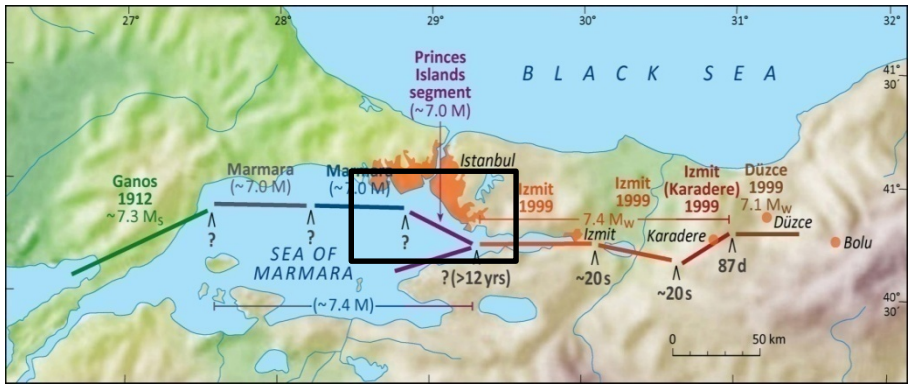

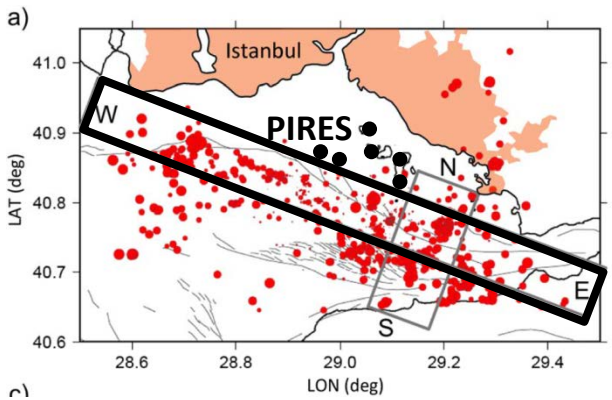

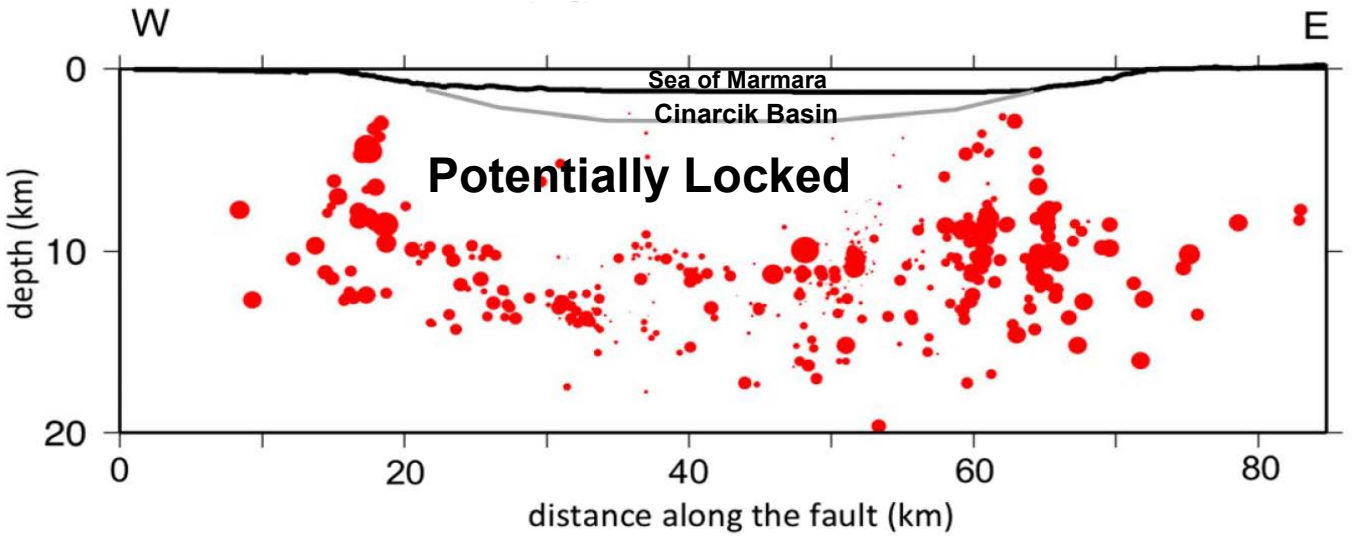

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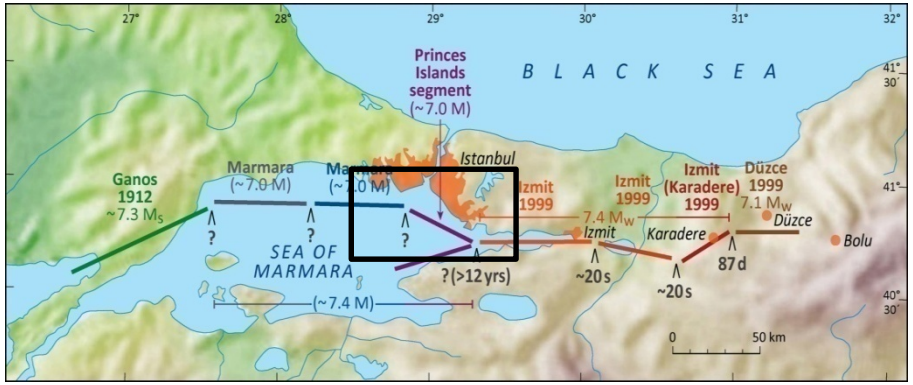

