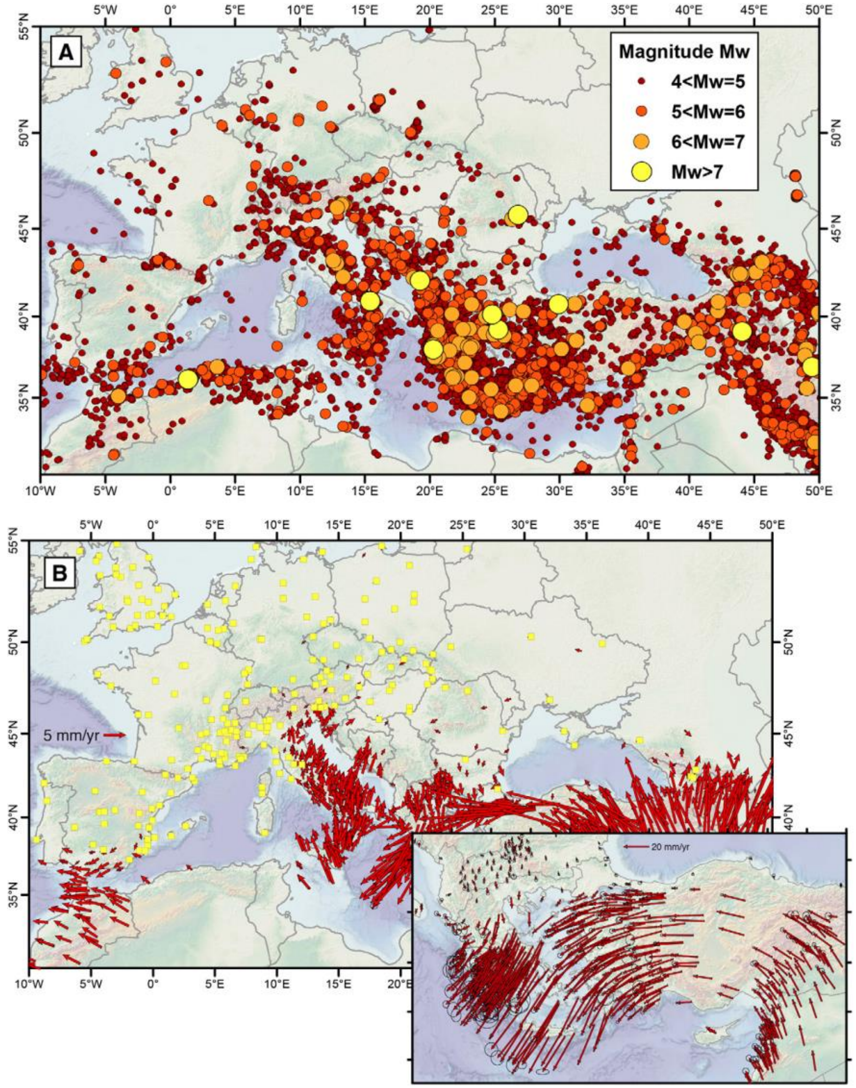
On-going motion in the Alps-Mediterranean



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&

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SPP-Short Course "Understanding the Alpine Mediterranean chain – a primer"

Berlin, January 31 2019

LECTURE OUTLINES

- GNSS
  - strength & limits
  - A few definitions
  - High precision positioning principles
  - Precision/accuracy
  - Reference frame

- Analyzing GNSS horizontal velocity field
  - Block models
  - Elastic blocks models
  - Strain rate from horizontal velocities
  - The thin viscous sheet model
  - Alternative models

- Plate and non-plate motion in the Mediterranean
  - Western Mediterranean
  - Central Mediterranean
  - Eastern Mediterranean

- Perspectives

GEODESY STRENGTHS & LIMITATIONS

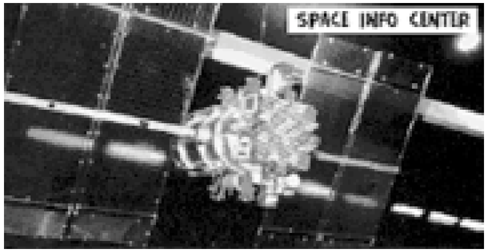
- Geodesy provides a quantitative description of motion at the surface of the Earth

- Strengths
  - Consistent over spatial scales: from meters to global scale
  - Time scales: a few Hz (seismic waves) to a few decades
  - Precision: ~mm for position, a few tenth of mm/yr for rates
  - 3D displacements, although the vertical component is less precise

- Limitations
  - The measurements are only at the surface
    - Physical models are required to make inference of processes at depth
  - Spatial geodesy only works for emerged lands
    - Sea floor geodesy is difficult, expensive and little developped in Europe
  - Time scale is short for some geological and geophysical problems
    - Mantle dynamics
    - GIA

FROM GPS TO GNSS

GNSS is the Global Navigation Satellite System



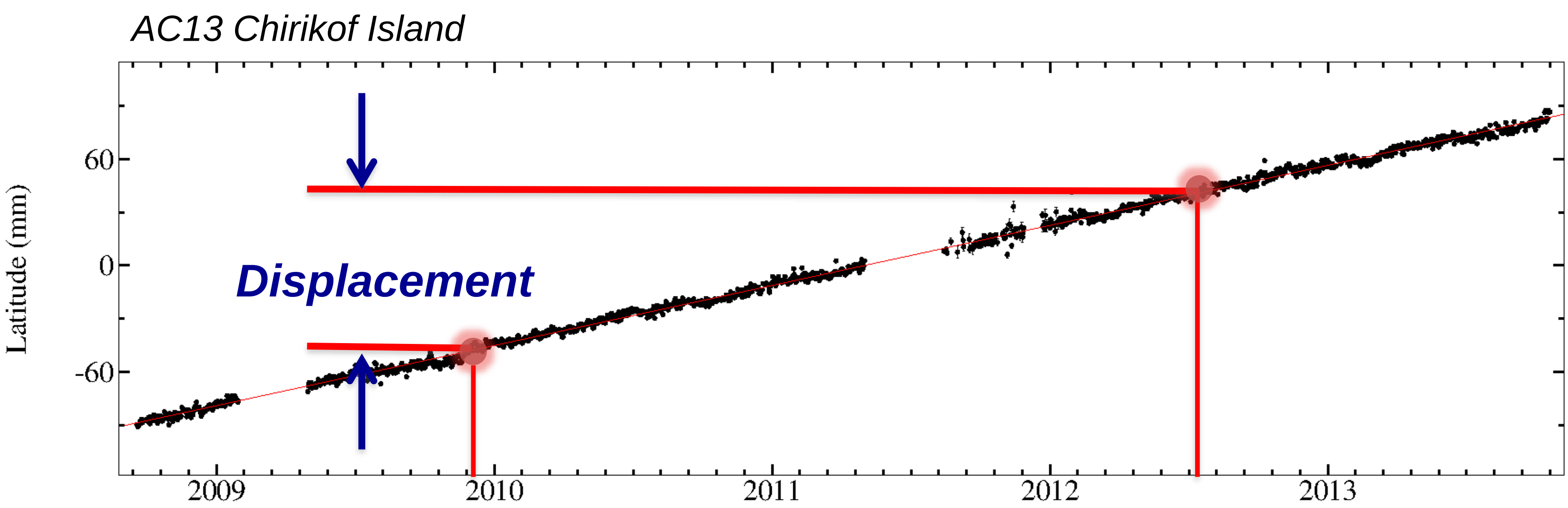
It includes

- GPS and its enhancement (additionnal code)
- GLONASS : russian system
- SBAS (Satellite Based Augmentation System) is a system that supports wide-area or regional augmentation through the use of additional satellite-broadcast messages.
- European Galileo
- Chine COMPASS
- Indian IRNSS
- Japanese QZSS

All systems are (or should be) inter-operable

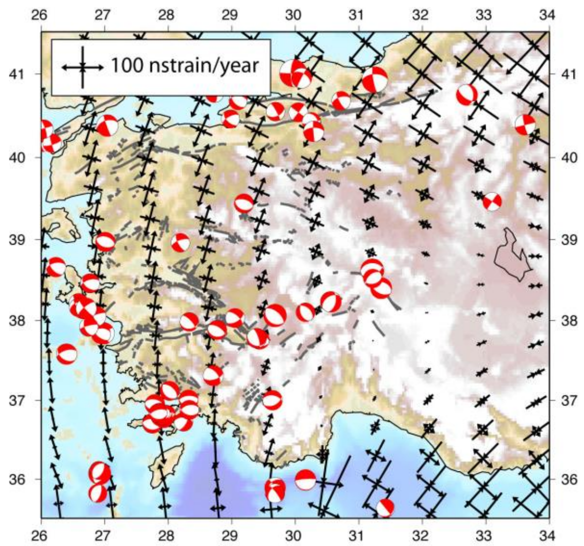
- Raw data (rinex v3)
- Orbits

Some definitions:Time Series and Displacement



- ***Displacement*** is the change in position from one time to another time – units are m or mm
- ***Velocity*** is the displacement rate, the time derivative of displacement, usually assumed to be constant over time – units are m/yr, mm/yr or m/s
- Displacement and velocity depend on the ***reference frame***, the coordinate system adopted.

Some definitions: Strain & Strain rate



- ***Strain*** or ***deformation*** is the relative displacement divided by the distance – it is dimensionless, although nstrain (10^{-9}= 1 mm over 1000 km) is often used. Strain is a 2D 2x2 (horizontal) or 3x3 tensor.

- ***Strain rate*** is the time derivative of strain, usually assumed to be constant over time – units is 1/s or nstrain/yr

- Strain and strain rate are largely independent of the ***reference frame***

- Strain & strain rate can be related to stress using rheology

Not all Displacements are Tectonic

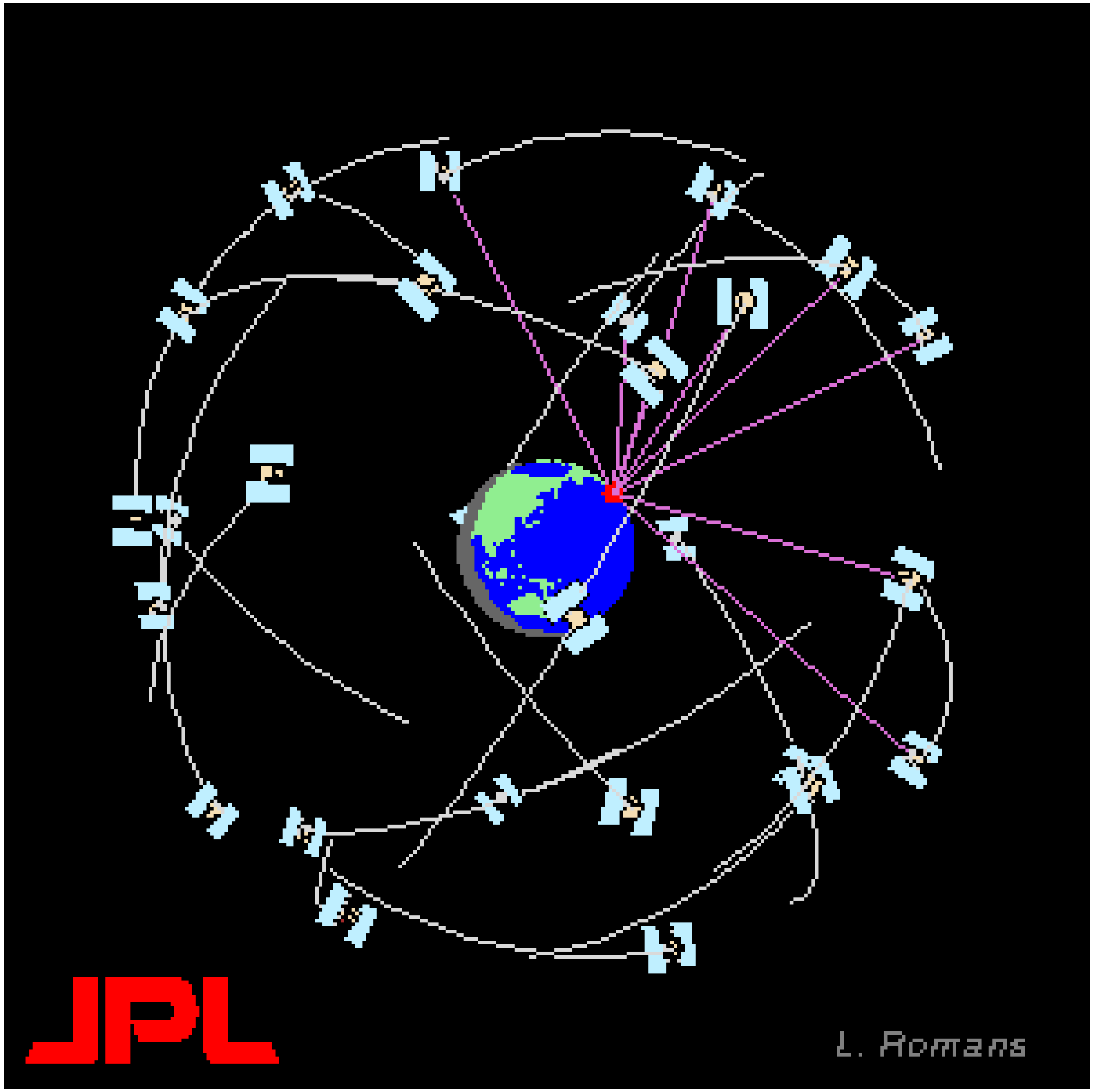
- Measurement biases can cause apparent displacements
  - GPS antenna changes
  - Inadequate modeling of sub-daily movements

- Real deformation caused by
  - Surface loading (hydrology, cryosphere)
  - Subsurface fluid addition/removal
  - Volcanism

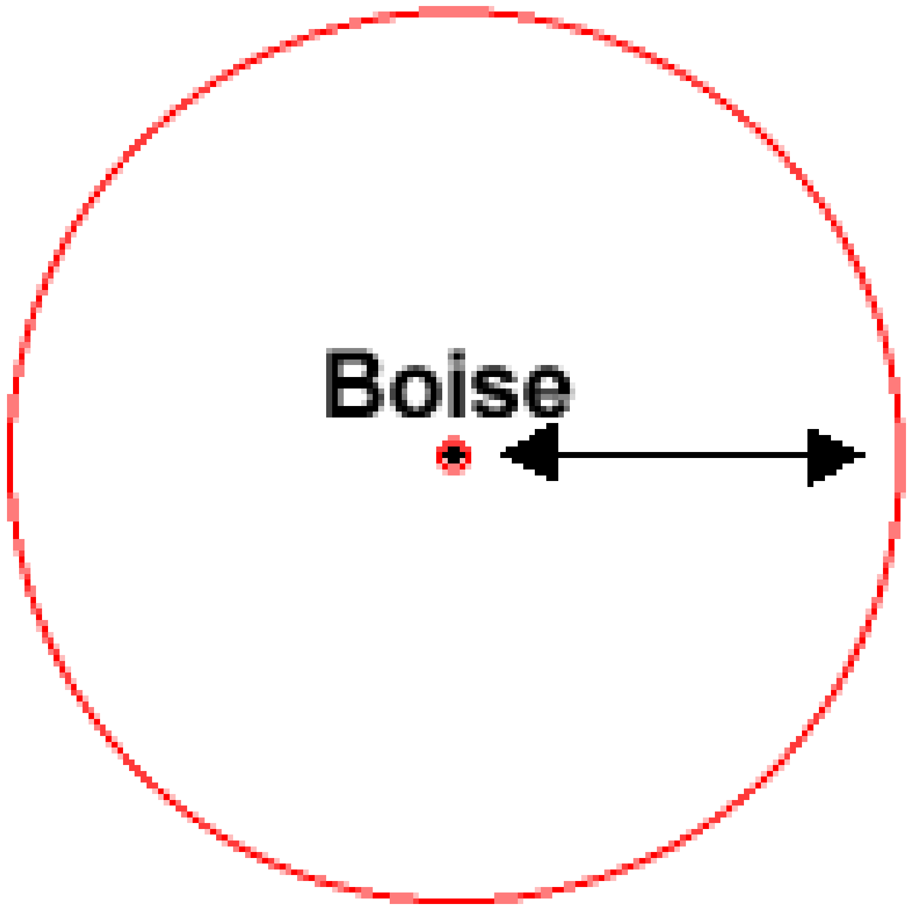
Not all Motions are Steady in Time

- Loading, non-tectonic deformation
- Sudden events (earthquakes)
- Slip Transients
- Postseismic Deformation
  - Afterslip on fault plane
  - Viscoelastic relaxation in the mantle
  - Poroelastic relaxation

GPS: the space segment

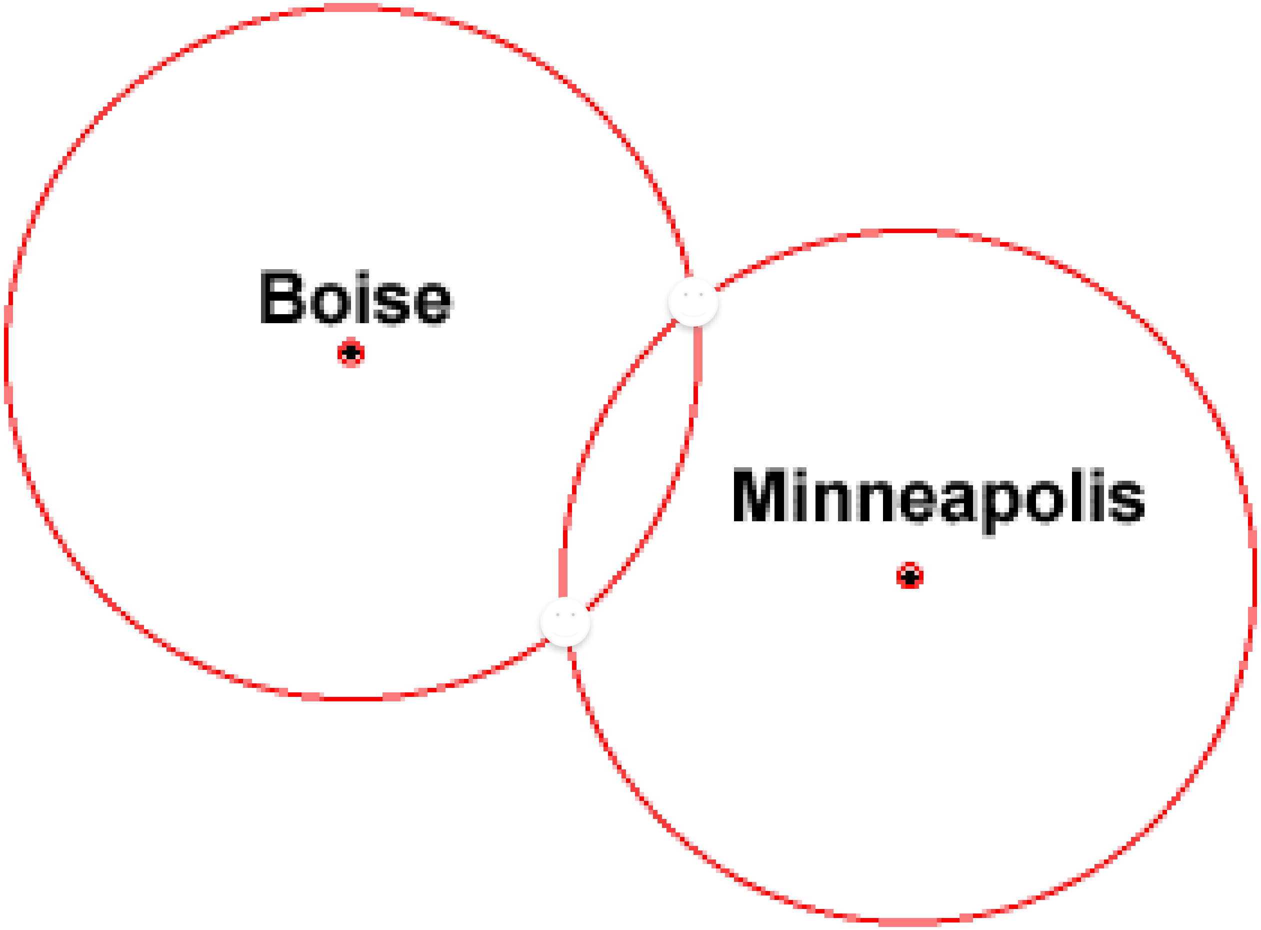


Positioning By Ranging 1



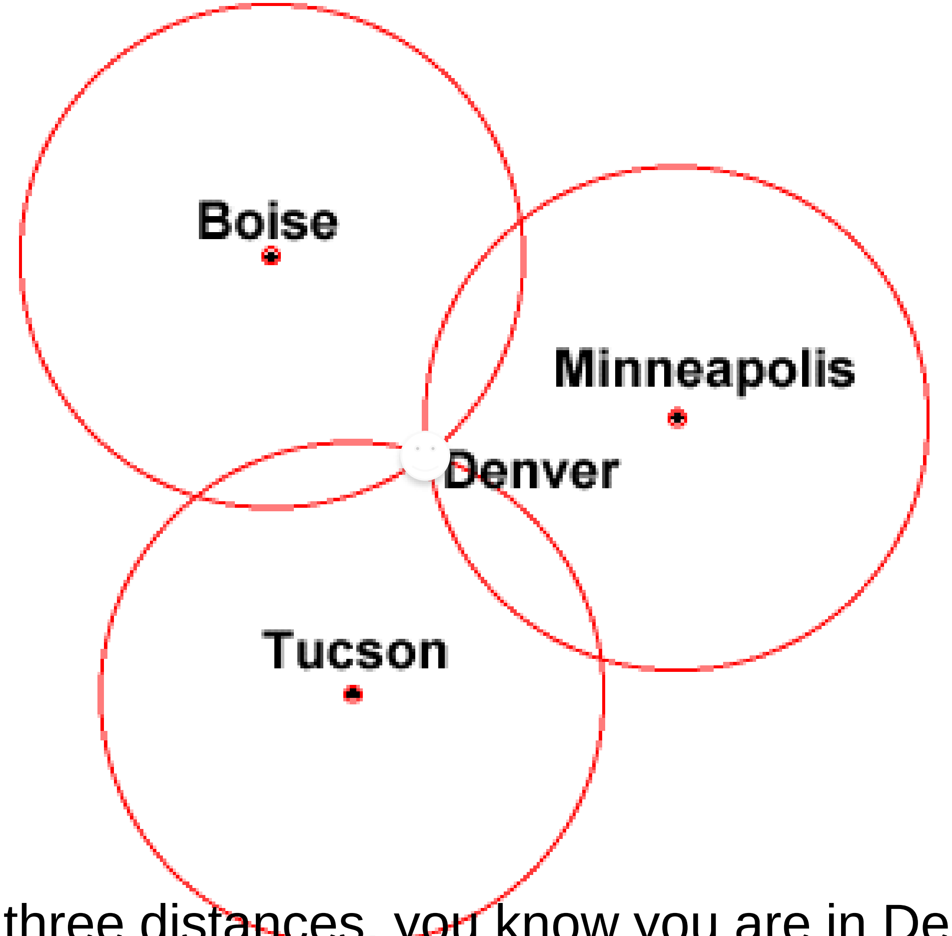
A 2D example: If you know you are a certain distance from Boise, your position could be anywhere on the circle.

