# Electromagnetic studies in the Eastern Mediterranean Region with Special Reference to Major Strike-slip Faults

## Faults and fluids: an essential combination for (major) earthquakes?

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EARTHQUAKE RESEARCH INSTITUTE

EMIW 2022
XXV ELECTROMAGNETIC INDUCTION WORKSHOP
11-17 September 2022
Grand Hotel Ontur Çeşme-Turkey

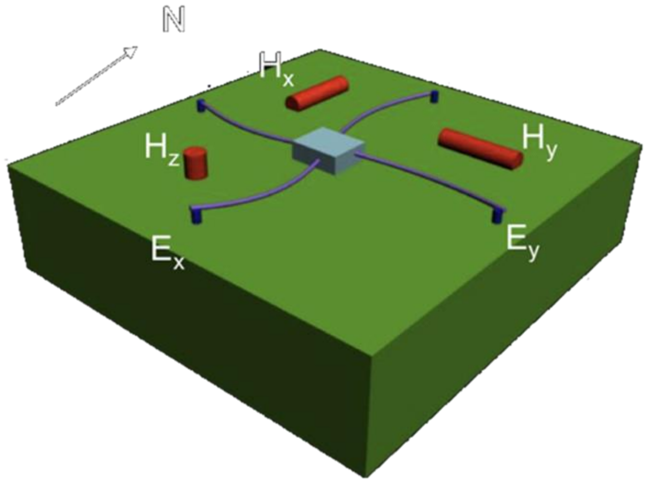
MTNet
Eminars


Türkoğlu, Kahramanmaraş prefecture, PC: TRT

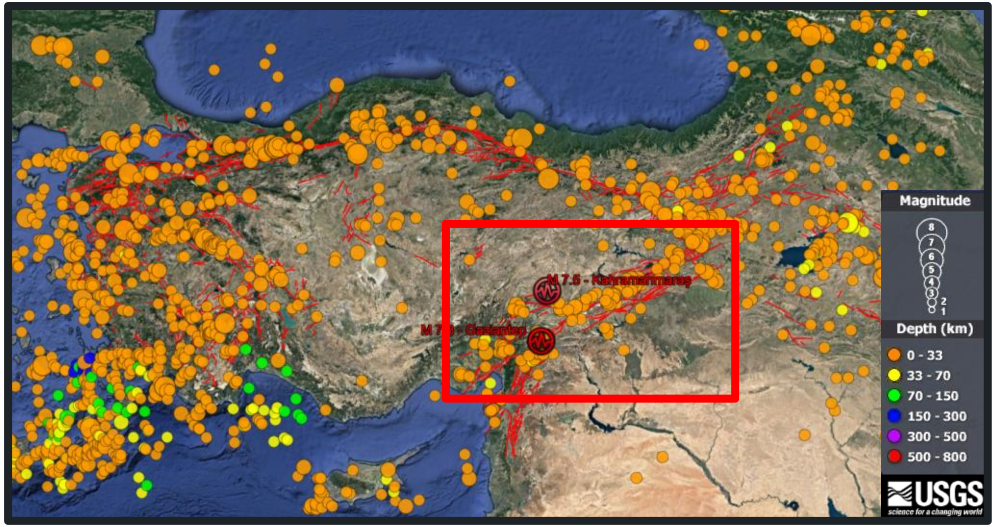

Tepehan, Hatay prefecture, PC: TRT

# Outline

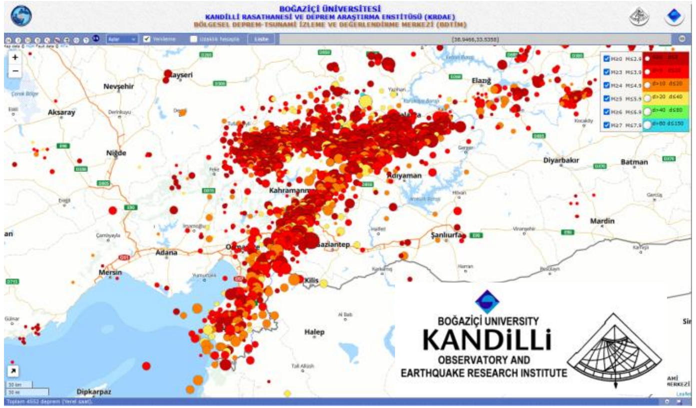
- Recent activity
  - 2023 Earthquakes
  - Coulomb stress maps
- (I) Strike-slip (transform) faults
  - Fault zone architecture and Earthquakes
  - EM studies on (strike-slip) faults:
    - Theory
    - Global examples:
      - Alpine Fault, New Zealand
      - San Andreas Fault, California, the USA
      - Atotsugawa Fault, Central Honshu, Japan
      - AltynDagh Fault, W. China
      - Phayao Fault, N. Thailand
      - Bogd, Trans Altai, Tienshan faults, Mongolia
- (II) Tectonics of the Study Area (Eastern Mediterranean)
- (III) EM on the major strike-slip faults in the Eastern Mediterranean
  - A collage of transform faults
  - Dead Sea Transform Fault
  - East Anatolian Fault
  - North Anatolian Fault
- (IV) Discussion
  - 2D vs 3D
  - Shallow structure
  - Deep structure
- (V) Conclusion
- Call for projects



# 2023 Earthquakes



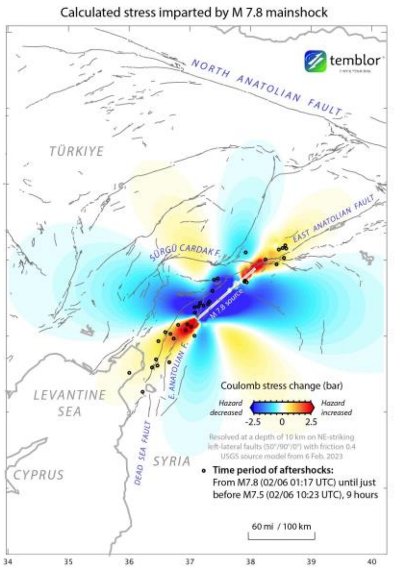

Earthquakes 1900 – 2023 (Source: USGS)

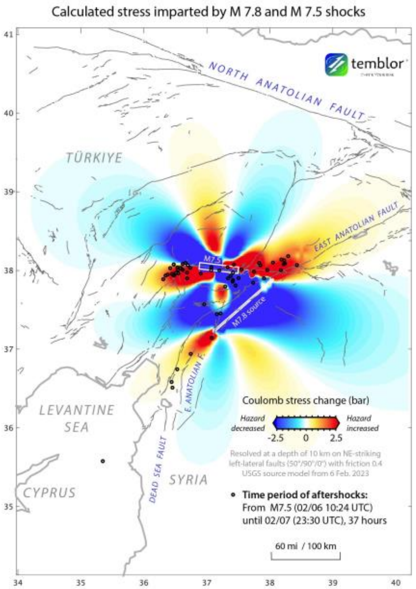



**Distributions of aftershocks (06.02.2023 – 13.02.2023)**

Kandilli Observatory And Earthquake Research Institute, Boğaziçi University. (1971). Bogazici University Kandilli Observatory And Earthquake Research Institute [Data set]. International Federation of Digital Seismograph Networks. https://doi.org/10.7914/SN/KO

# Coulomb Stress Change




Change in Shear Stress

Change in Normal Stress

$$\Delta\sigma_c = \Delta\tau_r - \mu(\Delta\sigma_n - \Delta p)$$

Coulomb Stress Failure

Friction coef.

Pore Fluid Pressure

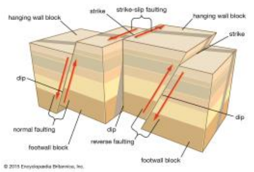
$$\Delta\sigma_c = \Delta\tau_r - \mu'(\Delta\sigma_n)$$

Effect of fluids

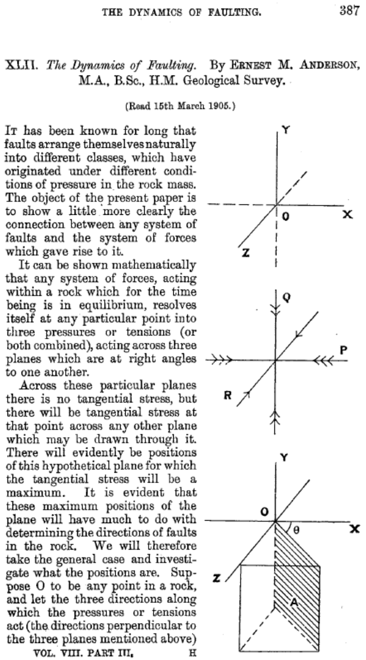
Scholtz, The Mechanics of Eq. and Faults, 2002
Beeler et al., JGR, 2000

**Toda, S., Stein, R. S., Özbakir, A. D., Gonzalez-Huizar, H., Sevilgen, V., Lotto, G., and Sevilgen, S., 2022, Stress change calculations provide clues to aftershocks in 2023 Türkiye earthquakes, Temblor, http://doi.org/10.32858/temblor.295**

# Faults: Zones Of Deformed Rock




## Transform (strike-slip) Faults:


THE DYNAMICS OF FAULTING. 387

XLII. *The Dynamics of Faulting.* By ERNEST M. ANDERSON, M.A., B.Sc., H.M. Geological Survey.

(Read 15th March 1905.)

It has been known for long that faults arrange themselves naturally into different classes, which have originated under different conditions of pressure in the rock mass. The object of the present paper is to show a little more clearly the connection between any system of faults and the system of forces which gave rise to it.

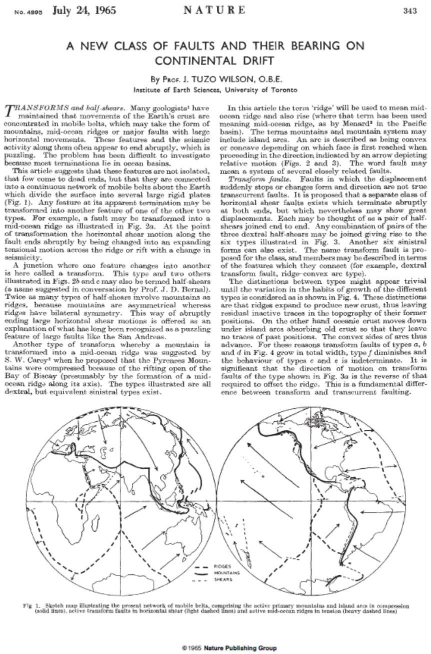
It can be shown mathematically that any system of forces, acting within a rock which for the time being is in equilibrium, resolves itself at any particular point into three pressures or tensions (or both combined), acting across three planes which are at right angles to one another.

Across these particular planes there is no tangential stress, but there will be tangential stress at that point across any other plane which may be drawn through it. There will evidently be positions of this hypothetical plane for which the tangential stress will be a maximum. It is evident that these maximum positions of the plane will have much to do with determining the directions of faults in the rock. We will therefore take the general case and investigate what the positions are. Suppose O to be any point in a rock, and let the three directions along which the pressures or tensions act (the directions perpendicular to the three planes mentioned above)

VOL. VIII. PART III. H



Anderson, Lyell Coll. (1905)


No. 4995 July 24, 1965 NATURE 343

A NEW CLASS OF FAULTS AND THEIR BEARING ON CONTINENTAL DRIFT

By PROF. J. TUZO WILSON, O.B.E.

Institute of Earth Sciences, University of Toronto



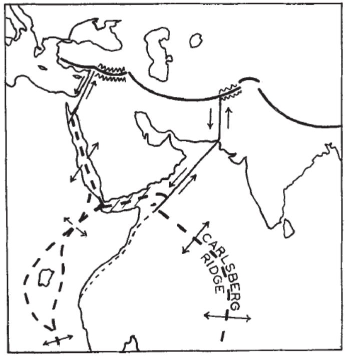
Fig. 1. Sketch map illustrating the present network of mobile belts, comprising the active primary mountains and island arcs in compression (solid lines), active transform faults in horizontal shear (light dashed lines) and active mid-ocean ridges in tension (heavy dashed lines)

© 1965 Nature Publishing Group

Wilson, Nature (1965) – Transform Faults

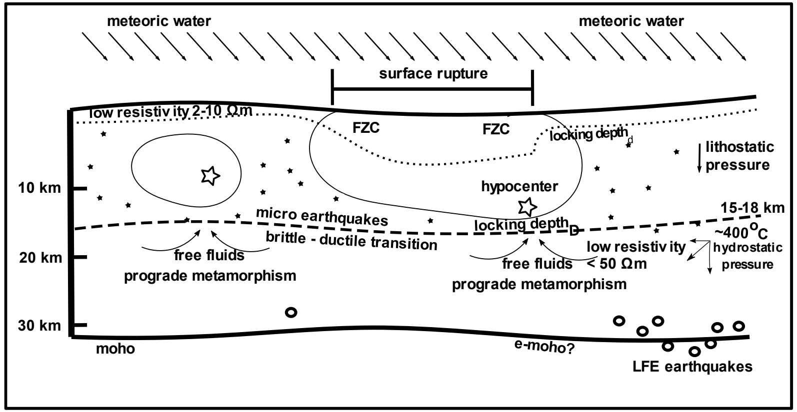
"A transform fault is a strike-slip fault cutting the lithosphere and connecting two zones of divergent or convergent deformation or even another transform fault."

