

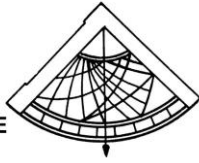
Electromagnetic studies in the Eastern Mediterranean Region with Special Reference to Major Strike-slip Faults

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

Sabri Bülent Tank¹

bulent.tank@boun.edu.tr

¹*Boğaziçi University, Kandilli Obs. & E.R.I., İstanbul*



Türkoğlu, Kahramanmaraş prefecture, PC: TRT

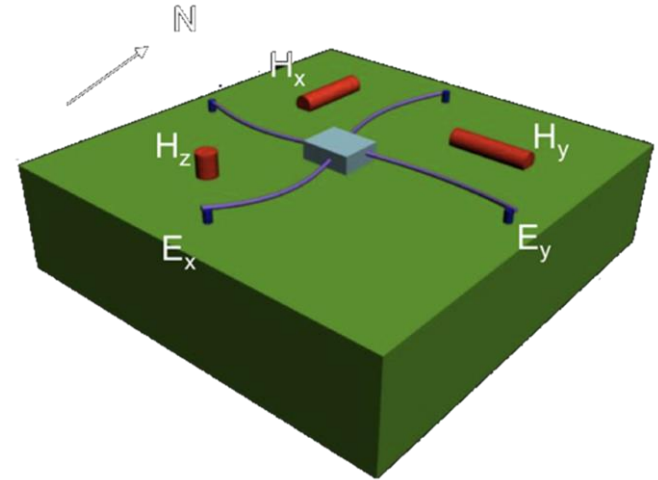


Tepehan, Hatay prefecture, PC: TRT

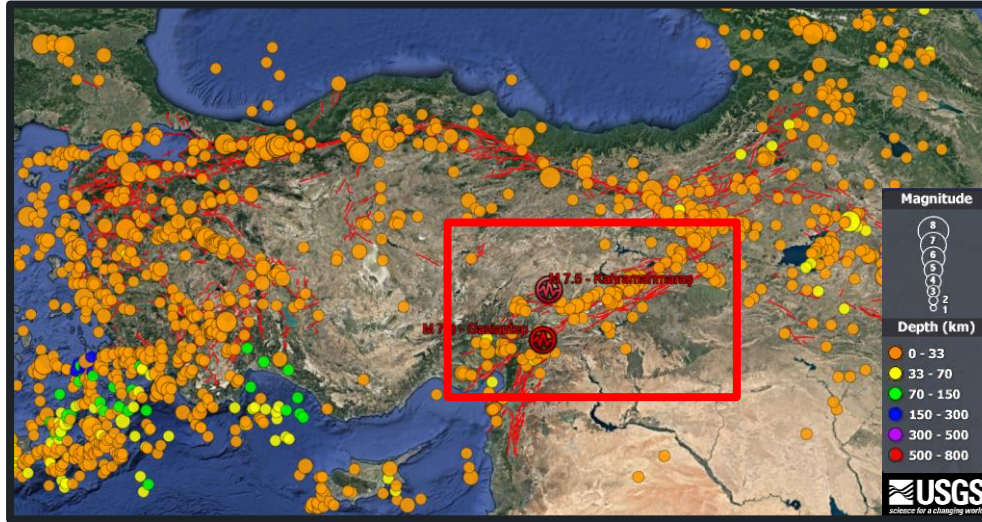


Outline

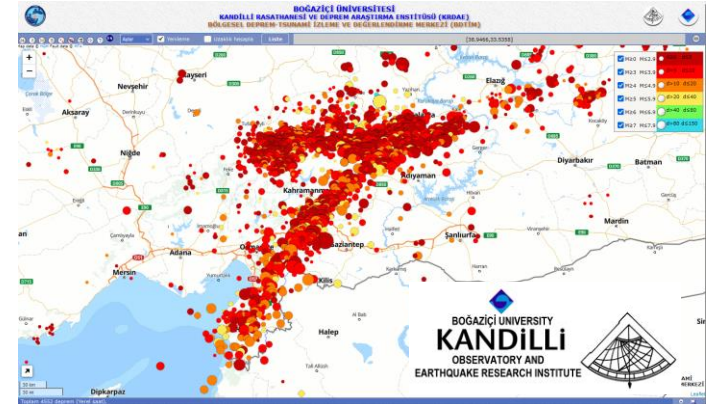
- **Recent activity**
 - **2023 Earthquakes**
 - **Coulomb stress maps**
- (I) **Strike-slip (transform) faults**
 - **Fault zone architecture and Earthquakes**
 - **EM studies on (strike-slip) faults:**
 - **Theory**
 - **Global examples:**
 - **Alpine Fault, New Zealand**
 - **San Andreas Fault, California, the USA**
 - **Atotsugawa Fault, Central Honshu, Japan**
 - **AltynDagh Fault, W. China**
 - **Phayao Fault, N. Thailand**
 - **Bogd, Trans Altai, Tianshan 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



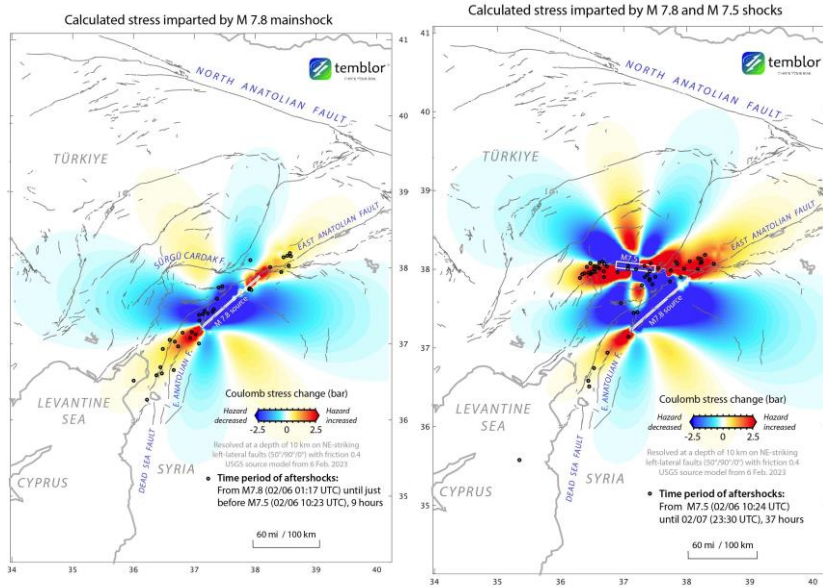
Earthquakes 1900 – 2023 (Source: USGS)



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

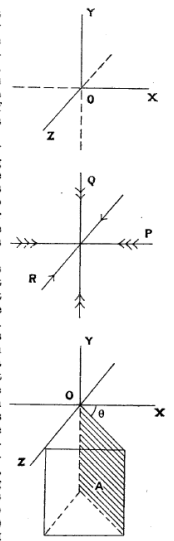
XLIII. *The Dynamics of Faulting.* By ERNEST M. ANDERSON, M.A., B.Sc., H.M. Geological Survey.

(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. 11

no. 4893 July 24, 1965

NATURE

343

A NEW CLASS OF FAULTS AND THEIR BEARING ON CONTINENTAL DRIFT

By PIERI J. TUZO WILSON, O.B.E.
Institute of Earth Sciences, University of Toronto

TRANSFORMS and half-abores. Many geologists have maintained that movements of the Earth's crust are concentrated in mobile belts, which may take the form of mountain, mid-ocean, ridge or major faults with large horizontal movements. These features and the seismic activity along them often appear to end abruptly, which is puzzling. The problem has been difficult to investigate because most mountains lie in ocean basins.

This article suggests that these features are not isolated, but for convenience tend to be considered into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates (Fig. 1). Any feature at its apparent termination may be transformed into another feature of one of the other two types. For example, a fault may be transformed into a mid-ocean ridge as illustrated in Fig. 2a. At the point of transformation the horizontal shear motion along the fault ends abruptly by being changed into an expanding tensional motion across the ridge or rift with a change in sensitivity.

A junction where one feature changes into another is here called a transform. This type and two others illustrated in Figs. 2b and c may also be termed half-abores (a name suggested in conversation by Prof. J. D. Bernal). Twice as many types of half-abores involve mountains as ridges, because mountains are asymmetrical whereas ridges have bilateral symmetry. This way of abruptly ending large horizontal shear motions is offered as an explanation of what has long been recognized as a puzzling feature of large faults like the San Andreas.

Another type of transform whereby a mountain is transformed into a mid-ocean ridge was suggested by S. W. Carey¹ when he proposed that the Pyrenean Mountains were compressed because of the rising coast of the Bay of Biscay (presumably by the formation of a mid-ocean ridge along its axis). The types illustrated are all dextral, but equivalent sinistral types exist.

In this article the term 'ridge' will be used to mean mid-ocean ridge and also rise (where that term has been used meaning mid-ocean ridge, as by Minard² in the Pacific basin). The terms mountain and mountain system may include island arcs. An arc is described as being convex or concave depending on which face is first reached when proceeding in the direction indicated by an arrow depicting relative motion (Figs. 2 and 3). The word fault may mean a system of several closely related faults.

Transform faults. Faults in which the displacement suddenly stops or changes form and direction are not true transform faults. It is proposed that a separate class of horizontal shear faults exists which terminate abruptly at both ends, but which nevertheless may show great displacements. Each may be thought of as a pair of half-abores joined end to end. Any combination of pairs of the six types illustrated in Fig. 3. Another six sinistral forms can also exist. The same transform fault is proposed for the ocean, and can also be described in terms of the features which they connect (for example, dextral transform faults, ridge-converge sea types).

The distinctions between types might appear trivial until the variation in the habits of growth of the different types is considered as is shown in Fig. 4. These distinctions are that ridges expand to produce new crust, thus leaving residual inactive traces in the topography of their former positions. On the other hand oceanic crust moves under island arcs absorbing old crust so that they leave no traces of past positions. The oceanic side of new this advance. For these reasons transform faults of types a, b and c (in Fig. 4) give in total width type f (distinctions and the behaviour of types c and f is indeterminate). It is significant that the direction of motion on transform faults of the type shown in Fig. 3a is the reverse of that required to offset the ridge. This is a fundamental difference between transform and transcurrent faulting.

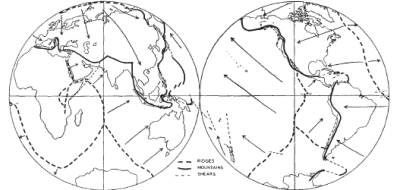
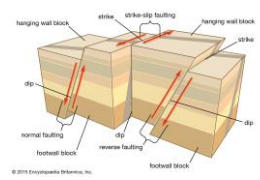


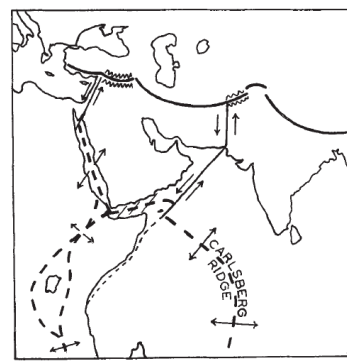
Fig. 1. Sketch map illustrating the general network of mobile belts, comprising the active primary mountain and island arcs in compression (solid lines), active transform faults in horizontal shear (light dashed lines) and active mid-ocean ridges in tension (heavy dashed lines).

© 1965 Nature Publishing Group



© 2013 Encyclopædia Britannica, Inc.