Positioning By Ranging 2



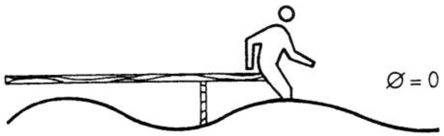
With two distances, you know you are at one of two points.

Positioning By Ranging 3



With three distances, you know you are in Denver.
In 3D the circles become spheres, and with three distances you still have two possible locations – one on the surface and one out in space.

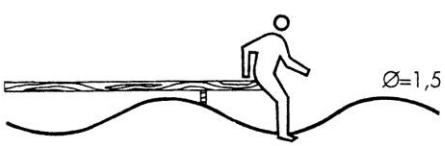
GPS: the phase measurement



On commence à compter quand l'amplitude est maximum : la phase vaut 0.

Une demi période plus tard, l'amplitude est minimum et la phase vaut 0,5.

Chaque fois qu'on retrouve l'amplitude maximum, on augmente le nombre de cycles d'une unité.

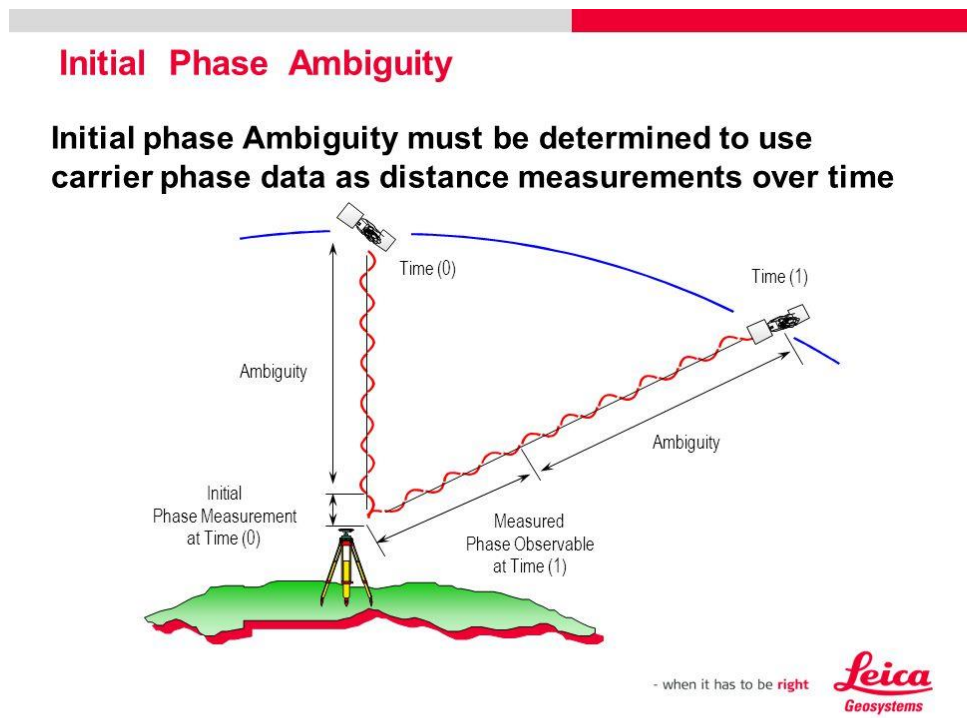


Une amplitude minimum correspond à un nombre non entier de phases.
Au fait, combien de vagues sont passées?

- Millimeter precision positioning requires to record another type of observation called "phase"

- This was first proposed by geodesists from the University of Bern (Switzerland)

- The phase can be measured with a 0.3 mm accuracy



Millimeter accuracy positionning requires a lot of corrections and processing

- Satellite and Clock errors
  - Removed by differentiating the phase
  - Absolute information is partially lost: see the reference frame issue

- Propagation errors
  - Ionosphere:
    - Ionosphere as effect of up to 20 m
    - Ionosphere is dispersive for electro-magnetic waves, so GNSS use several frequencies to be able to correct for this effect
  - Troposhere
    - Both the effect of pressure, temperature and water content induce delays of the waves
    - Models + stochastic parameters corrections

- Small short term motion
  - Solid earth tide induce ~30 cm motion every 12 hours
  - Ocean dynamics induces loading and elastic deformation

- Antennas have bias which depend on the elevation and azimuth of the line of sight
  - Antenna need to be calibrated

SURVEY MODE GPS & CONTINUOUS GPS (CGPS)

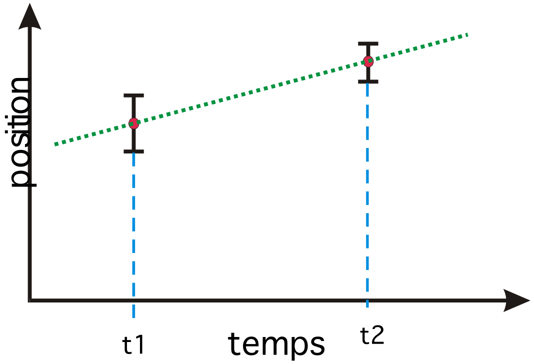
GPS measurements for tectonic can be used in two modes: survey mode & continuous GPS (CGPS)

Survey-mode: a small marker in drilled in a rock. A system ensure that the antenna is set up at the vertical of the marker. The marker is observed from 8 to 48 hours

Survey-mode is

- less expensive
- does not require continuous power
- does not require security
- enables dense network

$$V=(X_2-X_1)/(t_2-t_1)$$

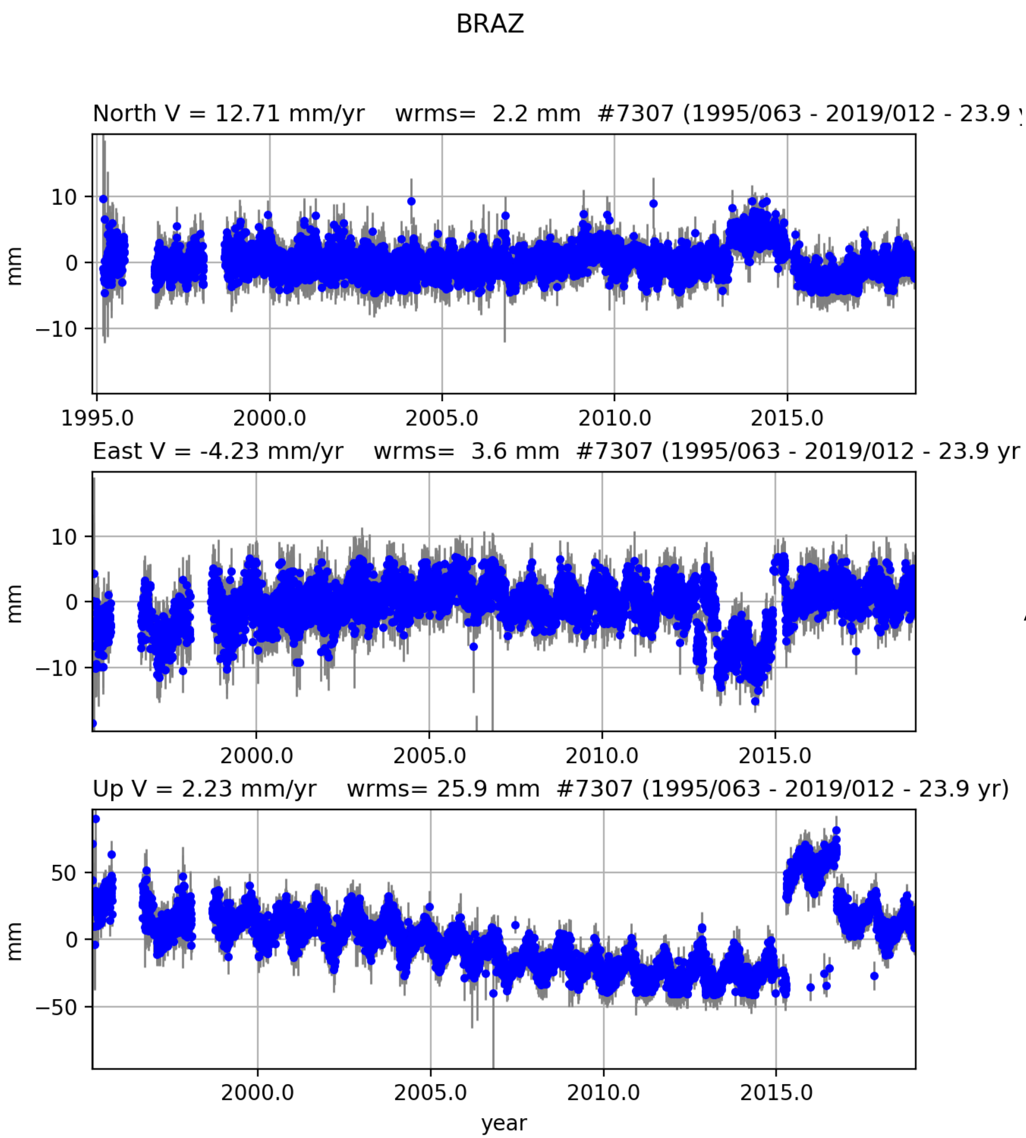


It often requires the assumption that velocity are constant over time

Less precise: centering errors, change of equipment

Ignore seasonal variations

CONTINUOUS GPS (CGPS)



A permanent fixation system is used

Requires power and security

Provides the highest accuracy

- daily solutions
- Enables error analysis

EPOS will publically provide velocity field, time series, strain rate map in the next years

https://www.epos-ip.org/

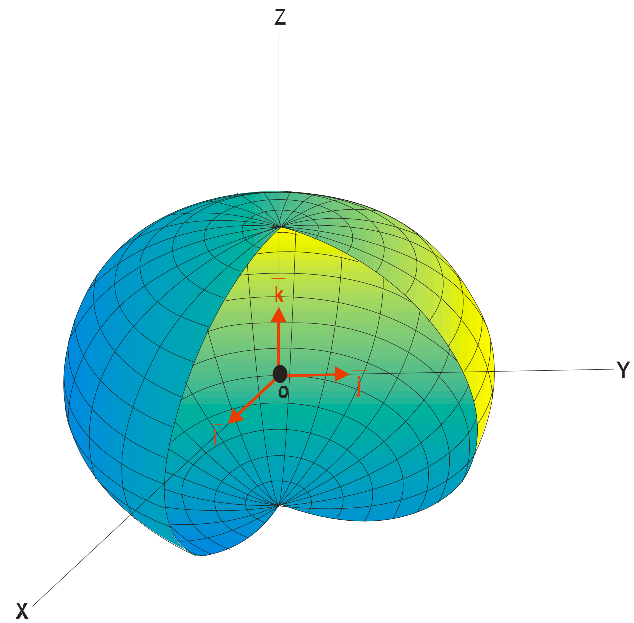
The Reference Frame Issue (1)

• Because the most accurate positioning is obtained using double-differences of phase, free solutions are produced where part of the information about the "absolute » position is lost during the data reduction

• A second step in the processing is required to express coordinates (position & velocity) in a reference frame, which should be stable through time

• This procedure is known as reference definition or stabilization

• It consists in estimating a translation, a small rotation and a scale factor (and possibly their rate of change) with respect to an external reference frame. This transformation is known as Helmert transformation



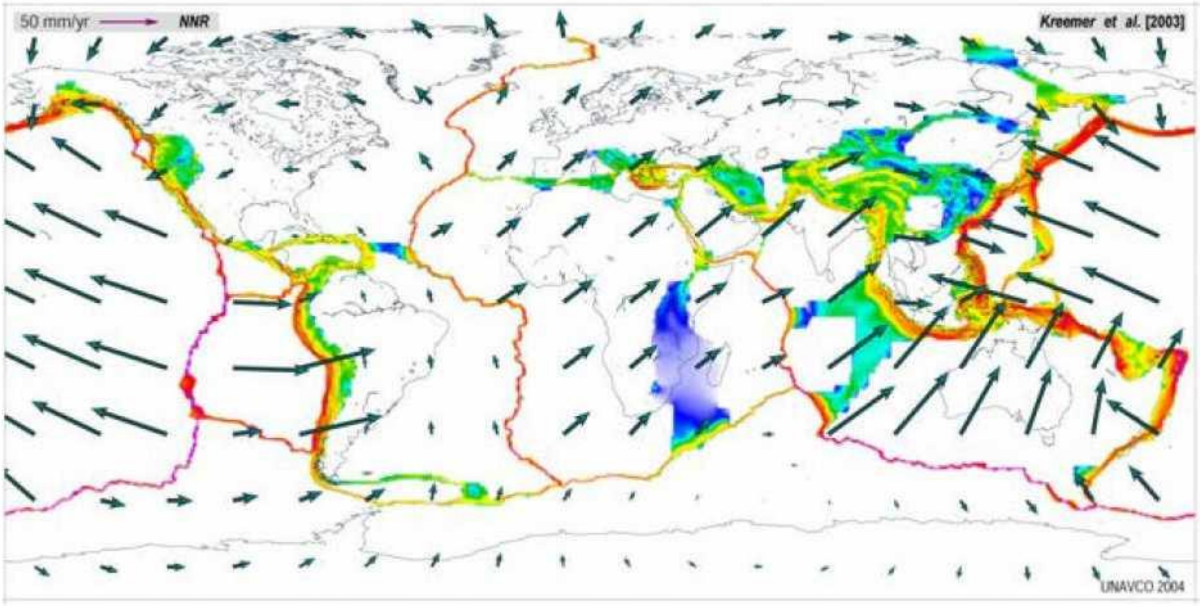
The Reference Frame Issue (2)

• The external reference frame is usually the International Terrestrial Reference Frame (ITRF) which is updated every 3-4 years by the IERS

• The ITRF is derived from a combination of VLBI (scale), SLR (origin) and GPS global solutions. The orientation is conventional. The combination is made at IGN-France

• The orientation rate is taken as a No-Net-Rotation condition (NNR). It provides a pure geodetic reference frame for velocities

• The physical meaning of the global (horizontal) NNR-frame is not clear. It is significantly different from the Hot Spot frame (up to 4-5 cm/yr)



INTERPRETING GPS VELOCITY FIELDS

- When reading a GPS paper, the first question to ask is

  In which reference frame is the velocity field expressed?

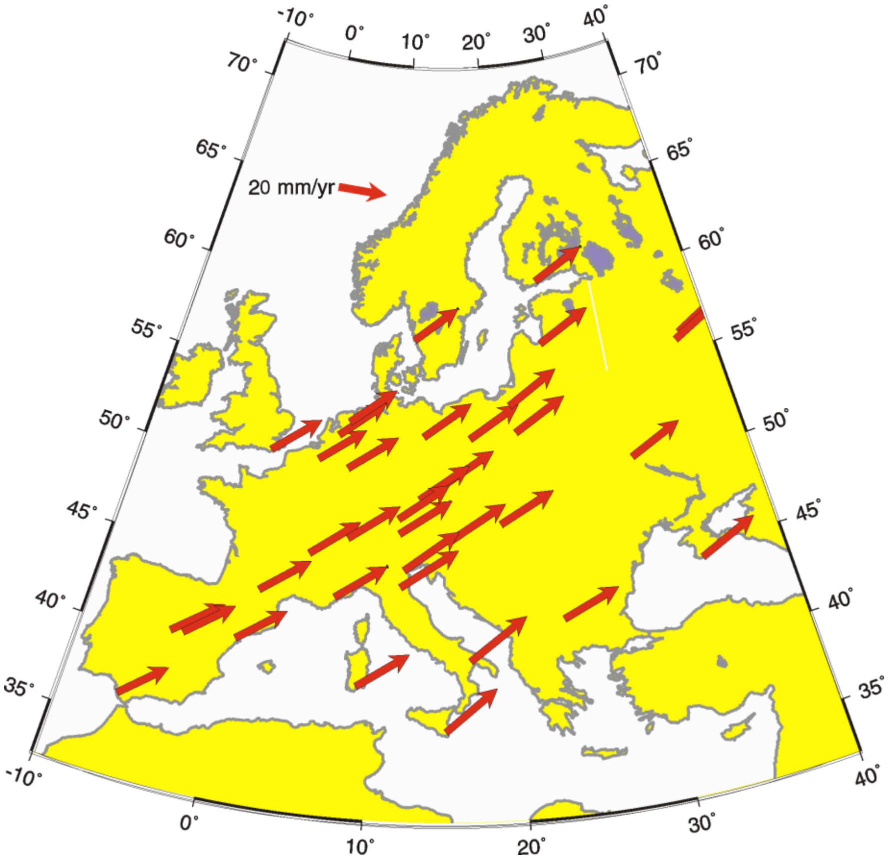
- Since orbits are expressed in the global reference frame ITRF, positions are expressed in the ITRF and hence the raw velocity field is expressed in the ITRF in XYZ geocentric coordinates

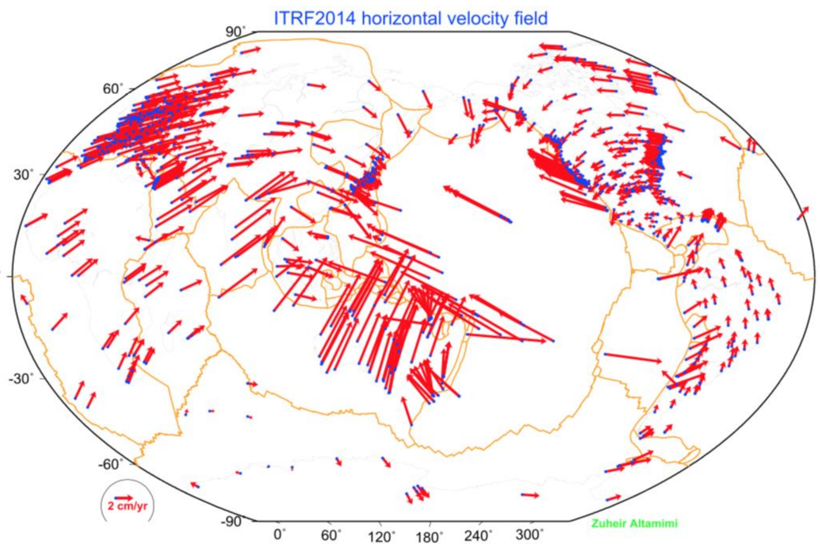
- In many papers, the supplementary material provides the velocity field expressed in the ITRF, but in East-North (and Up) coordinates

- At a first order, the horizontal velocity field in the ITRF shows the motion of plate in a NNR reference frame

- This is not very usefull for tectonic interpretation and further analysis is required

Velocity field in Europe wrt ITRF





Rigid block (or plate) analysis

- Constant velocities do not mean that there is no deformation
- Different velocities do not mean that there is deformation
- Hypothesis: localized deformation
  - Some areas show a small level of internal deformation
  - Narrow zones accommodates the relative motions of blocks or plates
- If true, the kinematics can be described in terms of rotation on the sphere. The searched parameters are the rotation rate vectors
- Rotation rates vectors have units of rad/yr. They also can be expressed as Euler poles (long./lat./angular velocity in deg./Myr)
- If true, the deformation pattern at the block or plate boundaries is correctly predicted by the relative motion of blocks (or plates)

Plate kinematics

- The motion on the sphere (that is the horizontal motion) for any point belonging to a rigid shell (that is a plate) can be written as:

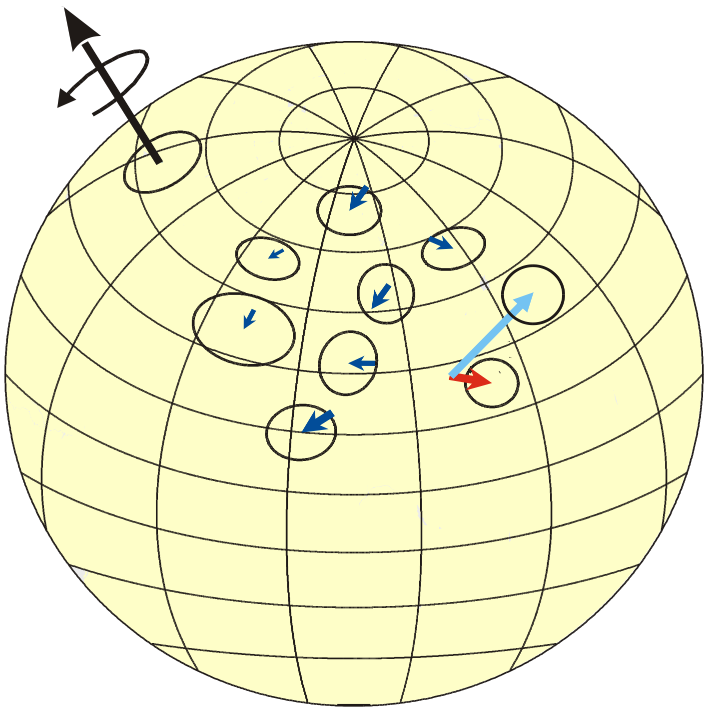
$$v(M) = \dot{\omega} \times r_{OM}$$

where v(M) is the horizontal motion, w is the rotation rate vector and r_{OM} is the vector joining the center of the Earth to point M

- This relation is linear. It is used:
  - To estimate w, usuall by least-squares
  - To estimate the relative displacement along plate boundaries
  - To evaluate the level of possible internal deformation of plates
  - To find the location of block boundaries (together with additional information)