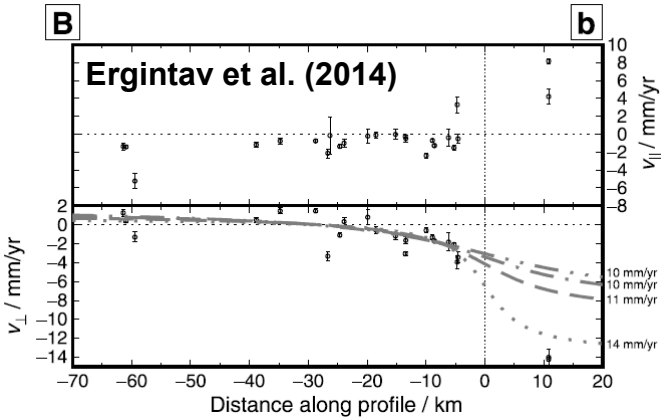

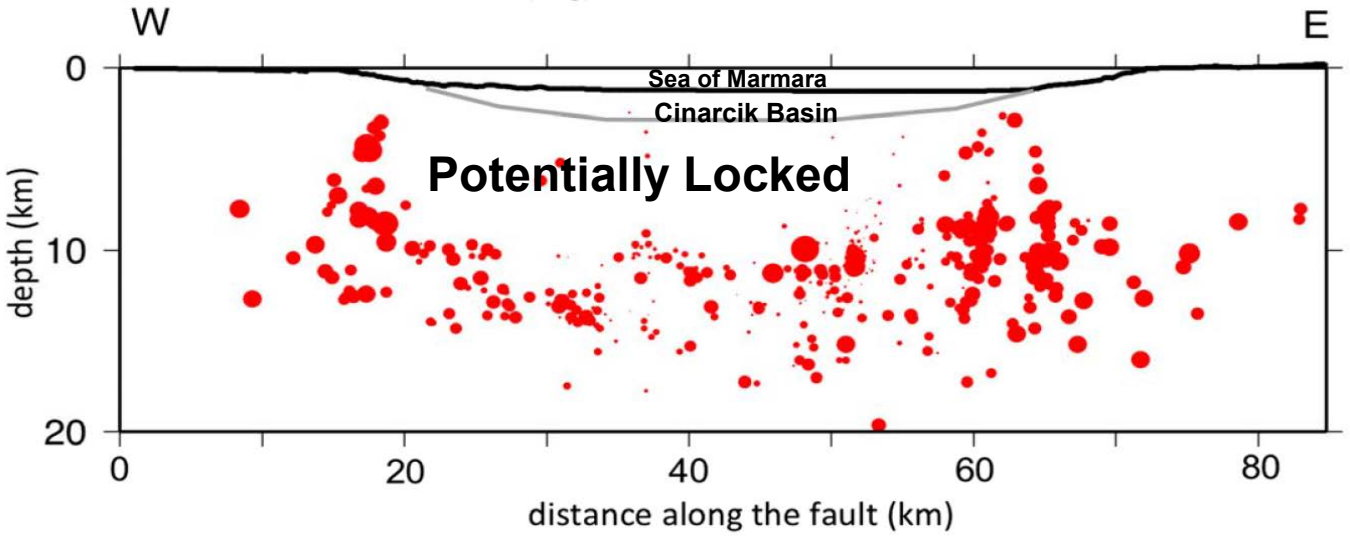

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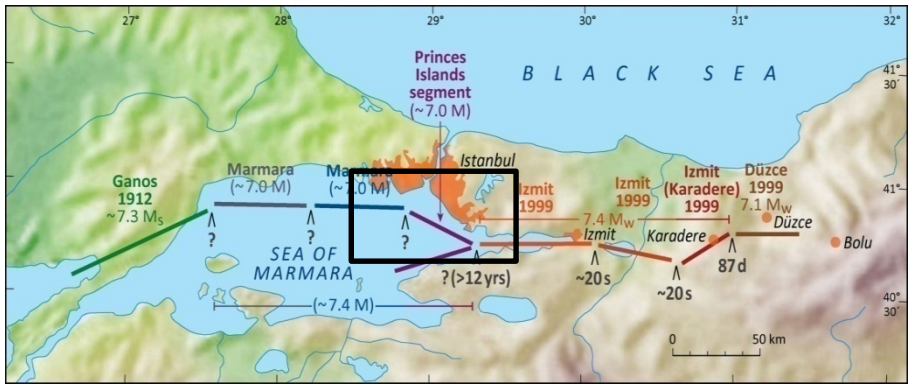
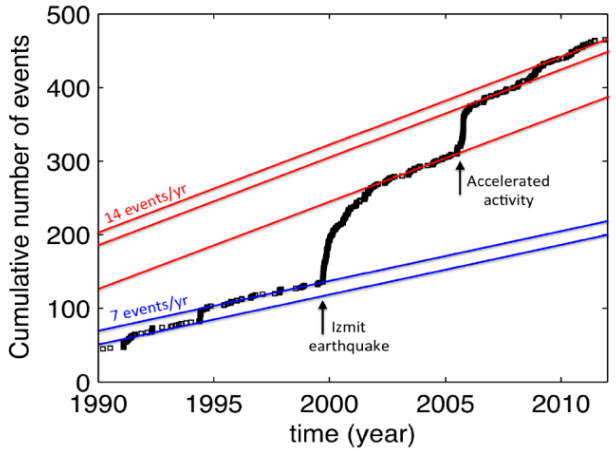
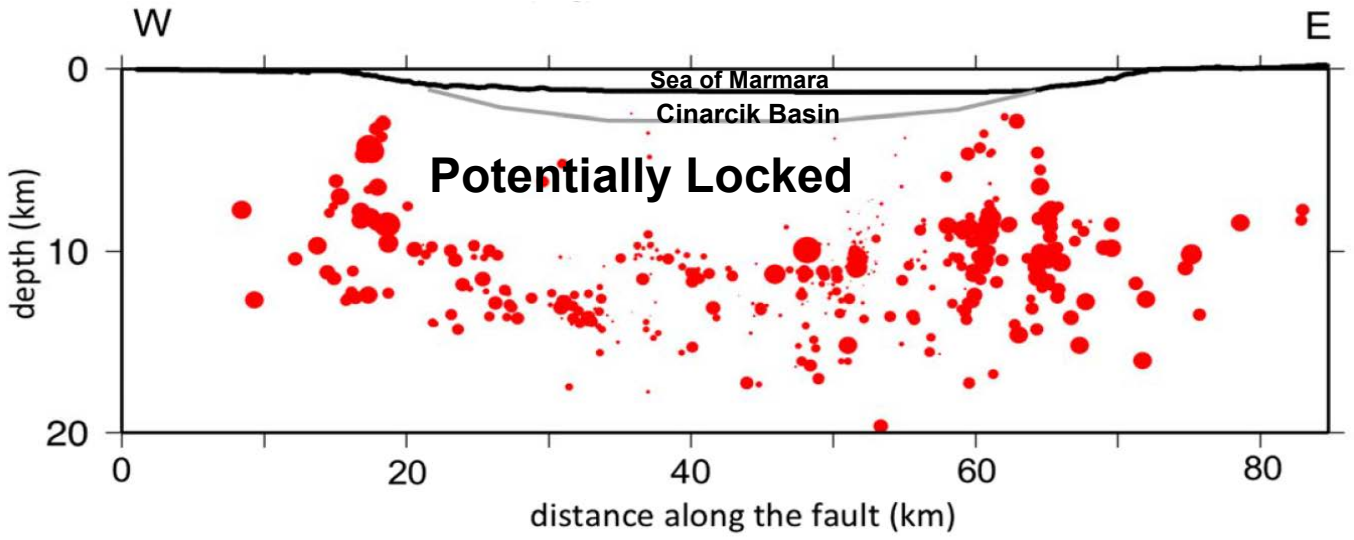