**Şengör et al., Tr. Plate Boun. & Fract. Zones, (2019)**

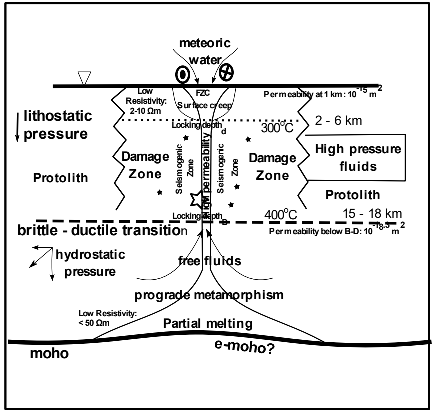


# Fault Zone Architecture – Continental Seismogenic Zone

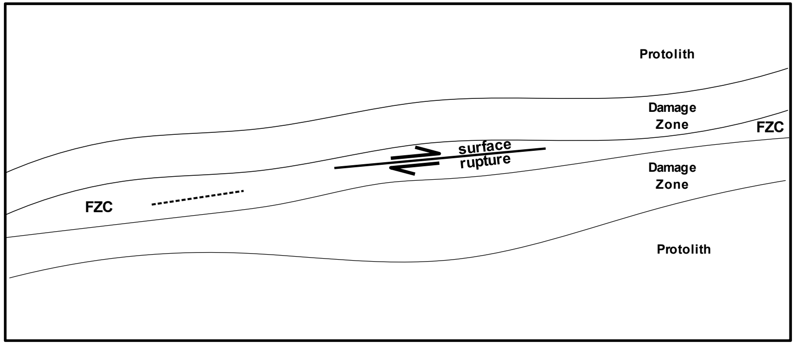
**A. Along**




**B. Across**




**C. Mapview**




Caine et al., GRL, 1996
Eberhart-Phillips et al., JGR, 1996
Unsworth et al., Geology, 1997
Becken et al., GJI, 2008
Wibberley et al., Geo.Soc.SP, 2008
Wannamaker et al., Nature, 2009
Sibson, Geo.Soc.SP, 2011
Jones, Tectonophysics 2013
Sibson et al., Pure and App. Geophys. 2014
Meqbel et al., GJI, 2016
Karaş et al., Tectonophysics, 2020

**Earthquake occurrence**

Mechanical weakening

Pressure build – up/Reduction of shear stress

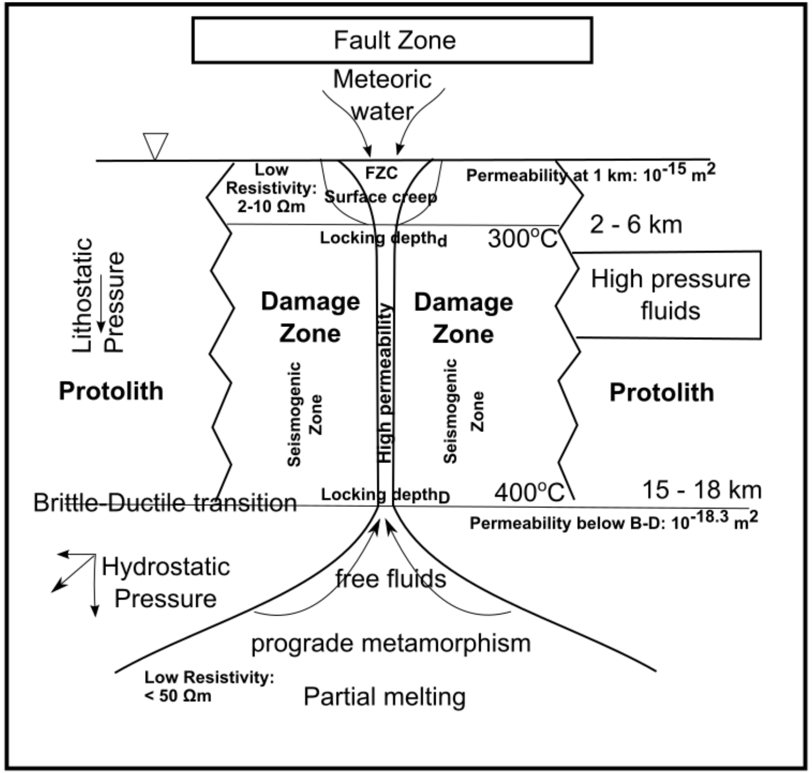
Lubrication – talc/clay

Hydrofracturing and chemical dissolution
Retrograde metamorphism – hydration

Seismic pumping – Fault valve model

Dehydration – free fluids

Prograde metamorphism



# Early EM studies on (strike-slip) faults - Theory

30's
The telluric method


Schelkunoff,
Bell systems, 1938

**The Impedance Concept and Its Application to Problems of Reflection, Refraction, Shielding and Power Absorption**

By S. A. SCHELKUNOFF

This paper calls attention to the practical value of a more extended use of the impedance concept. It brings out a certain underlying unity in what otherwise appear diverse physical phenomena. Although an attempt has been made to trace the history of the concept of "impedance" and many interesting early suggestions have been found, reference to these lies beyond the scope of this paper. Apparently, Sir Oliver Lodge was the first to use the word "impedance," but the concept has been developed gradually as circumstances demanded through the efforts of countless workers.

The main body of the paper is divided into three parts: Part I, dealing with the exposition of the impedance idea as applied to different types of physical phenomena; Part II, in which the general formulæ are deduced for reflection and transmission coefficients; Part III, presenting some special applications illustrating the practical utility of the foregoing manner of thought.

Rikitake, 1948, Tikhonov,1950
Cagniard, Geophysics, 1953

BASIC THEORY OF THE MAGNETO-TELLURIC METHOD OF GEOPHYSICAL PROSPECTING*†‡

LOUIS CAGNIARD§

ABSTRACT

From Ampere's Law (for a homogeneous earth) and from Maxwell's equations using the concept of Hertz vectors (for a multilayered earth), solutions are obtained for the horizontal components of the electric and magnetic fields at the surface due to telluric currents in the earth. The ratio of these horizontal components, together with their relative phases, is diagnostic of the structure and true resistivities of subsurface strata. The ratios of certain other pairs of electromagnetic elements are similarly diagnostic.

Normally, a magneto-telluric sounding is represented by curves of the apparent resistivity and the phase difference at a given station plotted as functions of the period of the various telluric current components. Specific formulae are derived for the resistivities, depths to interfaces, etc. in both the two- and three-layer problems.

For two sections which are geometrically similar and whose corresponding resistivities differ only by a linear factor, the phase relationships are the same and the apparent resistivities differ by the same proportionality constant which relates the corresponding true resistivities. This "principle of similitude" greatly simplifies the representation of a master set of curves, such as is given for use in geologic interpretation.

In addition to the usual advantages offered by the use of telluric currents (no need for current sources or long cables, greater depths of investigation, etc.), the magneto-telluric method of prospecting resolves the effects of individual beds better than do conventional resistivity methods. It seems to be an ideal tool for the initial investigation of large sedimentary basins with potential petroleum reserves.

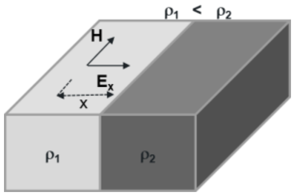
Wait, Geophysics, 1954

ON THE RELATION BETWEEN TELLURIC CURRENTS AND THE EARTH'S MAGNETIC FIELD*

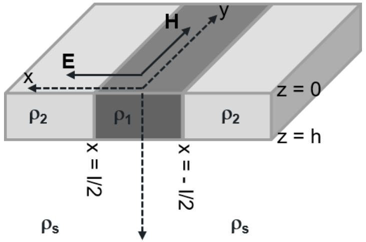
JAMES R. WAIT†

ABSTRACT

The validity of Cagniard's analysis of the behaviour of telluric earth currents is questioned in view of the fact that the harmonic components of the electric field and the magnetic field tangential to the ground are only proportional to one another if the fields are sufficiently slowly varying over the surface of the ground. His result is extended to include the effects of a layered ground with both conductivity and susceptibility variations. Finally the corresponding transient problem is solved for a two-layer horizontally stratified earth.


**d'Erceville and Kunetz,**
**Effect of a fault on the Earth's natural EM field,**
**1962**


**Rankin,**
**Magnetotelluric effect on a dike,**
**1962**

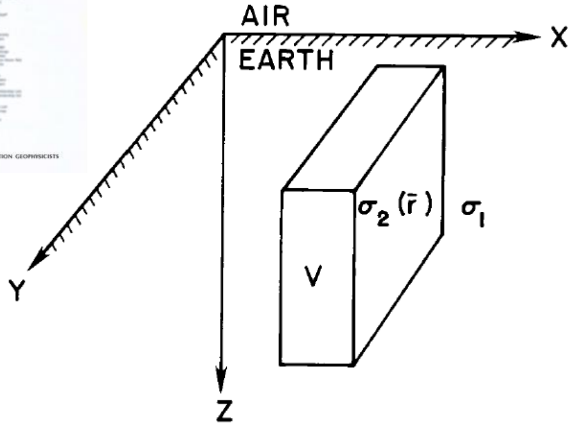

**Weaver,**
**Discussion,**
**1963**

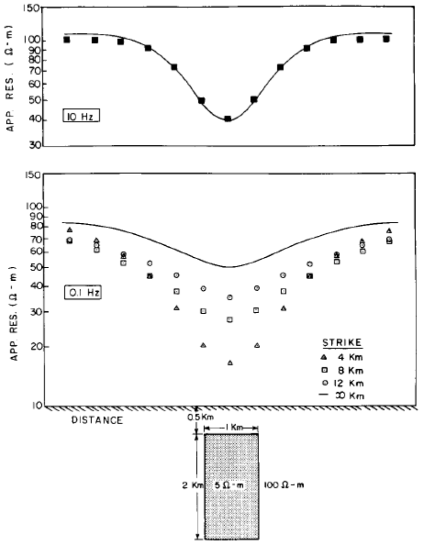
**Replies by:**
- **d'Erceville and Kunetz (1963)**
- **Rankin (1963)**

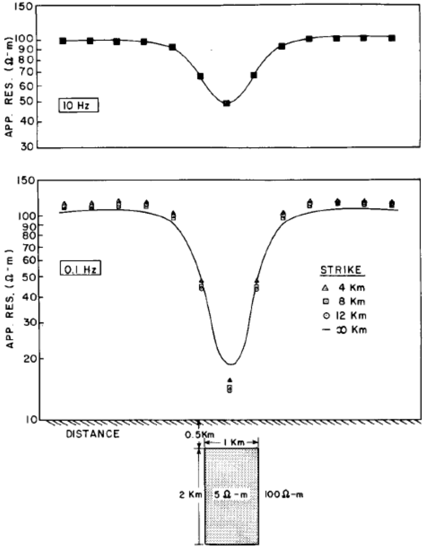
**"It seems therefore, that some caution must be exercised in trying to apply the theoretical solutions for the "fault" and "dike" models to a practical situation."**

# Early EM studies on (strike-slip) faults - Theory

## Integral equation modeling of three-dimensional magnetotelluric response

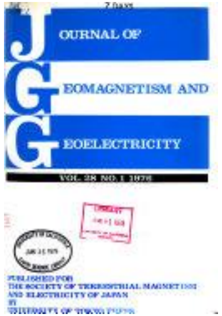



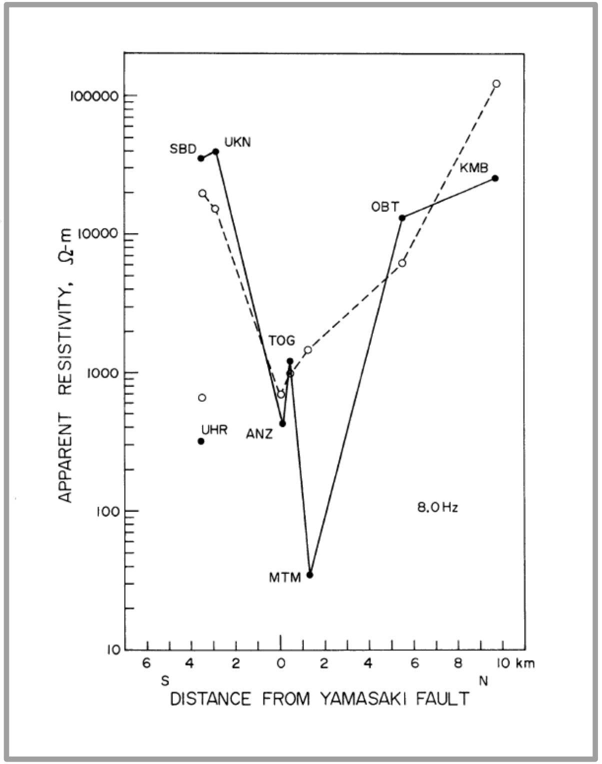



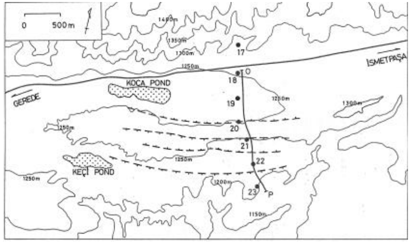

**Ting and Hohmann, Geophysics, 1981**

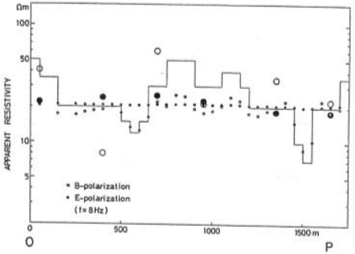
# Early EM studies on (strike-slip) faults - Practical




- Reddy et al., JGG, 1976 – SAF
- Lienert et al., JGG 1980 - SAF
- EM Research Group of the Active Fault, JGG, 1982 - Yamasaki F.