“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)

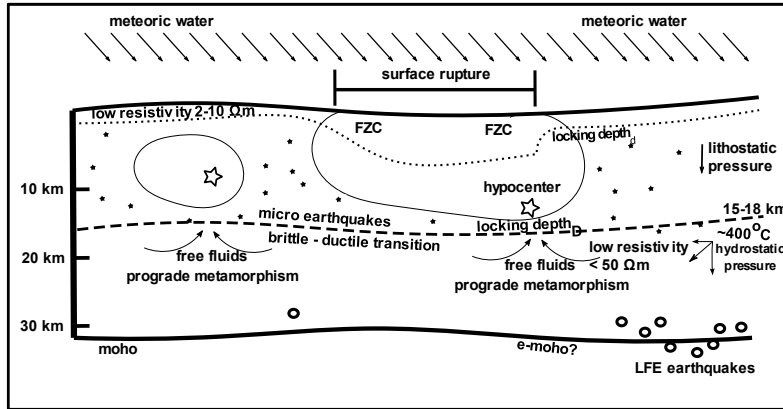


Anderson, Lyell Coll. (1905)

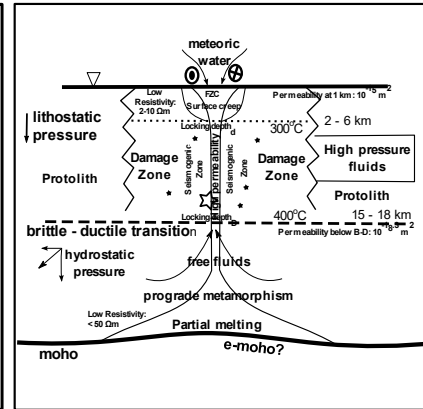
Wilson, Nature (1965) – Transform Faults

Fault Zone Architecture – Continental Seismogenic Zone

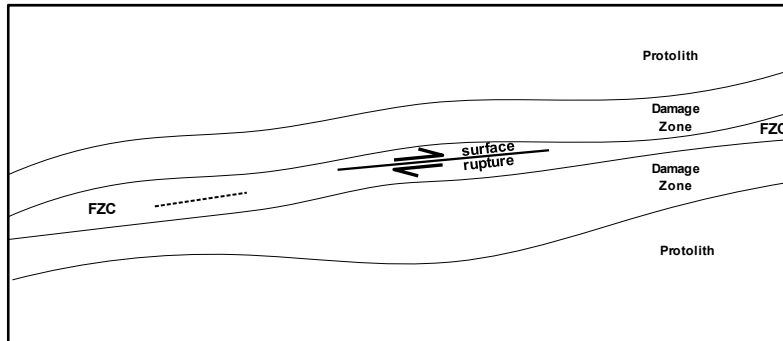
A. Along



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

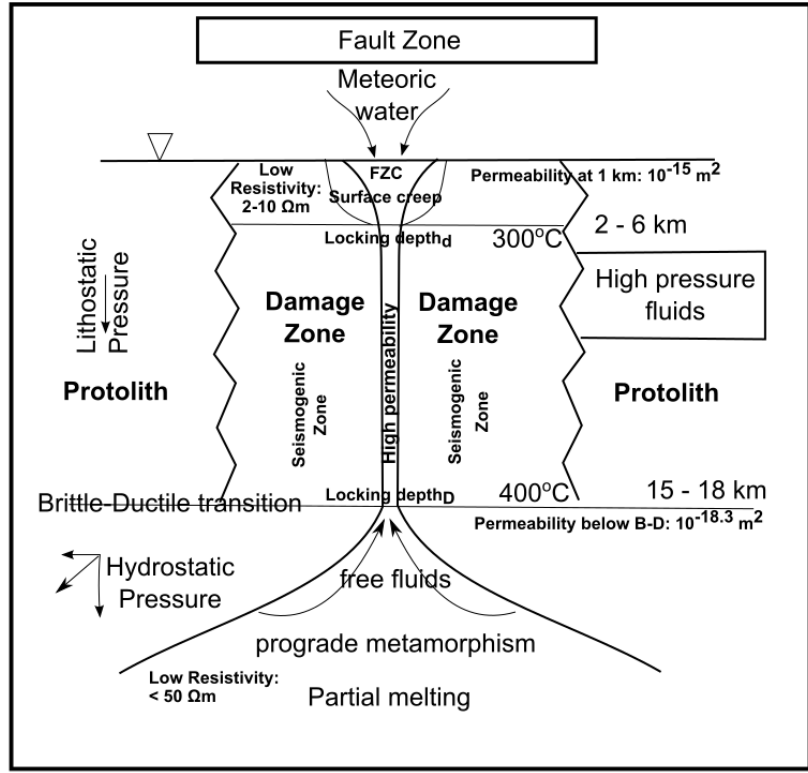
Lubrication – talc/clay

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 formulae 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 Heine series 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 interpreted by curves of the apparent resistivity and its 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 factor k , the above relationships are the same and the apparent resistivities differ by the same proportionally constant which enters 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 involves 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.

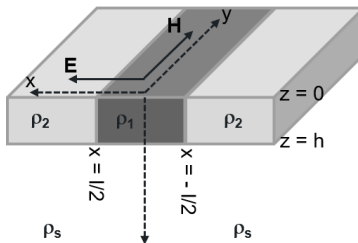
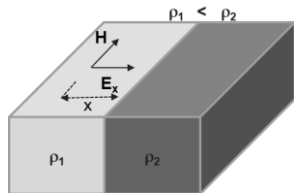
Wait, Geophysics, 1954

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.



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

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

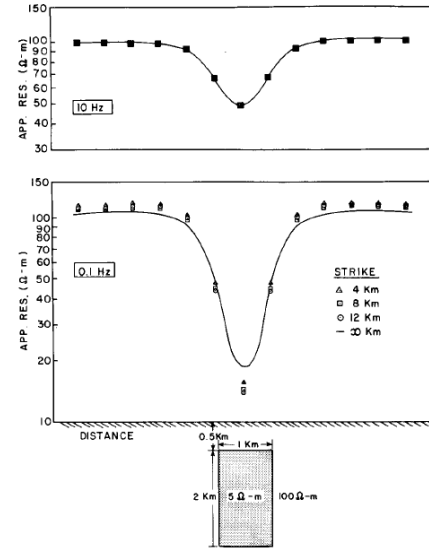
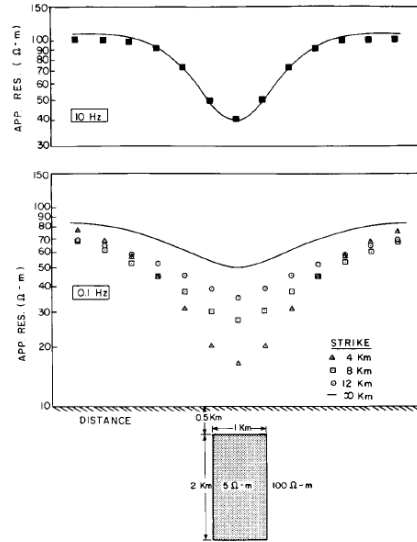
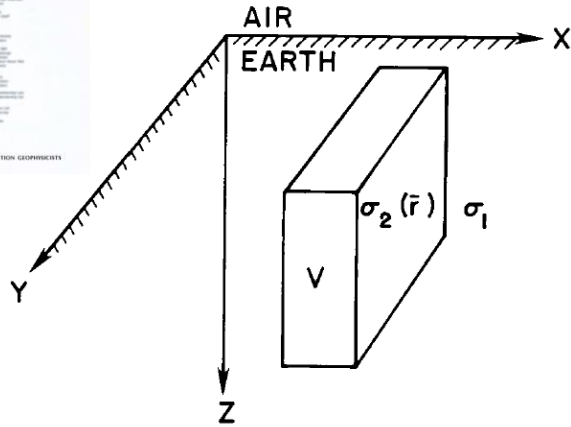
Rankin,
Magnetotelluric effect on a dike,
1962

Weaver,
Discussion,
1963

"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."

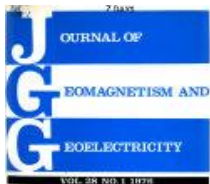
Early EM studies on (strike-slip) faults - Theory

Integral equation modeling of three-dimensional magnetotelluric response

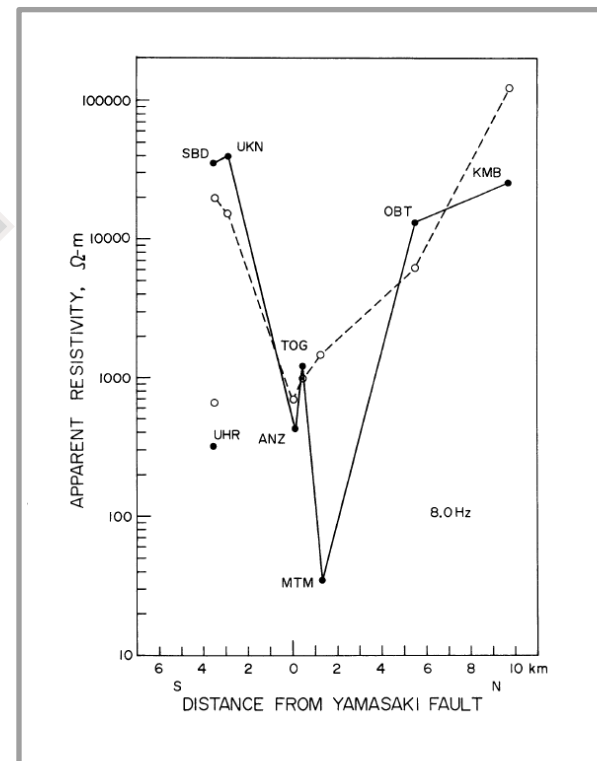
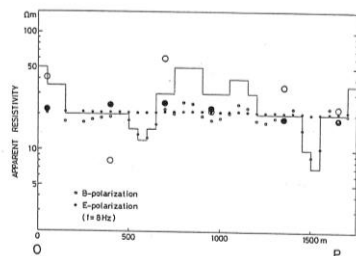
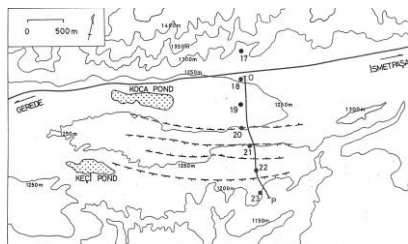


Ting and Hohmann, Geophysics, 1981

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

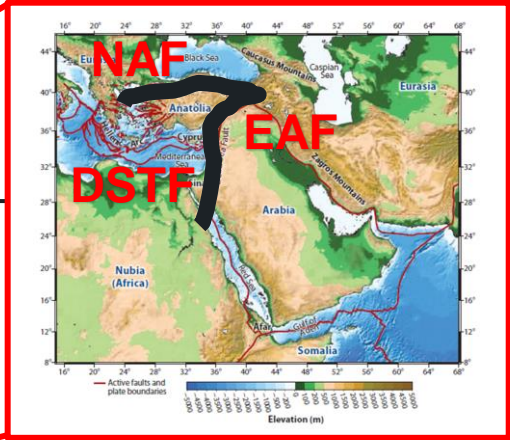


- Reddy et al., JGG, 1976 – SAF
- Lienert et al., JGG 1980 - SAF
- EM Research Group of the Active Fault, JGG, 1982 - Yamasaki F.

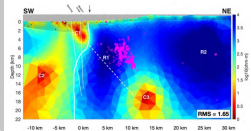


Honkura et al., Tech. paper
by Titech and Istanbul Uni., 1986

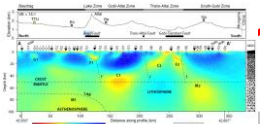
Magnetotelluric studies on major strike-slip fault zones



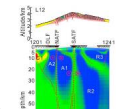
- Tintina F.
- GSLake F.
- Denali F.
- SAF



Share et al., GJI, 2022



Cômeau et al., EPS, 2020



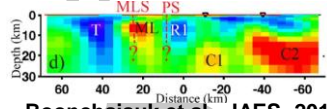
Xiao et al., JGR, 2017

- Waterberg F.

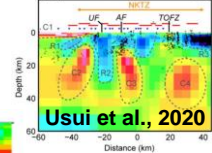


- West F.

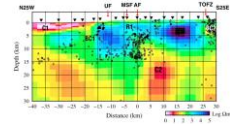
- Derbugan F.
- Bogd F.
- Altın Dagh F.
- Jiali F.
- Median Tectonic Line F.
- Niigata – Kobe TZ
- Atotsugawa F.
- Huya F.
- Phayao F.
- Red River F.
- Zhaotong-Lianfeng F.
- Tan Shear
- Longlin Ruiting
- Kachchh M. F.