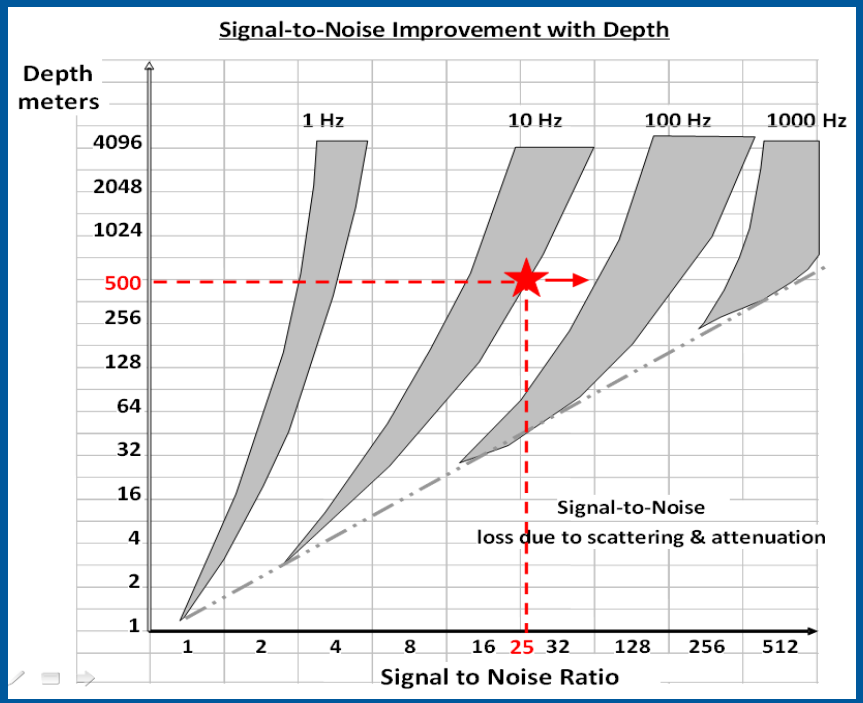


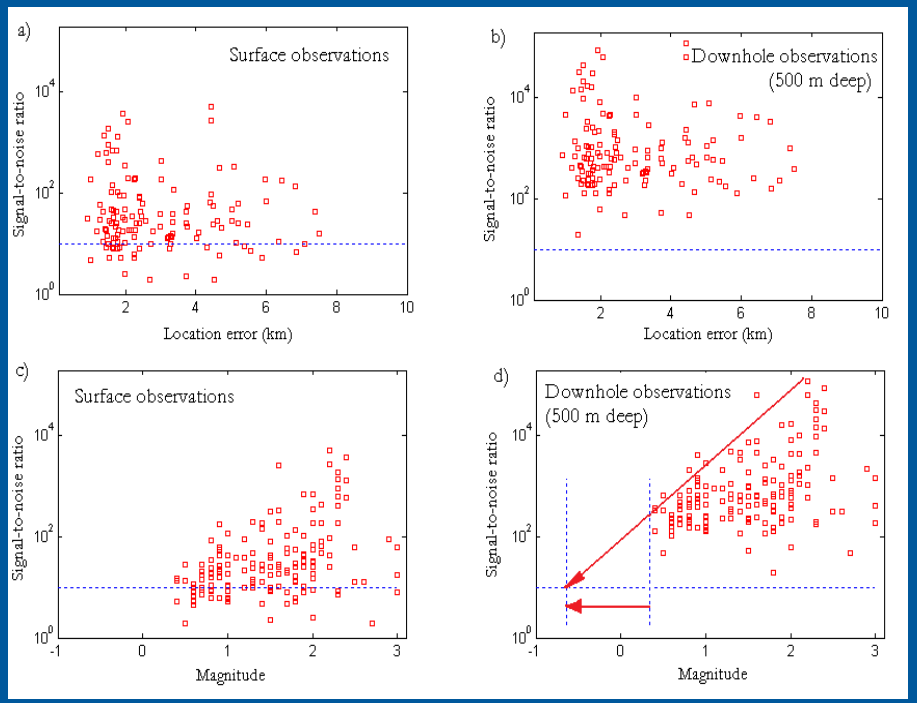


(Bohnhoff et al., Nat. Commun., 2013)

Next milestone: Going downhole…

Per magnitude unit ten times more earthquakes (Gutenberg-Richter law)
→ Decrease the magnitude detection threshold!





The GONAF Downhole Observatory

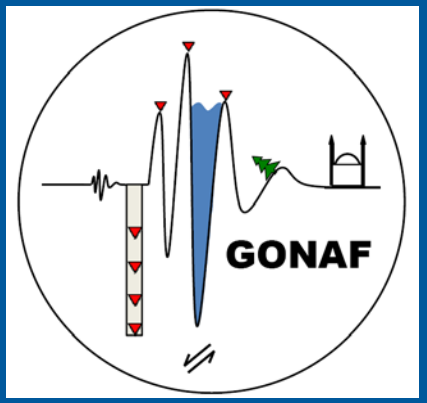
Principal Investigators:

Bohnhoff, Dresen, Bulut (GFZ*)
Ceken, Nurlu, Kartal, Kilic (AFAD*)

GONAF is co-funded by GFZ, AFAD, ICDP and the Helmholtz Association

Partners/Contractors:

Peter Malin (ASIR, US)
Rob Reilinger (MIT, US)
Dave Mencin (UNAVCO, US)
Hisao Ito (JAMSTEC, JP)
ICDP-OSG (GFZ)



Key questions and primary objectives of GONAF:

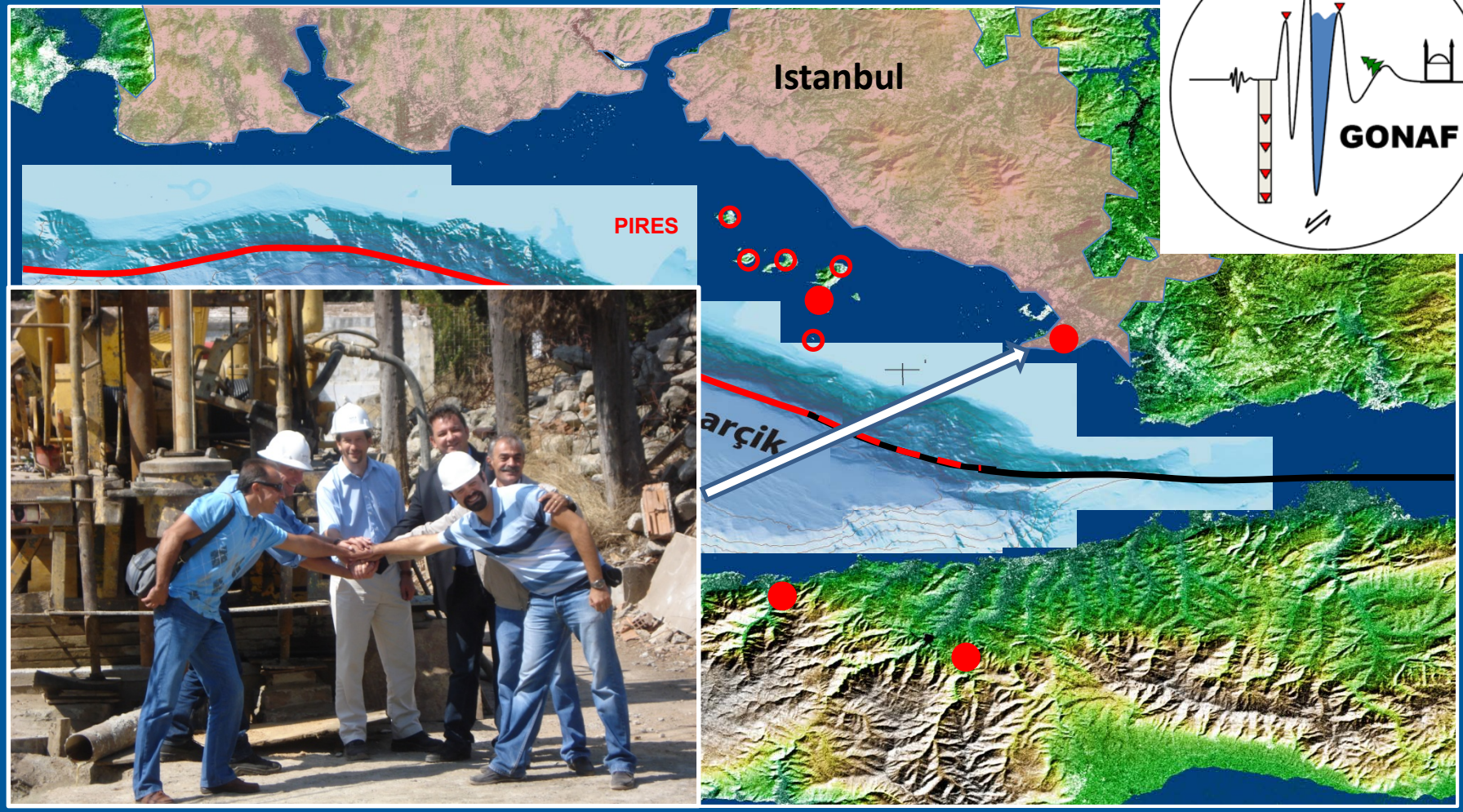
- What are the driving physical processes along a transform fault segment that is in the final state of its seismic cycle prior, during and after a large (M7+) earthquake?

- How does the structural heterogeneity of the NAFZ below the Sea of Marmara affects the slip distribution, nucleation process, and magnitude of the pending Marmara earthquake?

➡ GONAF aims at monitoring microseismic activity and deformation processes in the broader Istanbul region using downhole seismic observations over the entire seismic frequency band as well as GPS and strain meter measurements.