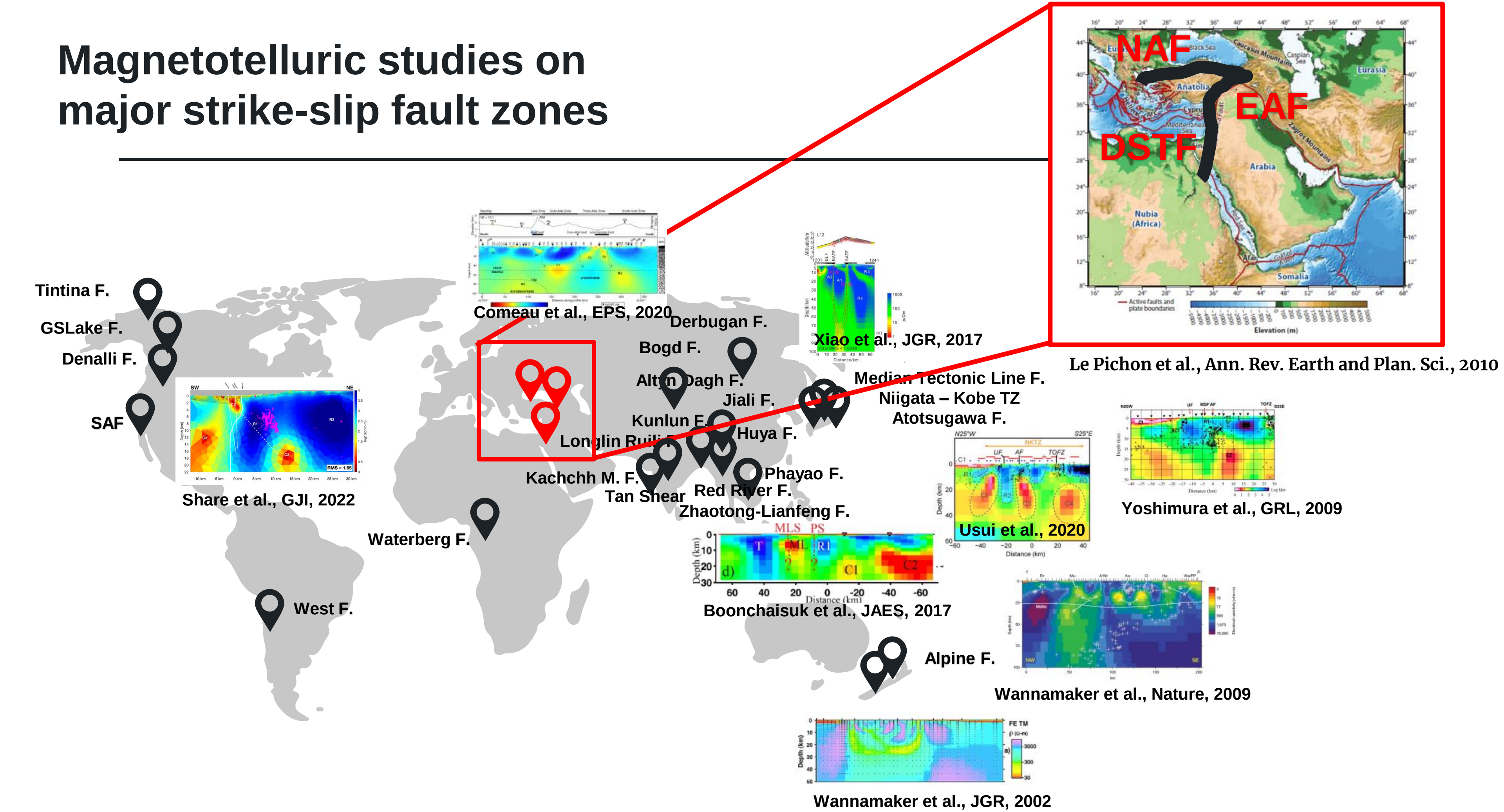


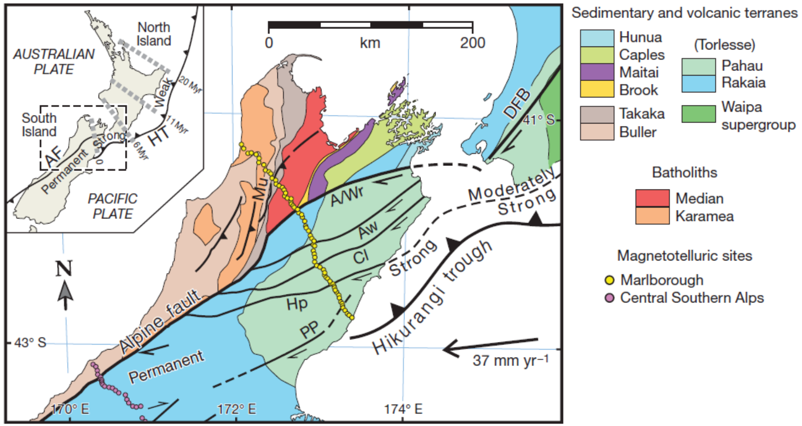

**Honkura et al., Tech. paper by Titech and İstanbul Uni., 1986**

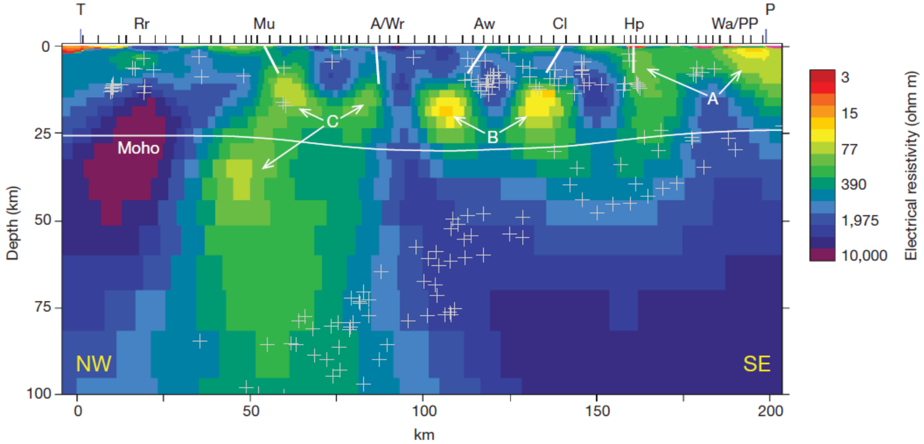
# Magnetotelluric studies on major strike-slip fault zones



MTNet Eminars

# Alpine Fault, New Zealand (2D)

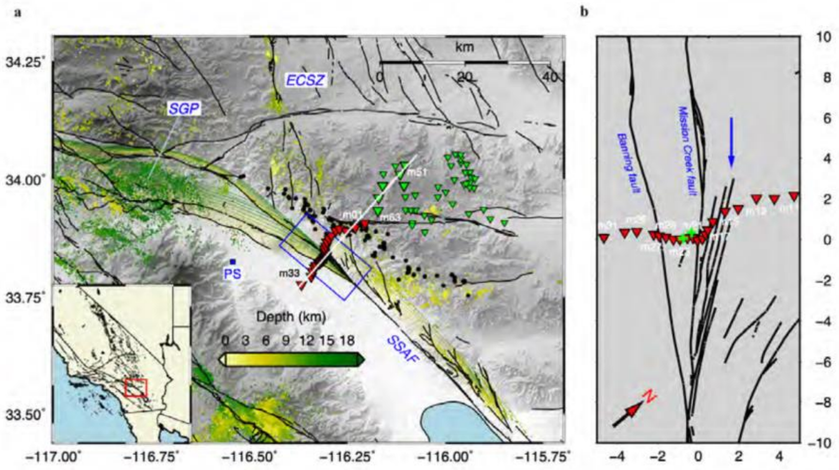


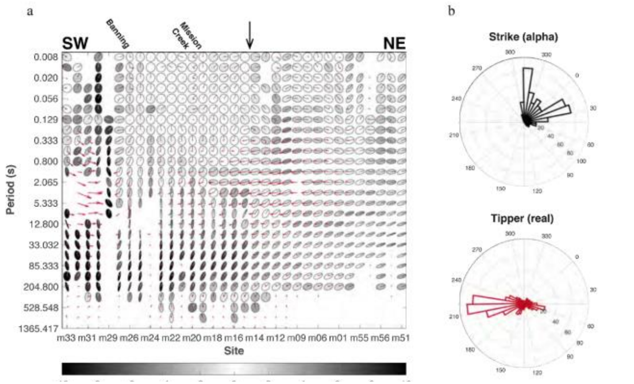

**Wannamaker et al., Nature, 2009**

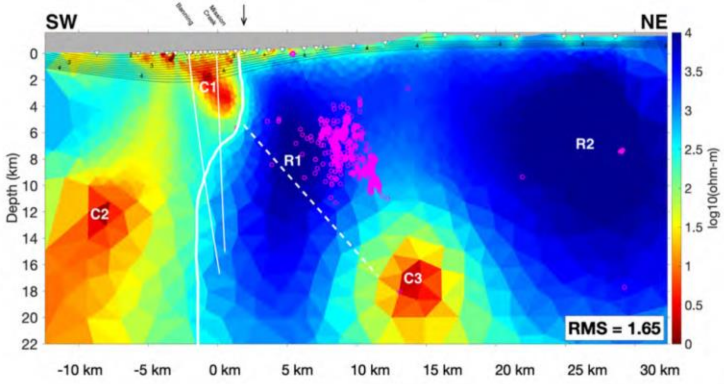
Global examples 2:

# Southern San Andreas Fault, California, the USA (2D & 3D)



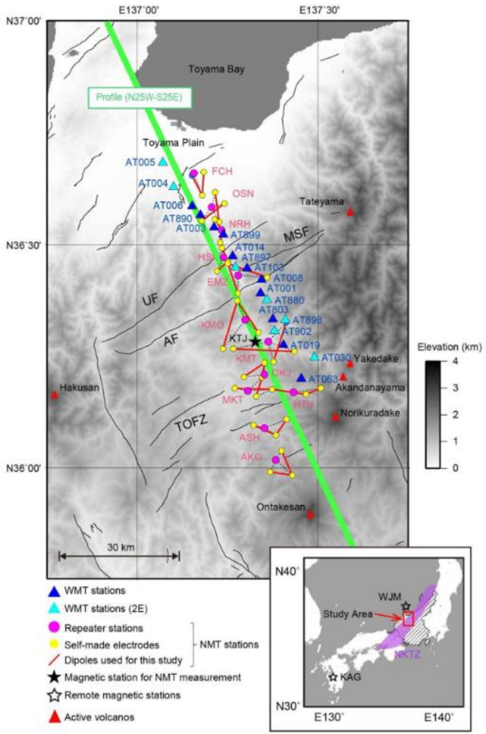

Share et al., GJI, 2022



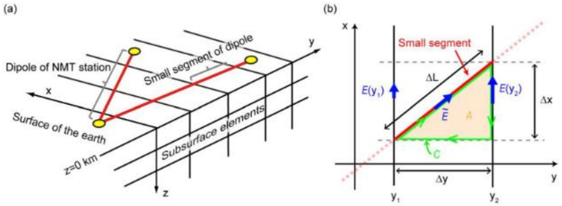



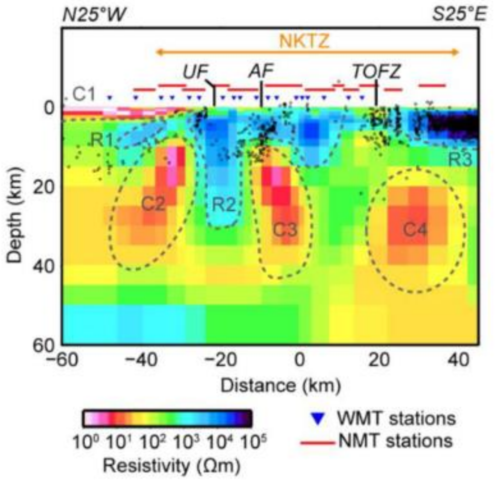
Global examples 3:

# Atotsugawa Fault, Central Honshu, Japan (2D)




Usui et al., JGR, 2020

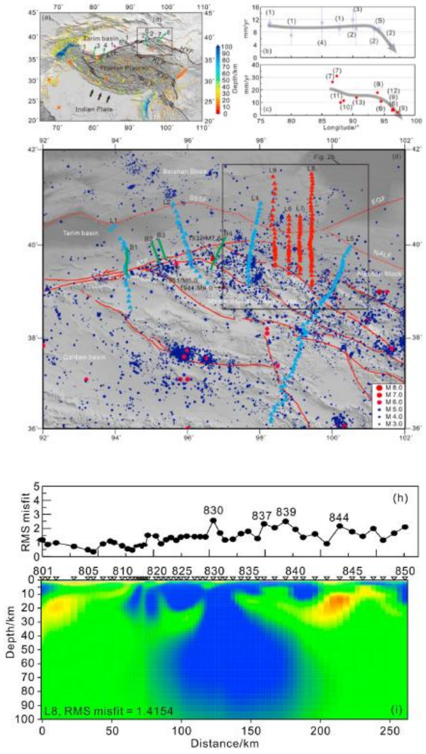


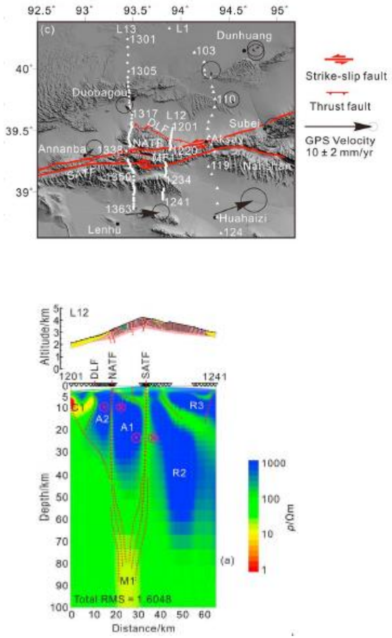

**Wideband MT**
**Wideband MT + Network MT**
**2D by Ogawa and Uchida, GJI, 1996**

Global examples 4:

# Altyndagh Fault, NW China (2D and 3D)



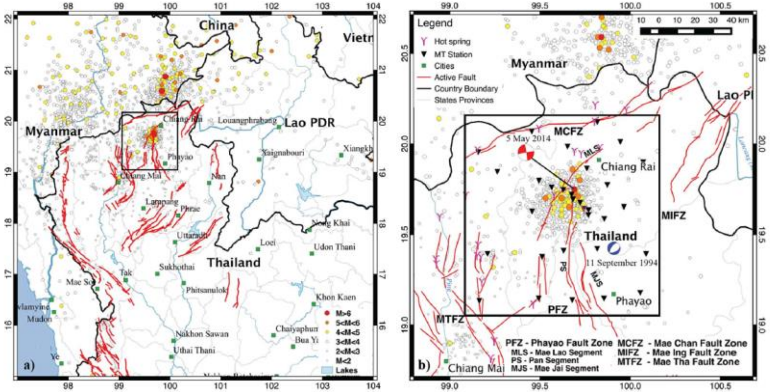

Xiao et al., JGR, 2015



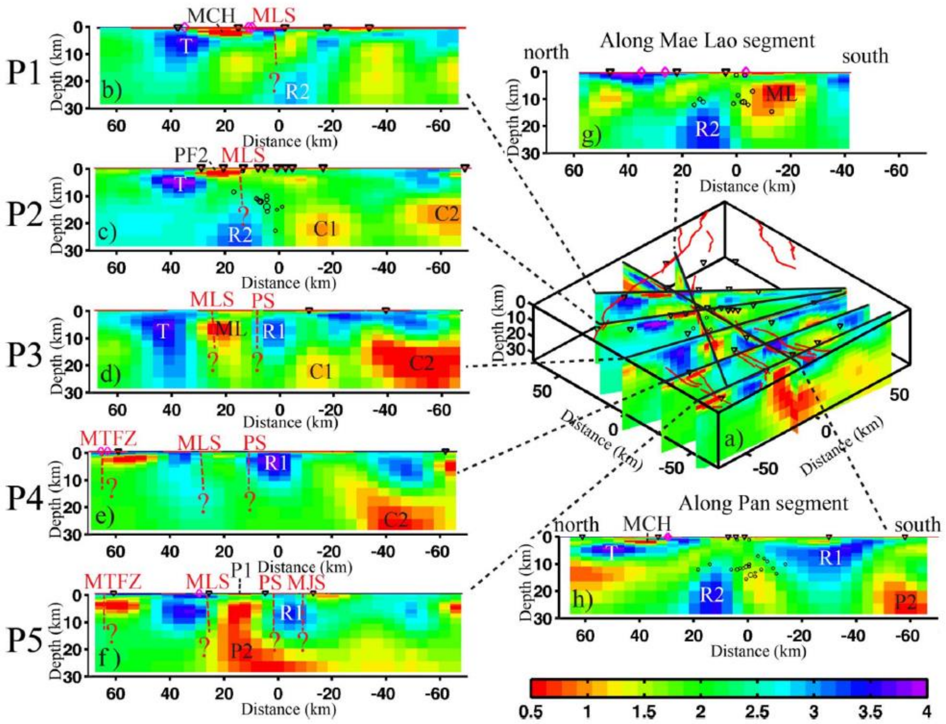

Xiao et al., GRL, 2017

Global examples 5:

# Phayao Fault Zone, N.Thailand (3D)

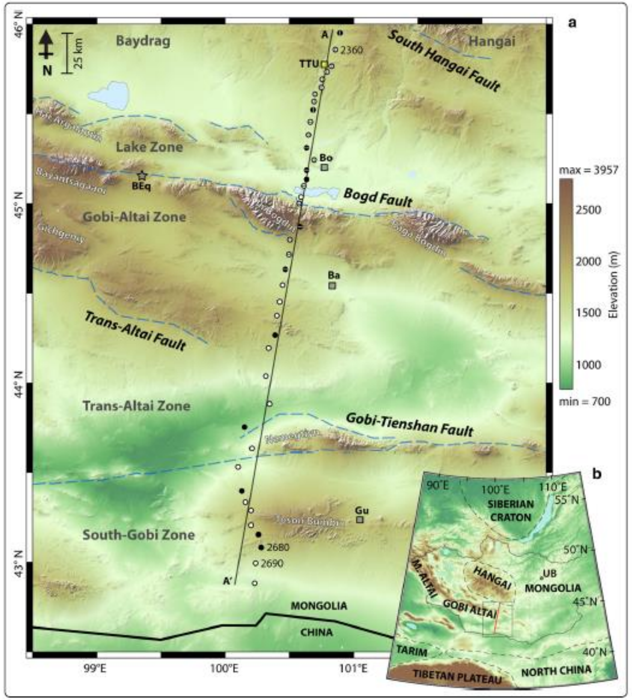


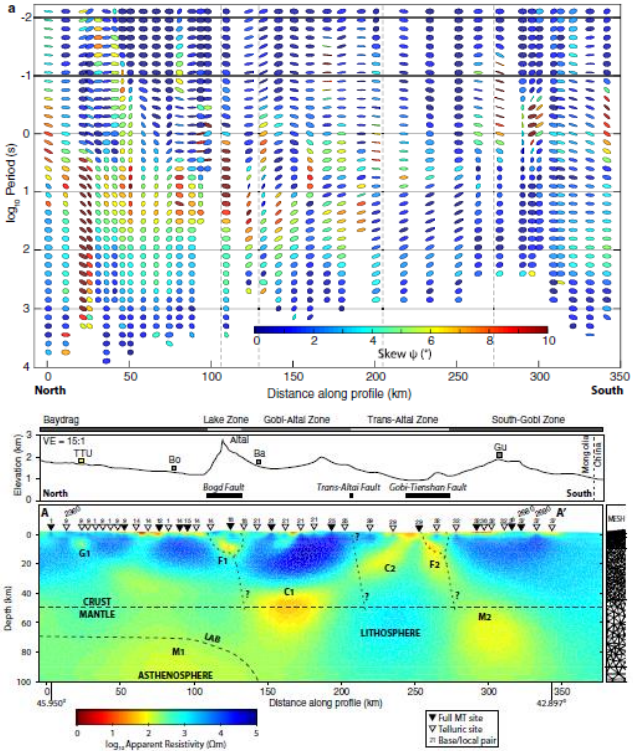

**Boonchaisuk et al., JAES, 2017**



Global examples 6:

# Bogd – Trans Altai – Gobi Tienshan faults, Mongolia (2D)



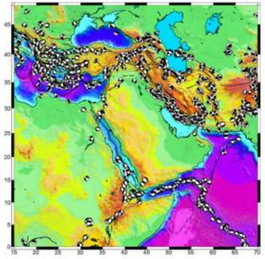




MARE2DEM
39 sites
39 frequencies
TM+TE
300 Ohmm initial model

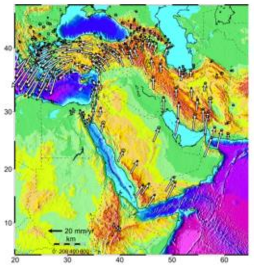
**Comeau et al., EPS, 2020**

# Eastern Mediterranean - Tectonics

1. Arabian Promontory
2. East Anatolian Contractional Province
3. North Anatolian Province (Pontides)
4. Central Anatolian “Ova” Province
5. West Anatolian Extensional Province