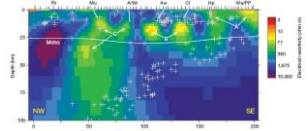
Boonchaisuk et al., JAES, 2017



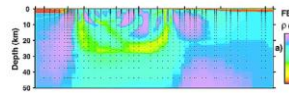
Usui et al., 2020



Yoshimura et al., GRL, 2009



Wannamaker et al., Nature, 2009

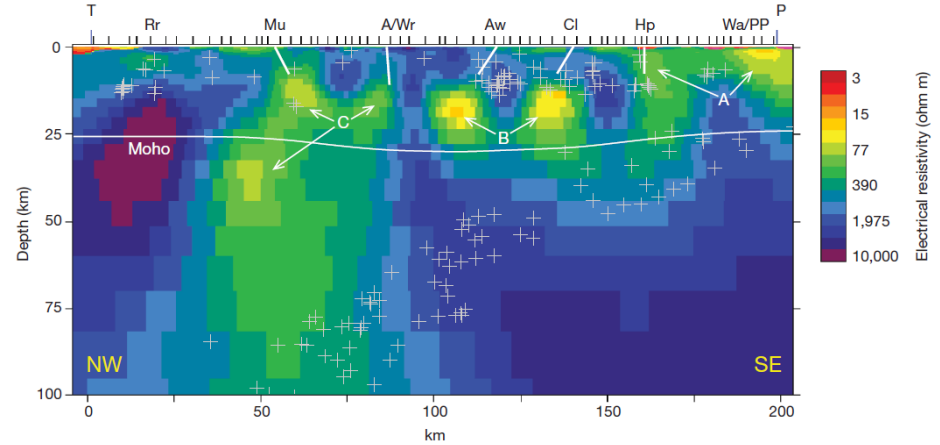
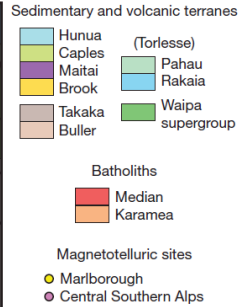
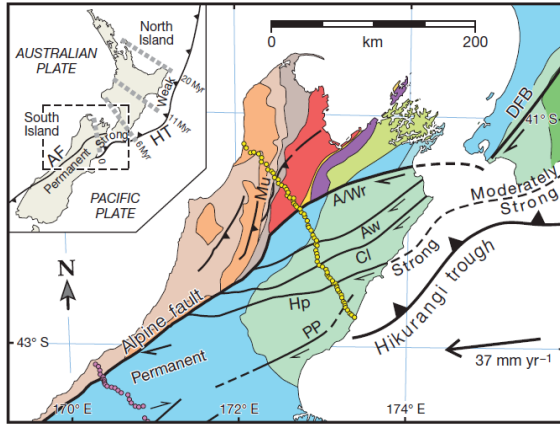


Wannamaker et al., JGR, 2002

Le Pichon et al., Ann. Rev. Earth and Plan. Sci., 2010

Global examples I:

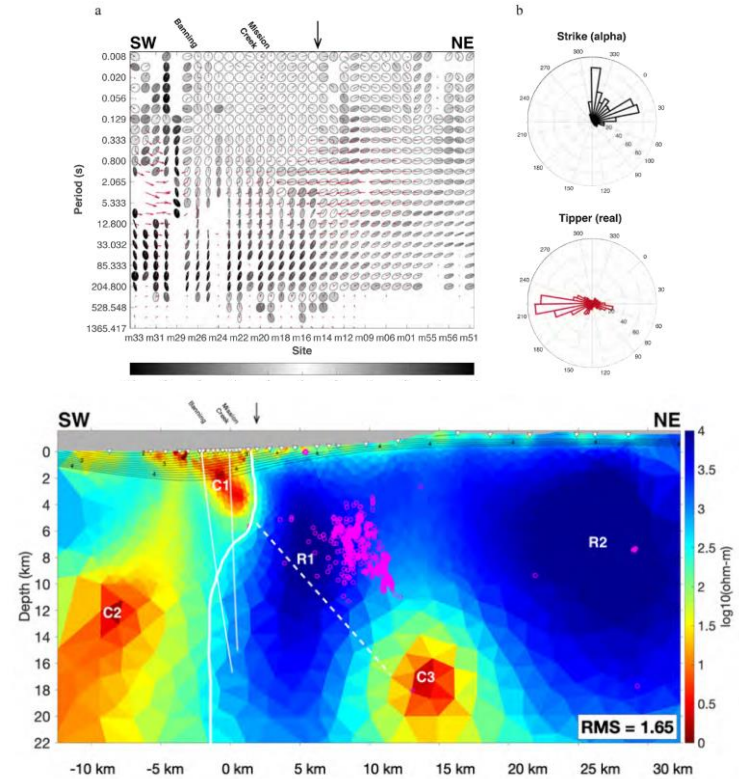
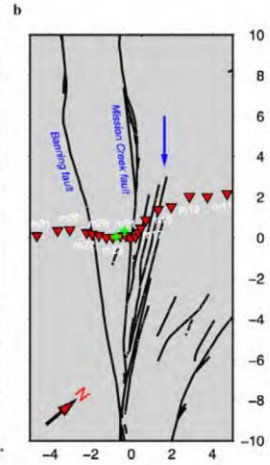
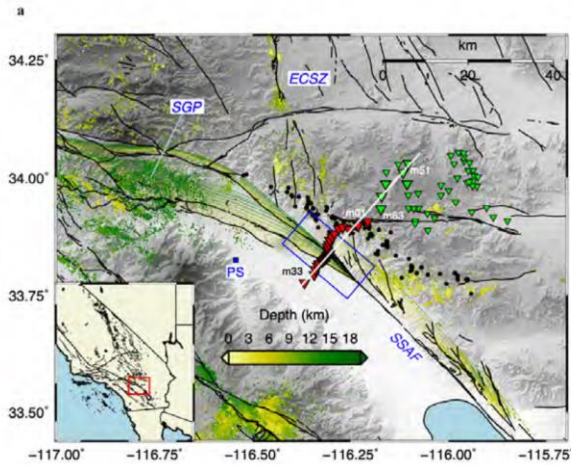
Alpine Fault, New Zealand (2D)



Wannamaker et al., Nature, 2009

Global examples 2:

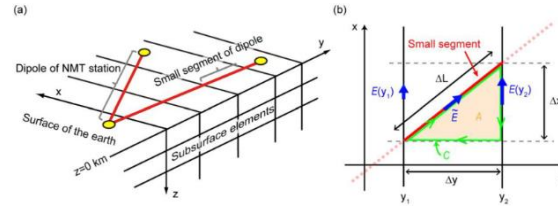
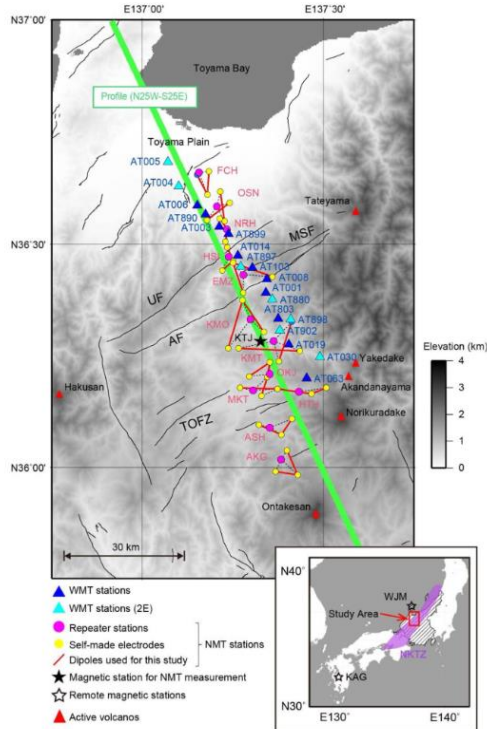
Southern San Andreas Fault, California, the USA (2D & 3D)



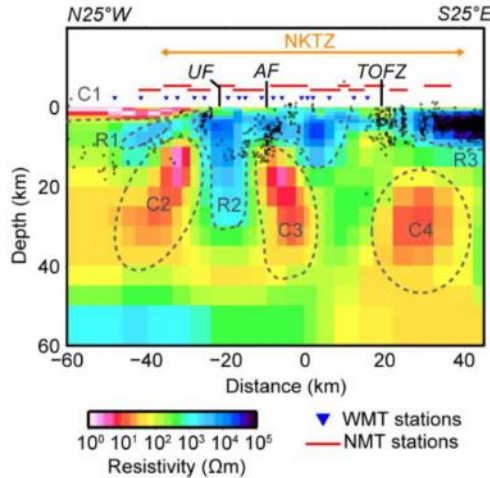
Share et al., GJI, 2022

Global examples 3:

Atotsugawa Fault, Central Honshu, Japan (2D)



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

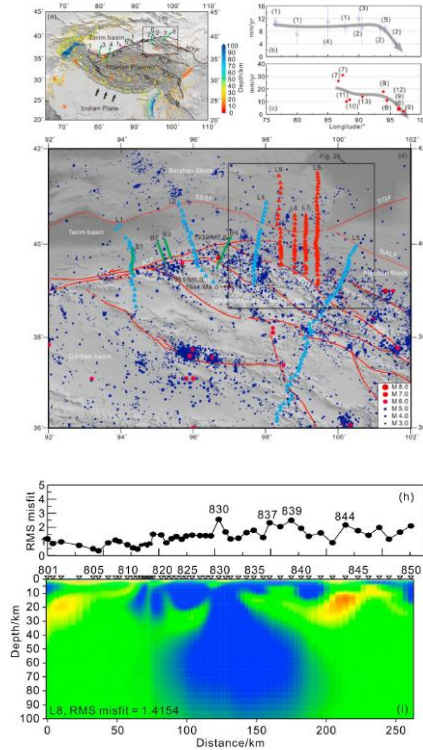


Usui et al., JGR, 2020

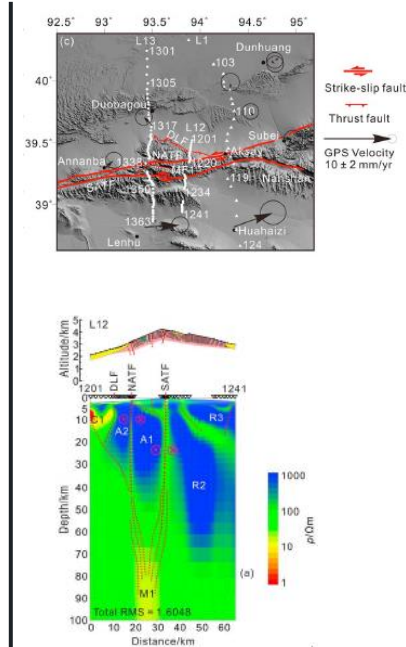
Global examples 4:

Altyndagh Fault, NW China

(2D and 3D)