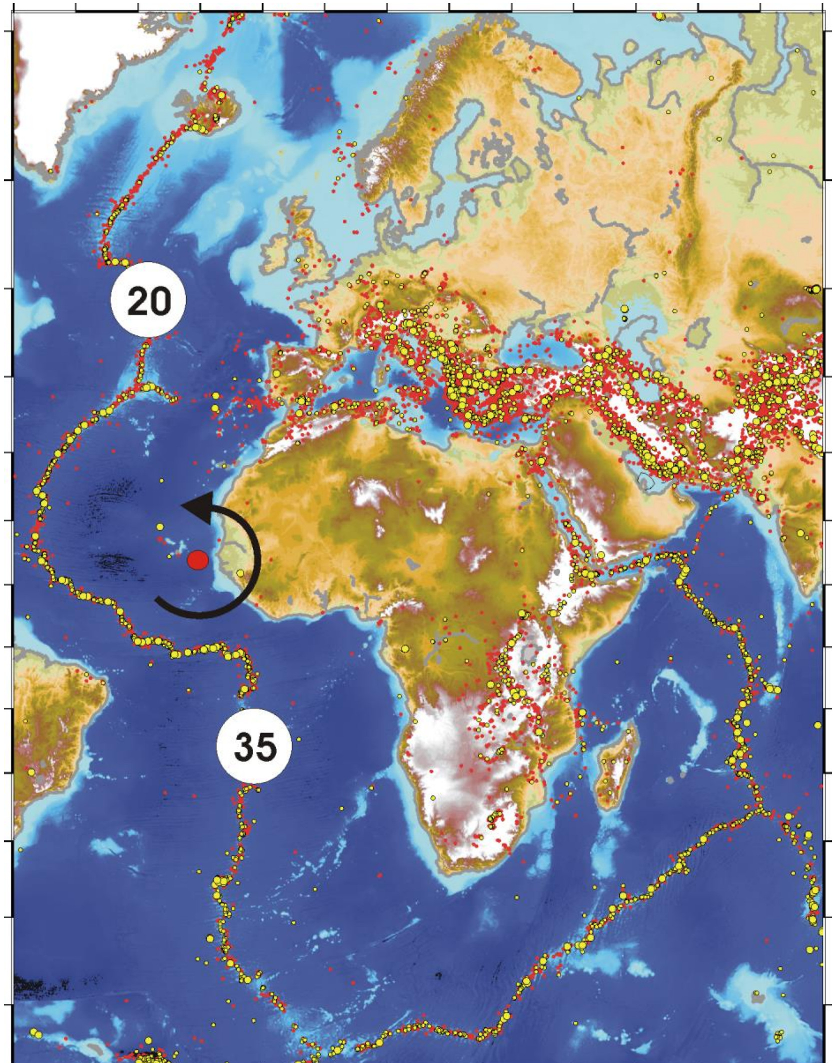
Euler pole

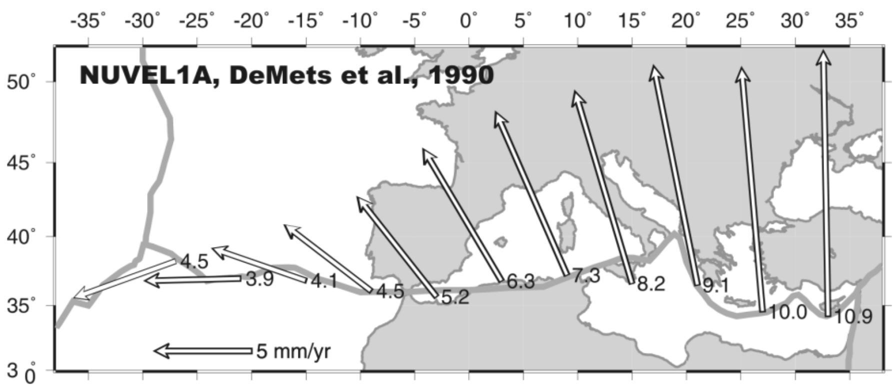
- w has units in rad/yr and 3 components in the XYZ geocentric cartesian frame
- Euler pole is a common representation of w. Euler parameters are (λ,ϕ) where w intersetcs the sphere with an angular velocity usually provided in deg/Ma.
- Euler pole is a useful repreresentation because the velocity is null at the pole location and velocities inside a plate rotate around the pole with a magnitude increasing with the sine of the angular distance to the pole.
- The uncertainties on the pole location are projection of the variance-covariance matrix in a local frame.



$$C_{\dot{\omega}}^{local} = T_{gen\rightarrow loc} C_{\dot{\omega}} T_{gen\rightarrow loc}^{T}$$

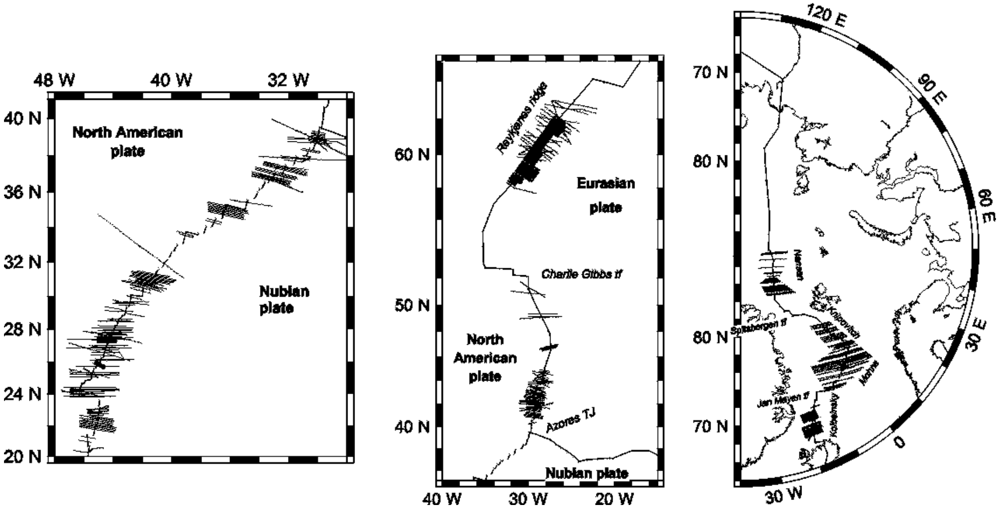
Africa (Nubia) / Eurasia (Europe) relative motion

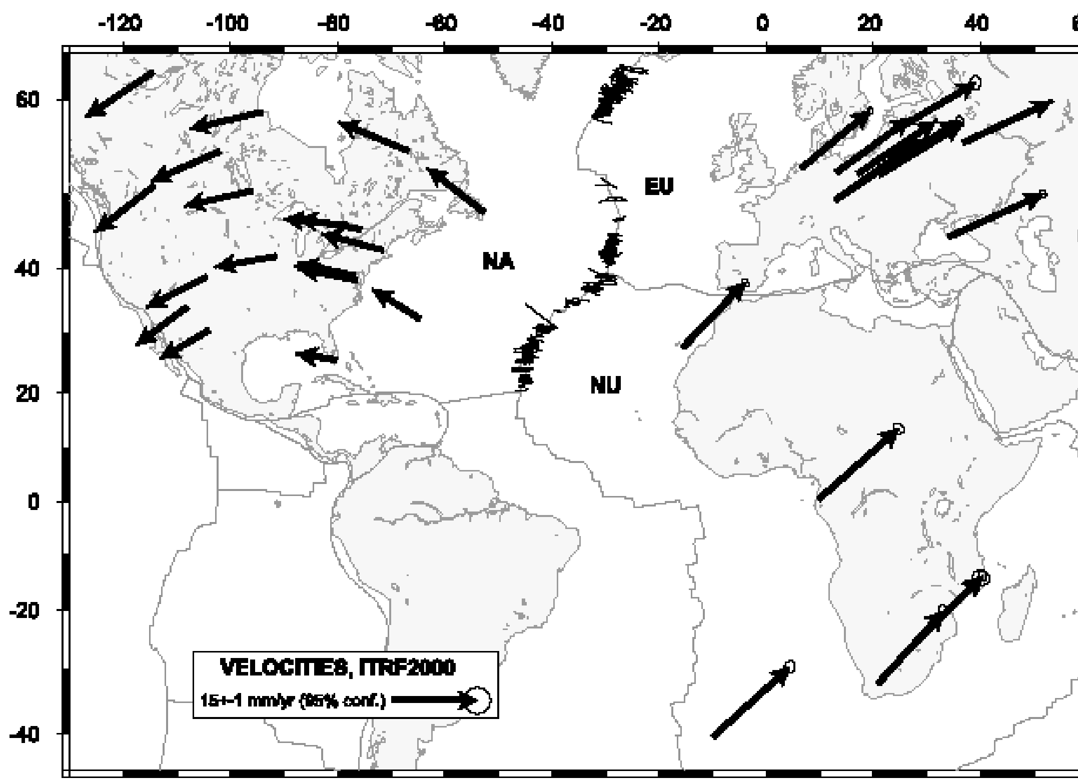




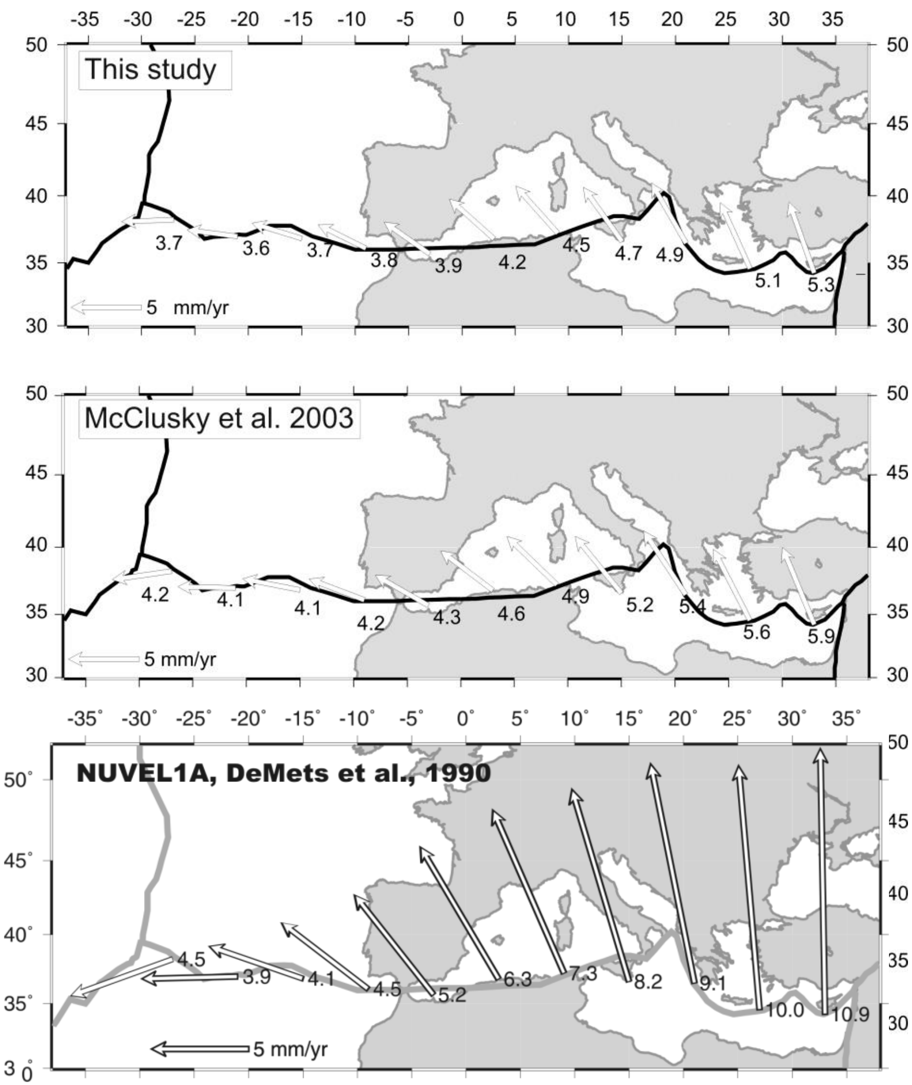
DeMets et al., 1990, 1994

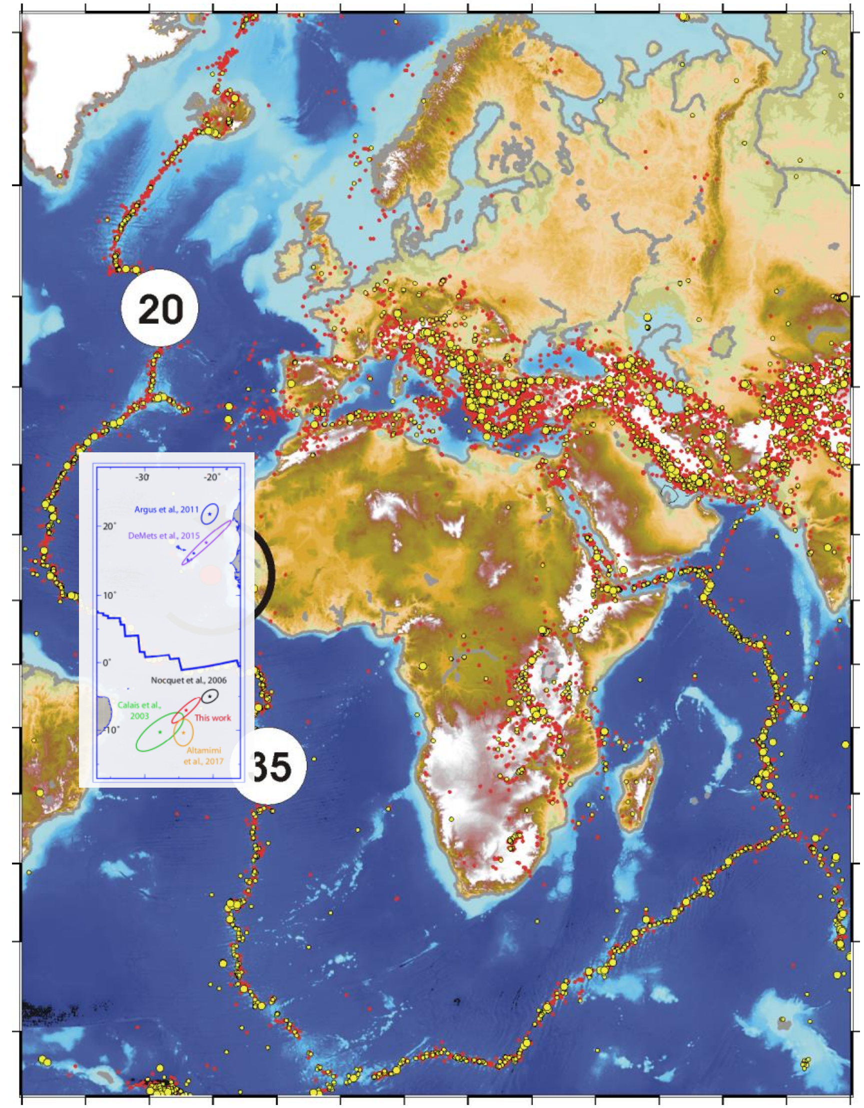
COMPARISON GEOLOGY (3 Myr) / GEODESY (20 years)



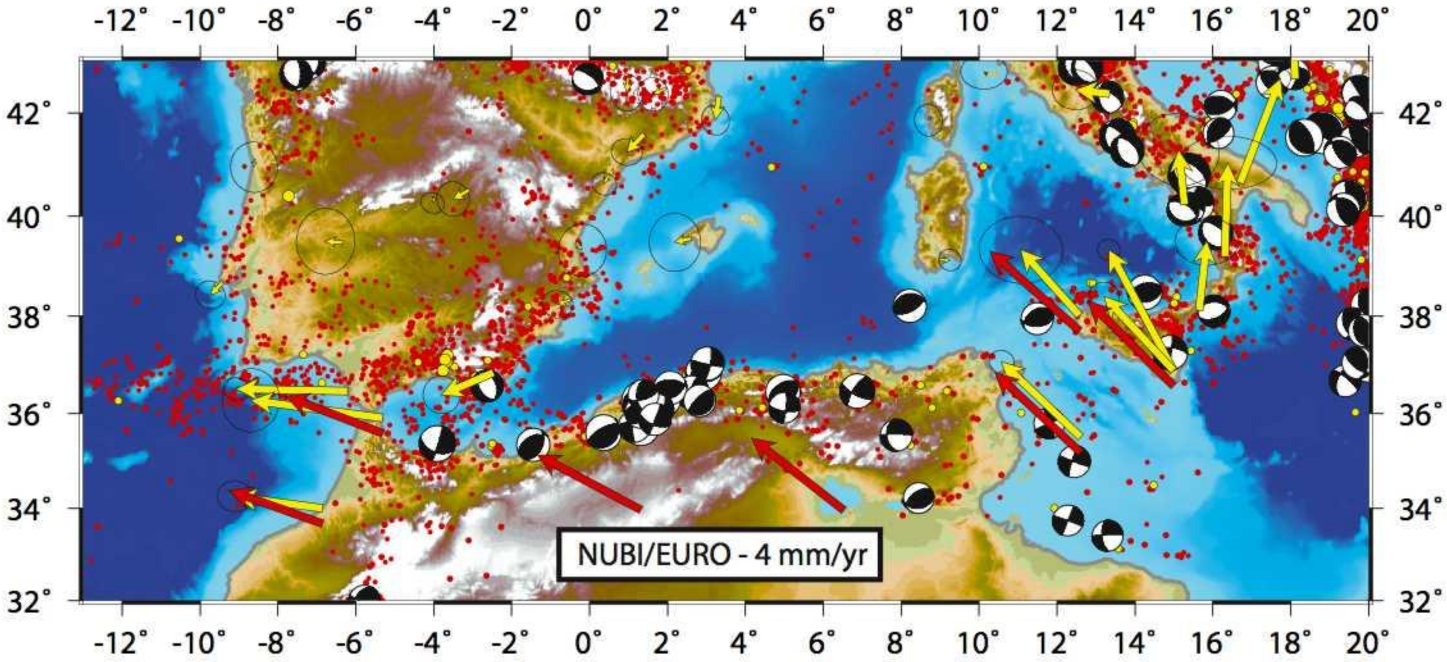


LA VITESSE AFRIQUE/EUROPE EN MEDITERRANEE





First insight into the Western Mediterranean



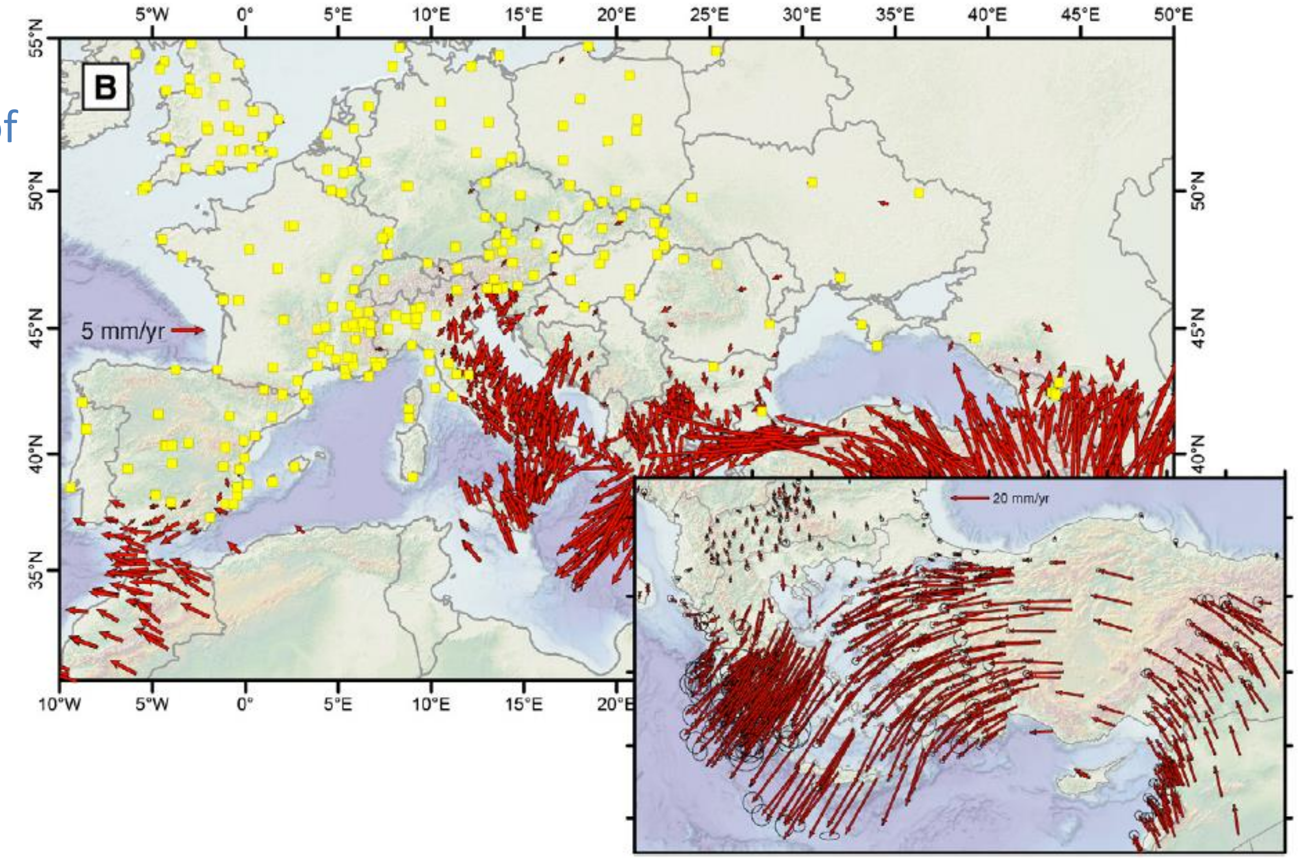
Review of GPS results in the Mediterranean

– Large scale organization of the kinematics

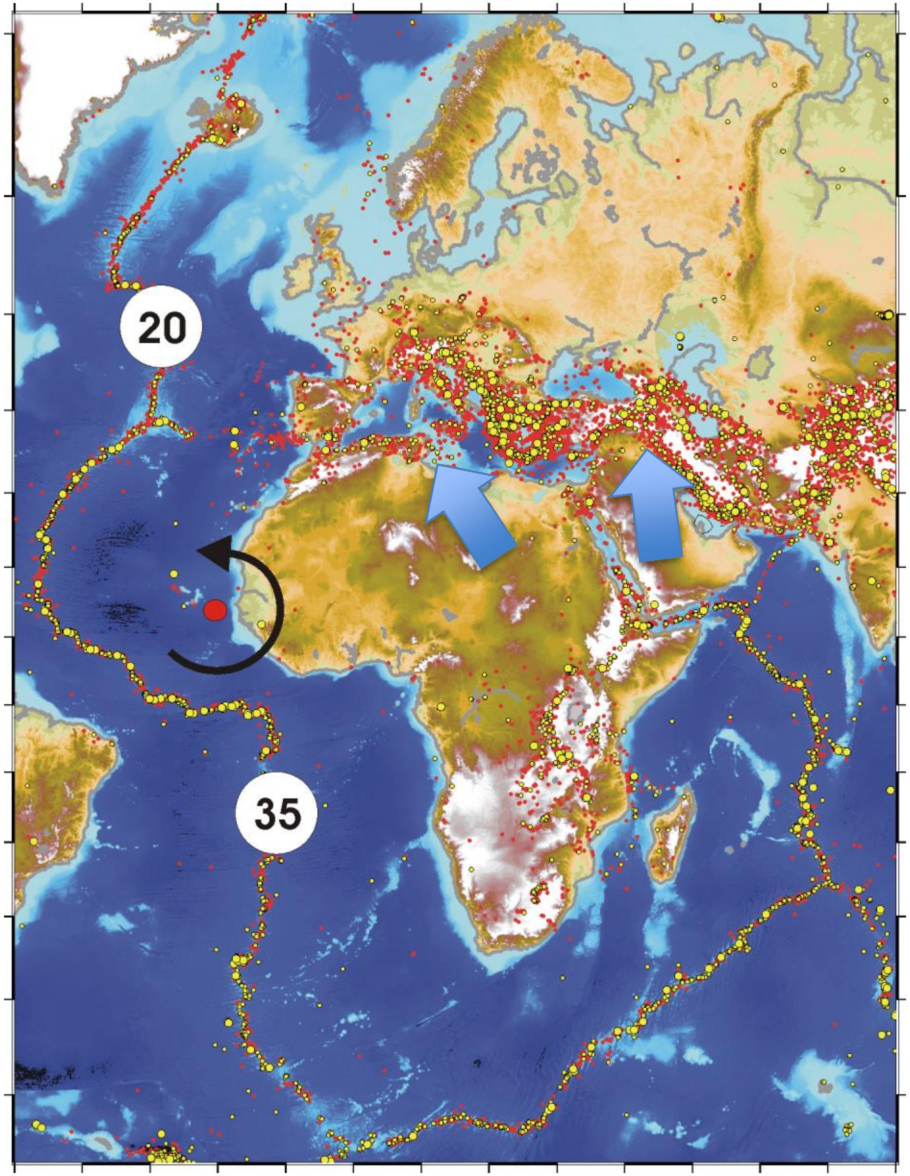
– Geodynamic processes – role of subduction – driving mechanisms of continental deformation