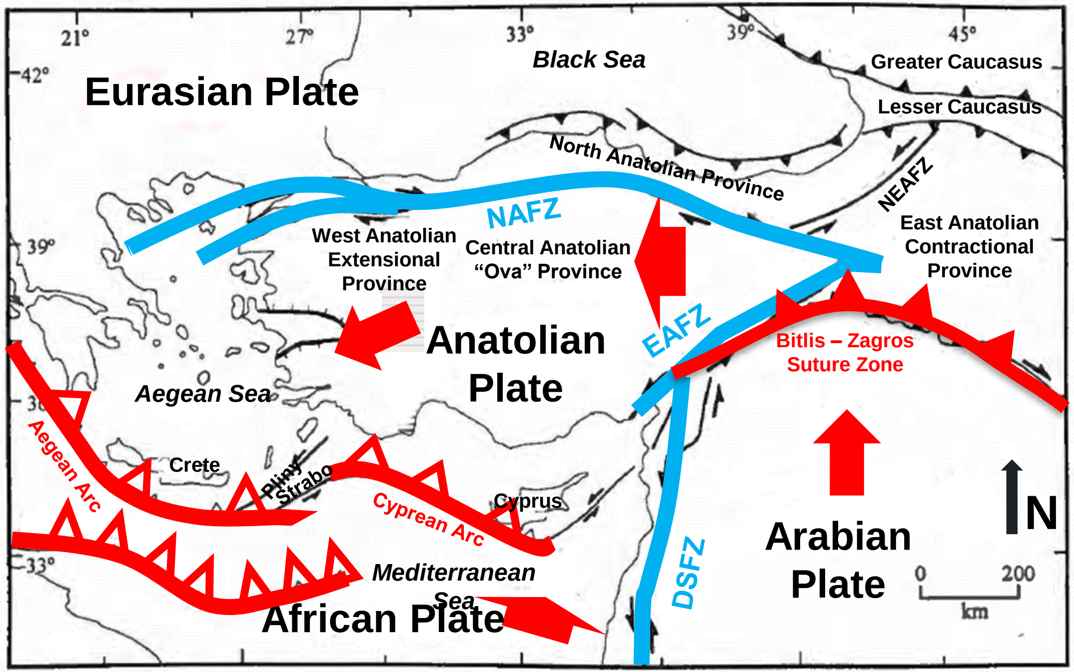


Focal Mechanisms
1976 – 2005 Harvard Catalog




Decimated GPS velocities relative to Eurasia


Slip rates

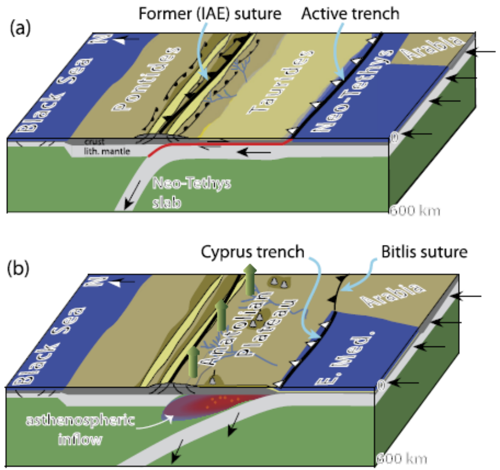



Reilinger et al., JGR, 2006

Bozkurt, GeoActa, 2001
Şengör et al., SEPM Society for Sedimentary Geology, 1985

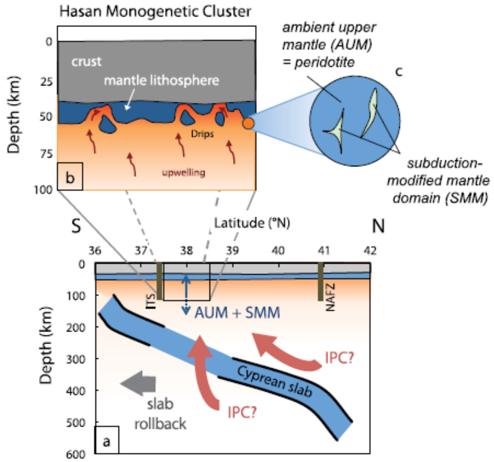
# Tectonic models

### Delamination



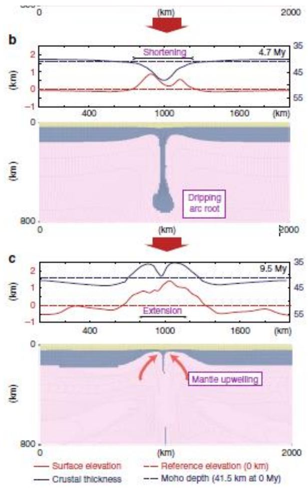

Govers and Fichtner, EPSL, 2016;
Bartol and Govers, Tectonophysics, 2014

### Delamination and drip

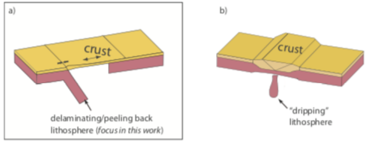



Reid et al., G-cubed, 2017

### Drip tectonics

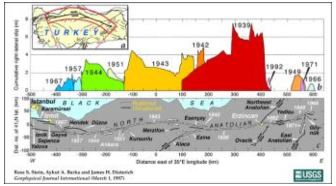


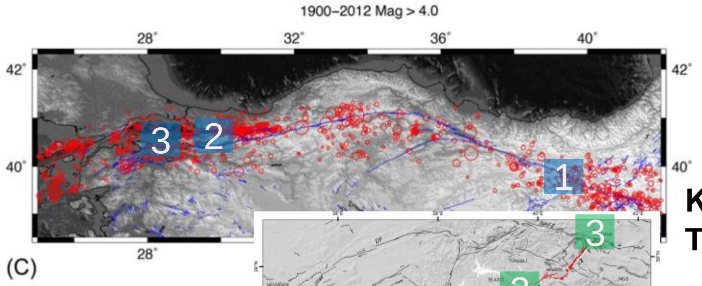

Göğüş et al., Nature Comm., 2018

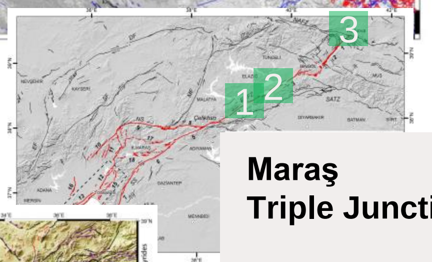



Göğüş and Ueda, JDyn, 2018

# A collage of transform faults:
# Dead Sea Transform – East and North Anatolian Faults



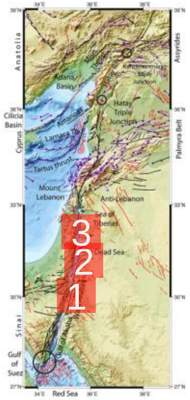


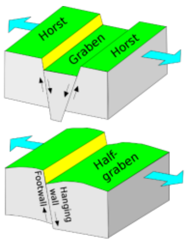

Karlıova
Triple Junction

Maraş
Triple Junction

Ben-Avraham et al., 2008
Division of DSTF
At 33°10′N




Hatay
Triple
Junction




**NAF: ~ 1500 km**
- Dextral - 85 km
- Westward progression of eqs.
  - 7.4 İzmit eq 1999
  - 7.2 Düzce eq 1999

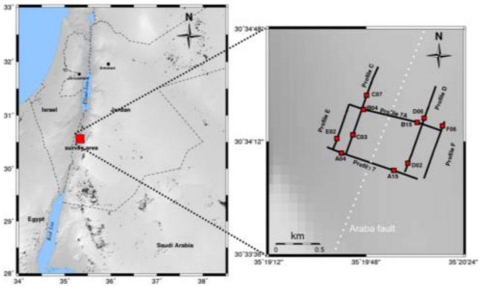
**EAF: ~ 500 km**
- Sinistral - 22 km
  - 6.3 Adana-Ceyhan eq. 1998
  - 6.4 Bingöl eq. 2004
  - 6.7 Elazığ eq. 2020
  - 7.7 Gaziantep eq. 2023
  - 7.6 Kahramanmaraş eq. 2023

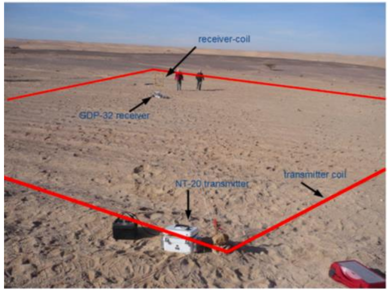
**DSTF: ~ 1000 km**
- North and south parts
- Sinistral – 100 - 107 km
  - 7.3 Aqaba eq. 1995

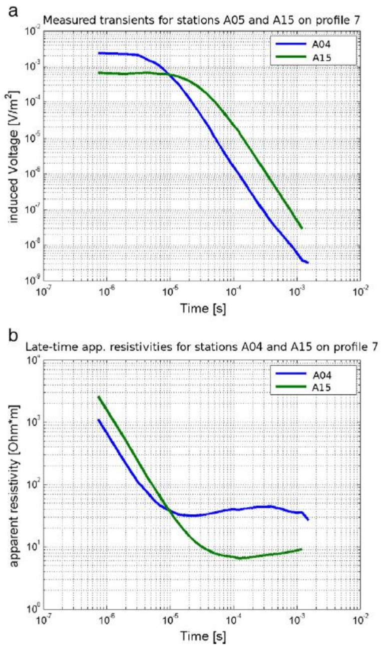
Şengör et al., Continental Transform Faults, 2019
Duman et al., Med. Geosci. Rev, 2020

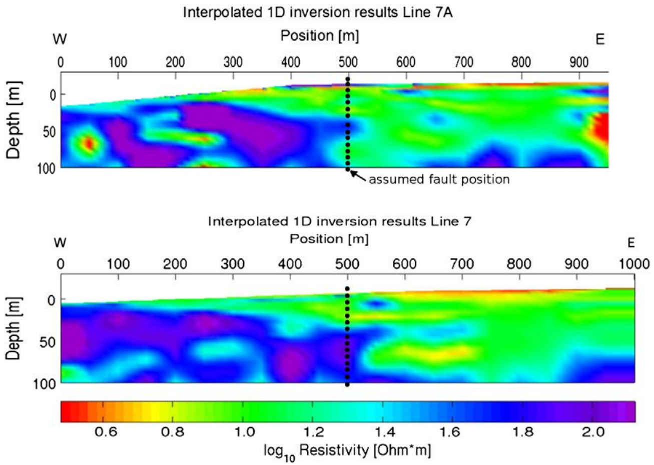
# Dead Sea Transform Fault (DSTF) (1D)

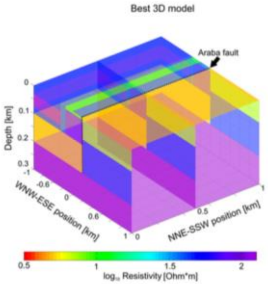
## Avara/Araba Fault - Short-Offset Transient Electromagnetics (SHOTEM)

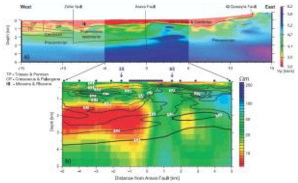


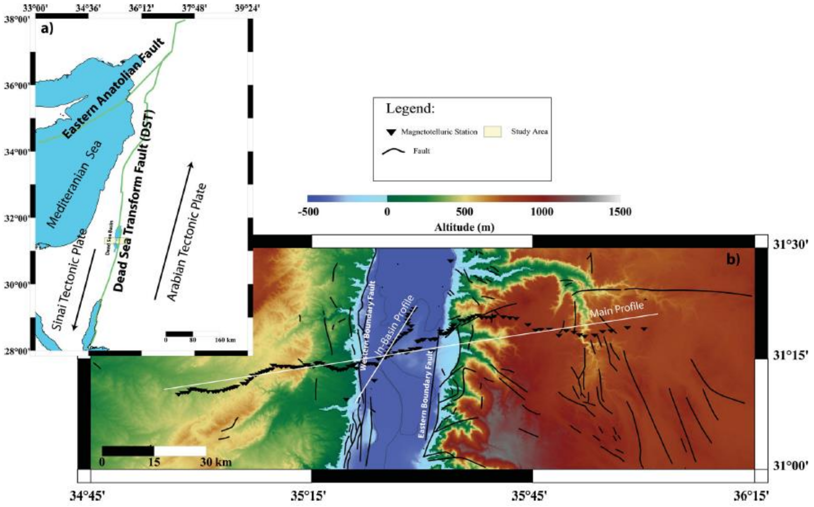
- 72 inloop soundings
- 6 profiles in varying length and orientations
- 50 m site separation
- 1D Occam – Marquardt inversions
- 2D and 3D fwd models

Ritter et al., GRL, 2003

Rödder and Tezkan, Journ. App. Geophys., (2013)

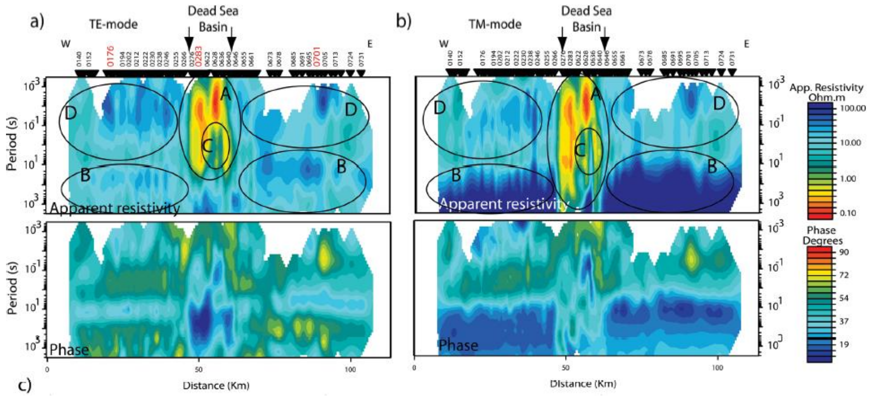
# Dead Sea Transform Fault (DSTF) (2D) and 3D

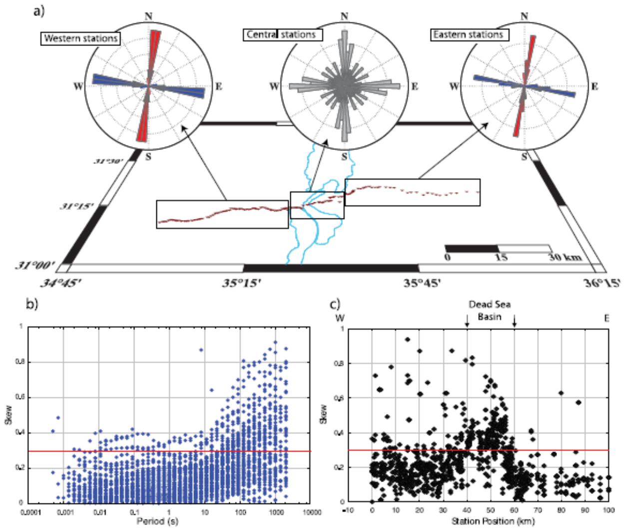
## Dead Sea Basin - DESIRE project




153 observations (94 main p. + 59 auxiliary p.)
3 days recording at each site
2 teams and 30 instruments
Main profile length: 110 km
2nd profile length: 20 km
Site separation: 0.5 – 2 km

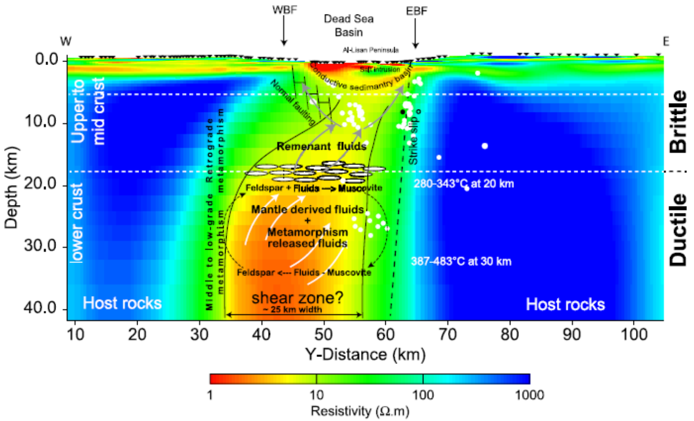
Meqbel et al., GJI, 2013



# Dead Sea Basin - DESIRE project

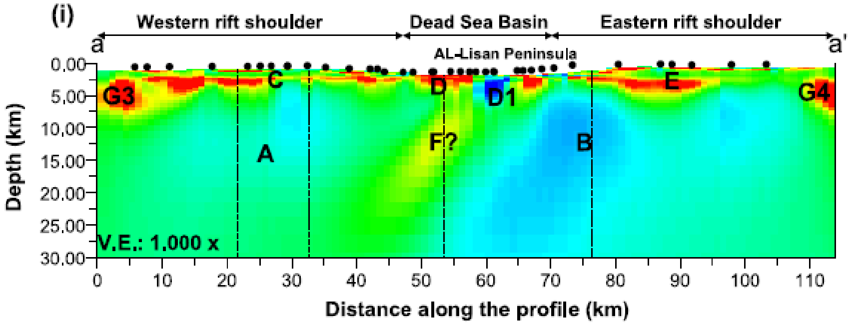
(2D)