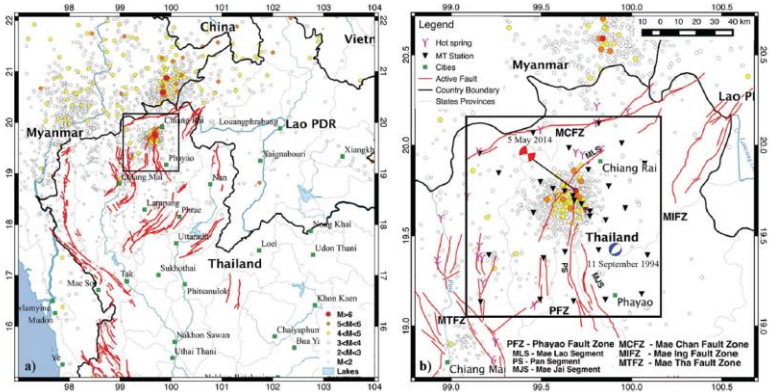
Xiao et al., JGR, 2015



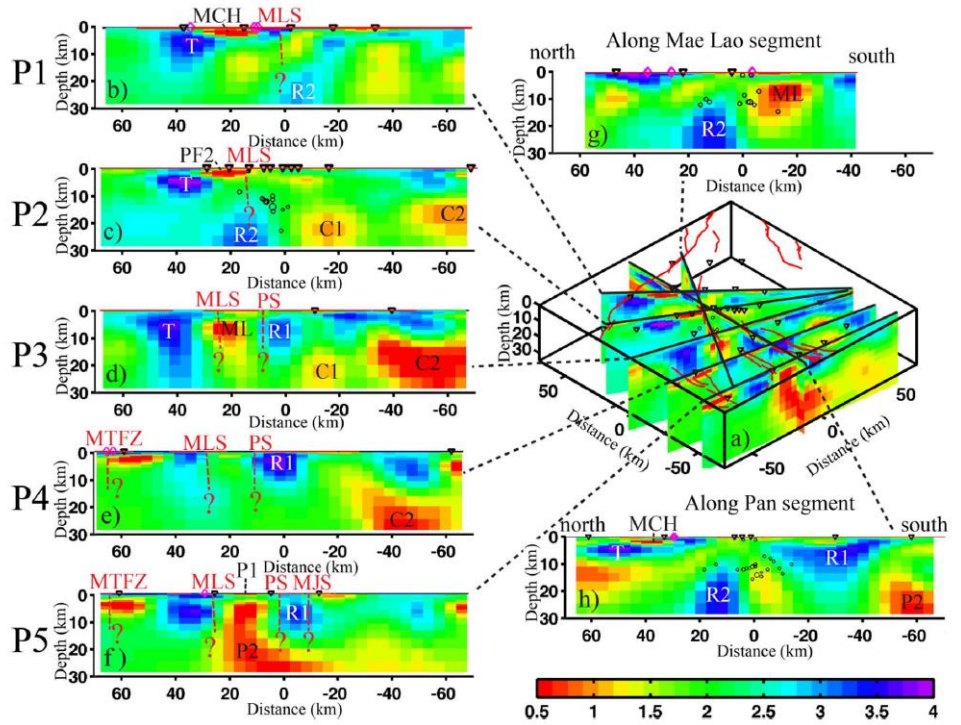
Xiao et al., GRL, 2017

Global examples 5:

Phayao Fault Zone, N.Thailand (3D)



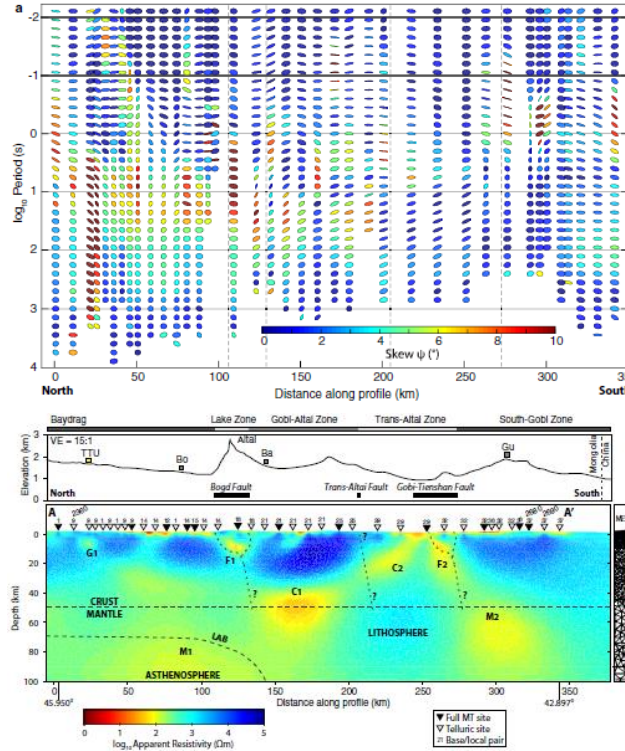
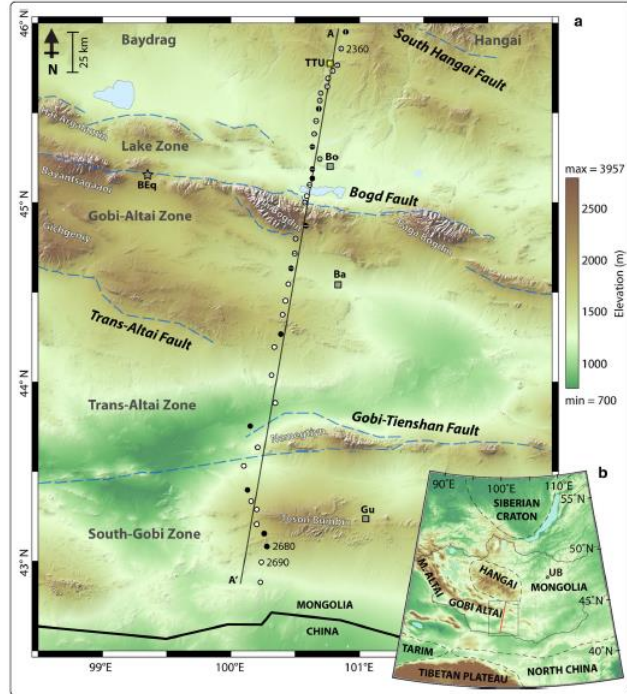
Boonchaisuk et al., JAES, 2017



Global examples 6:

Bogd – Trans Altai – Gobi Tien Shan faults, Mongolia

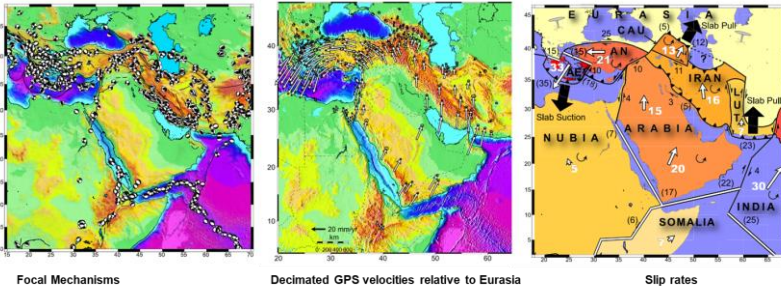
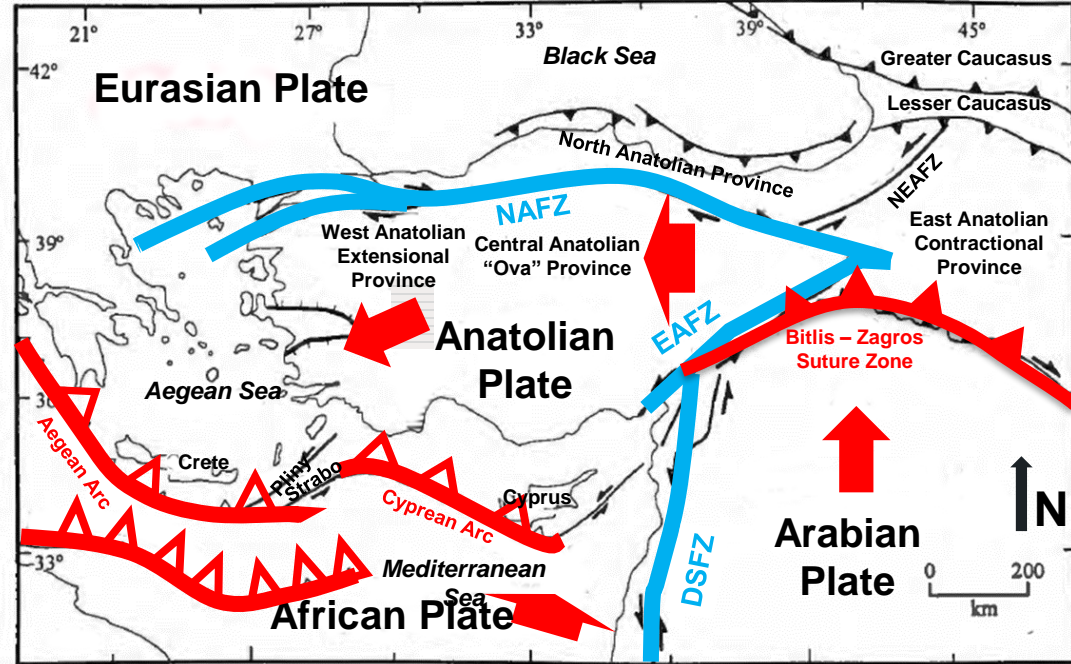
(2D)



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

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

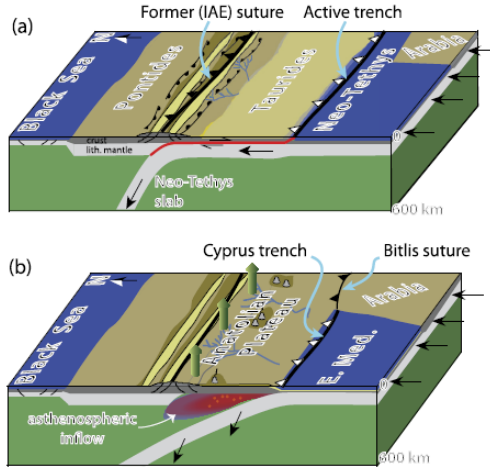
Reilinger et al., JGR, 2006

Bozkurt, GeoActa, 2001

Şengör et al., SEPM Society for Sedimentary Geology, 1985

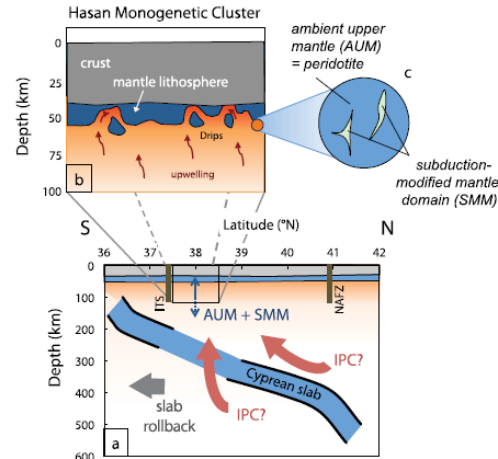
Tectonic models

Delamination



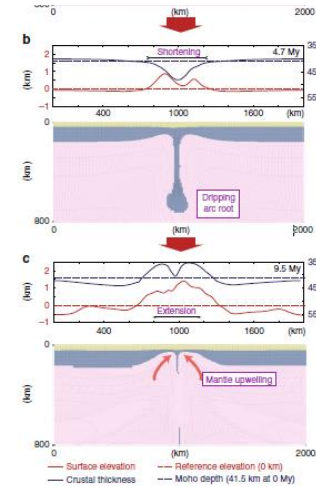
Govers and Fichtner, EPSL, 2016;
Bartol and Govers, Tectonophysics, 2014

Delamination and drip

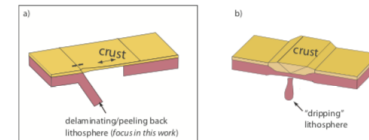


Reid et al., G-cubed, 2017

Drip tectonics

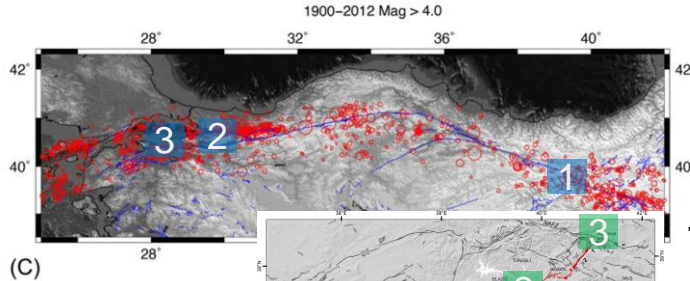
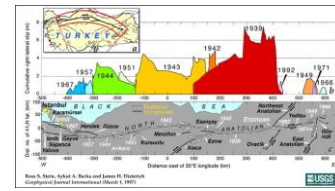