– Seismic hazard assessement: strain & fault slip rates

– Identify "holes" where kinematics remains unresolved

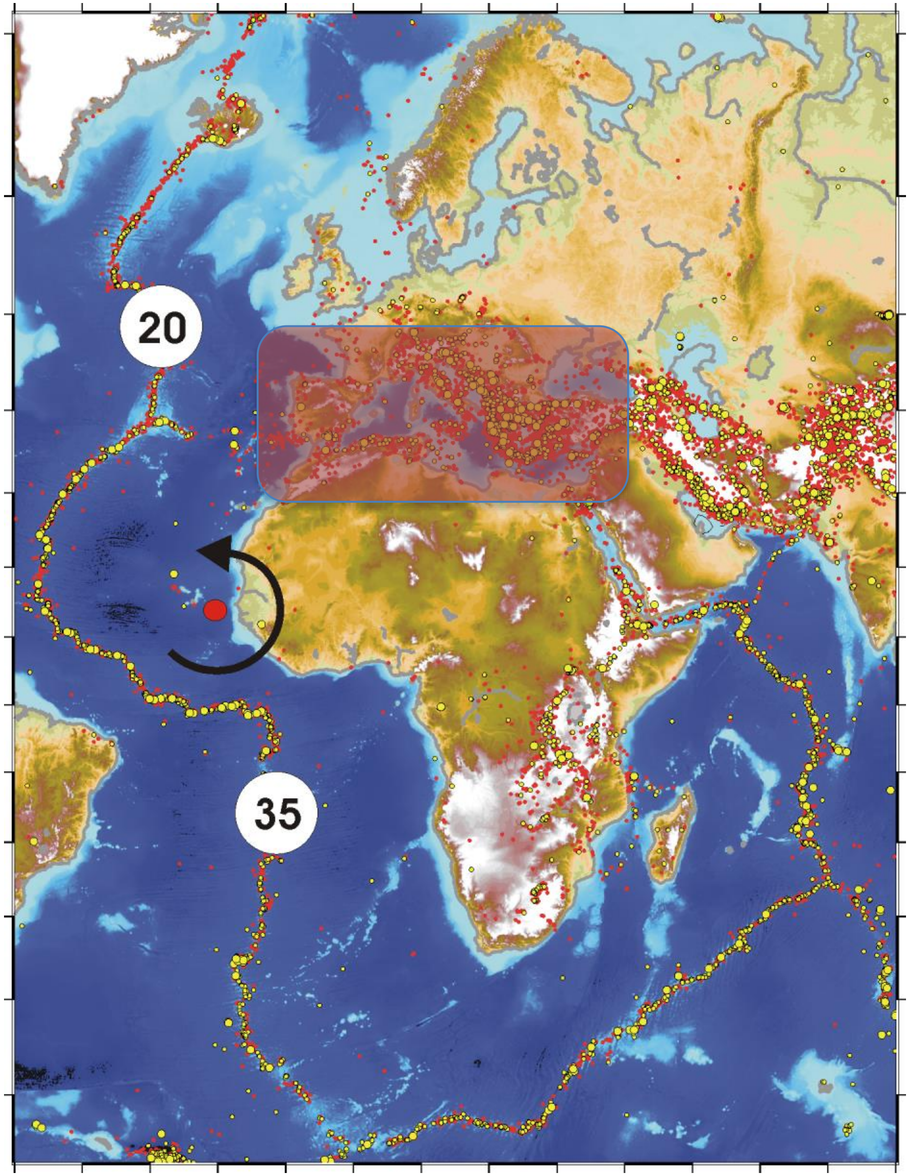


Large Scale Seismicity Distribution



- Ocean-ocean boundaries are narrow (<50 km)
- Continental lithosphere tends to broaden the plate boundary zone
- Plate boundary zone can be > 1000km wide in the Mediterranean

Large Scale Seismicity Distribution



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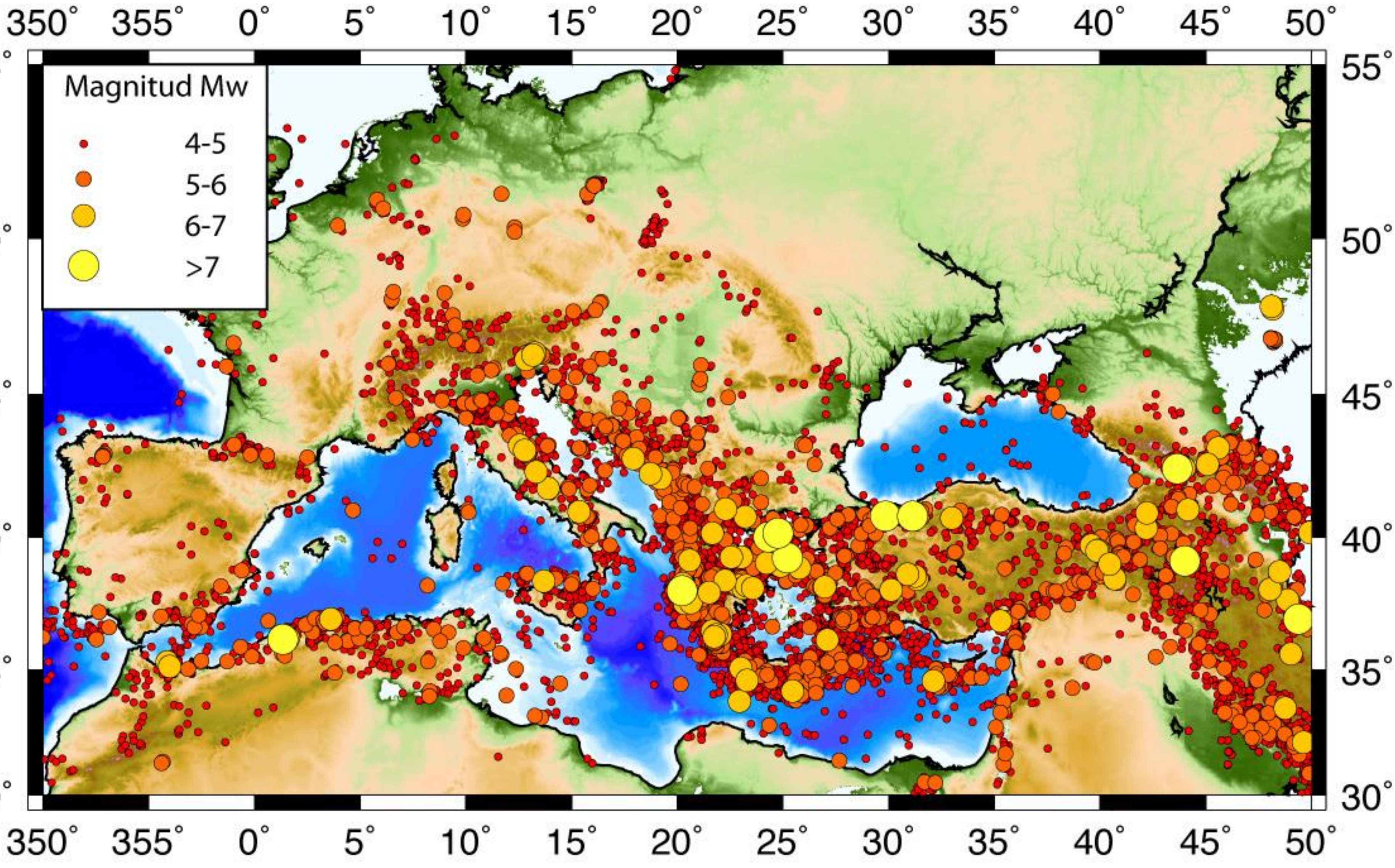
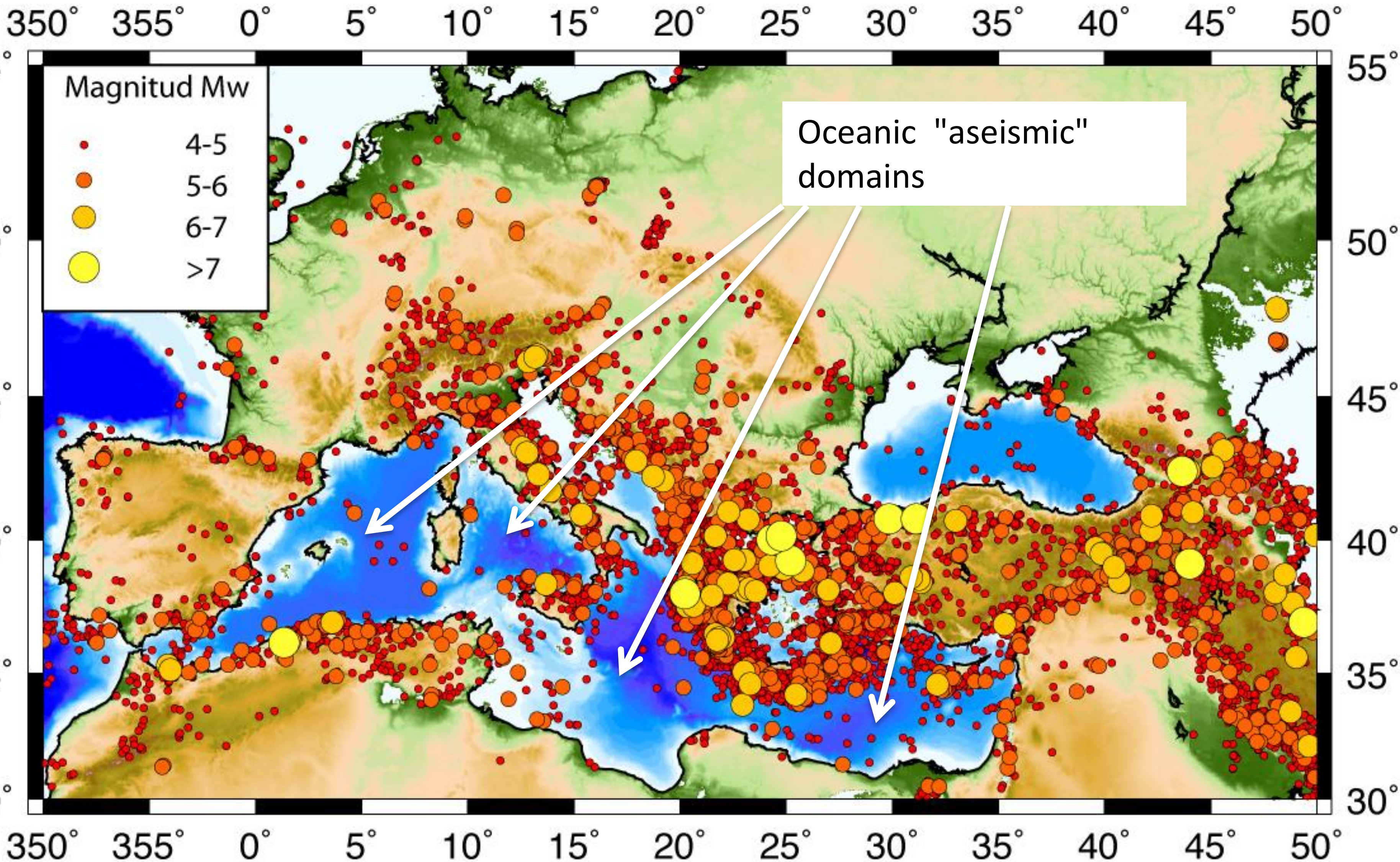
SEISMICITY DISTRIBUTION



SEISMICITY DISTRIBUTION



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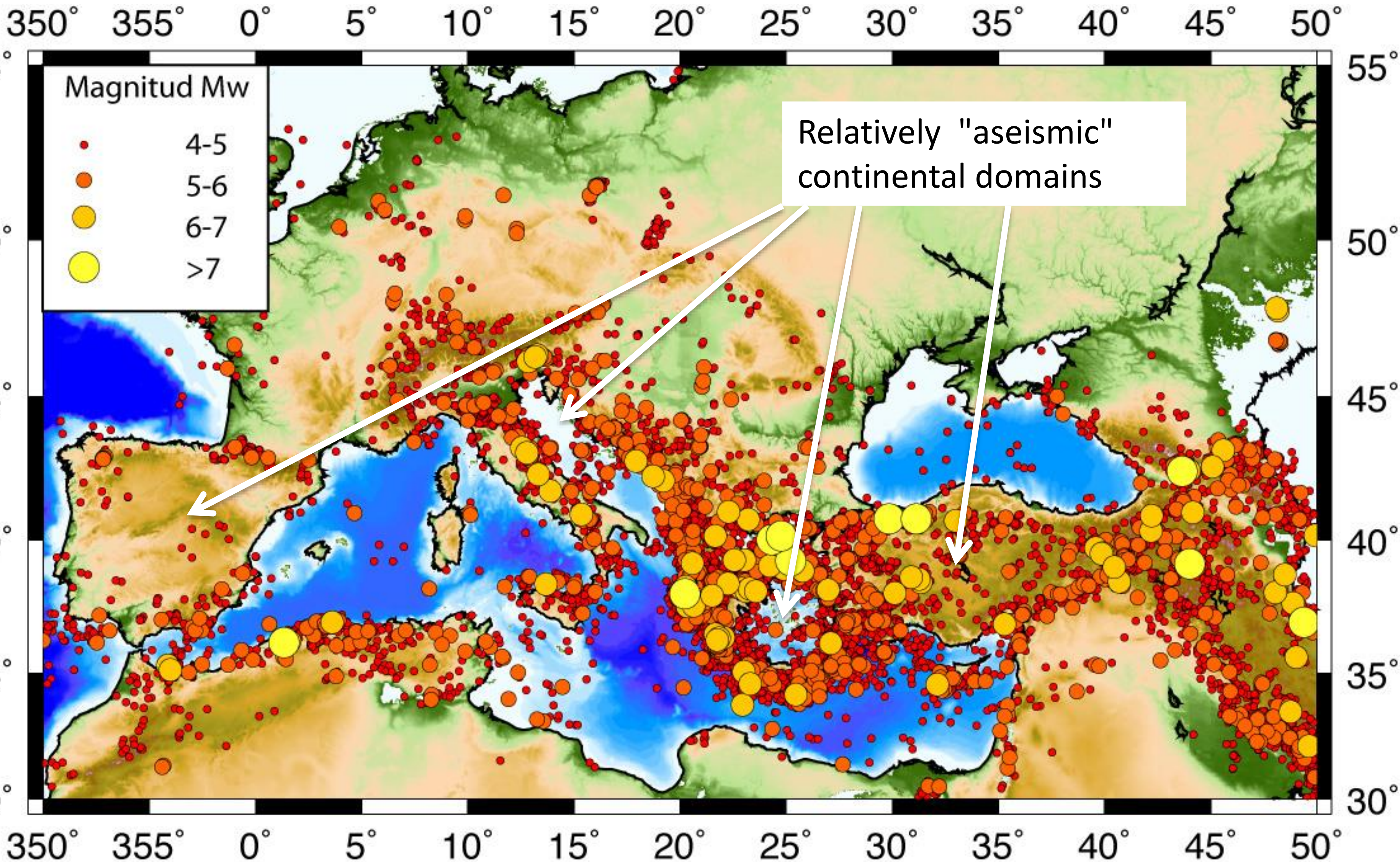
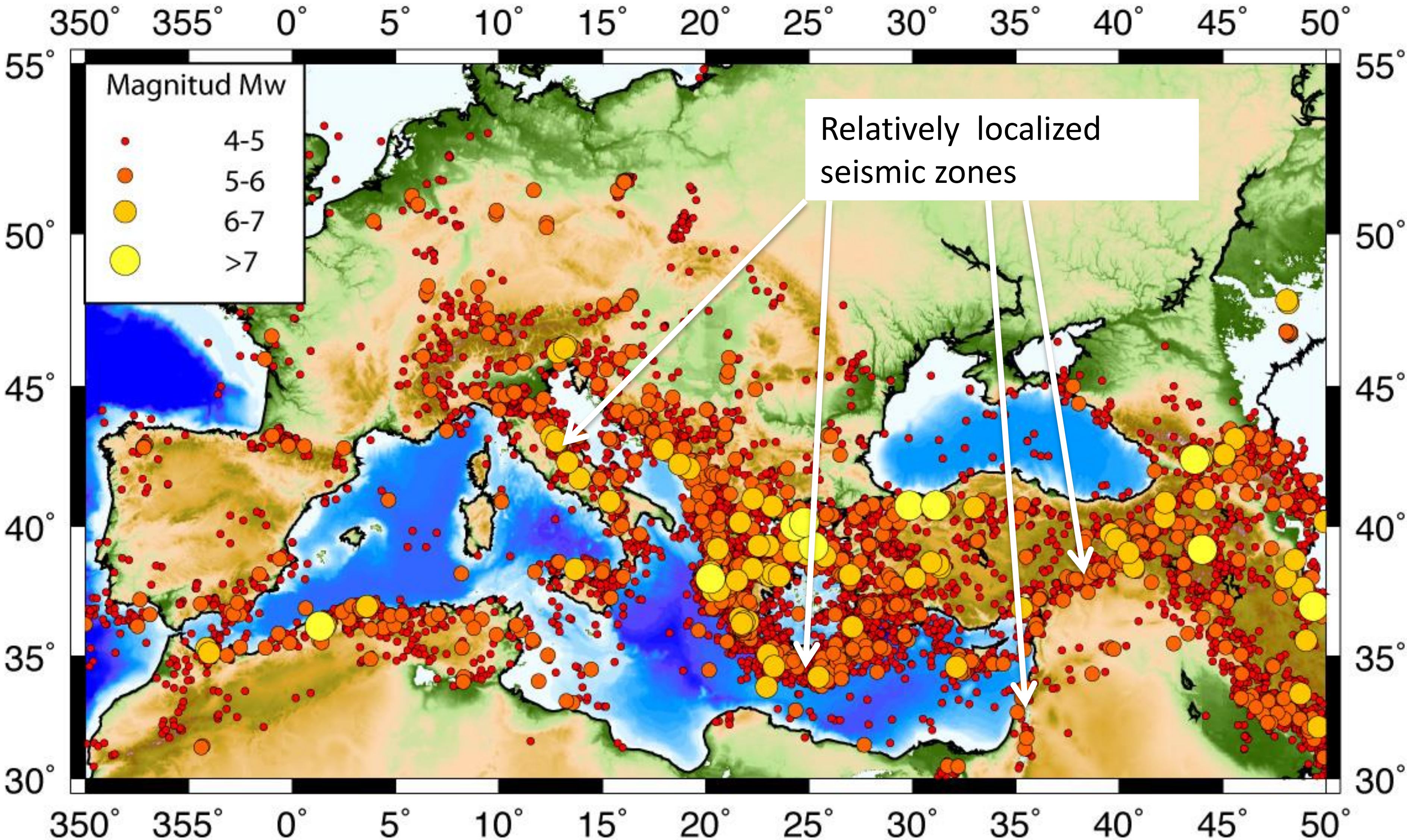