Meqbel et al., GJI, 2013

Remote reference
N12 E strike angle
2D
Rodi and Mackie (2001) - WinGLink - FD - NLCG
248 x 127 cells
1000 % error floor for TE Rhoa (to deal with static shifts)
5 % error floor for TM rhoa
0.6 error floor for both phase
0.03 error floor for Hz
RMS: 12.5 to 1.81 in 2000 iterations

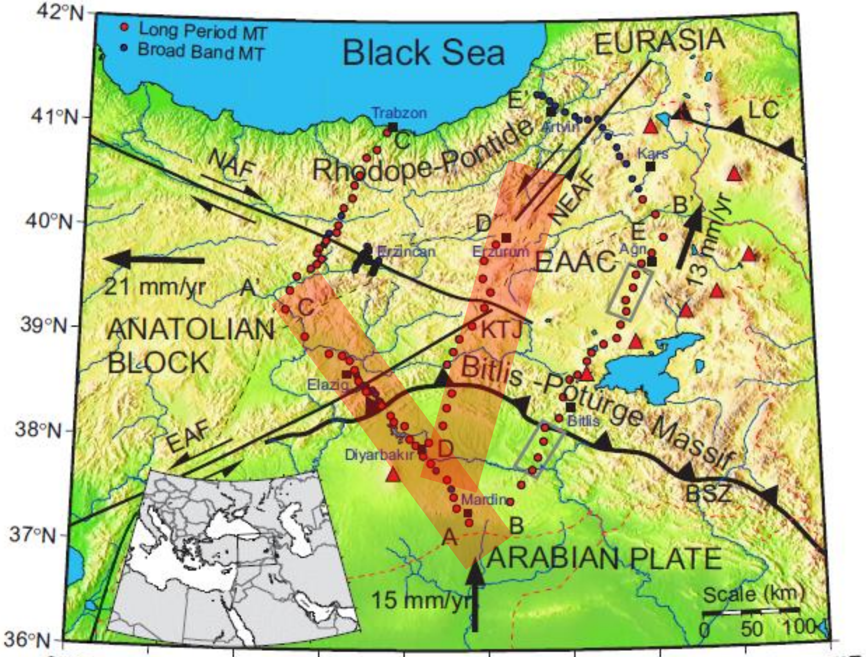
(3D)



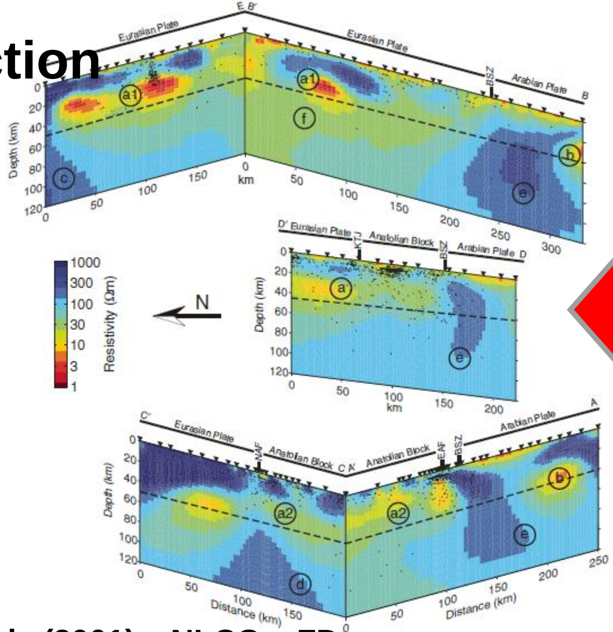

Meqbel et al., GJI, 2016

3D
ModEM
NLCG – FD
Nested mesh modeling
1st 70 x 70 (coarse grid)
100 layers including topography and air
20 periods
Error floor 5 %

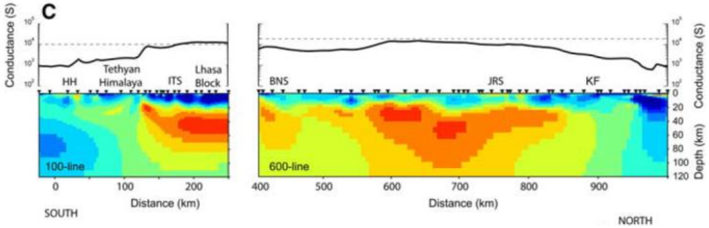
# East Anatolian Fault (2D)
# Elazığ segment and Karlıova Triple Junction
## Long period + Wideband




Türkoğlu et al., Geology, 2008



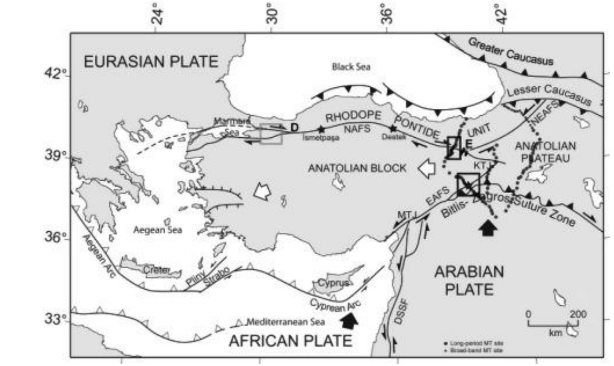

Rodi and Mackie (2001) – NLCG – FD
TE + TM + Tipper

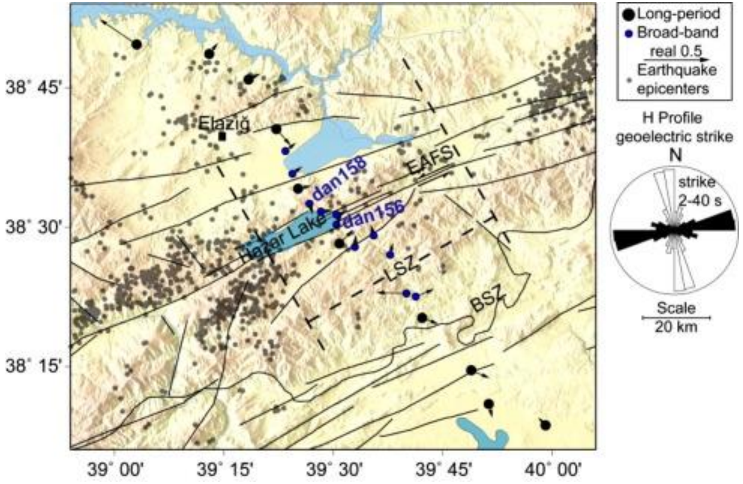


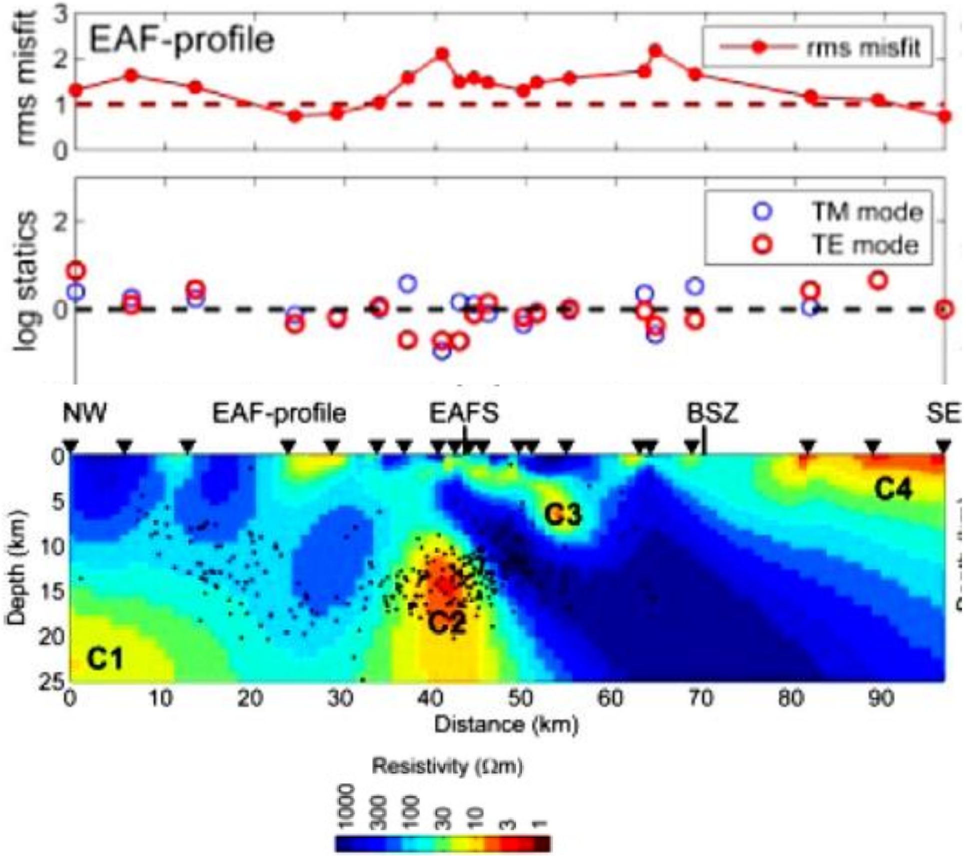

Unsworth., Surveys in Geophysics, 2010

# East Anatolian Fault (2D)

## Elazığ Segment



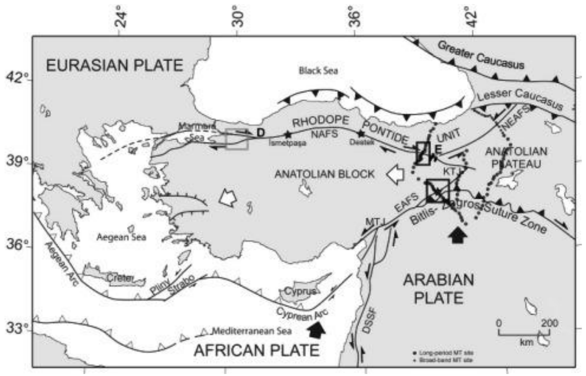



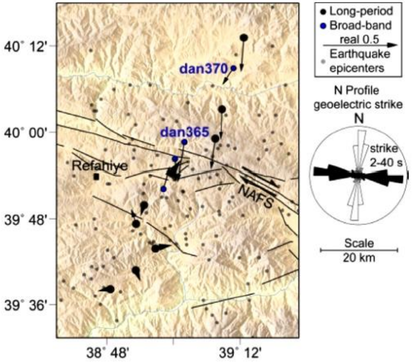



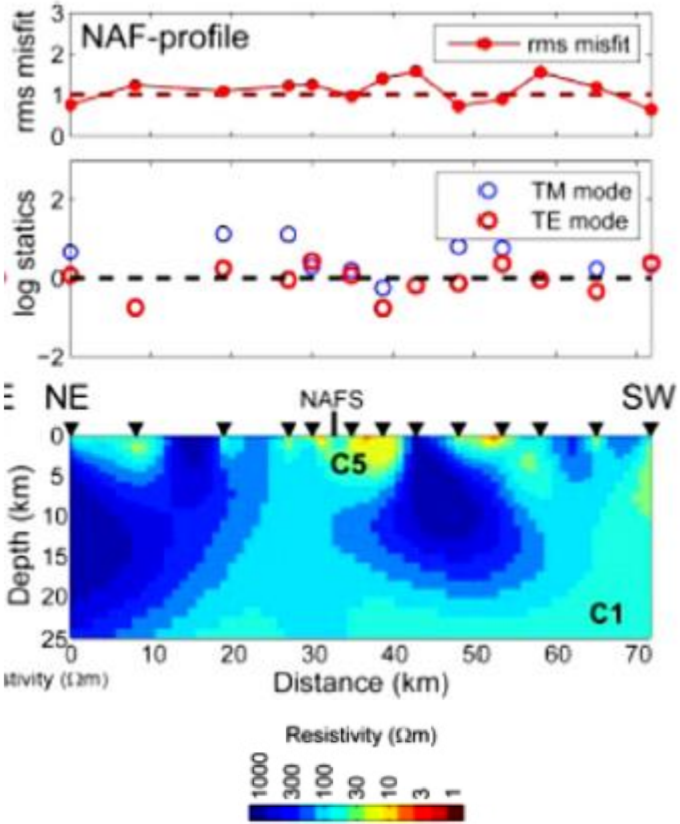

**Türkoğlu et al., PEPI, 2015**

# North Anatolain Fault (East) (2D)

## Erzincan segment



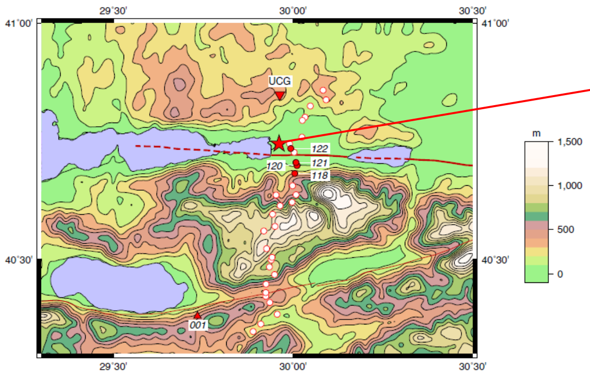



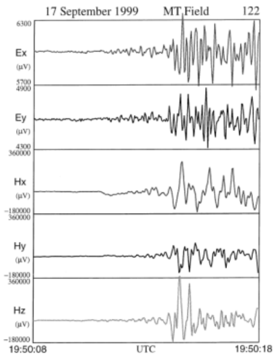

**Türkoğlu et al., PEPI, 2015**

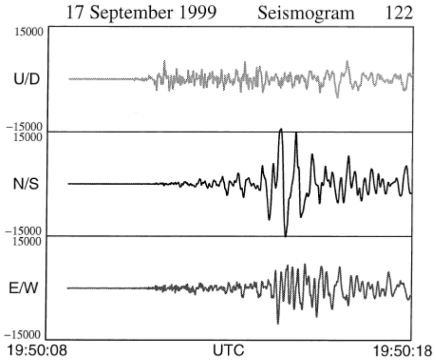
# North Anatolian Fault (West)