Göğüş et al., Nature Comm., 2018



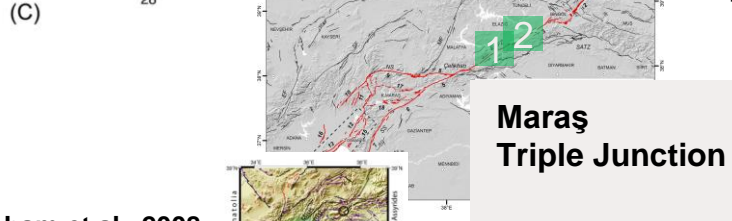
Göğüş and Ueda, JDyn, 2018

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



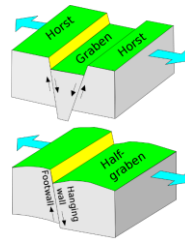
**Karlıova
Triple Junction**

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



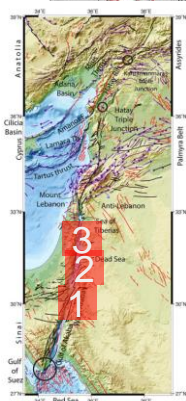
EAF: ~ 500 km
Sinistral - 22 km
6.3 Adana-Ceyhan eq. 1998
6.4 Bingöl eq. 2004
6.7 Elazığ eq. 2020
7.7 Gaziantep eq. 2023
7.6 Kahramanmaraş eq. 2023

**Hatay
Triple
Junction**



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

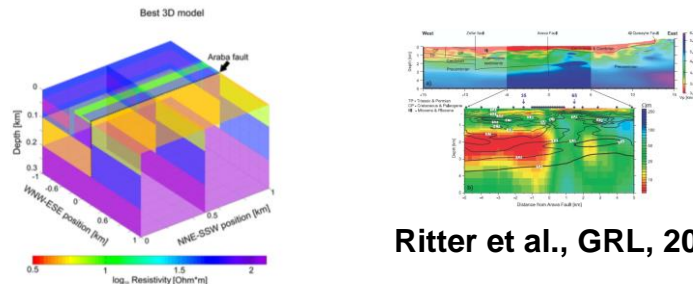
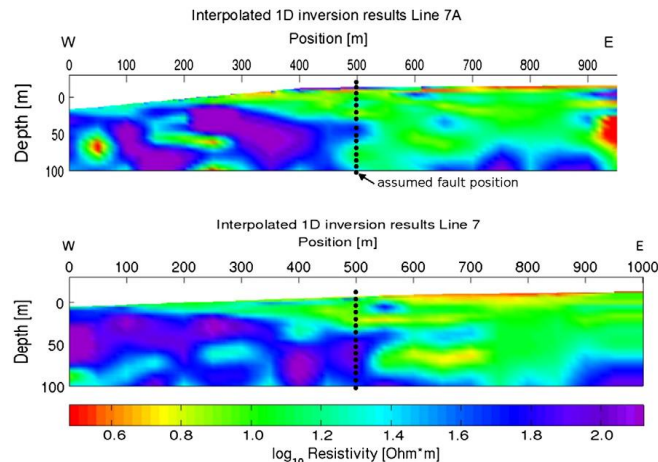
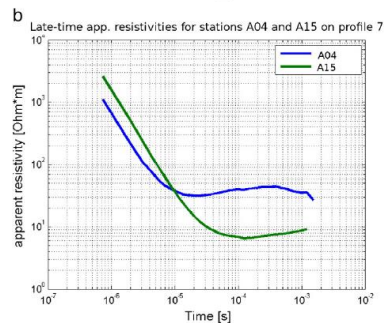
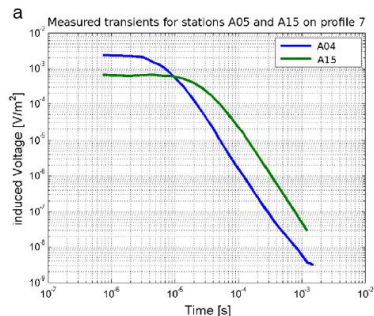
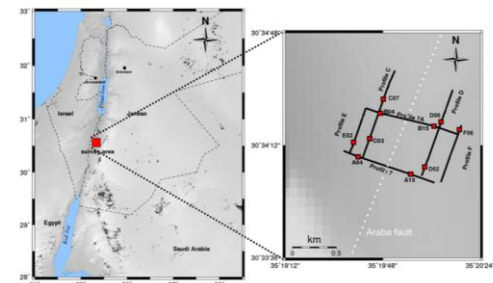
Ben-Avraham et al., 2008
Division of DSTF
At 33°10'N



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)



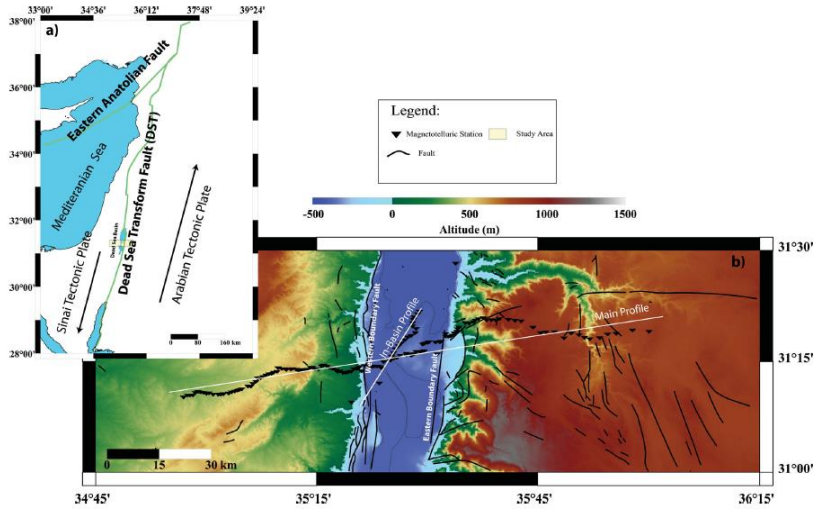
Ritter et al., GRL, 2003

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

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

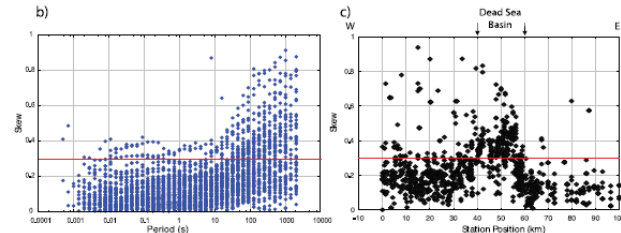
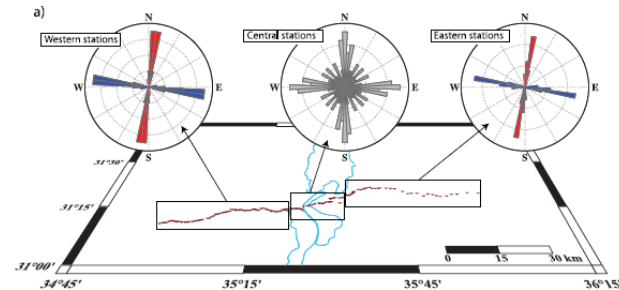
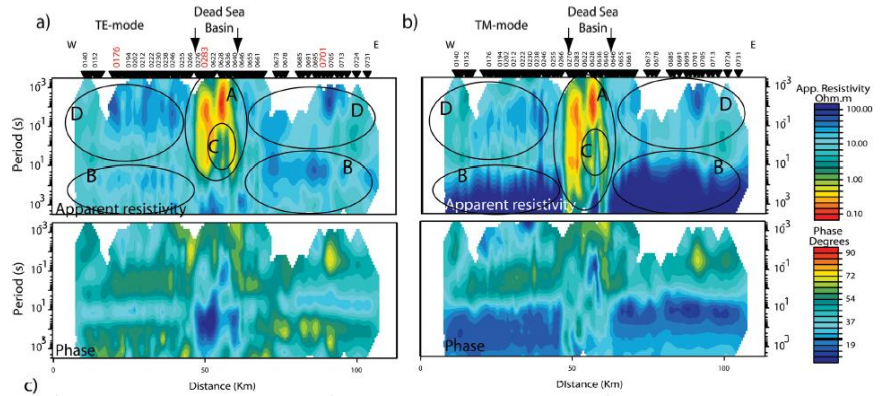
Dead Sea Transform Fault (DSTF) (2D) and 3D

Dead Sea Basin - DESIRE project



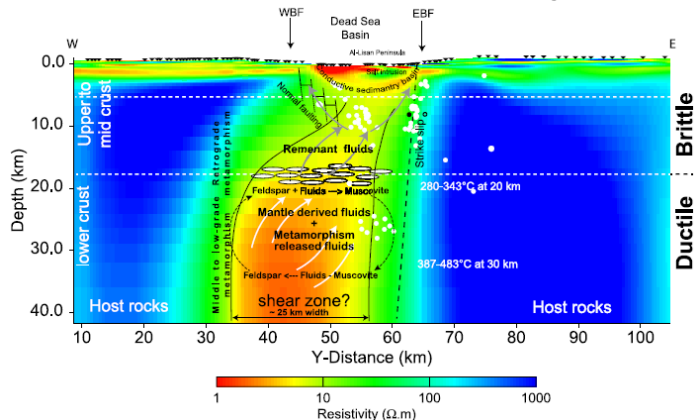
153 observations (94 main p. + 59 auxiliary p.)
3 days recording at each site
2 teams and 30 instruments
Main profile length: 110 km
2nd profile length: 20 km
Site separation: 0.5 – 2 km

Meqbel et al., GJI, 2013



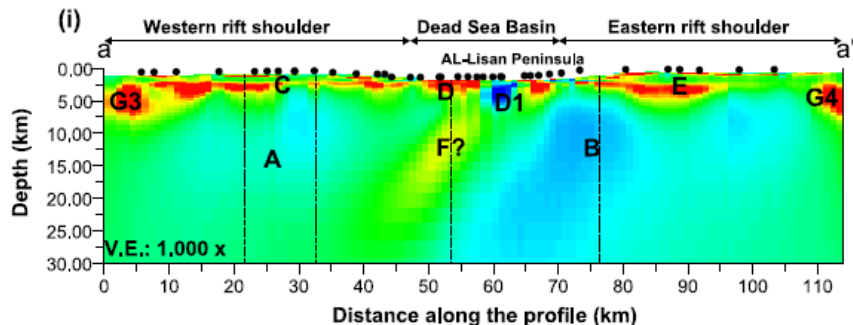
Dead Sea Basin - DESIRE project

(2D)



Meqbel et al., GJI, 2013

(3D)



Meqbel et al., GJI, 2016

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

ModEM

NLCG - FD

Nested mesh modeling

1st 70 x 70 (coarse grid)