SEISMICITY DISTRIBUTION



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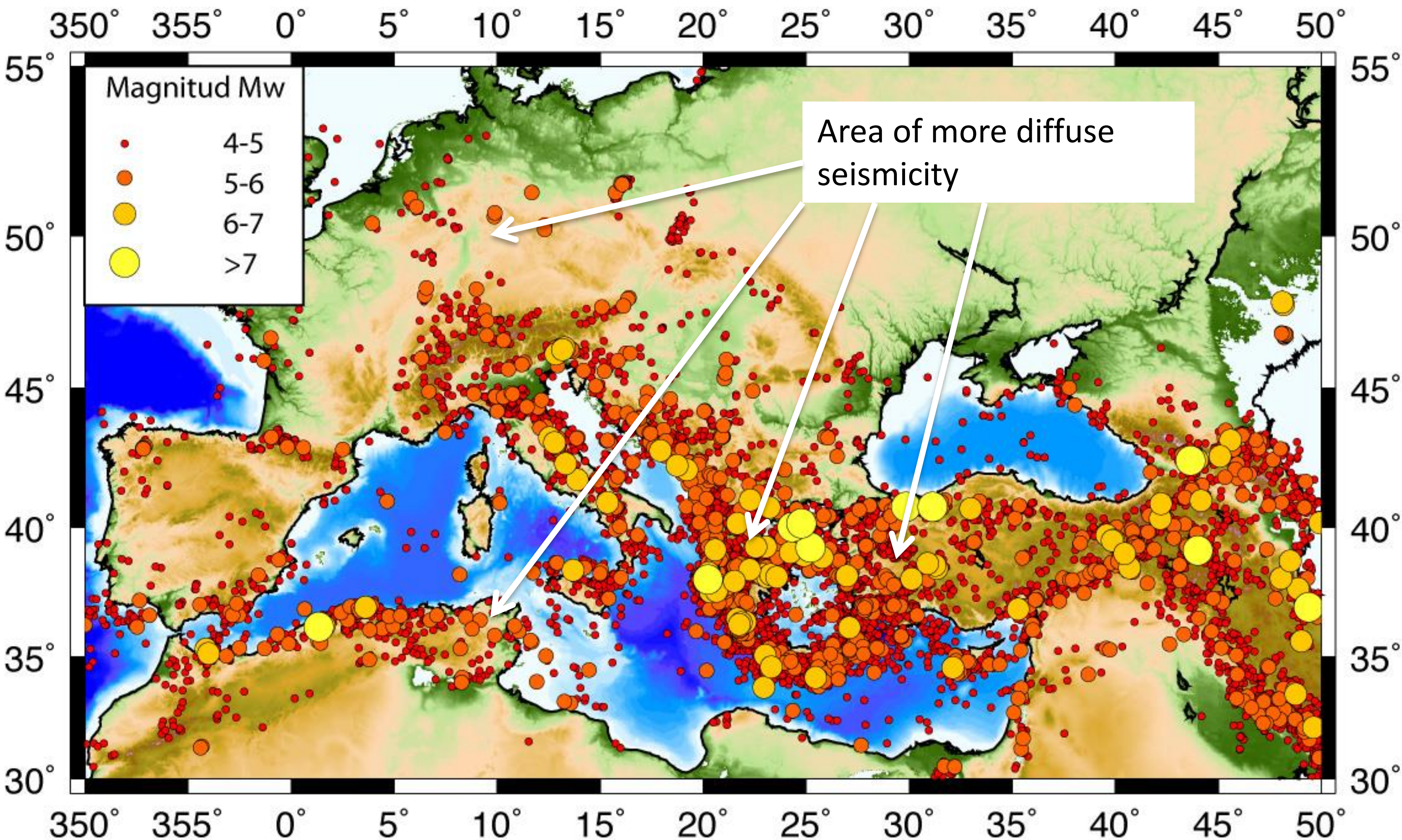
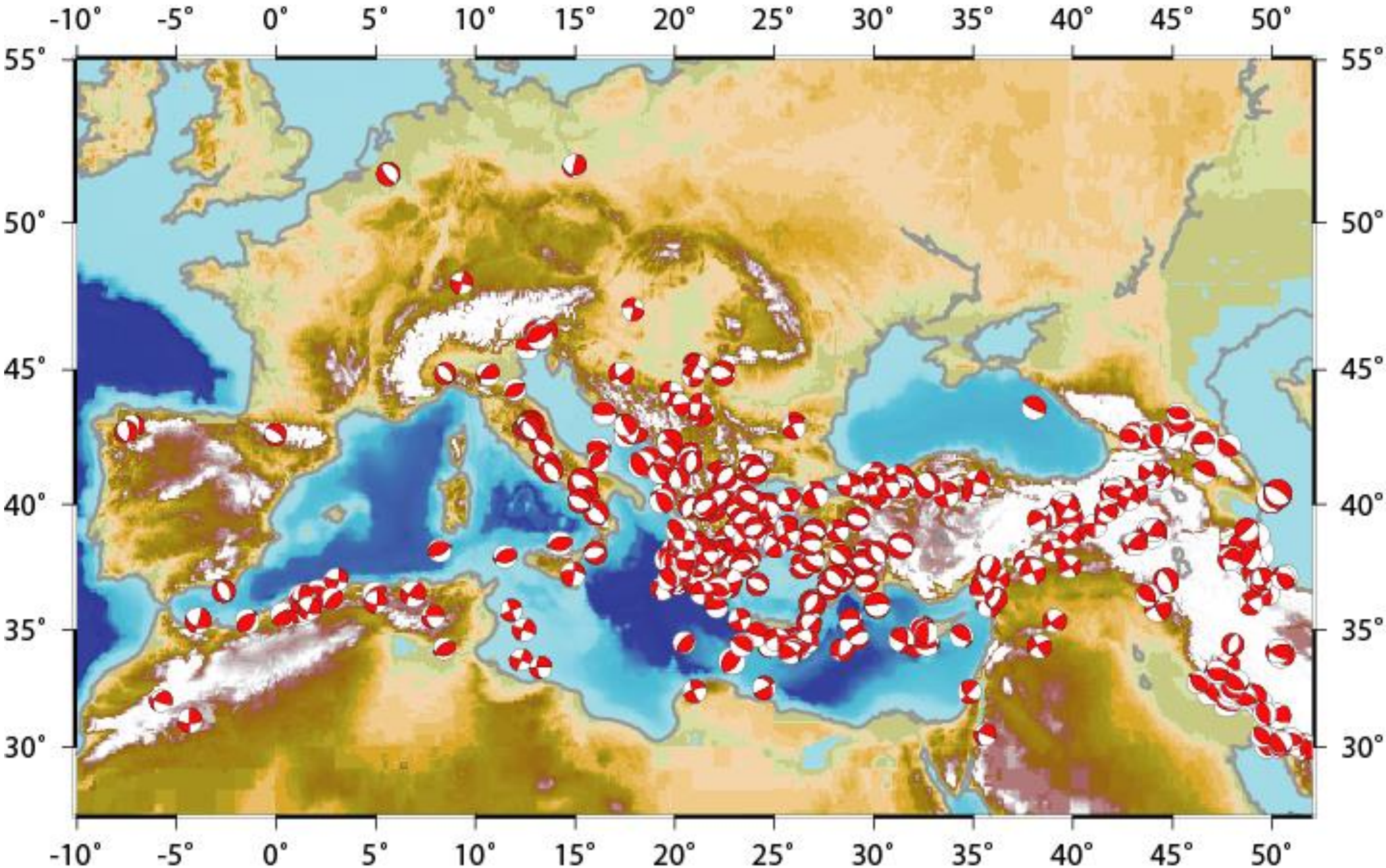


Seismicity Distribution & Focal Mechanism



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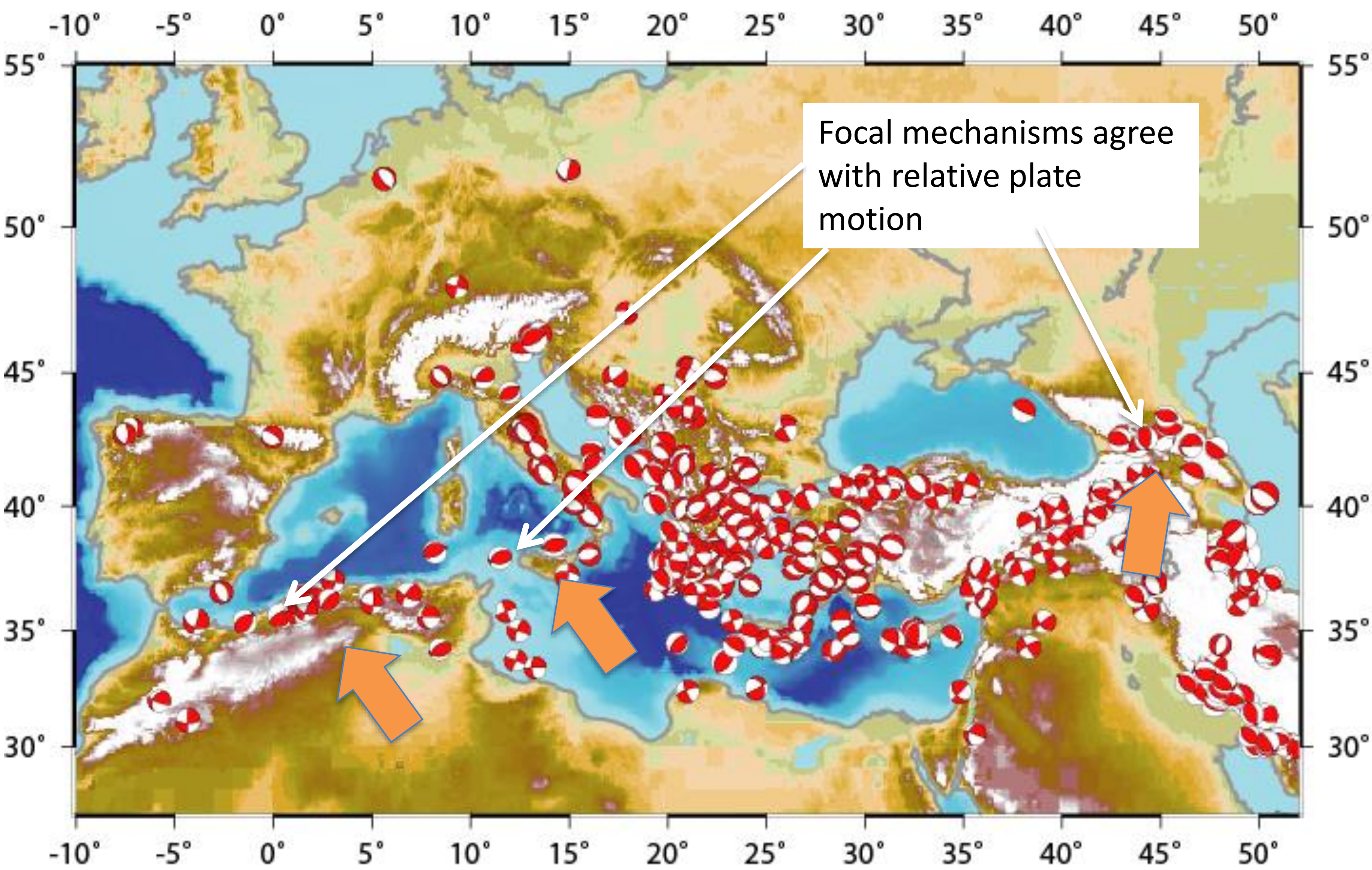
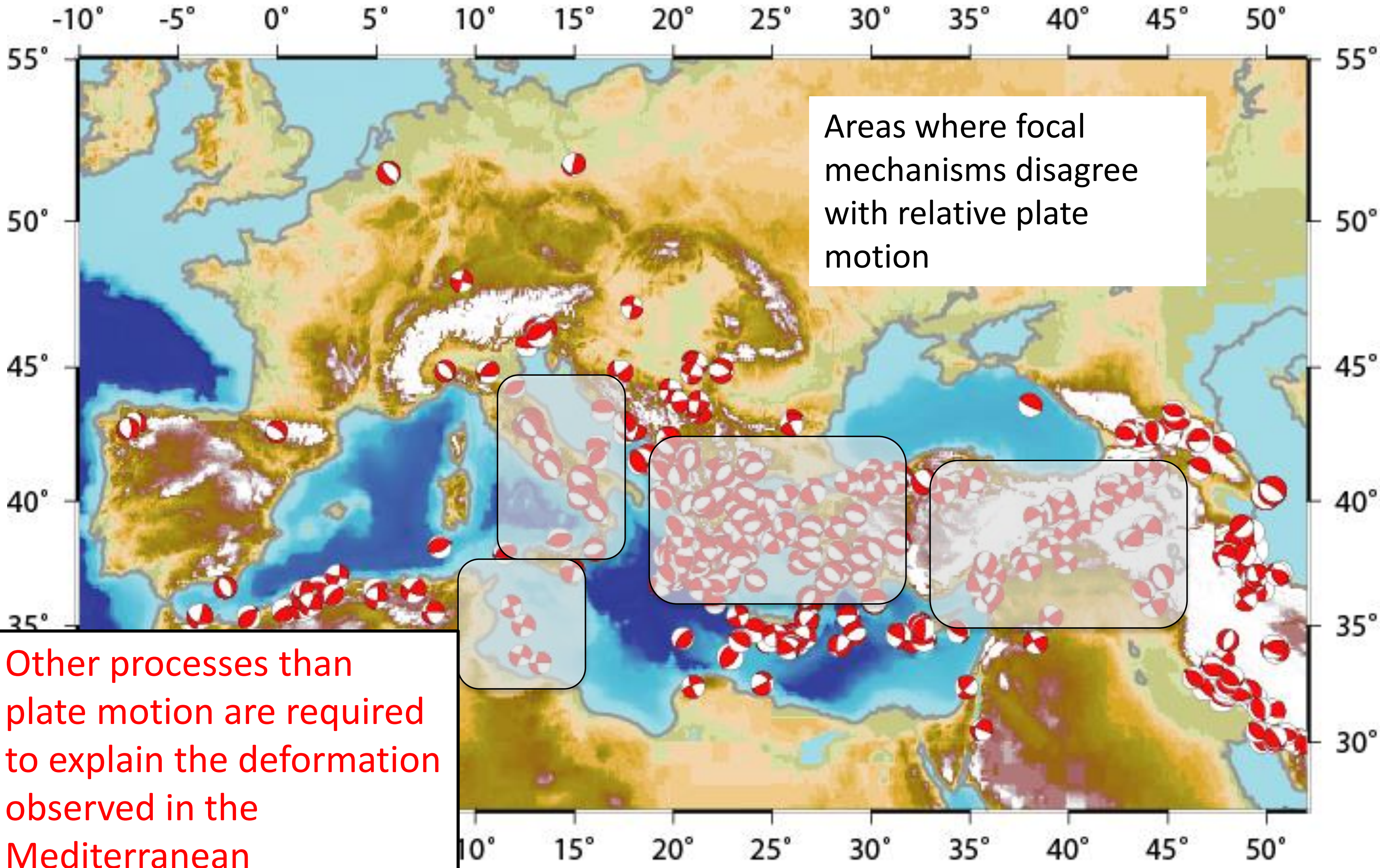
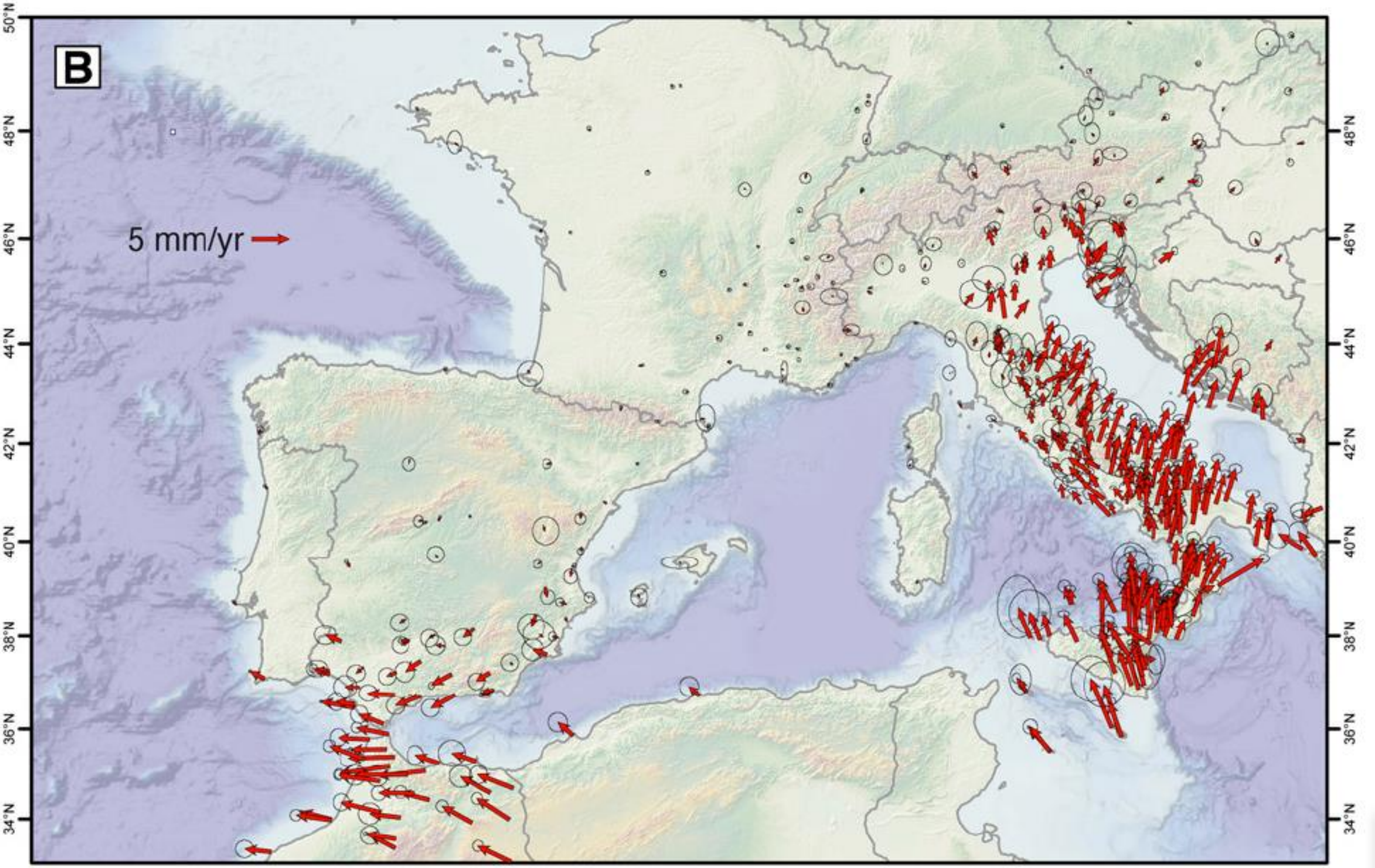


Seismicity Distribution & Focal Mechanism

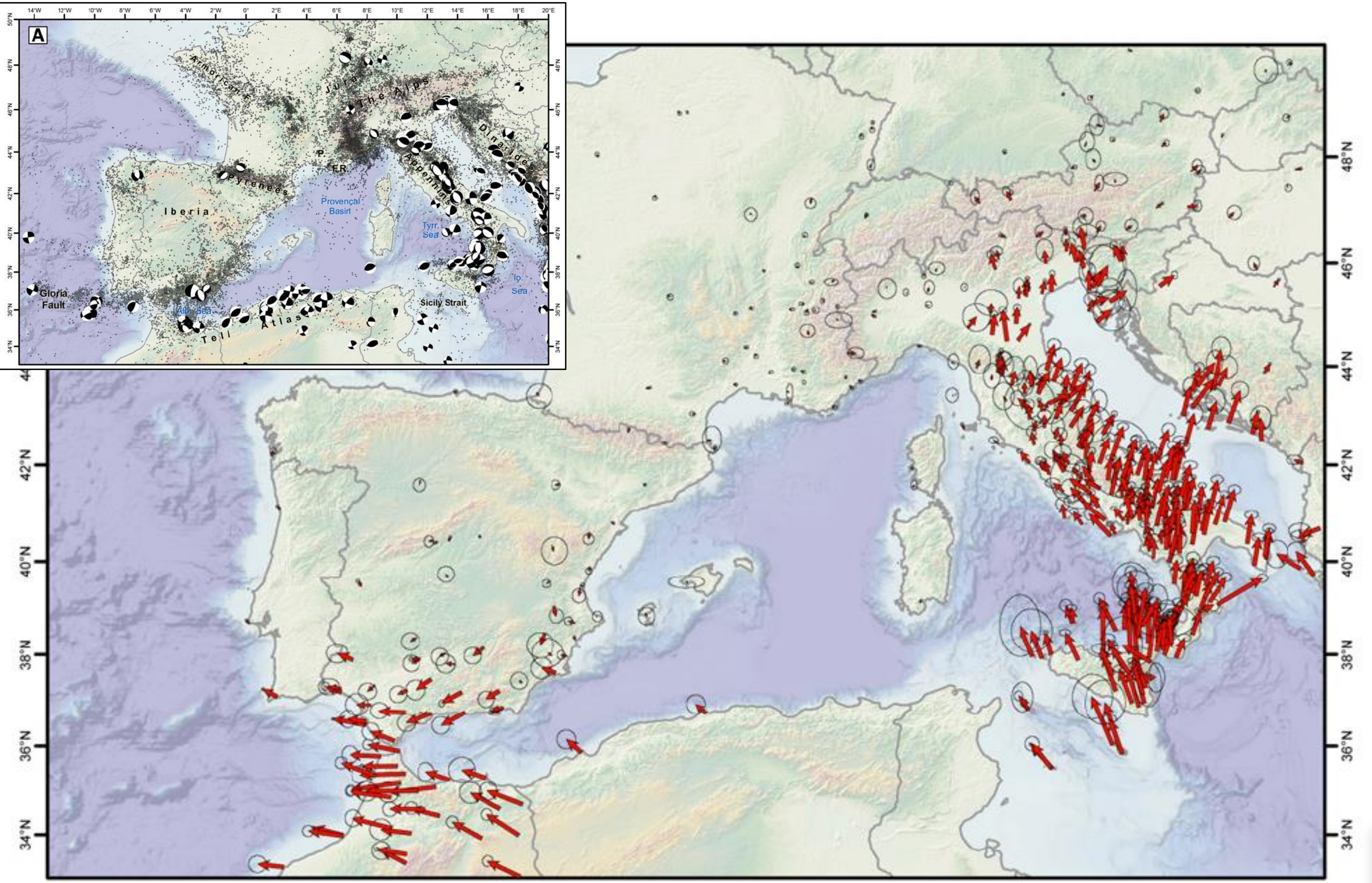


Other processes than plate motion are required to explain the deformation observed in the Mediterranean

Western Mediterranean (wrt Stable Europe)