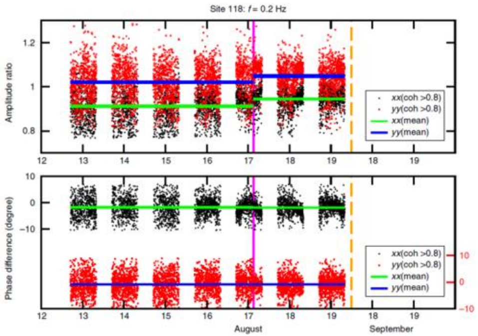
## 1999 İzmit Earthquake data

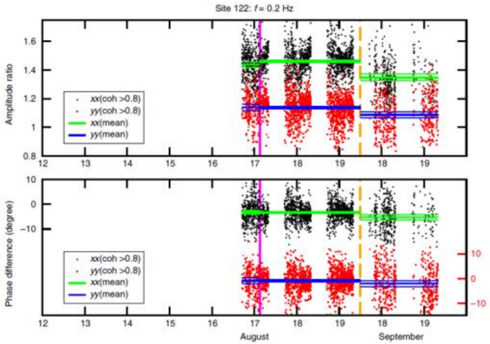



**17 August 1999 İzmit Earthquake**
**M: 7.4**



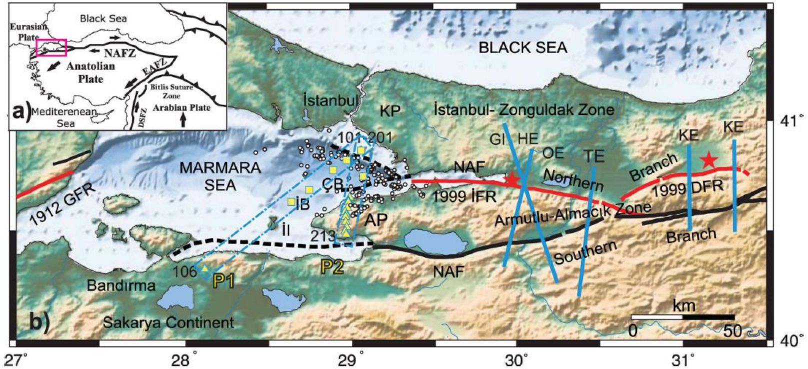




**Honkura et al., Nature Communications, 2013**

MTNet Eminars

# North Anatolian Fault (West) (2D)

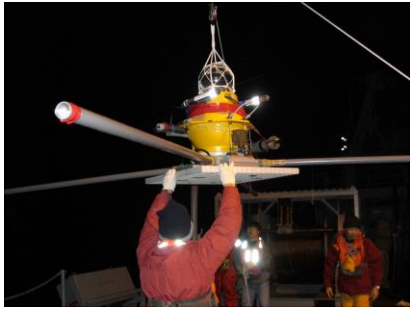
## Marmara Sea – OBEM




東京工業大学
Tokyo Institute of Technology

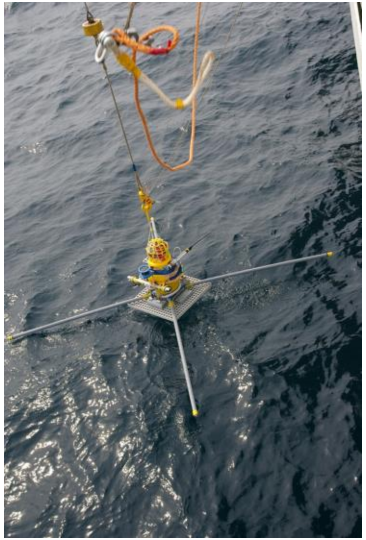
BOĞAZİÇİ UNIVERSITY
KANDİLLİ
OBSERVATORY AND
EARTHQUAKE RESEARCH INSTITUTE

JAMSTEC



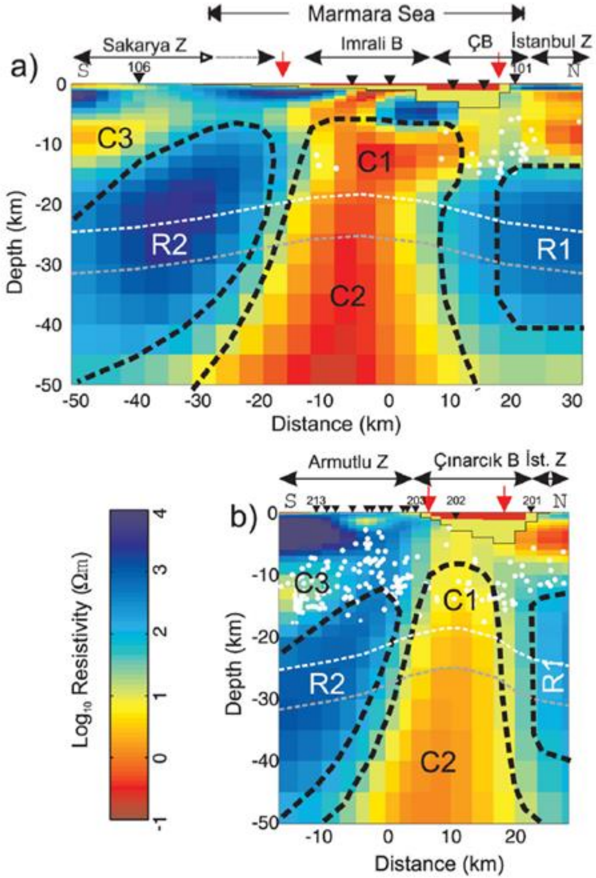
TCG Çeşme


Crew with OBEM JM100

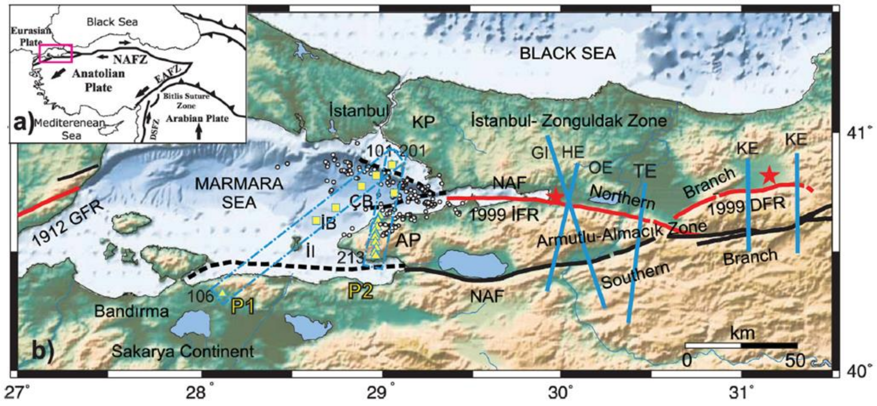


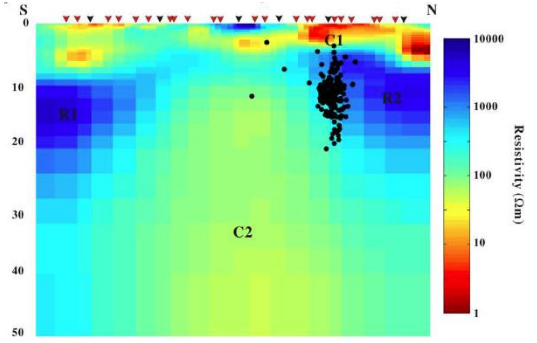
# North Anatolian Fault (West) (2D)

## Marmara Sea – OBEM




Kaya et al., GJI, 2013

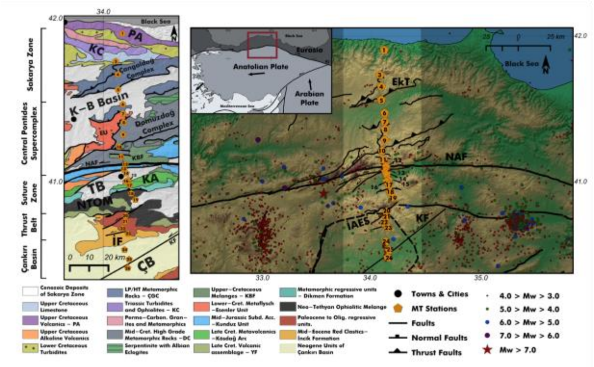



Tank et al., PEPI, 2005

# North Anatolian Fault (3D)

## Near Tosya



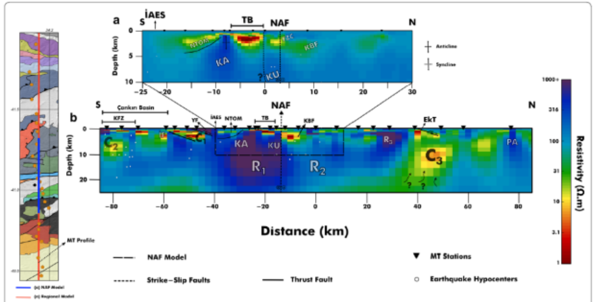
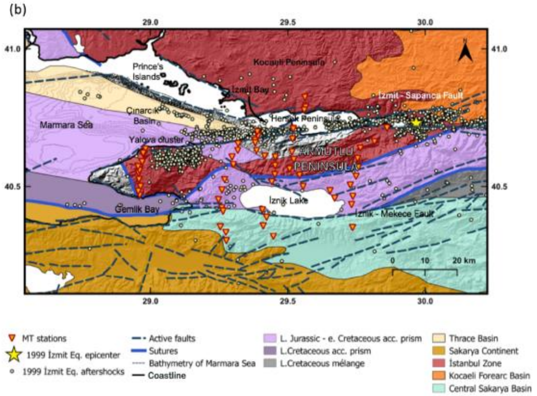
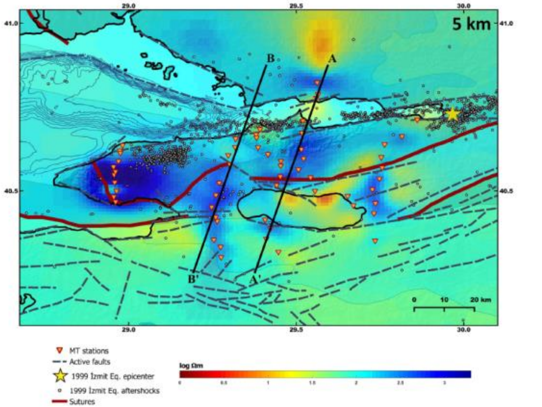




Fig. 4 Cross sections from the a regional and b NAF model with interpretation. White dots represent the earthquake hypocenters taken from the ISC catalogue, İAES İzmir–Ankara–Erzincan Suture, EKT Ekinveren Thrust İF İncik Formation, KA Kösdağ Arc, KU Kunduz Unit, KBF Kirazbaşı Formation, KFZ Kızılırmak Fault Zone, NAF North Anatolian Fault, NTOM Neo-Tethyan Ophiolitic Melange, PA Pontide Arc, TB Tosya Basin, YF Yaylaçayı Formation