100 layers including topography and air

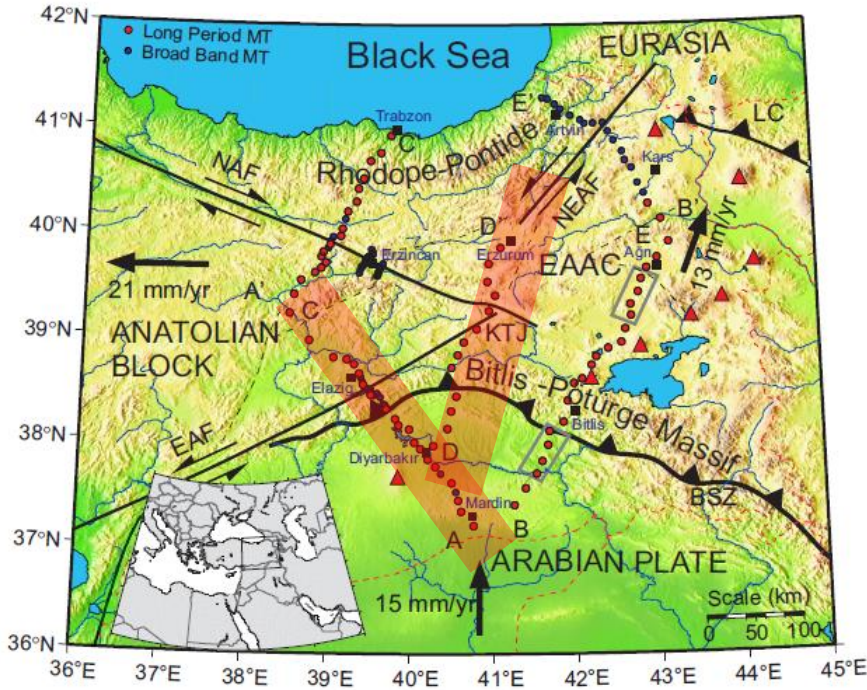
20 periods

Error floor 5 %

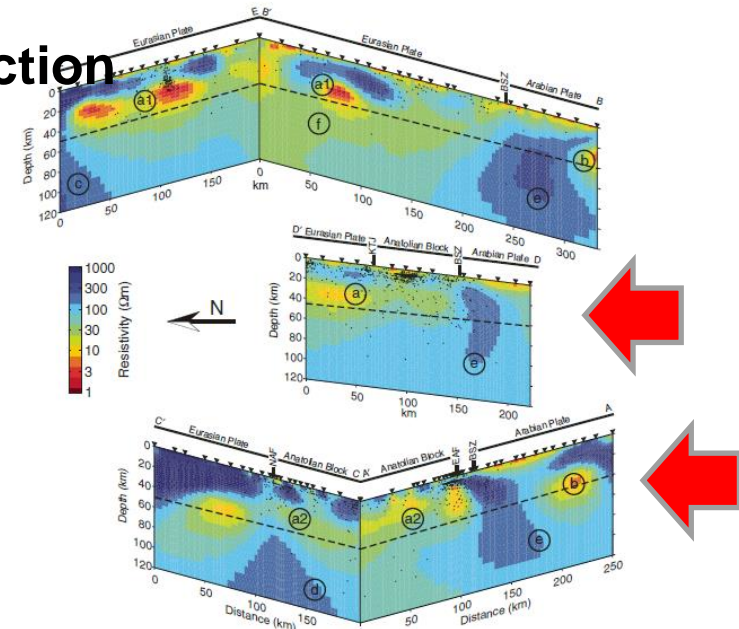
East Anatolian Fault (2D)

Elaziğ segment and Karliova Triple Junction

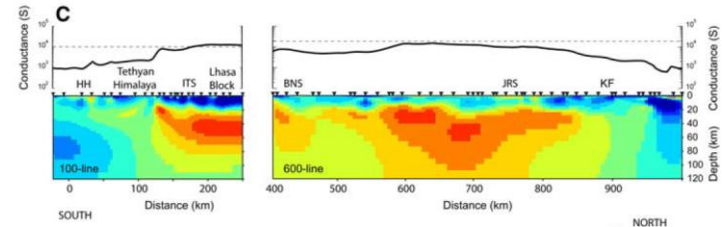
Long period + Wideband



Türkoğlu et al., Geology, 2008



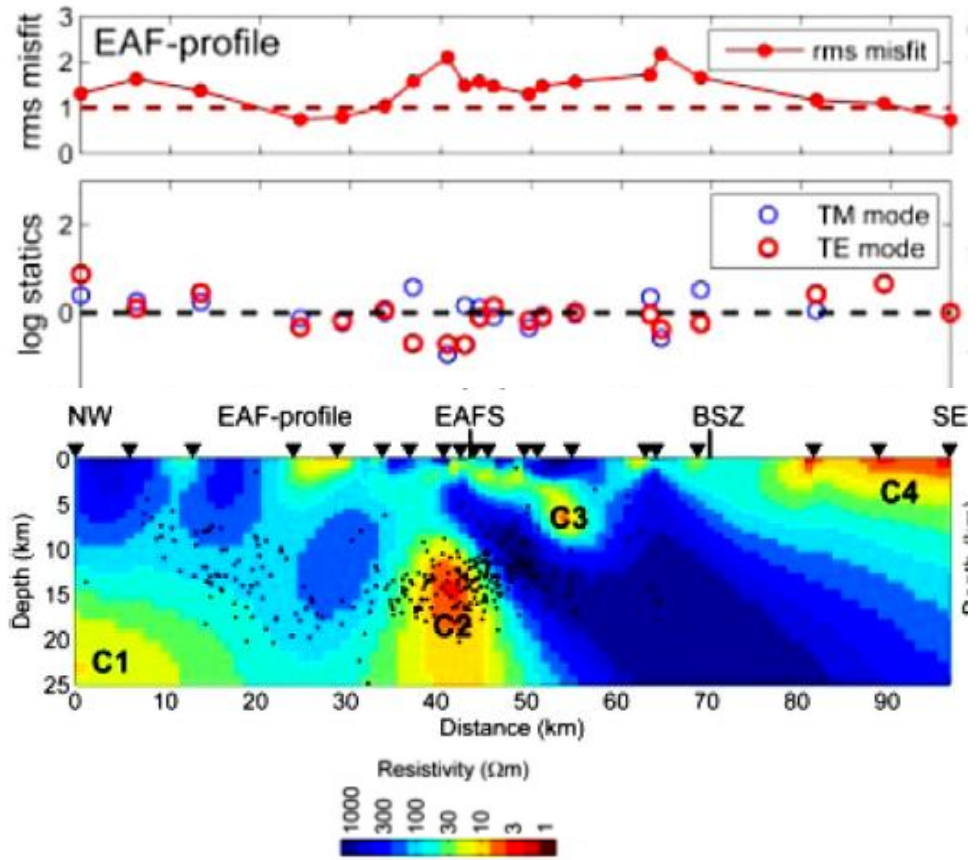
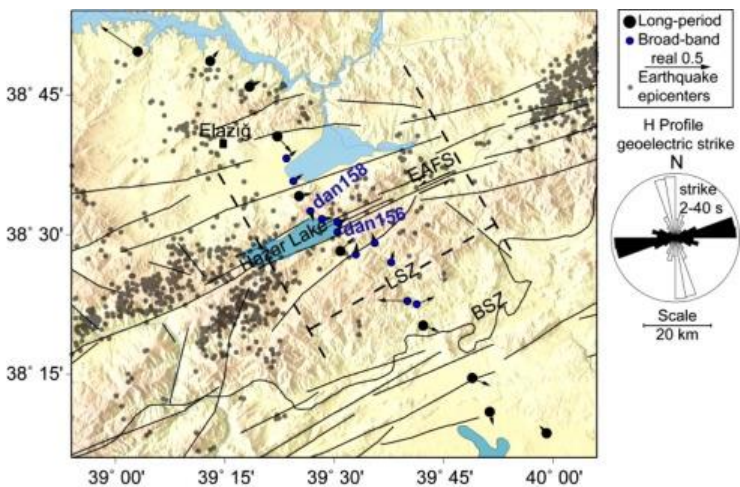
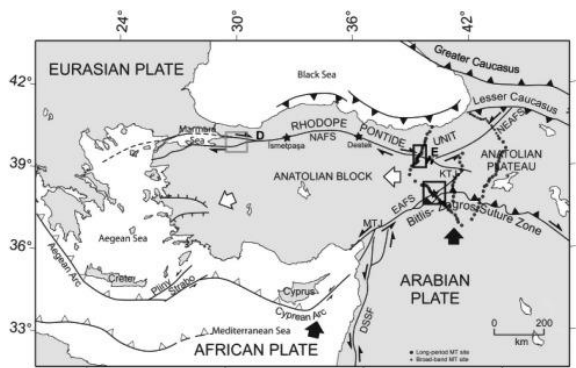
Rodi and Mackie (2001) – NLCG – FD
TE + TM + Tipper



Unsworth., Surveys in Geophysics, 2010

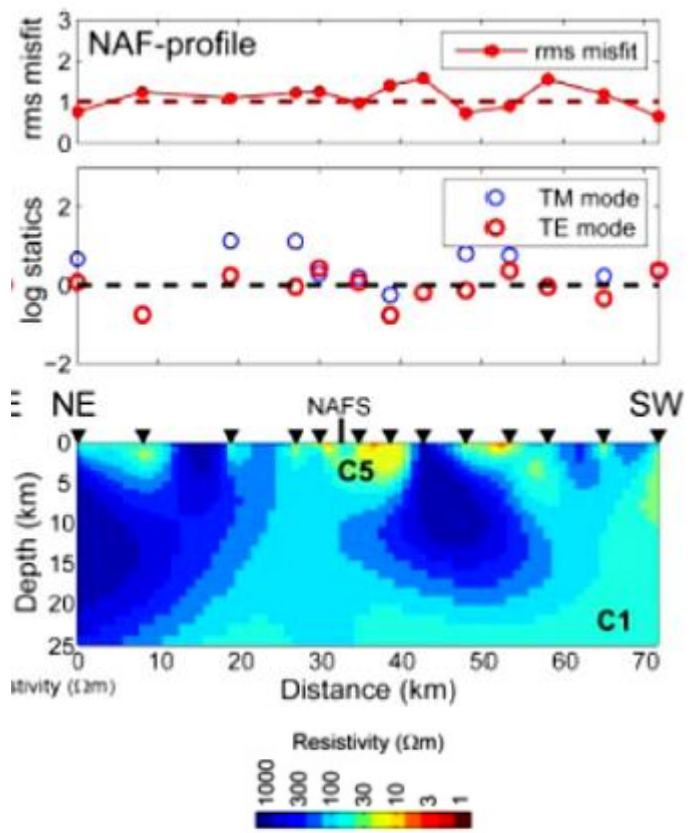
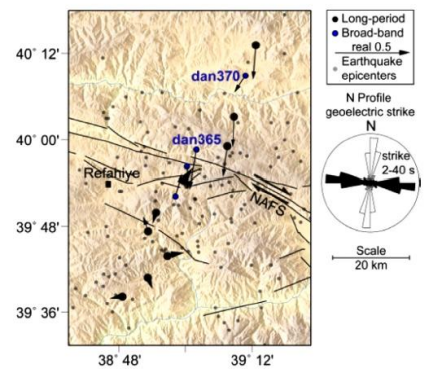
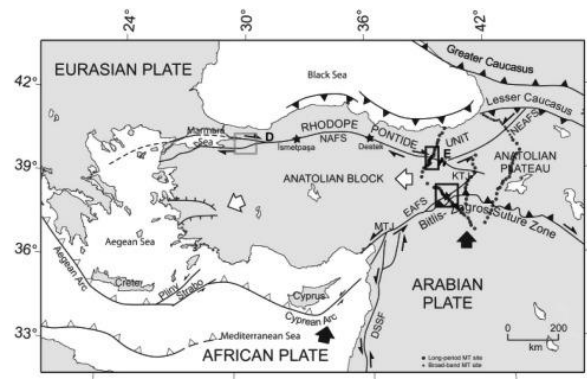
East Anatolian Fault Elazığ Segment

(2D)



North Anatolian Fault (East) (2D)