WESTERN MEDITERRANEAN



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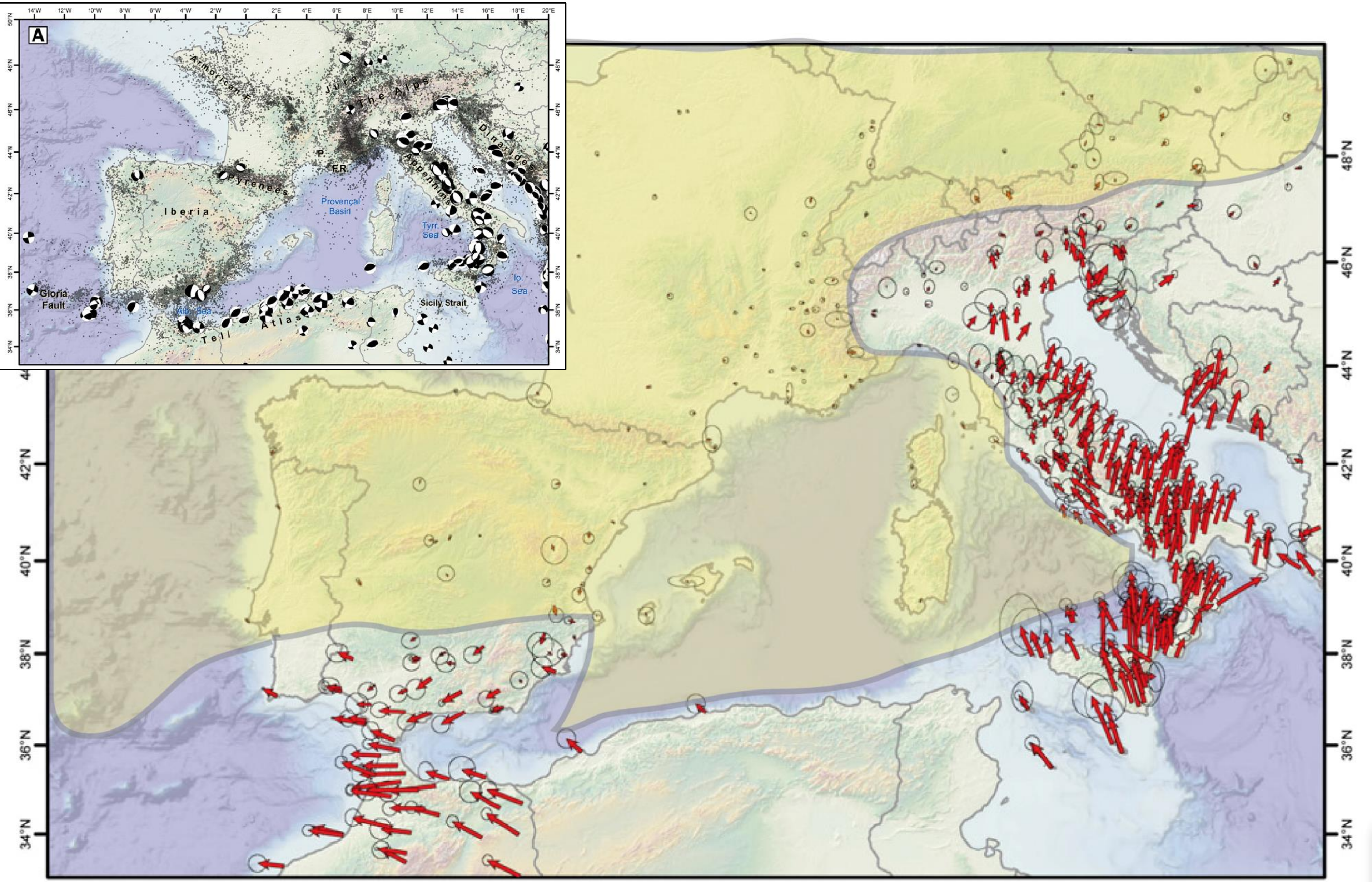
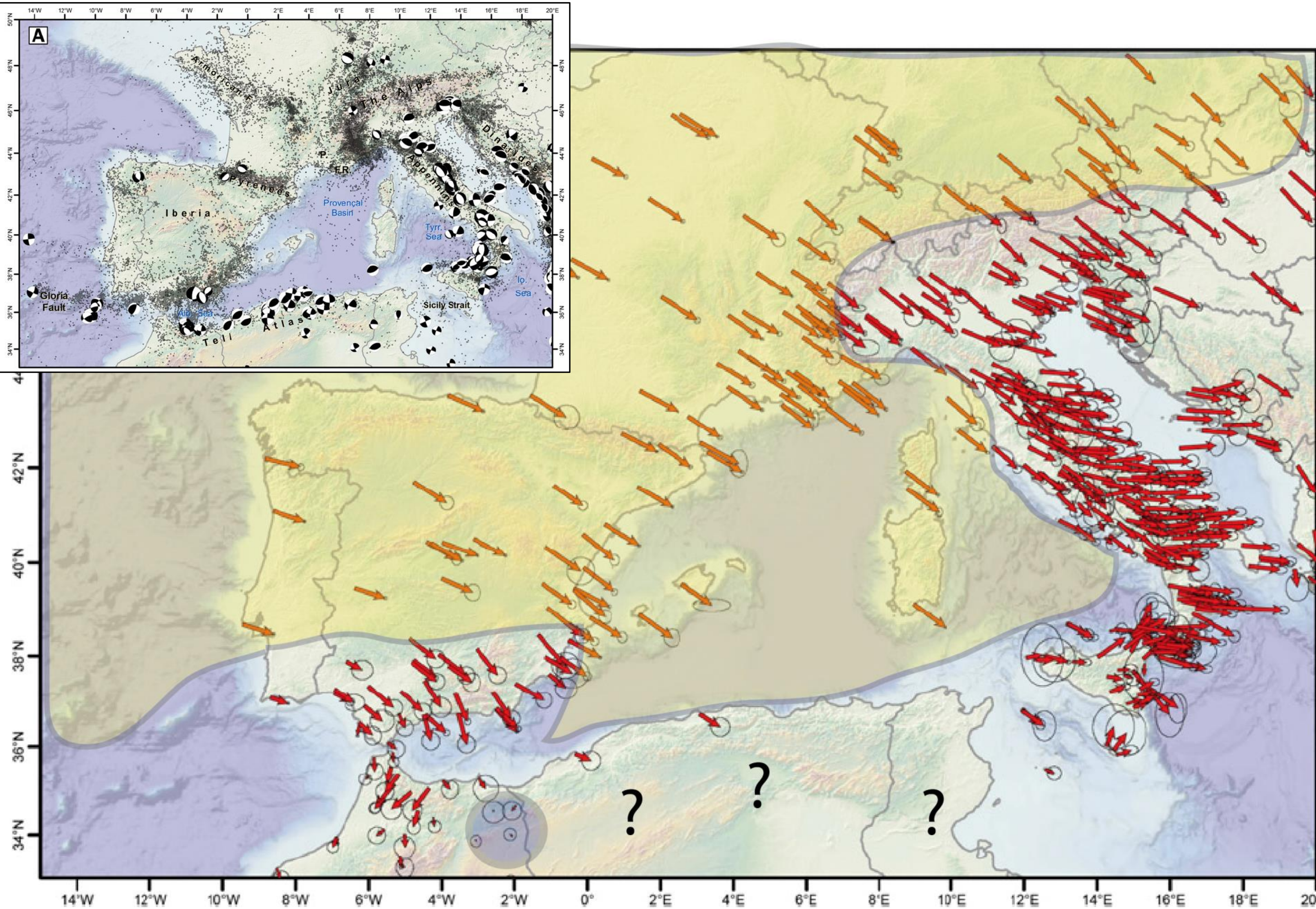


Western Mediterranean



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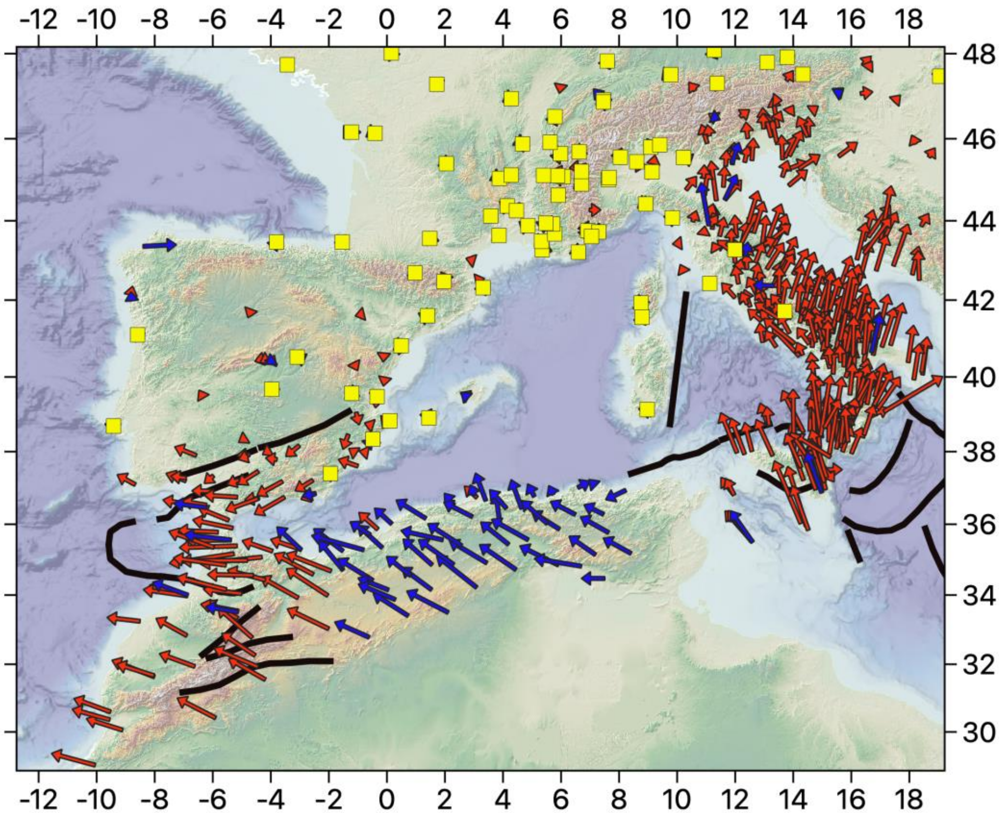
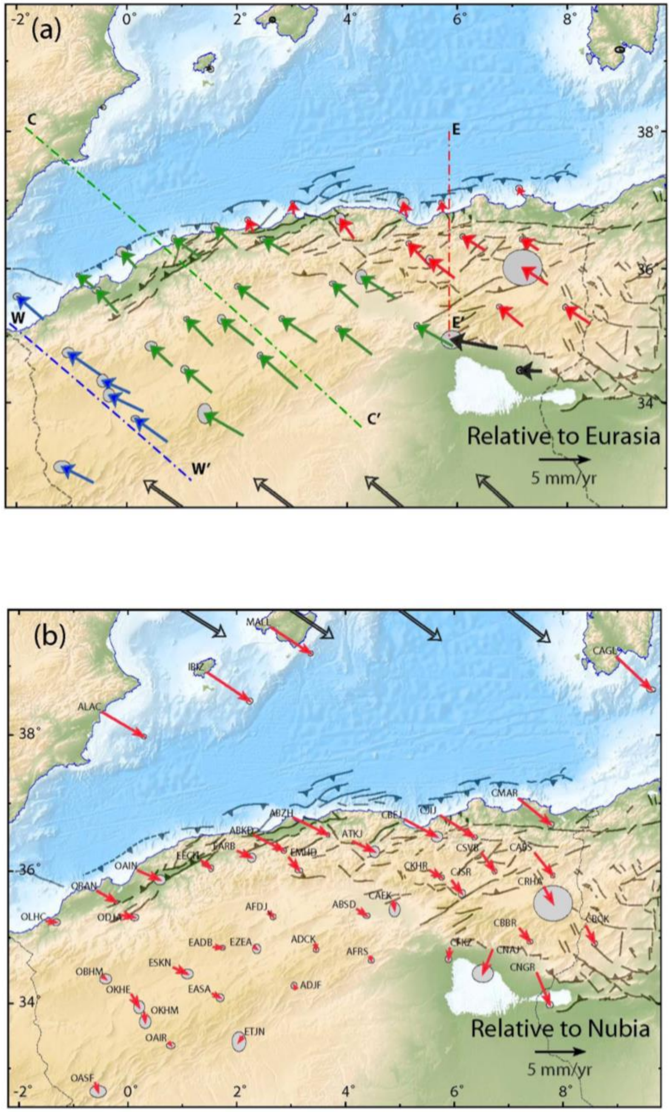
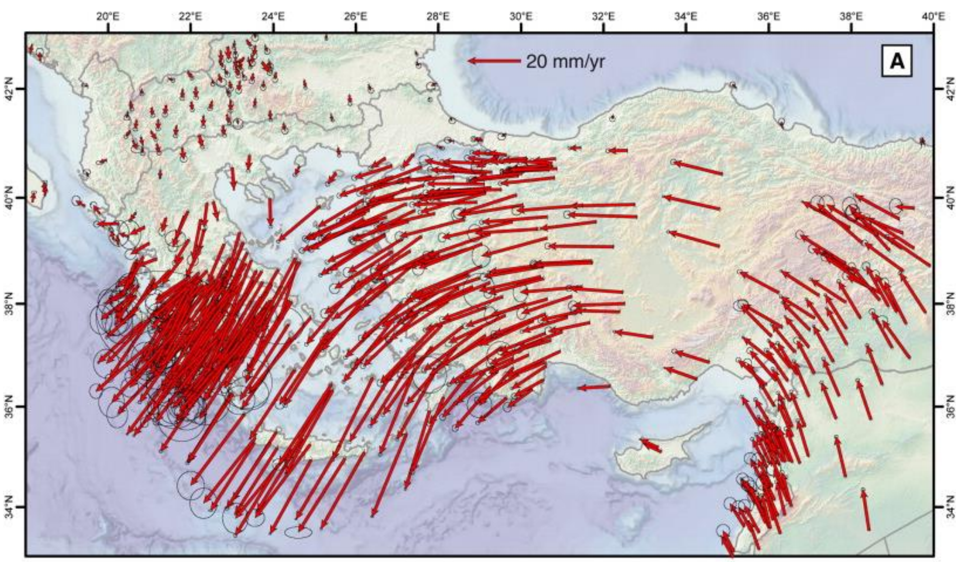
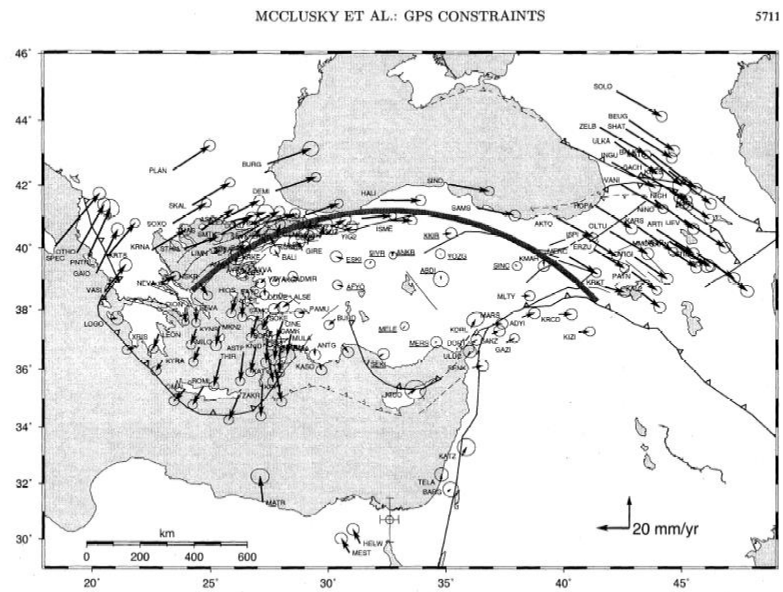




Bougrine et al. (2019)

THE RIGID ROTATION OF ANATOLIA



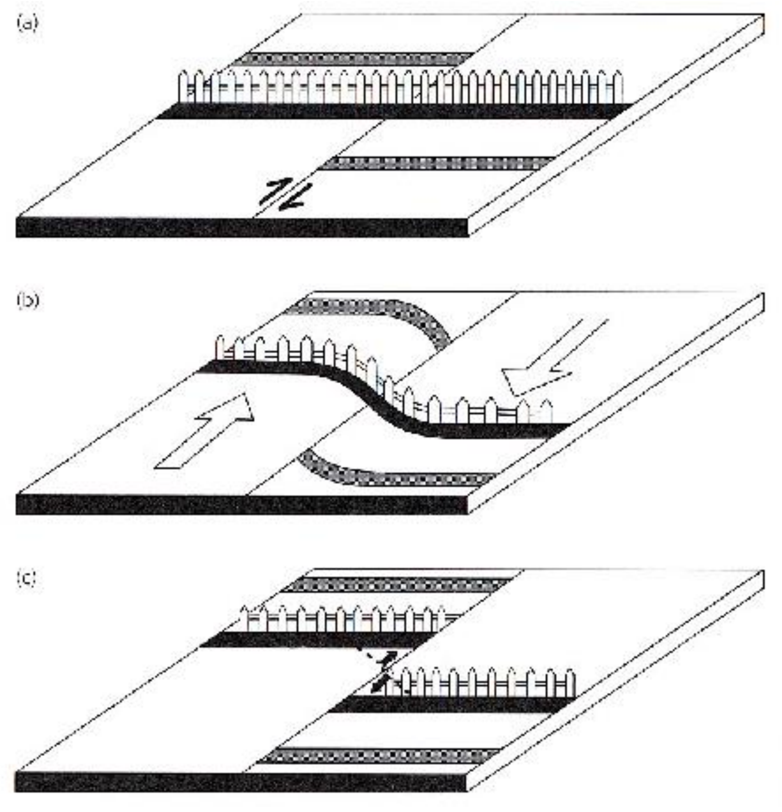


Mc Clusky et al. (2003)

The “Elastic Rebound” model

Reid’s model = “elastic rebound”

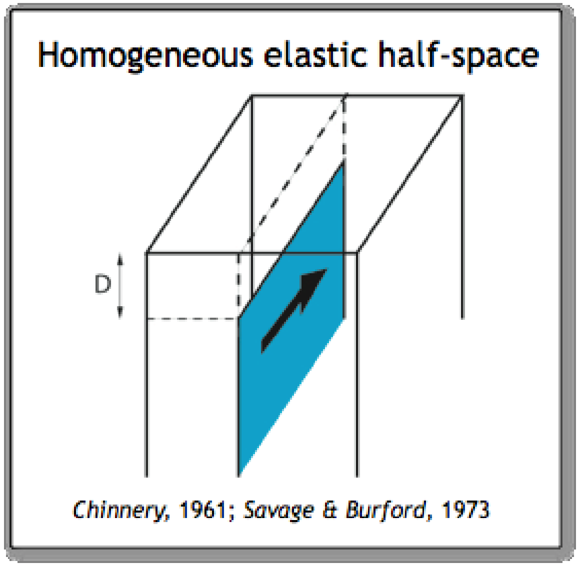
- Between earthquakes, steady motion in the far field, no motion on the fault ! loads the fault, strain accumulates in the vicinity of the fault.
- During earthquakes: the fault breaks, slip on the fault catches up with the far field displacements.
- Linear elastic system: the interseismic strain accumulation pattern is the exactly the opposite of the coseismic strain release ! no-net strain.



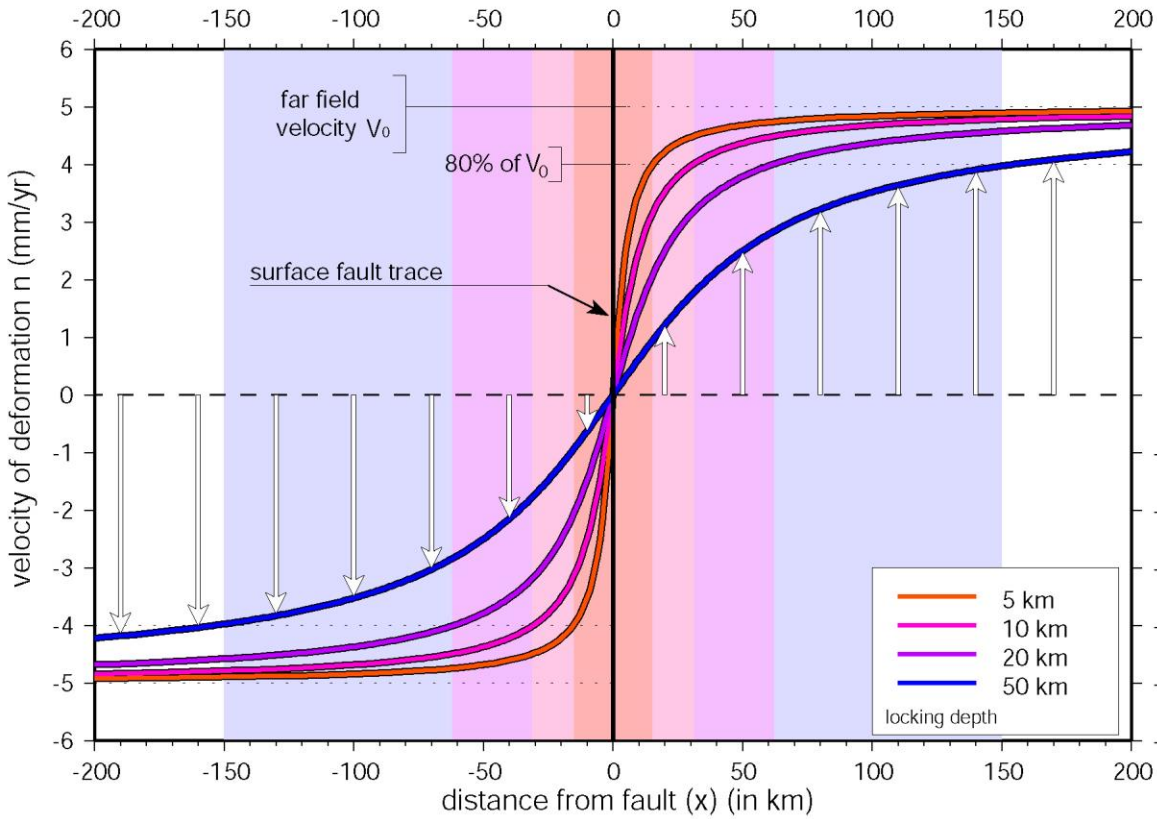
- The main difference with the slider experiment is that the whole medium can deform (because it is elastic)

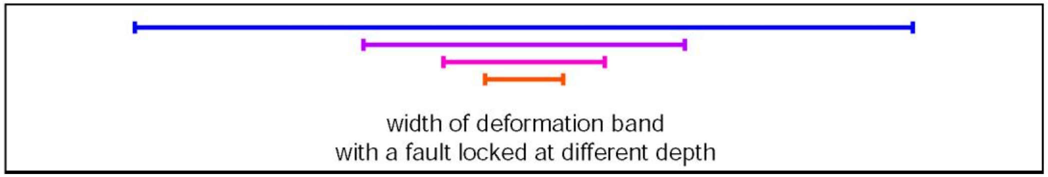
http://web.ics.purdue.edu/~ecalais/teaching/kinematics/deformation_cycle.pdf

Classical "homogeneous elastic half-space model"