* AFAD = Disaster and Emergency Management Presidency, Ankara/Turkey

The GONAF Downhole Observatory



The GONAF Downhole Observatory

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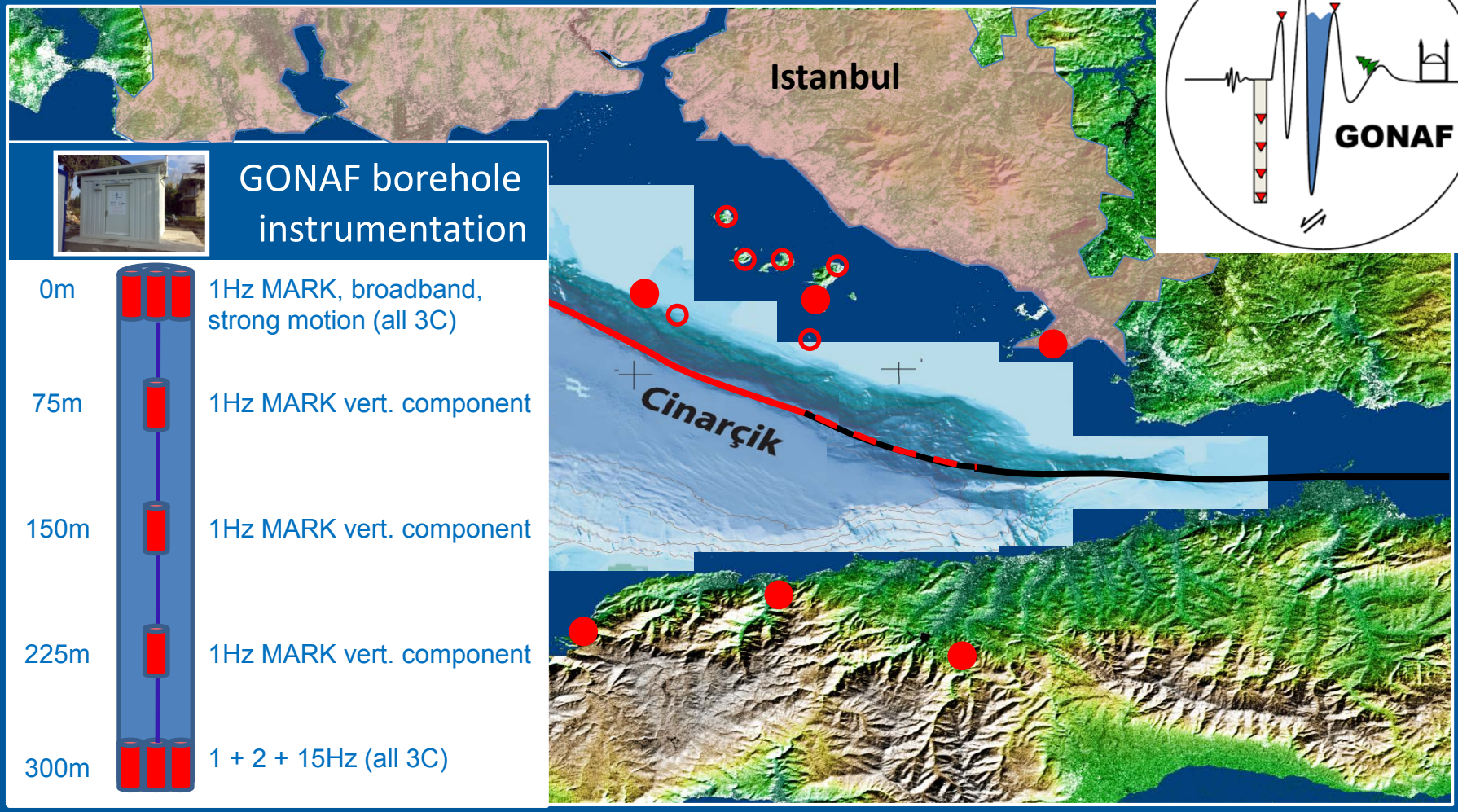
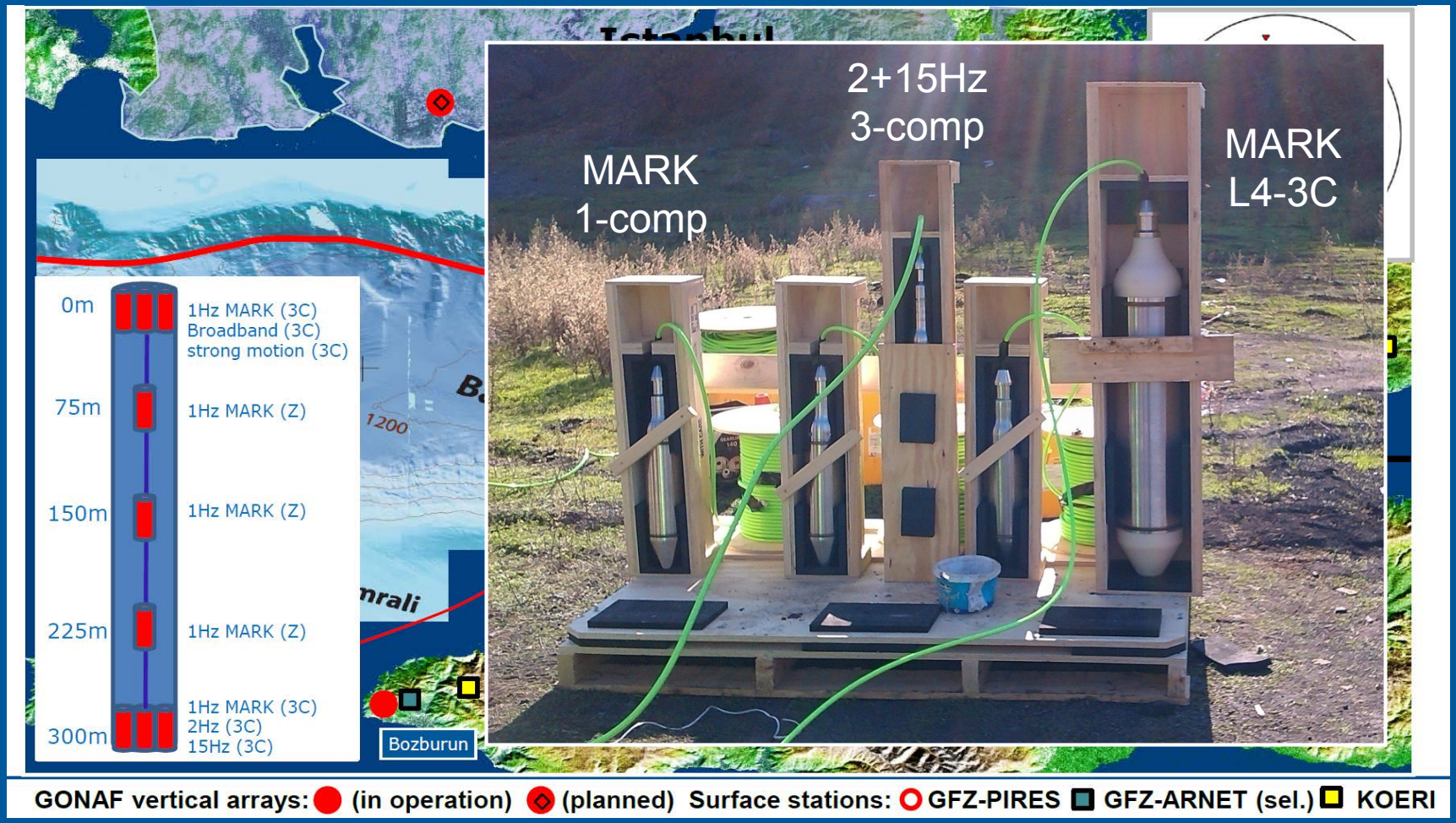
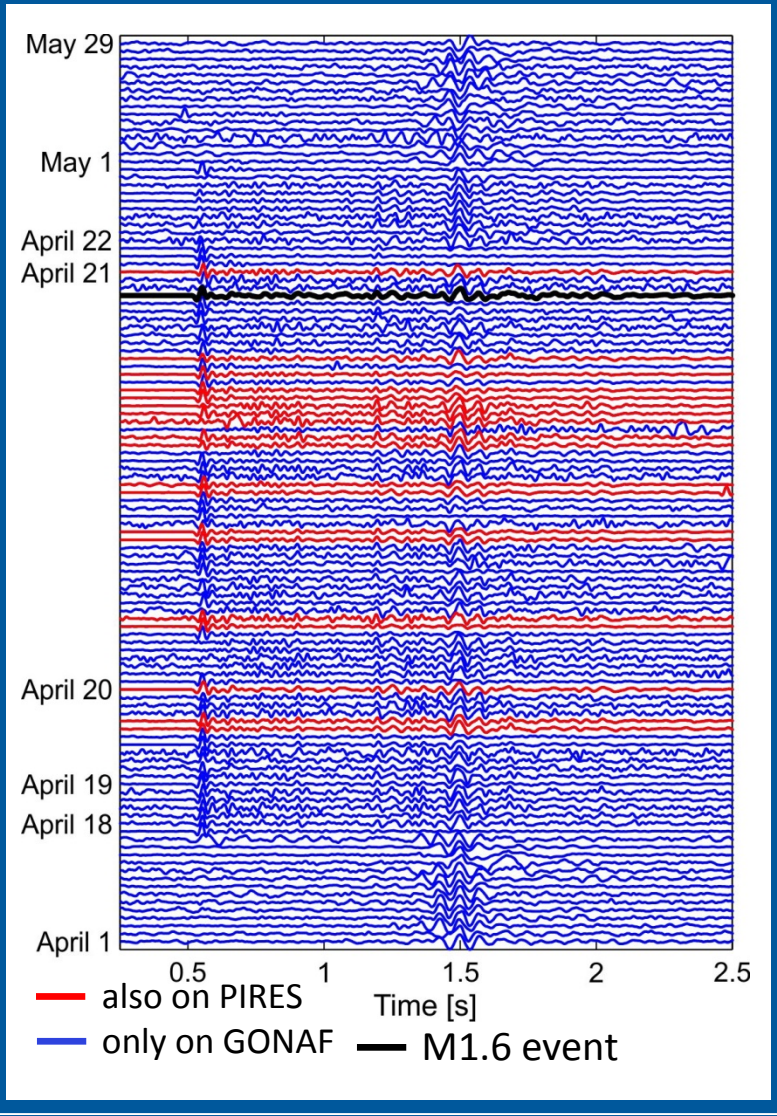
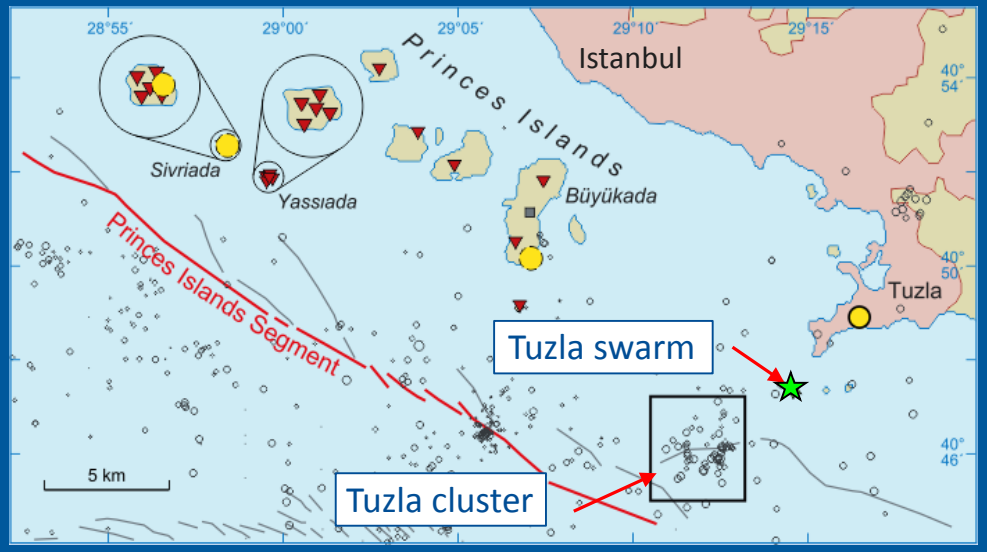