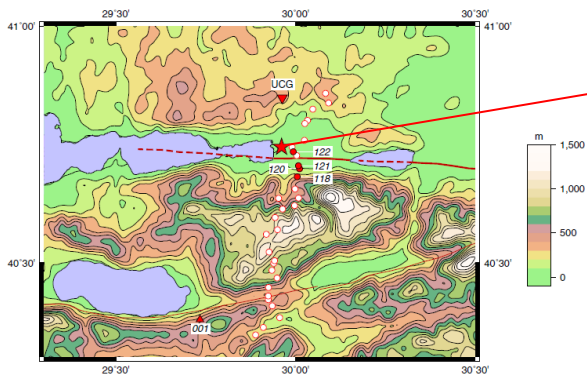
Erzincan segment



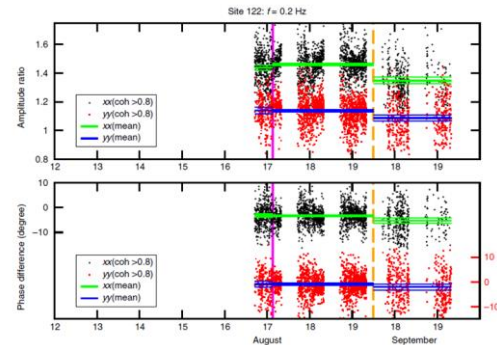
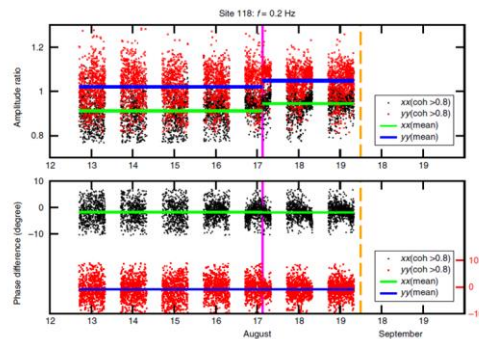
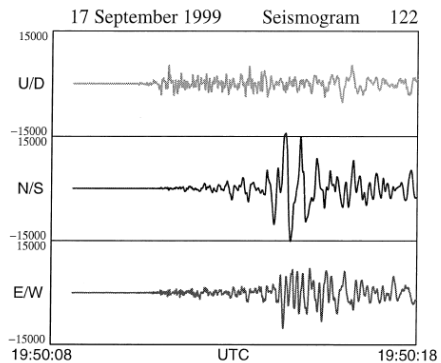
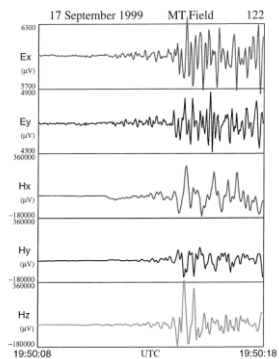
Türkoğlu et al., PEPI, 2015

North Anatolian Fault (West)

1999 İzmit Earthquake data

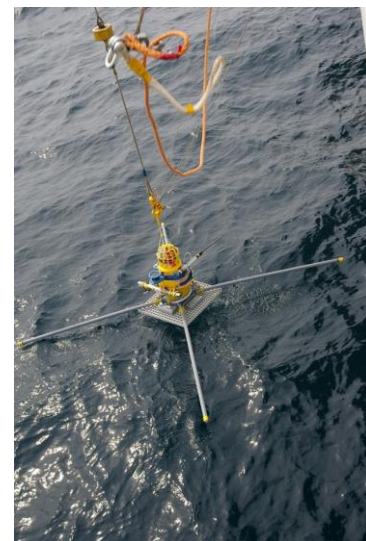
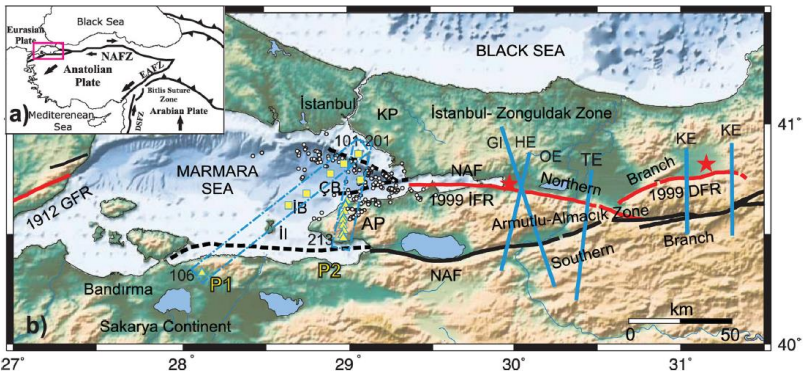


17 August 1999 İzmit Earthquake
M: 7.4



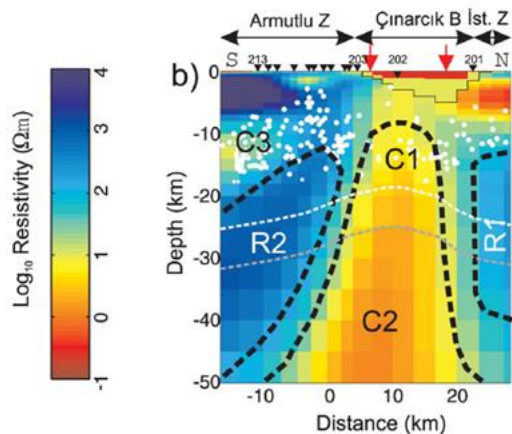
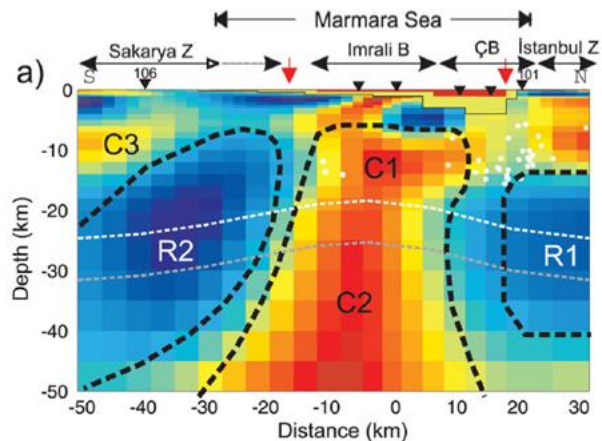
North Anatolian Fault (West) (2D)

Marmara Sea – OBEM

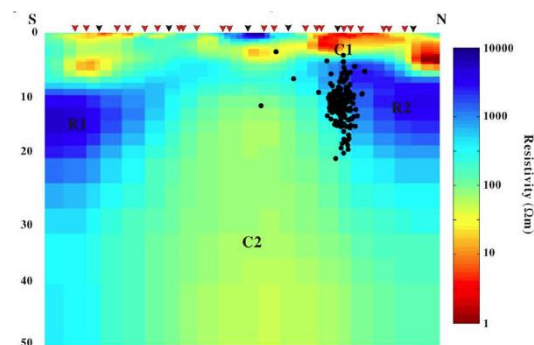
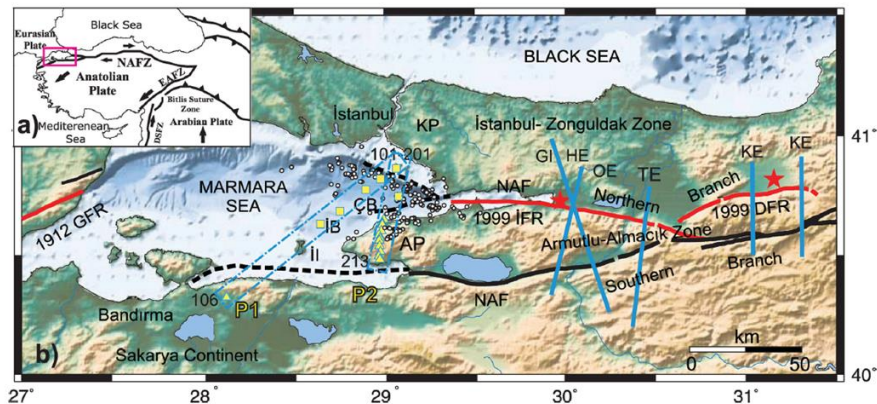


North Anatolian Fault (West) (2D)

Marmara Sea – OBEM



Kaya et al., GJI, 2013



Tank et al., PEPI, 2005

North Anatolian Fault (3D)

Near Tosya

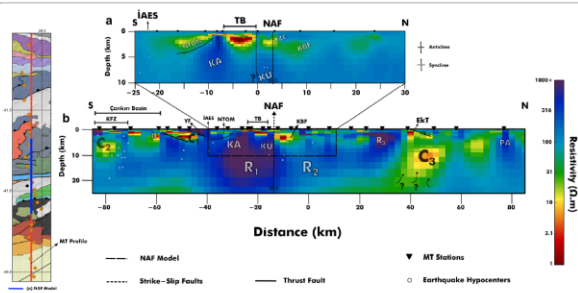
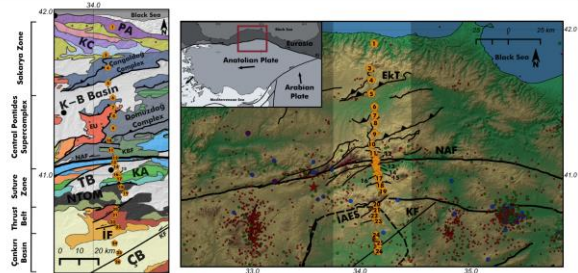
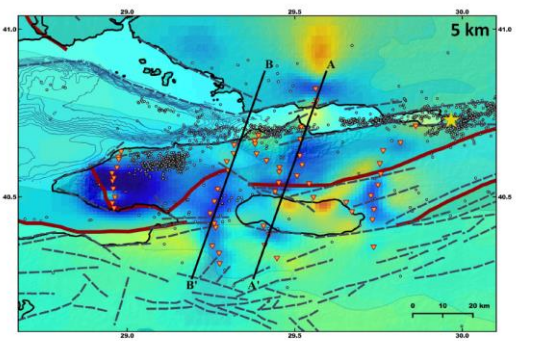
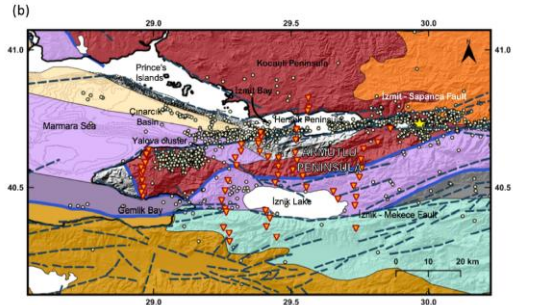
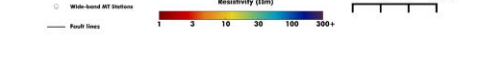
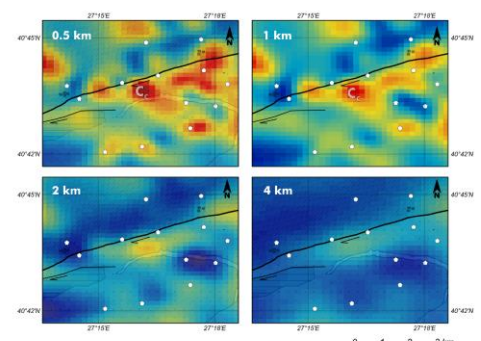
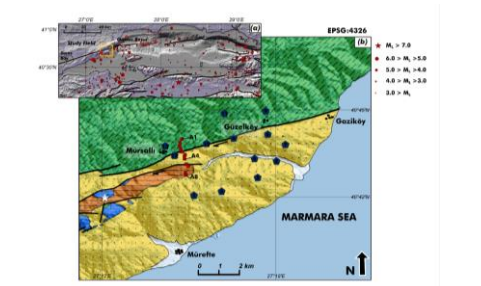


Fig. 4 Cross sections from the **a** regional and **b** NAF model with interpretation. White dots represent the earthquake hypocenters taken from the IC catalogue, IAES Izmir-Ankara-Erzincan Suture, EAF Ekinveren Thrust / Incek Formation, KA Kösdagı Arc, KU Kunduz Unit, ABF Kirazlıyay Formation, KZ2 Kızılkirmak Fault Zone, NAF North Anatolian Fault, NTGM Neo-Tethyan Ophiolitic Melange, PA Pontide Arc, TB Tosya Basin, YF Yayılagayı Formation.