Özaydın et al., EPS, 2018

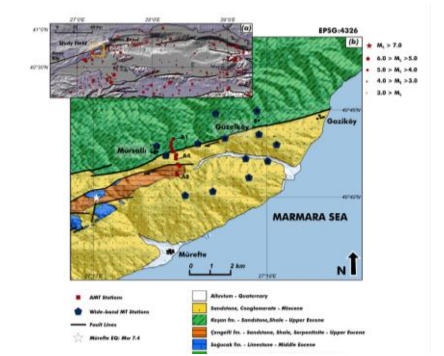
## West of İzmit

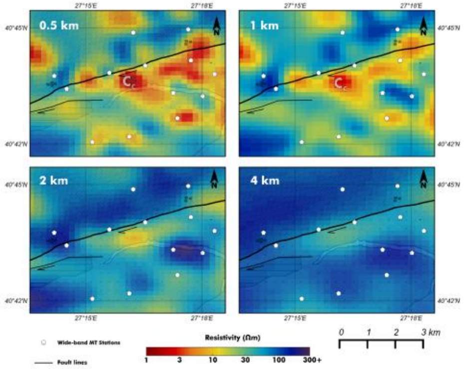



Karaş et al., Tectonophysics, 2020

## Ganos




Karaş et al., EPS, 2017

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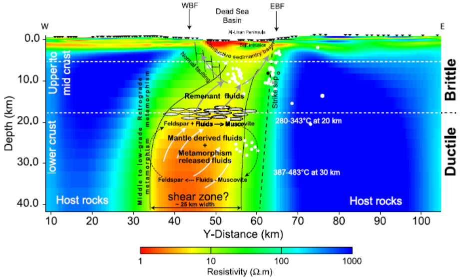
# Conclusion 1 – Eastern Mediterranean

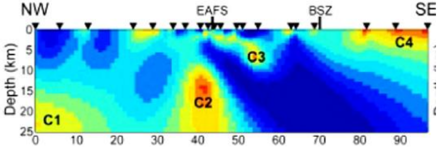
## 2D vs. 3D

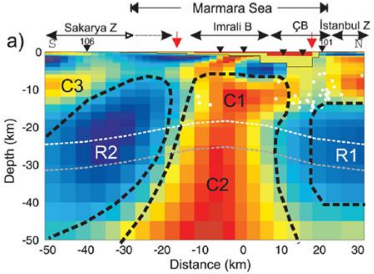
### NAF

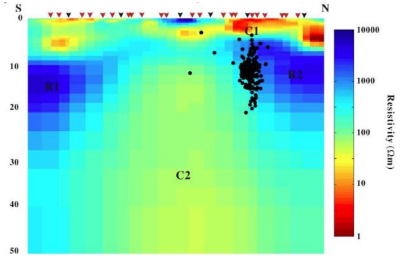
### DSTF | EAF | OBEM | Land

2D

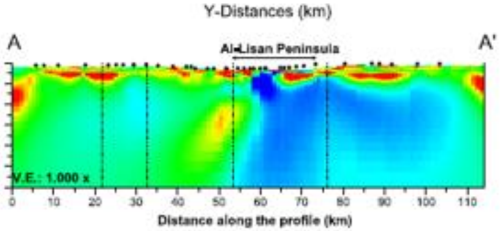


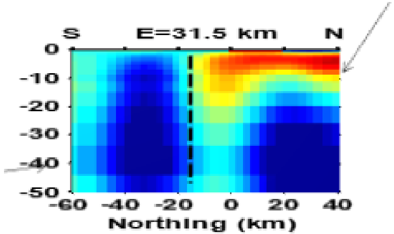



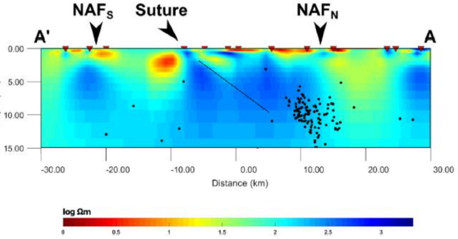




3D




Meqbel et al. GJI, 2013; 2016

Türkoğlu et al., PEPI, 2015; Geology, 2008

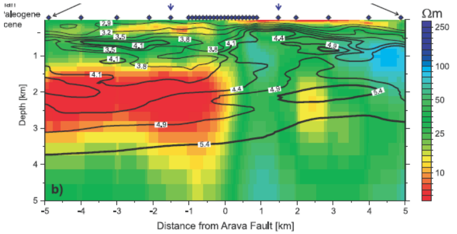
Kaya et al., GJI, 2013;
Karaş et al., Tectonophysics, 2020;
Tank et al., PEPI, 2005

# Conclusion 2

DSTF : No FZC
NAF : Surface – 0.7 km (locked)
SAF : Surface – 3 km (locked)
Surface – 6 km (creeping)

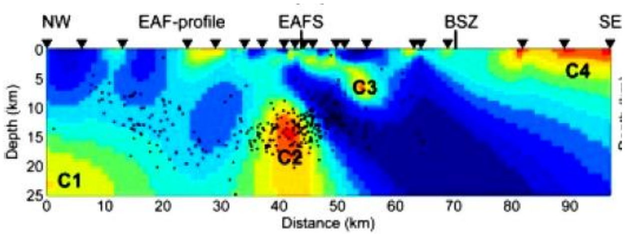
**Shallow structure**
**Fault Zone Conductors - Comparison**

## DSTF

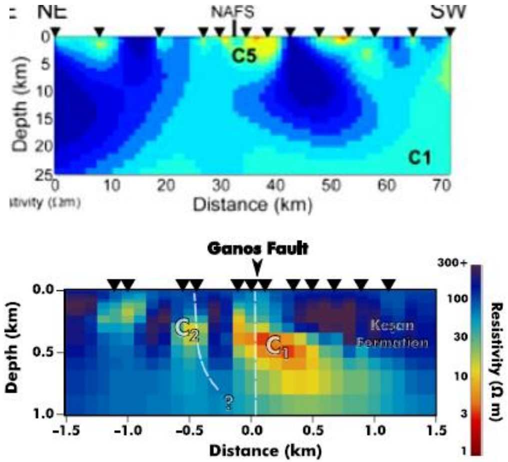



Ritter et al., GRL, 2003

## EAF



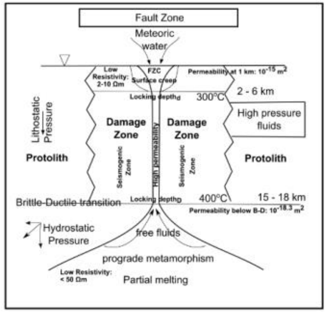

Türkoğlu, PEPI, 2015

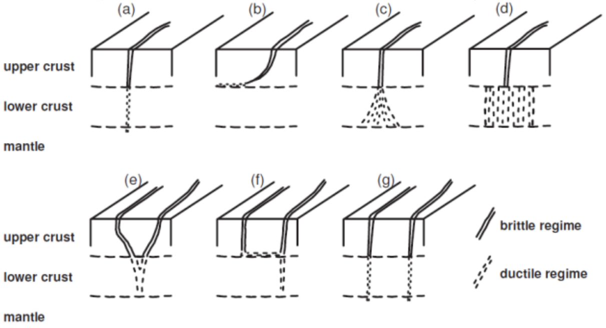



Karaş et al., EPS, 2017

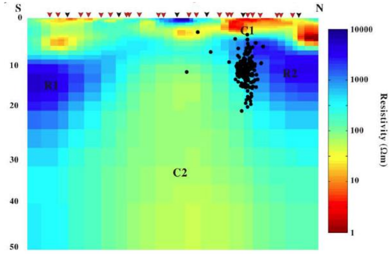
# Conclusion 3

## Deep structure
## Comparison

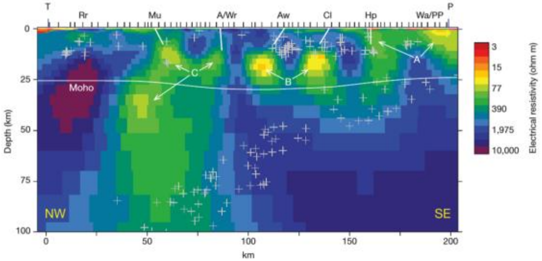


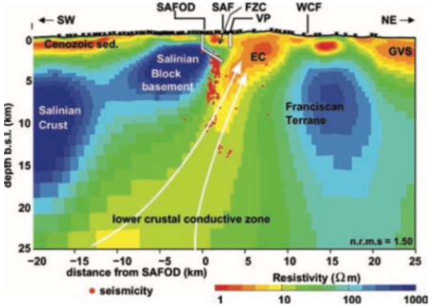

**Ritter et al., Spec. Pub, 2005**



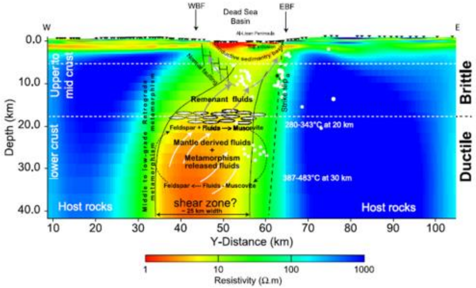

NAF – Tank et al., 2005




Alpine Fault – Wannamaker et al., 2009




SAF - Becken et al., 2008

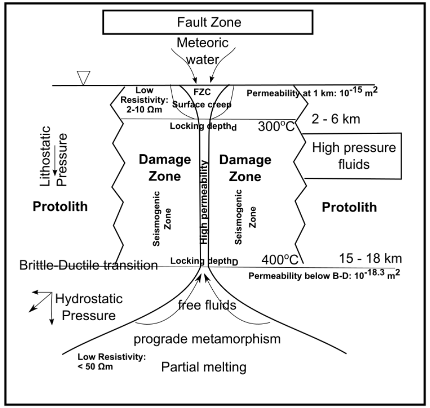


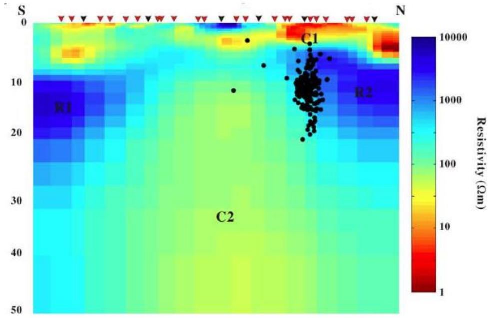

Meqbel et al., 2013; 2016

# Conclusion

- Fluids may have an essential role in the earthquake generation
- Fluid presence at a fault zone can be detected by using EM methods almost at all depths

- Narrative review based on electrical structure of transform faults
- Historical and global perspective to the topic
- Three major transform faults of the eastern Mediterranean



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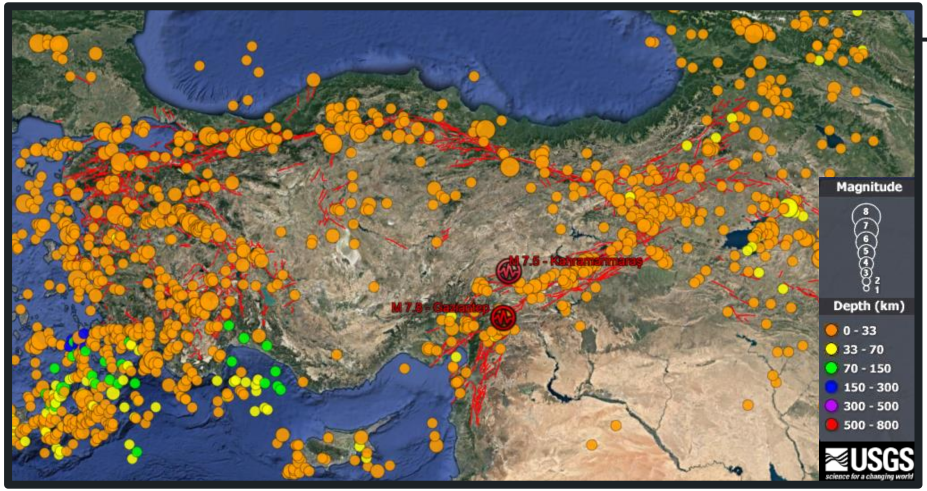
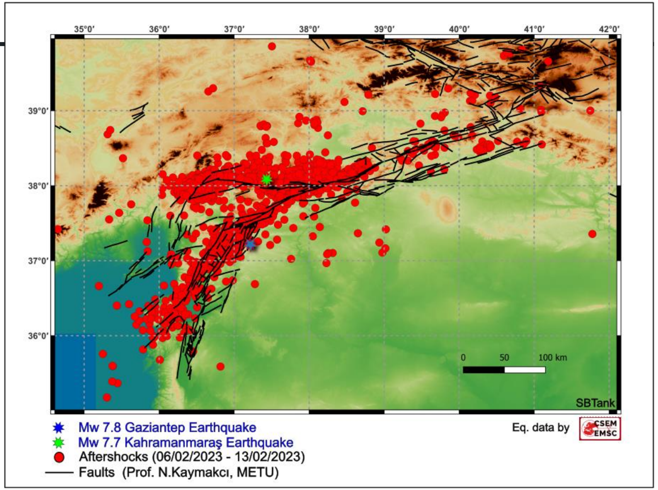
Eminars

# Invitation - Call for projects




Earthquakes 1900 – 2023 (Source: USGS)




Aftershocks 06/02 – 13/02/2023 (Source: EMSC )

- **Example for stress transfer**
- **Faults – Fluids**
- **Active seismicity**
- **Tectonics - triple junction(s)**
- **Multi - disciplinary approach**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