Monitoring of the Princes Islands Segment: ICDP GONAF Downhole Observatory



2013 Tuzla Swarm Detected by GONAF Sensors

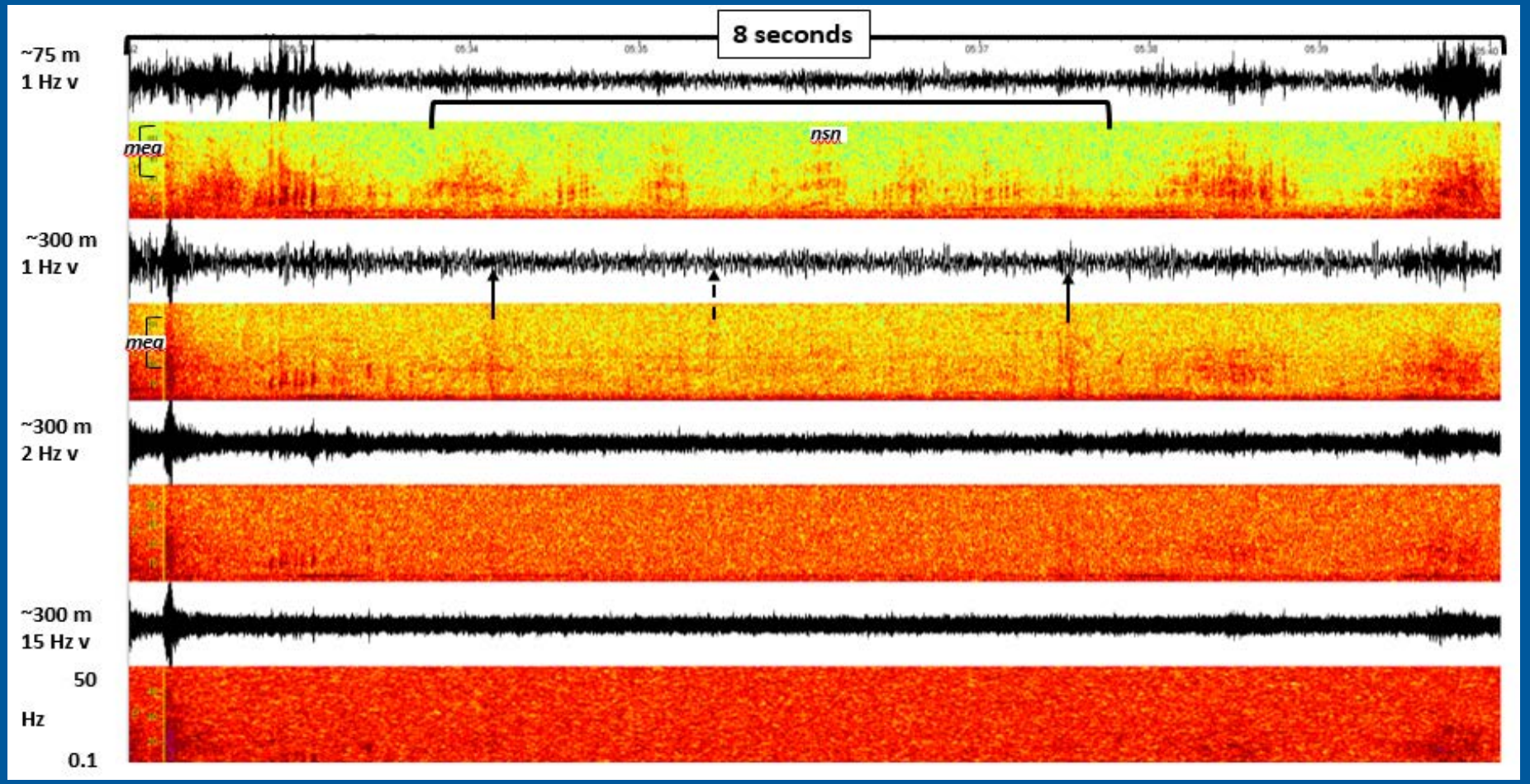




- Apr/May 2013 earthquake swarm activity near Tuzla cluster (largest event: M1.6, 20th Apr. 2013).
- 114 events detected by waveform cross-correlation (only one event seen by regional networks).
- Mean duration magnitude of -0.42. Constant S-P time (σ~0.01s) indicate stationary source locations.