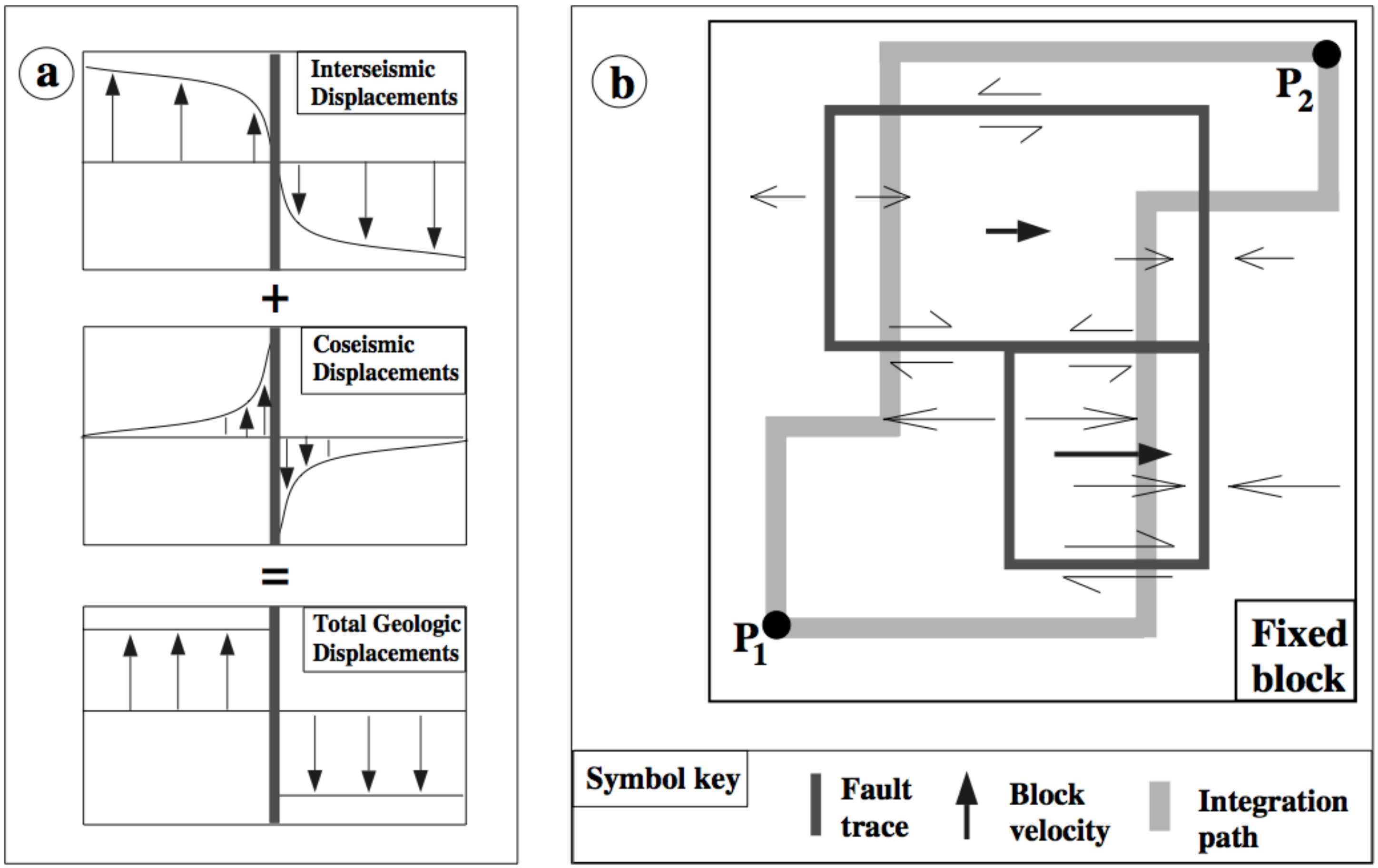


$$U_y = 2 \, . \, {}^{V_0}/_{\Pi} \arctan\!g \, ({}^{x}/_{D})$$

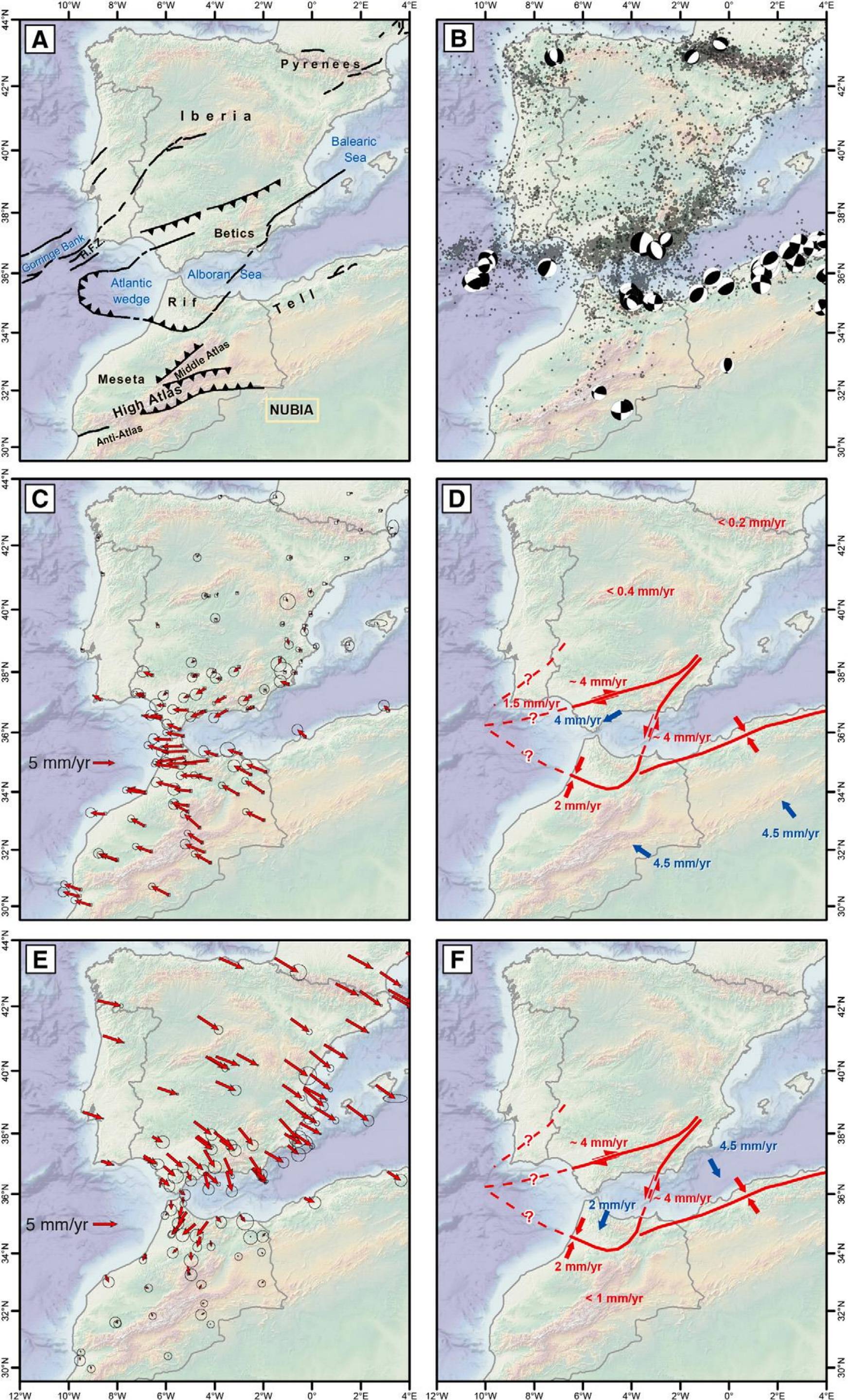




Elastic Block Modeling Methods



Meade et al. (2002)



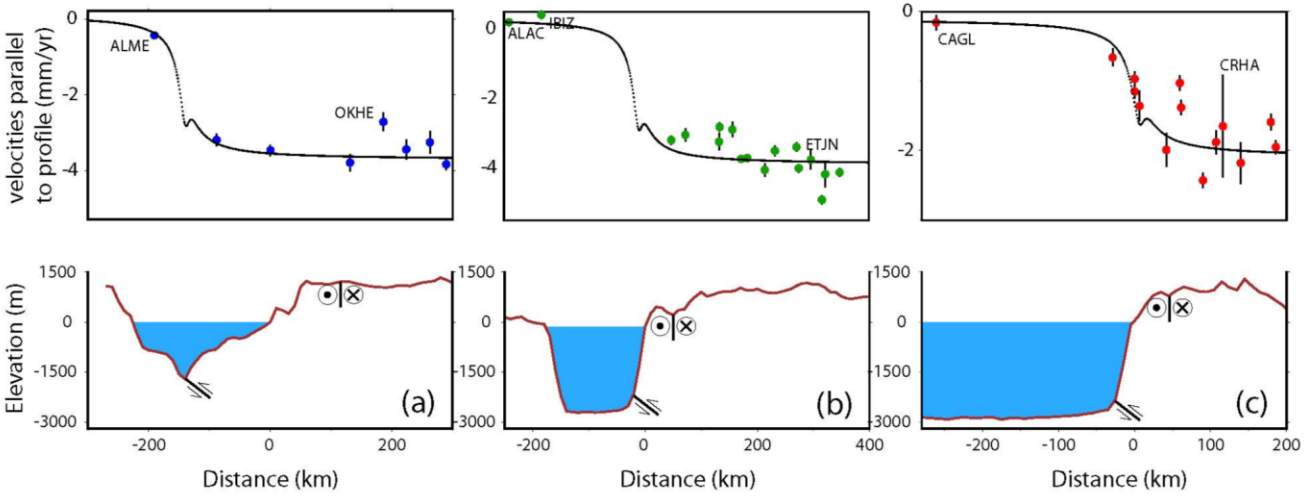
Alboran domain & Moroccan Rif

- 3-4 mm/yr Southwestward motion in the Betics wrt Iberia
- 3-4 mm/yr South-southwestward motion in the Moroccan rif wrt Nubia
- Motion not controlled (at least directly) by Nubia/Eurasia convergence
- Single block ? – Offshore boundary ?

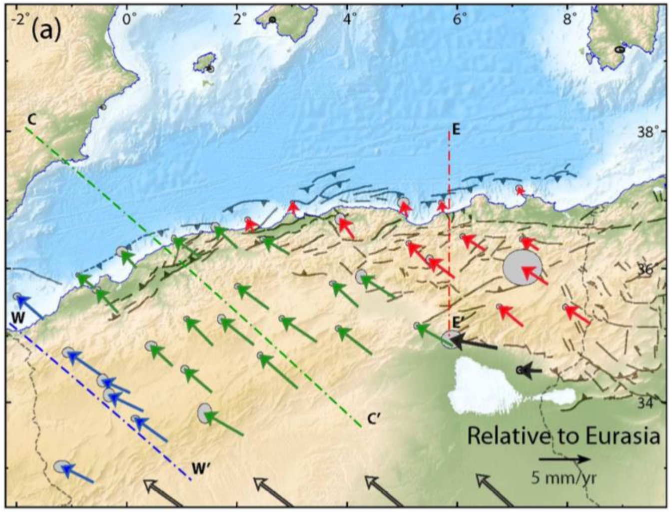
- East of the Rif, the very few results available suggests that most deformation is localized along the coast

Koulali et al. (2012), Pérouse et al. (2010)

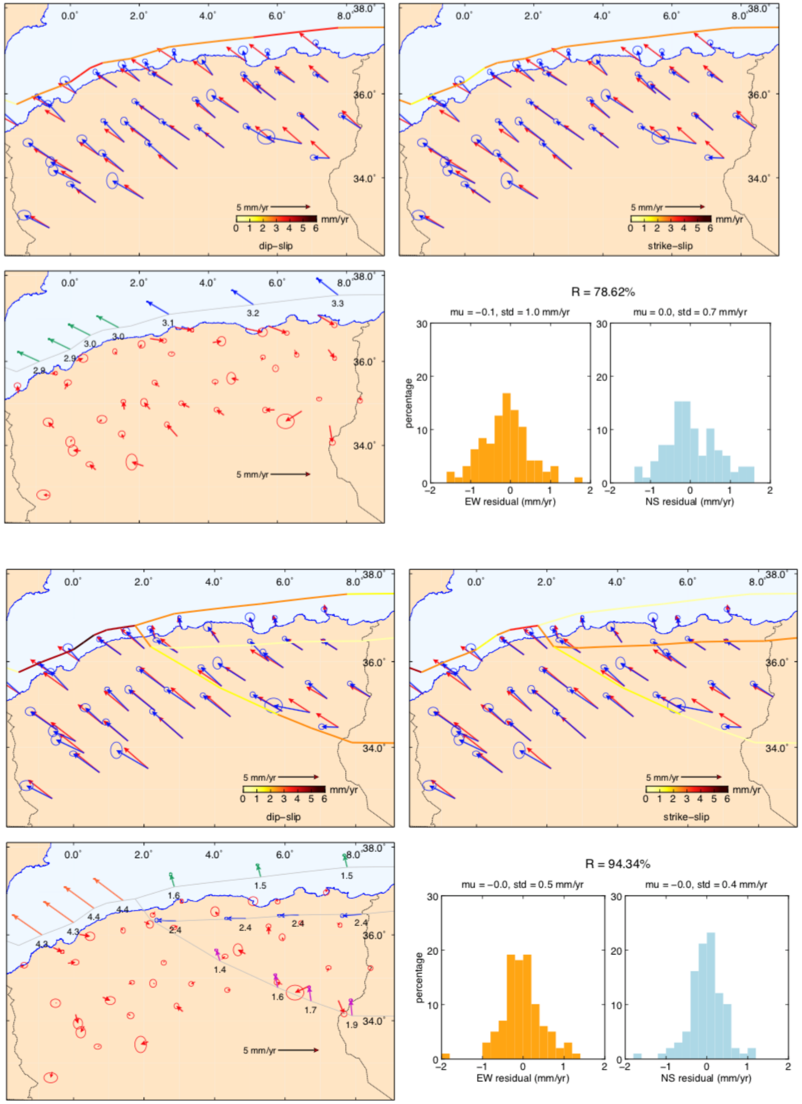
ALGERIA



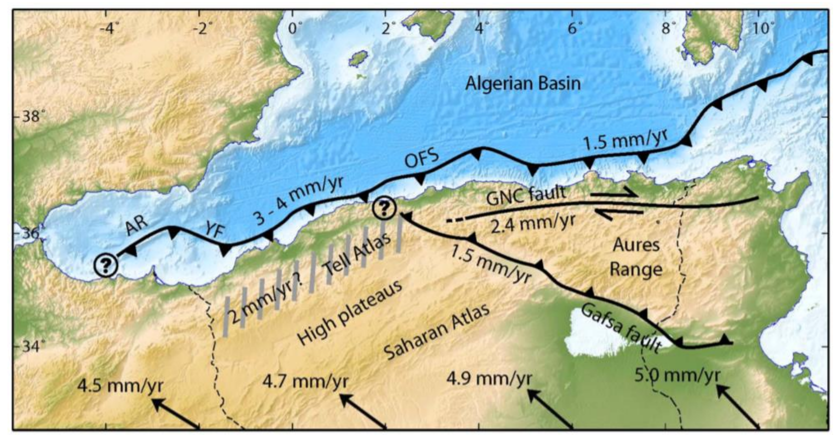
Bougrine et al. (2019)



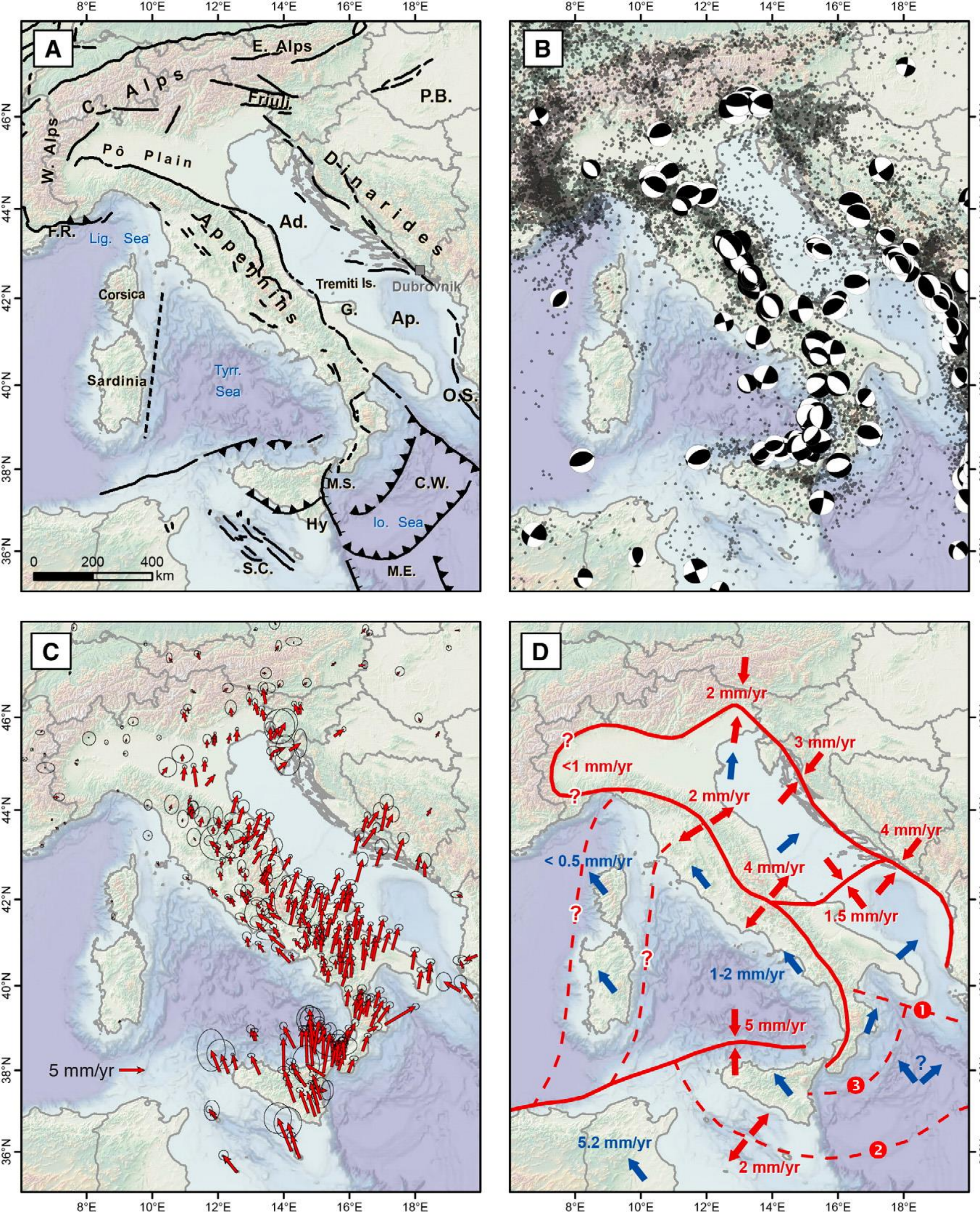
ALGERIA



- Offshore localized deformation in western Algeria
- Partitionning in Eastern Algeria



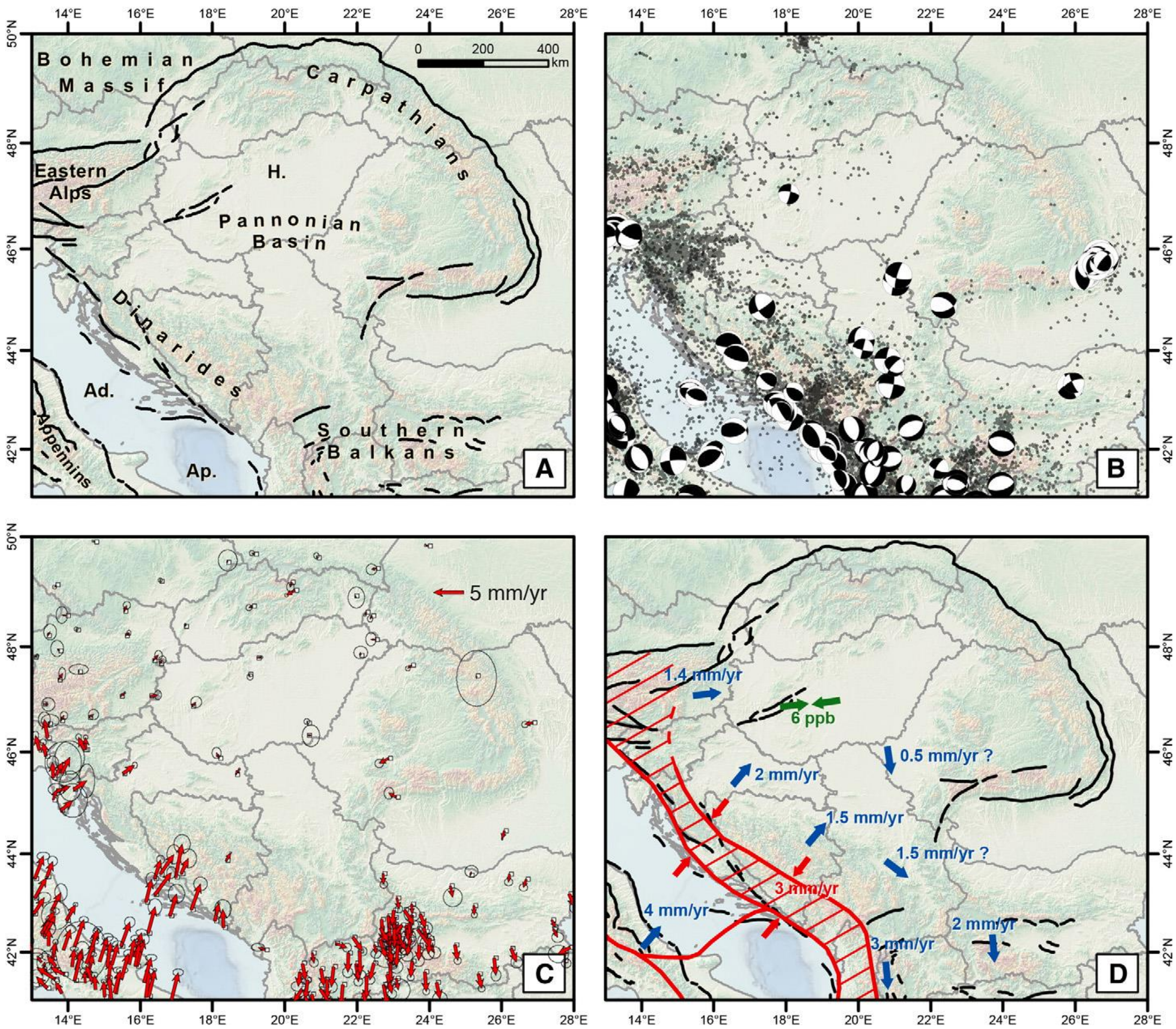
Bougrine et al. (2019)



The Adriatic

- Counter-clockwise rotation of the Adriatic domain
- Needs several blocks
- Calabria subduction active ?
- Northwestward motion along the Tyrrhenian coast of Italy
- No or very indirect control of the Nubia/Eurasia convergence on the kinematics in the Adria.

Pannonian Bassin



- NE-SW shortening
- Distribution of shortening ?
- Weak compression of the Pannonian bassin
- Juxtaposition of shortening and extension in southeastern Adriatic.