West of Izmit



Ganos



Conclusion 1 – Eastern Mediterranean

2D vs. 3D

NAF

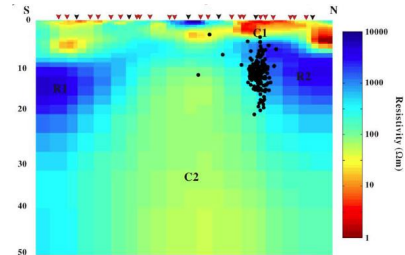
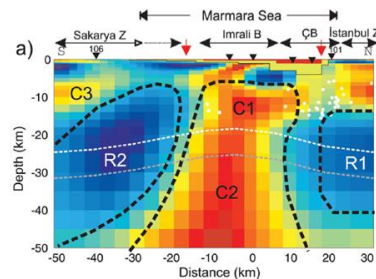
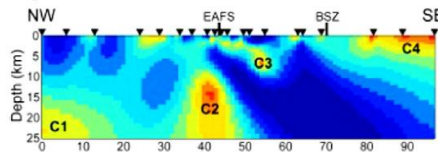
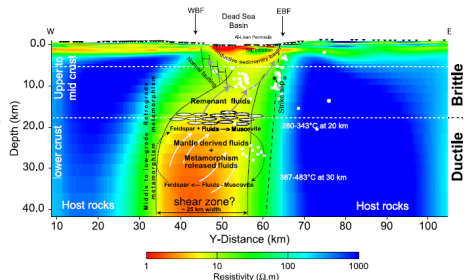
DSTF

EAF

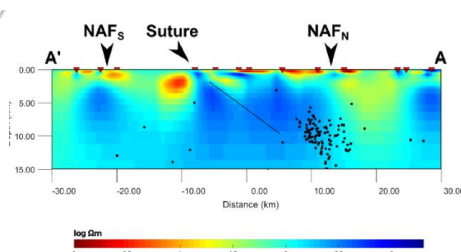
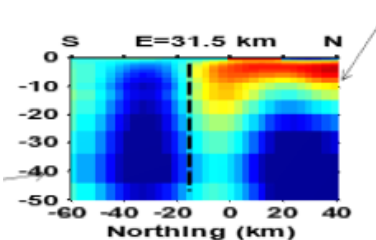
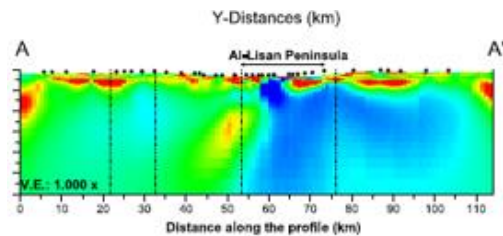
OBEM

Land

2D



3D



Meqbel et al. GJI, 2013; 2016

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

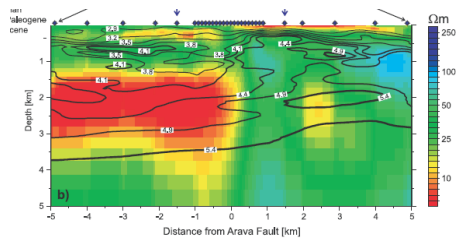
Kaya et al., GJI, 2013;
Karaş et al., Tectonophysics, 2020;
Tank et al., PEPI, 2005

Conclusion 2

Shallow structure
Fault Zone Conductors - Comparison

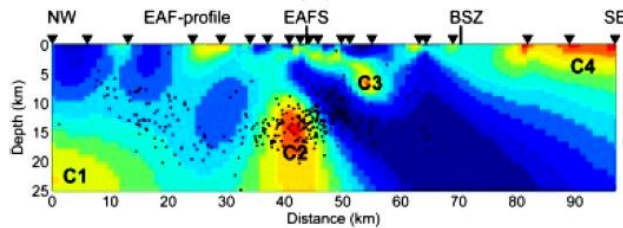
DSTF : No FZC
NAF : Surface – 0.7 km (locked)
SAF : Surface – 3 km (locked)
Surface – 6 km (creeping)

DSTF

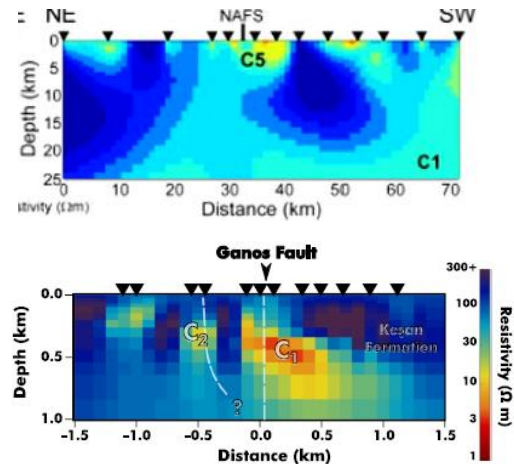


Ritter et al., GRL, 2003

EAF



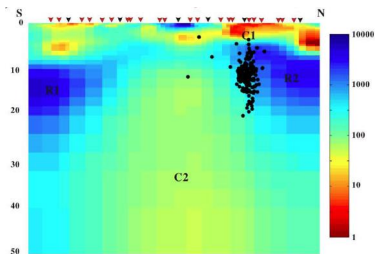
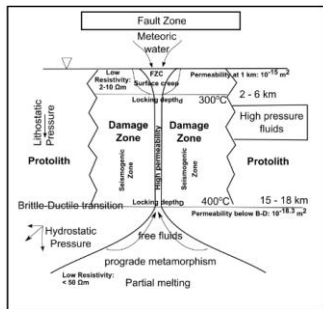
Türkoğlu, PEPI, 2015



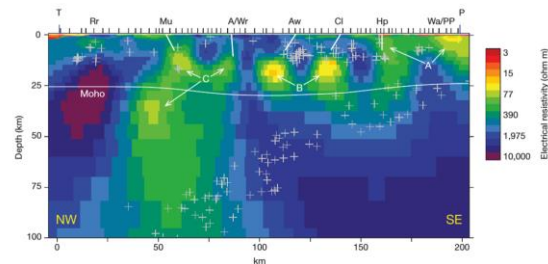
Karaş et al., EPS, 2017

Conclusion 3

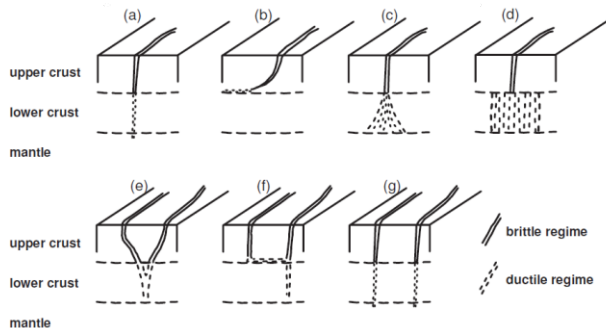
Deep structure Comparison



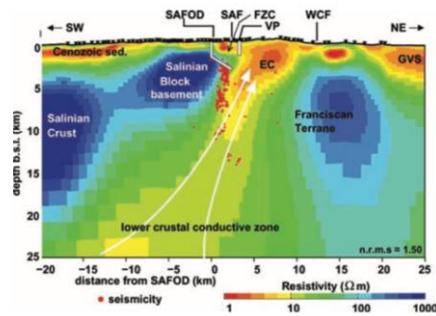
NAF – Tank et al., 2005



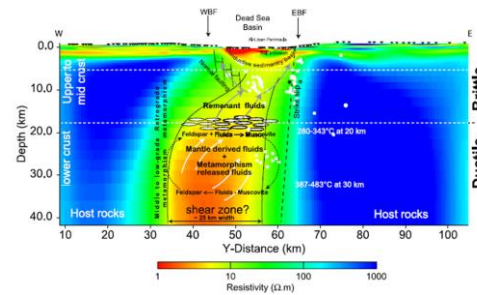
Alpine Fault – Wannamaker et al., 2009



Ritter et al., Spec. Pub, 2005



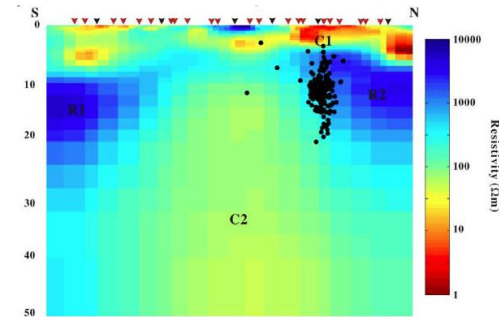
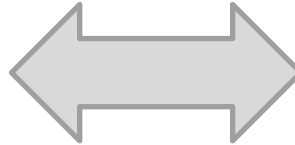
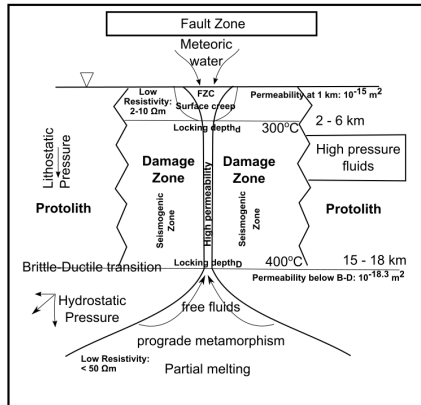
SAF - Becken et al., 2008



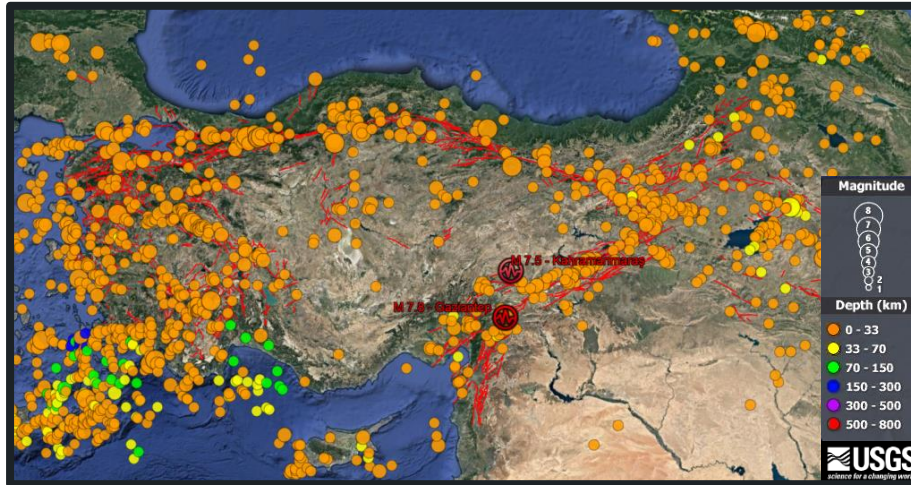
Meqbel et al., 2013; 2016

Conclusion

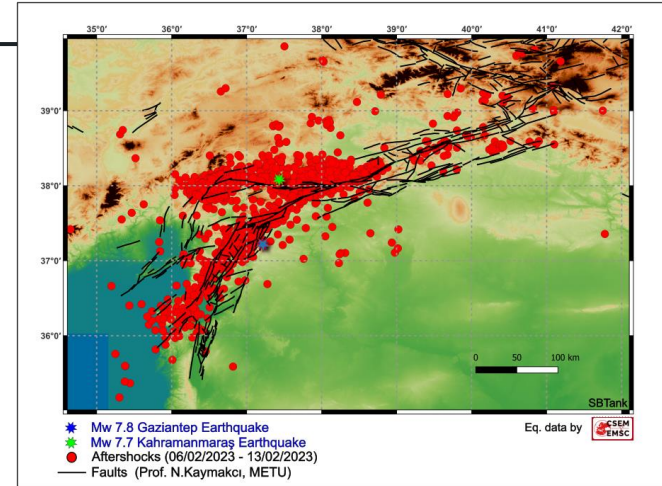
- Fluids may have an essential role in the earthquake generation
- Fluid presence at a fault zone can be detected by using EM methods almost at all depths
- Narrative review based on electrical structure of transform faults
- Historical and global perspective to the topic
- Three major transform faults of the eastern Mediterranean



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

S.Bülent Tank: bulent.tank@boun.edu.tr
 B.U. Kandilli Obs. E.R.I., Geophysics Dept.
 34684, Çengelköy, İstanbul, Turkey