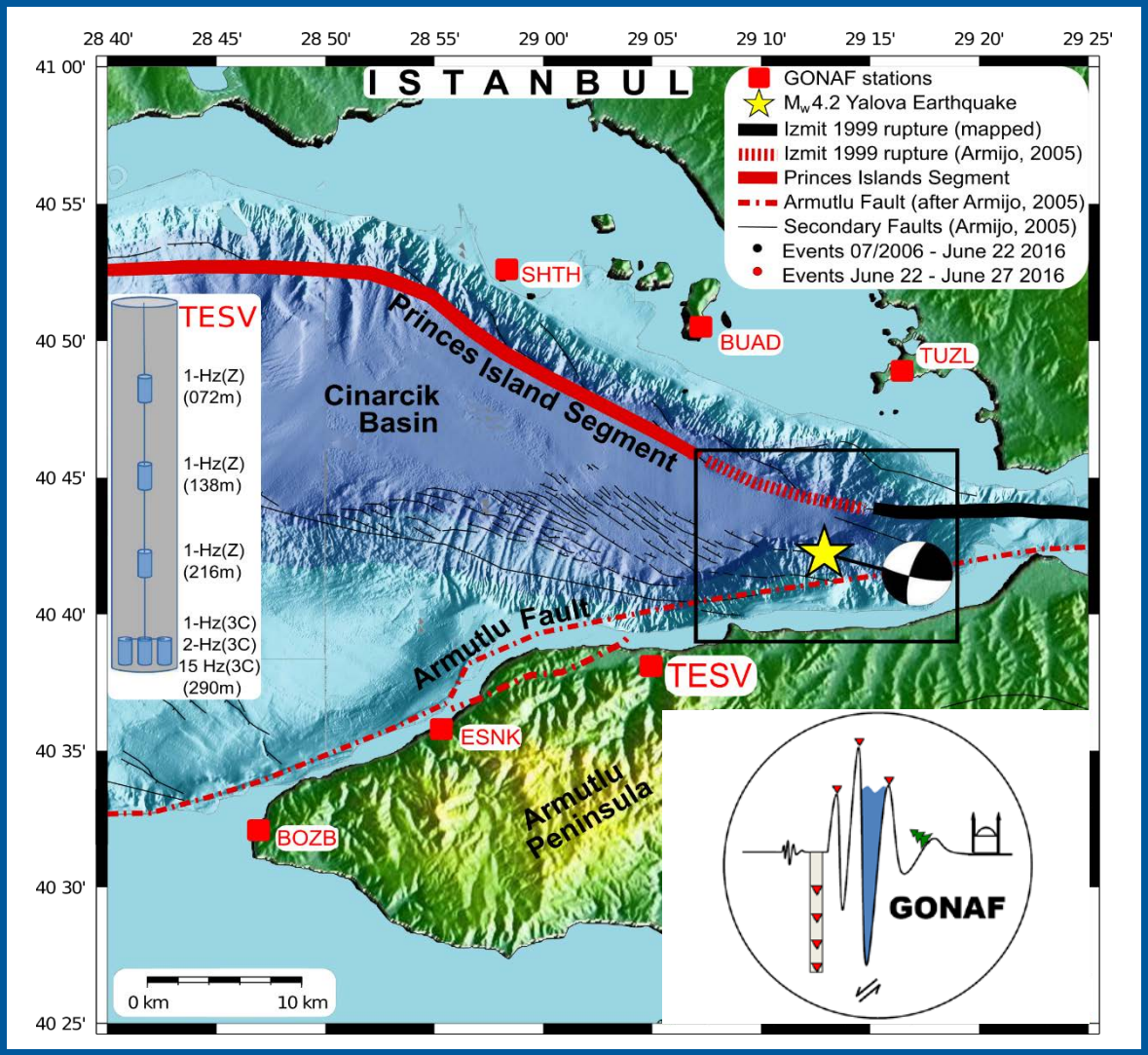
(Prevedel et al., Int. J. Geosc., 2015; Raub et al., BSSA, 2016)

Low-Noise Waveform Recordings from a Downhole MARK L4-3C Seismometer



(Bohnhoff et al., Scientific Drilling, 2017)

GONAF Observatory: Station Location



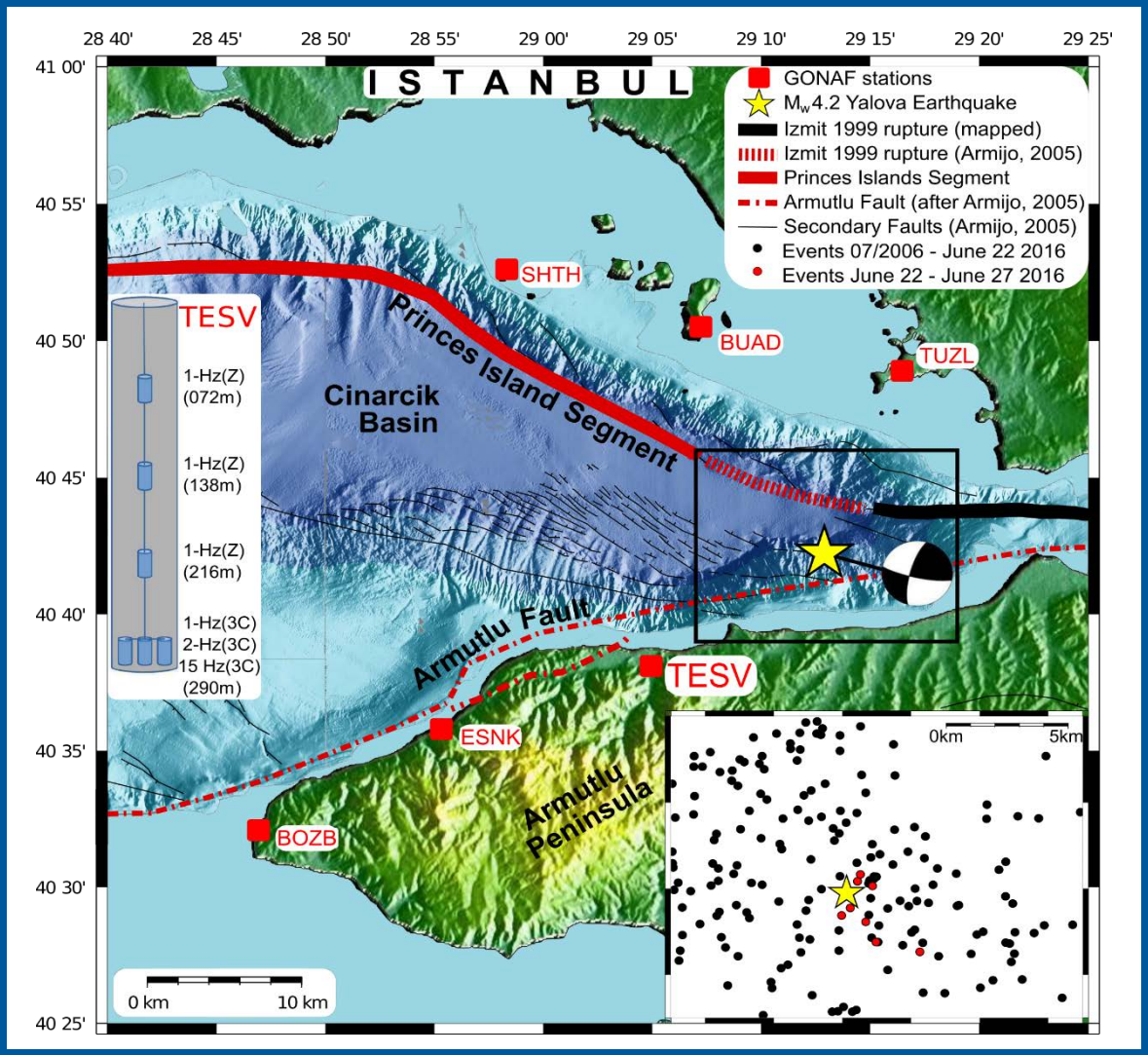
Eastern Marmara section hosts a potential nucleation point for the overdue M>7 earthquake.

The recently implemented GONAF observatory decreases the local magnitude-detection threshold by two orders of magnitude.

GONAF aims at monitoring seismic and aseismic deformation processes based on downhole recordings and includes downhole arrays with Z and 3C sensors at 4 levels.

(Bohnhoff et al., 2010; 2013; 2017; Prevedel et al., 2015; Raub et al., 2016)

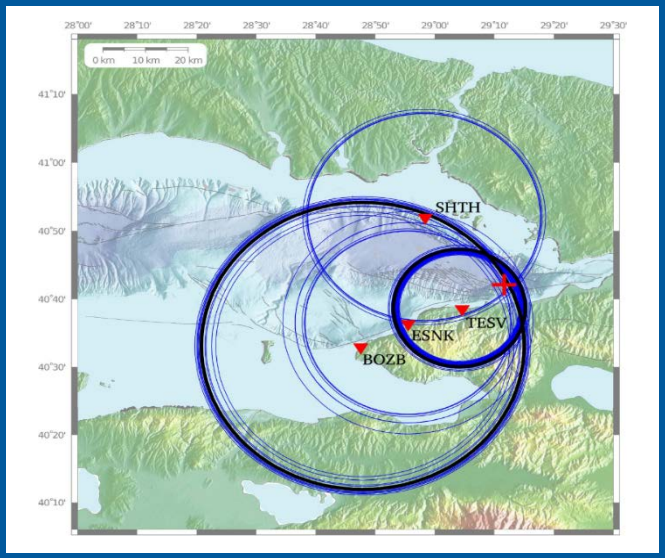
Location of the M_w4.2 2016 Yalova event



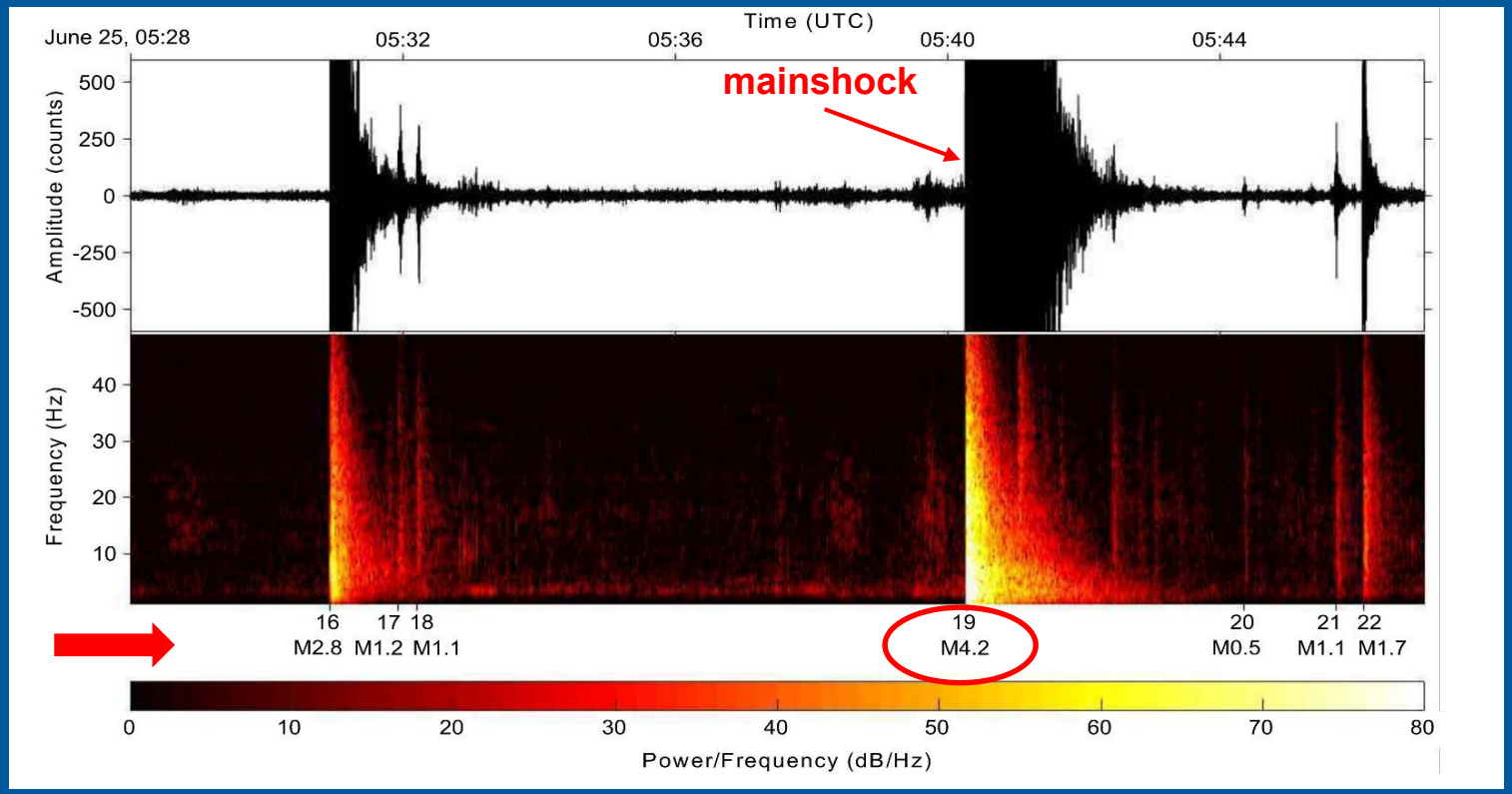
M_w4.2 earthquake 10 km away from GONAF-TESV array.

9 more events located by regional network.

TESV detected at least 61 more events including 18 foreshocks down to M~0.



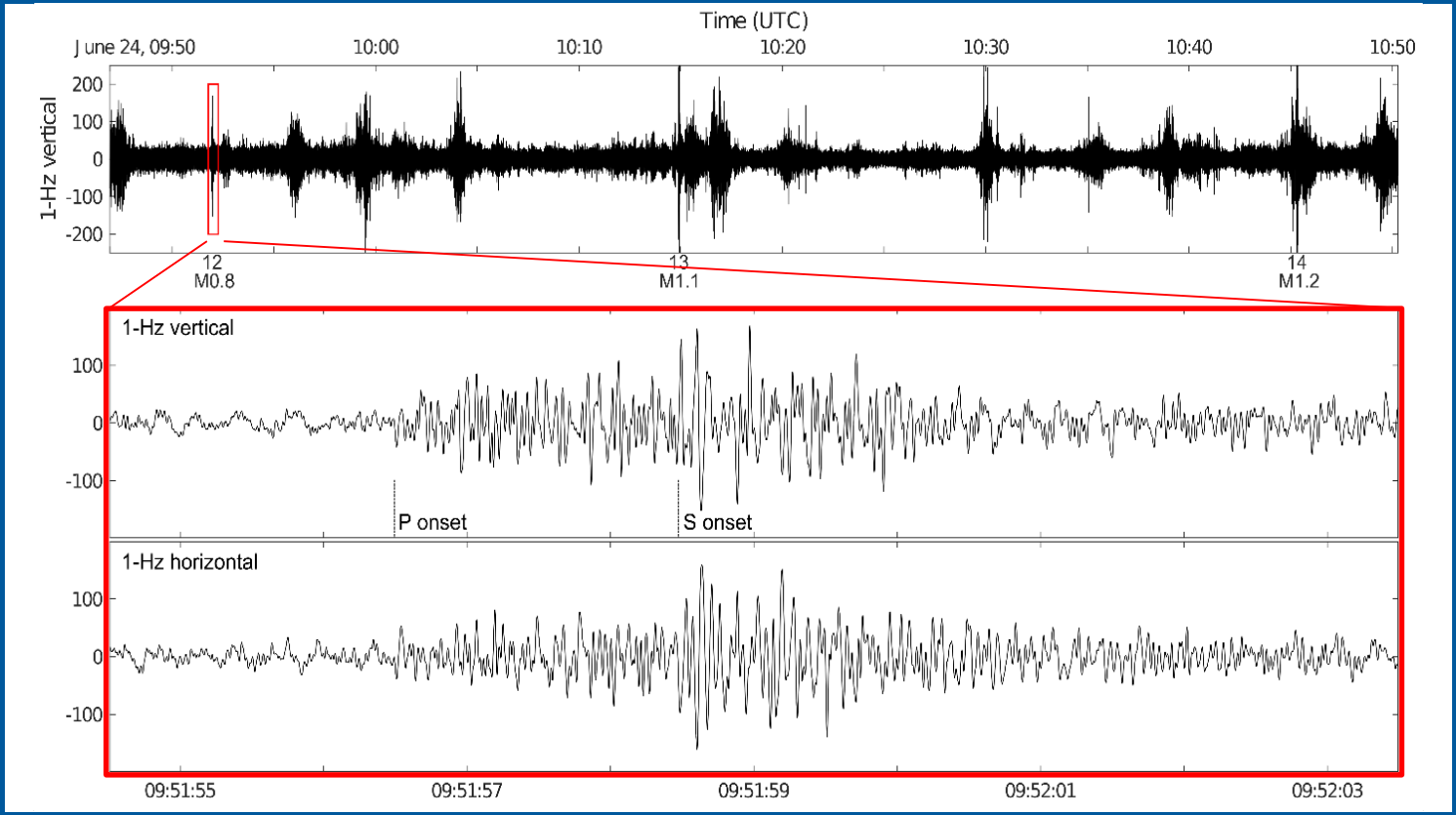
Waveforms and spectra framing the M_w4.2



20 min data from the 290 m-deep 1 Hz vertical sensor at TESV indicates pre-shock seismicity including an M2.8 foreshock and at least four more events down to M0.5.

The spectrogram indicates several more smaller events not seen in the waveforms.

Waveform Example for an M0.8 event



During the 3 days before the M_w4.2 include at least 18 foreshocks occurred such as the M0.8 event with reasonably clear P and S wave onsets.

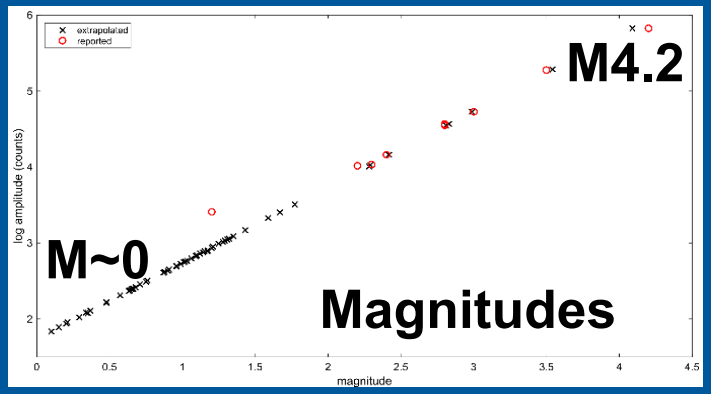
Data shown here are from the 1 Hz 3C seismometer at 290 m depth.

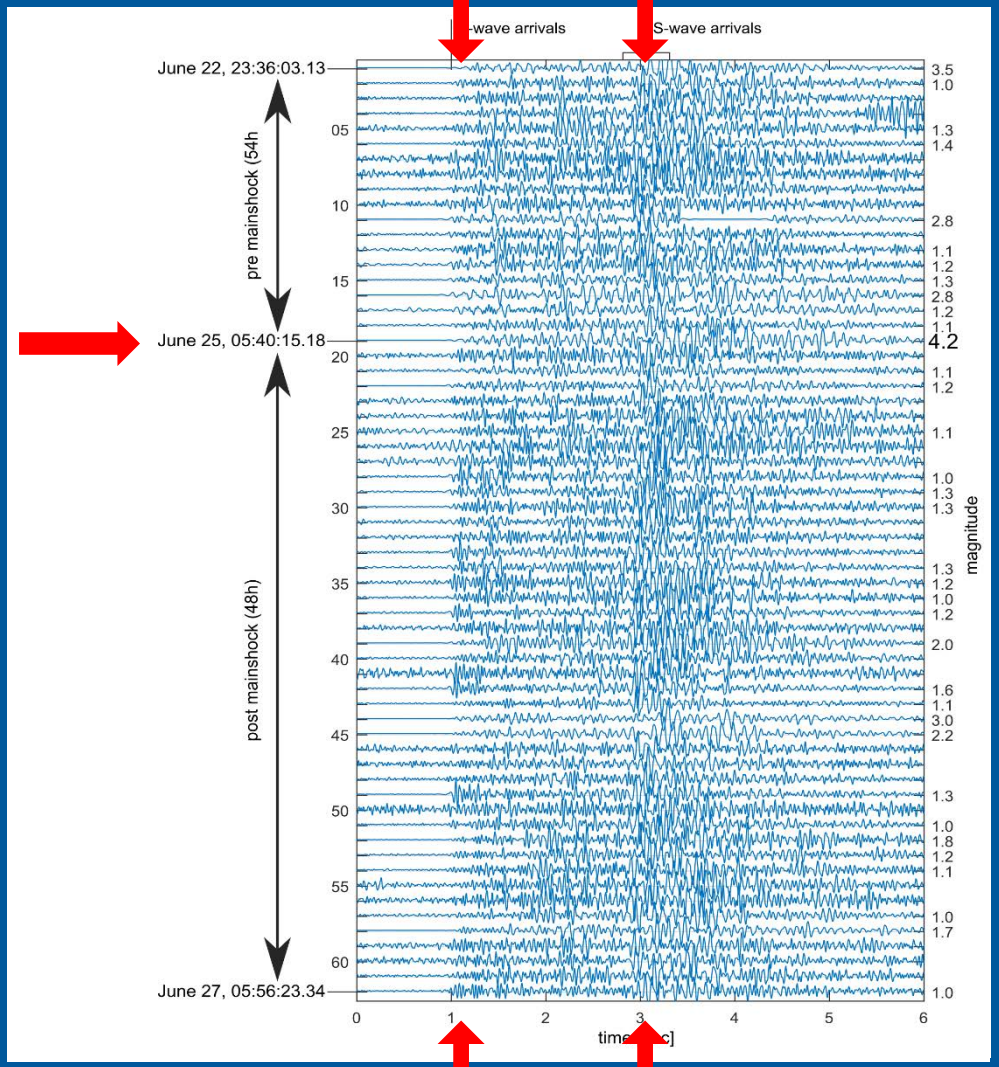
Entire 62-event sequence seen at GONAF-TESV

Vertical seismograms for all 62 events forming the seismic sequence framing the M_w4.2 mainshock.

Magnitudes extend down to ~M0, two orders of magnitude lower than the regional detection threshold.

All 62 events have similar S-P times of 2+/- 0.07 sec indicating the originate from the same fault patch that was activated by the mainshock.





Summary and Conclusions

- Large earthquakes along tectonic plate boundaries pose a substantial hazard and risk to ever growing population centers. Modern high-resolution seismic monitoring is a pre-requisite for state-of-the-art hazard assessment towards risk reduction. This is is particularily important in the Istanbul region where a M up to 7.4 event is expected in direct vicinity to the nearby population center.

- Intense research efforts are currently carried out to monitor the hazardous fault below the Sea of Marmara. These include near-fault surface and downhole seismic arrays to detect small-scale seismicity in order to better understand their physical processes as a proxy to better forecast the pending 'big one'.

- Microseismic data from the GONAF plate boundary observatory at the eastern Sea of Marmara indicate that the Princes Islands segment offshore Istanbul is currently locked and needs to be considered as a potential nucleation point for the M>7 event, just 20 km offshore Istanbul.

Thank you for your attention!