Grenerczy et al. (2005), Bennett et al. (2008)

Strain rate analysis

- Strain rate characterizes the <u>local</u> variation of the velocity field

- Strain rate is largely independent from the reference frame

The velocity gradient tensor

$M_0(x_0,\, y_0)$

$$\begin{aligned} x &= x_0 + \delta x \\ y &= y_0 + \delta y \end{aligned}$$

$$\delta X = \left[\begin{array}{c} \delta x \\ \delta y \end{array} \right]$$

$$v(x, y) = v(x_0, y_0) + \nabla v(x_0, y_0)\delta X$$

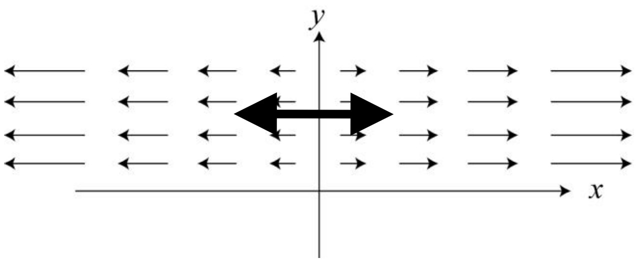
$$\nabla v(x_0, y_0) = \left[\begin{array}{cc} \frac{\partial v_x}{\partial x}(x_0, y_0) & \frac{\partial v_x}{\partial y}(x_0, y_0) \\ \frac{\partial v_y}{\partial x}(x_0, y_0) & \frac{\partial v_y}{\partial y}(x_0, y_0) \end{array} \right]$$

Strain rate tensor and local rotation rate

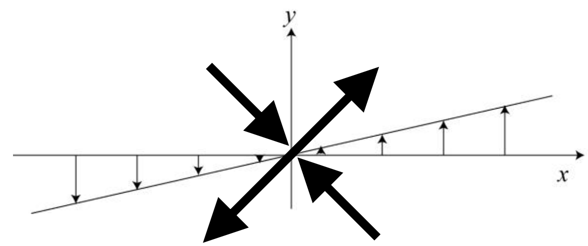
$$\begin{aligned} \nabla v &= \frac{\nabla v + \nabla v^T}{2} + \frac{\nabla v - \nabla v^T}{2} \\ &= \dot{\epsilon} + \dot{r} \end{aligned}$$

$$r = \begin{bmatrix} 0 & -\dot{w} \\ \dot{w} & 0 \end{bmatrix} \text{ and } \dot{\omega} = \tfrac{1}{2}(\tfrac{\partial V_x}{\partial y} - \tfrac{\partial V_y}{\partial x})$$

Some examples

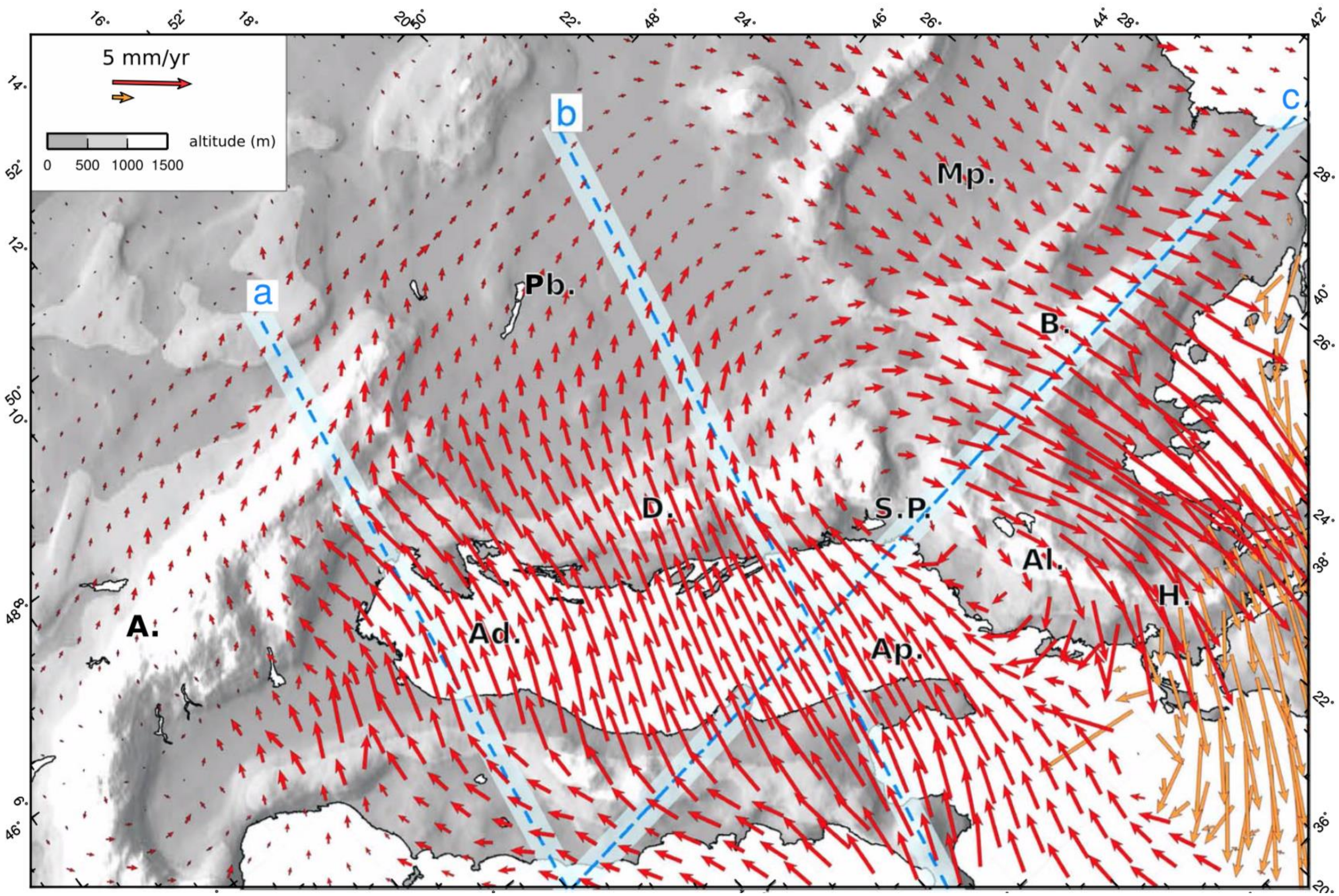


extension



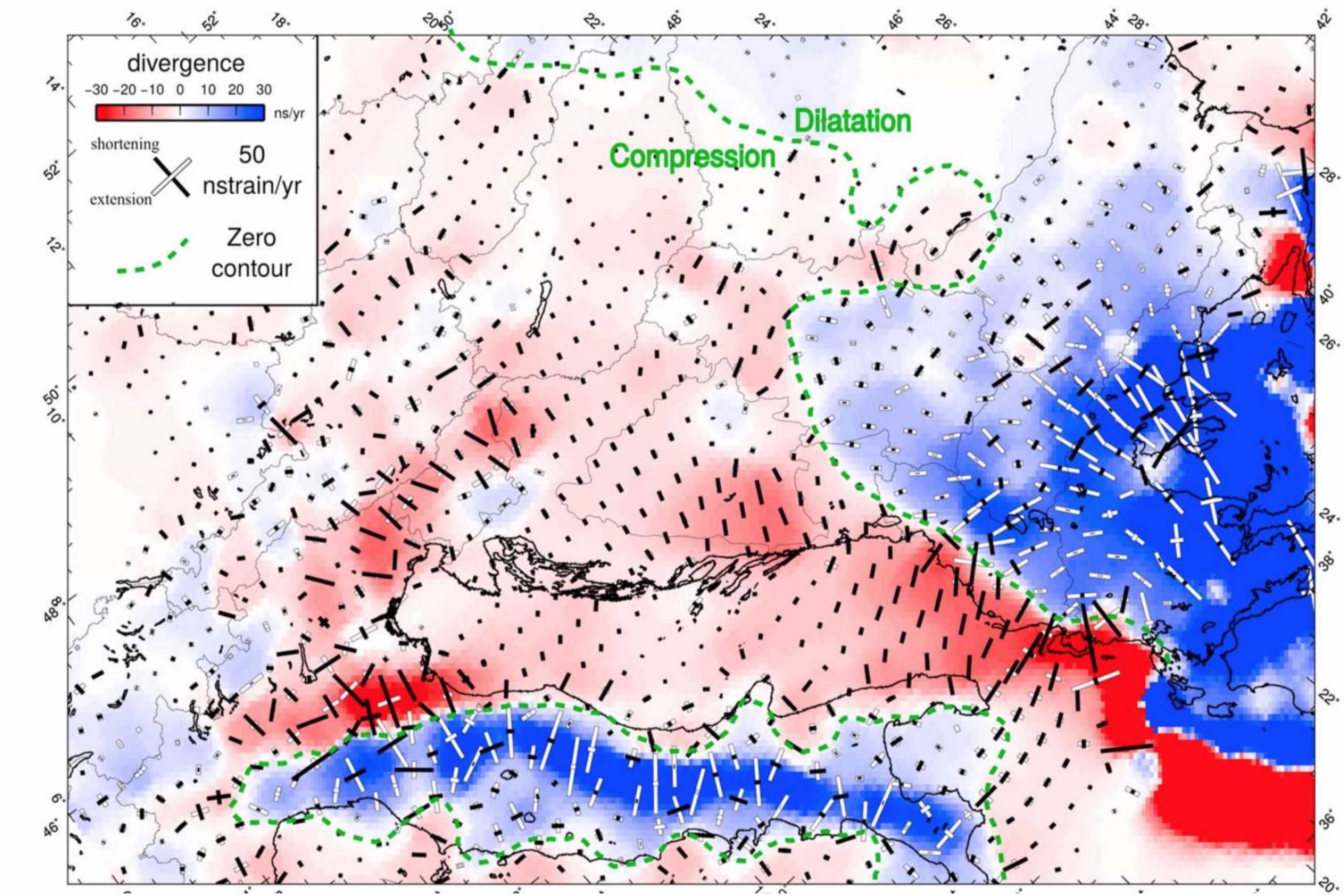
shear

INTERPOLATED VELOCITY FIELD FOR THE PERI-ADRIATIC DOMAIN



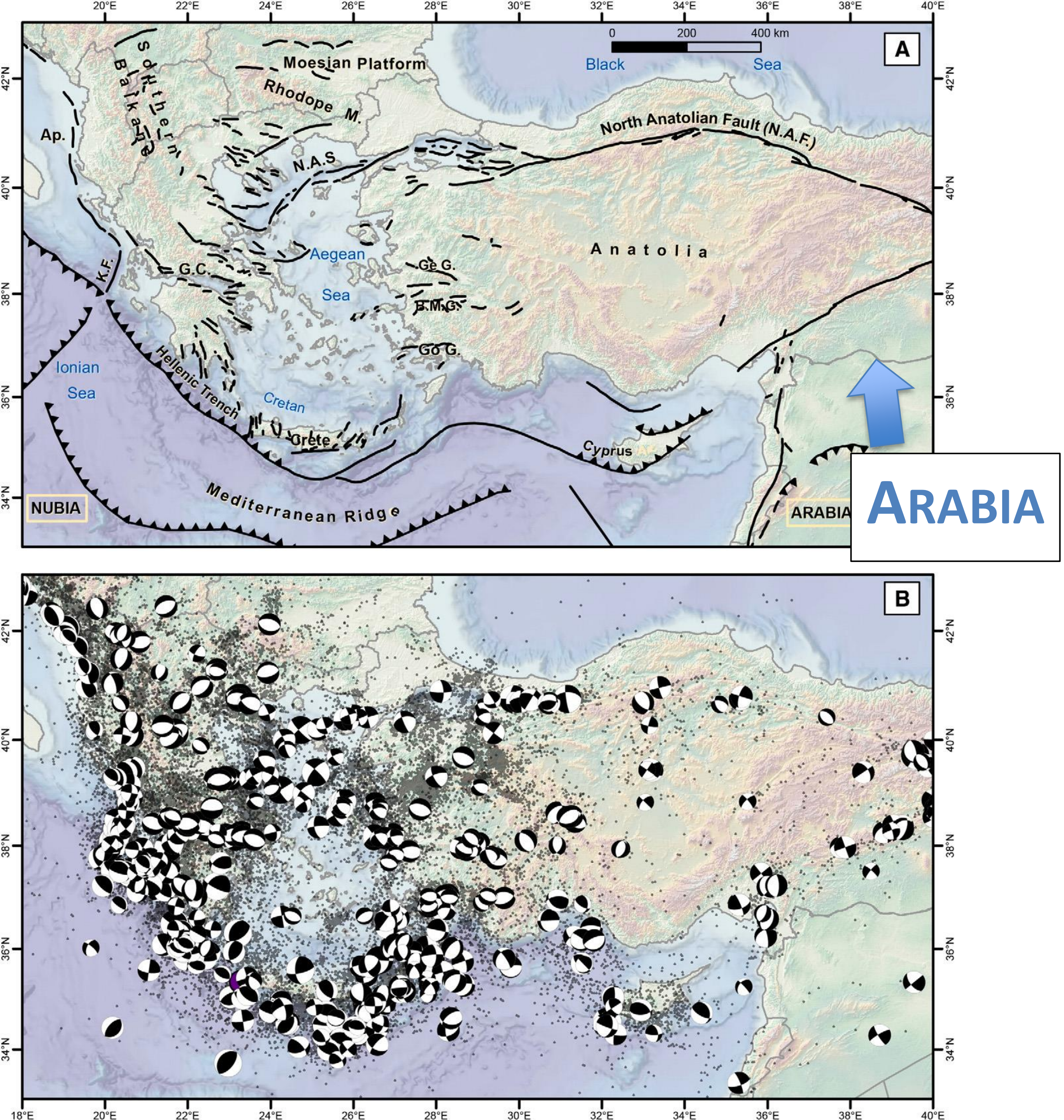
Metois et al. (2015)

STRAIN RATE FIELD FOR THE PERI-ADRIATIC DOMAIN

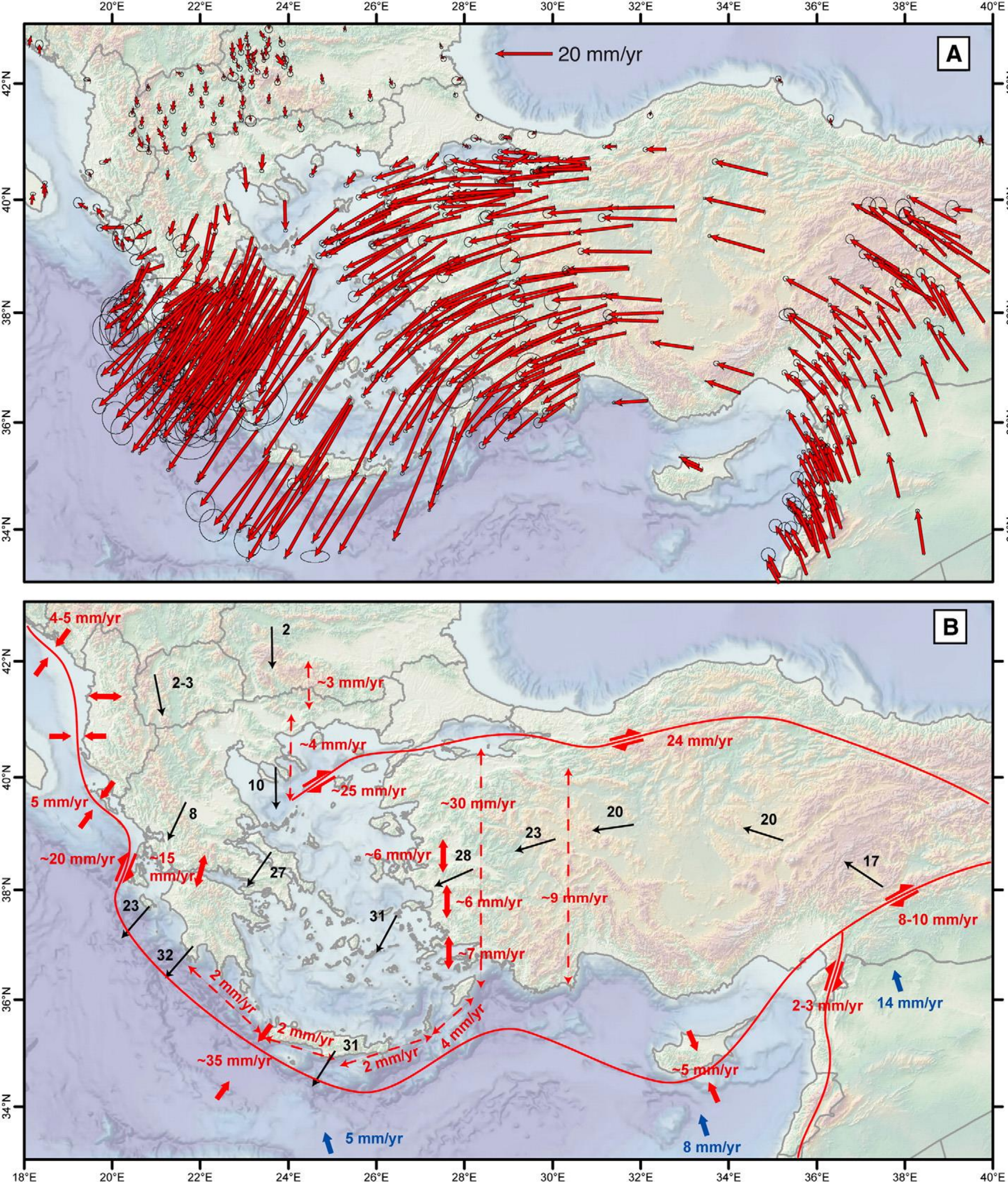


Metois et al. (2015)

THE AEGEAN



A
0
200
400 km
Black
Sea
Moesian Platform
Rhodope M.
Southern
Balkans
North Anatolian Fault (N.A.F.)
Ap.
N.A.S
Aegean
Sea
Anatolia
K.F.
G.C.
Ge G.
B.M.G.
Go G.
Ionian
Sea
Hellenic Trench
Cretan
Crete
Cyprus
Mediterranean Ridge
NUBIA
ARABIA
B
ARABIA

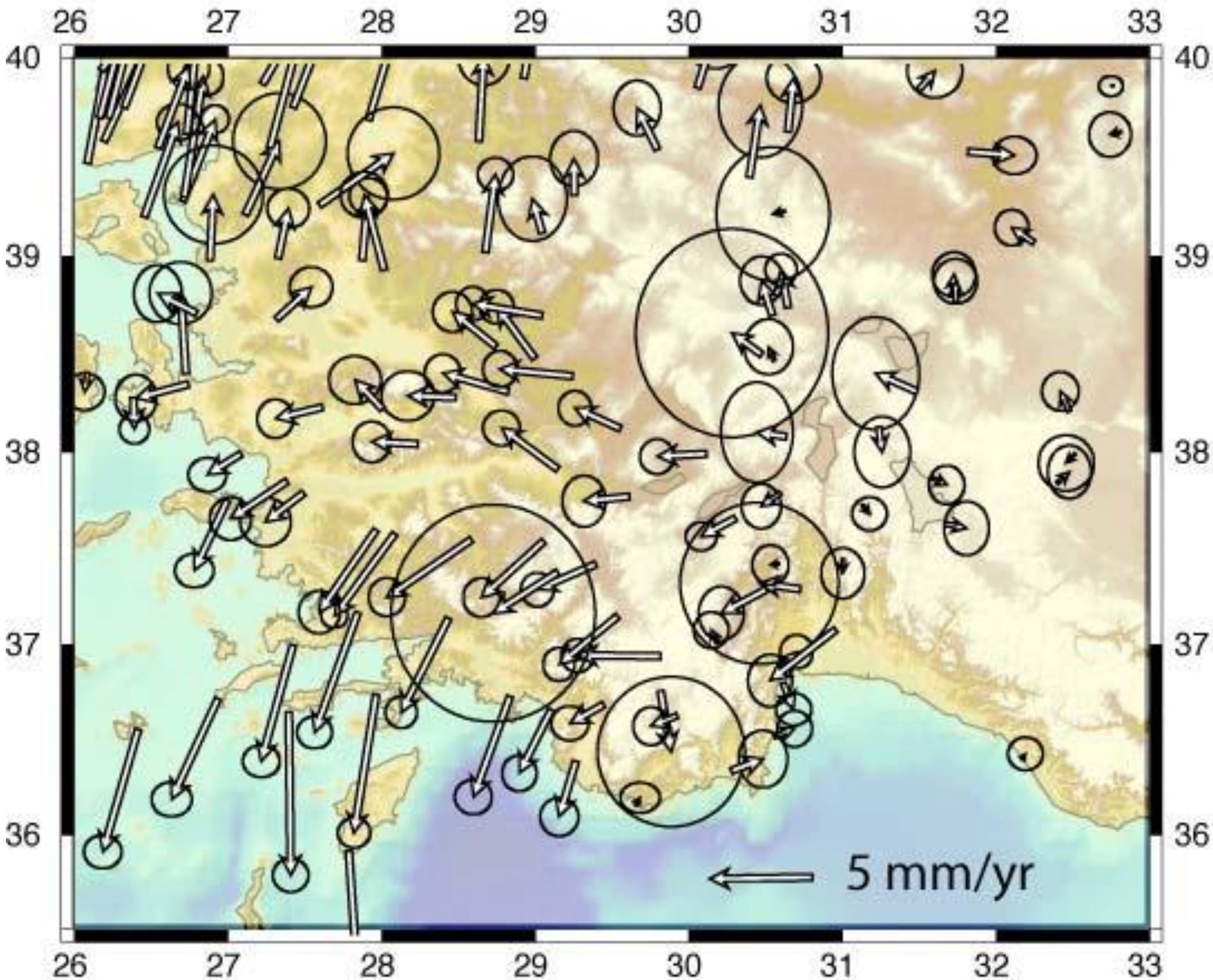


The Aegean

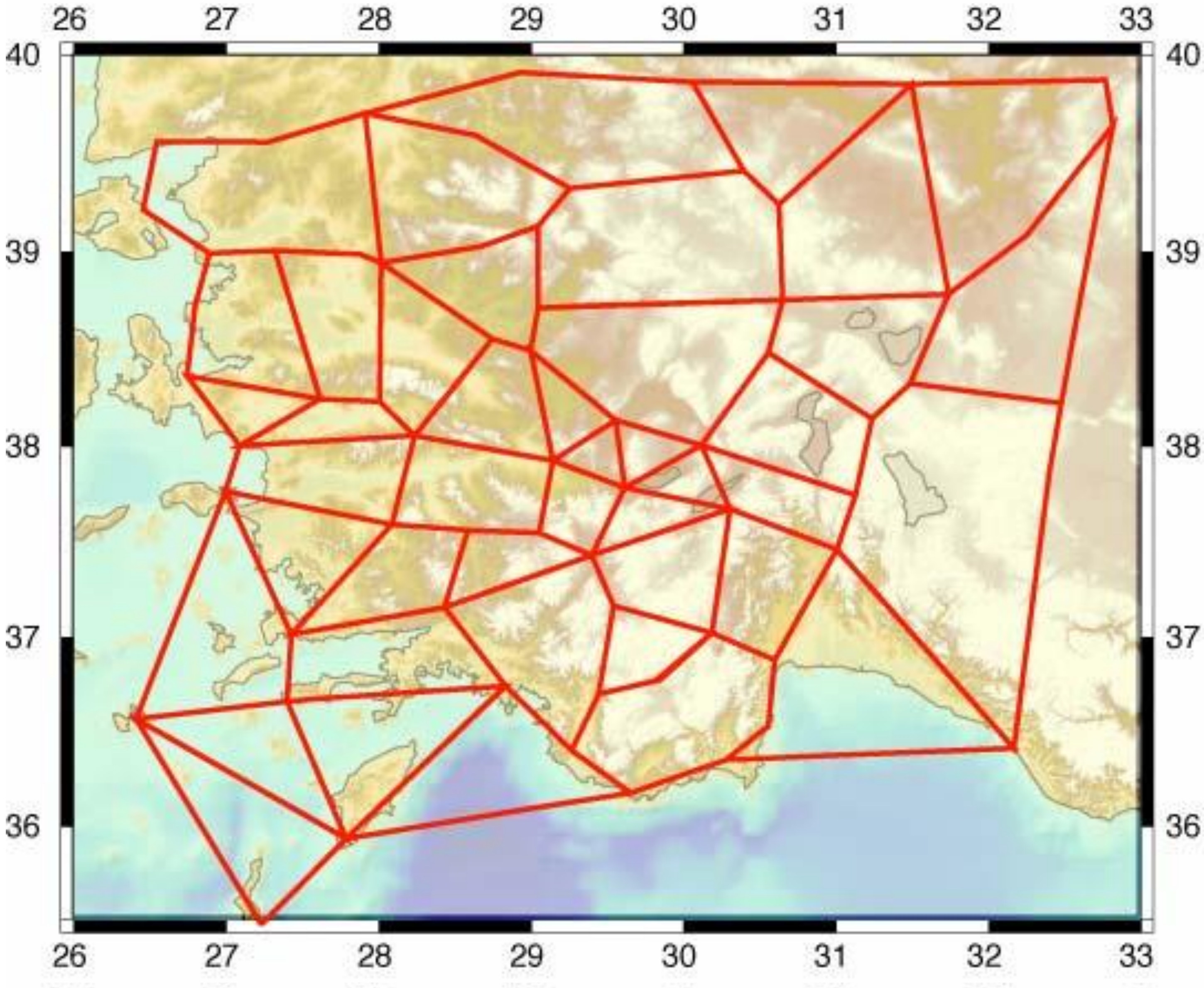
- Anti-clockwise rotation
- But, gradient of the velocity field toward the trench
- Trenchward motion starts north of the Aegean sea,possibly south of the Carpathians

Aktug et al. (2009), Floyd et al. (2010)

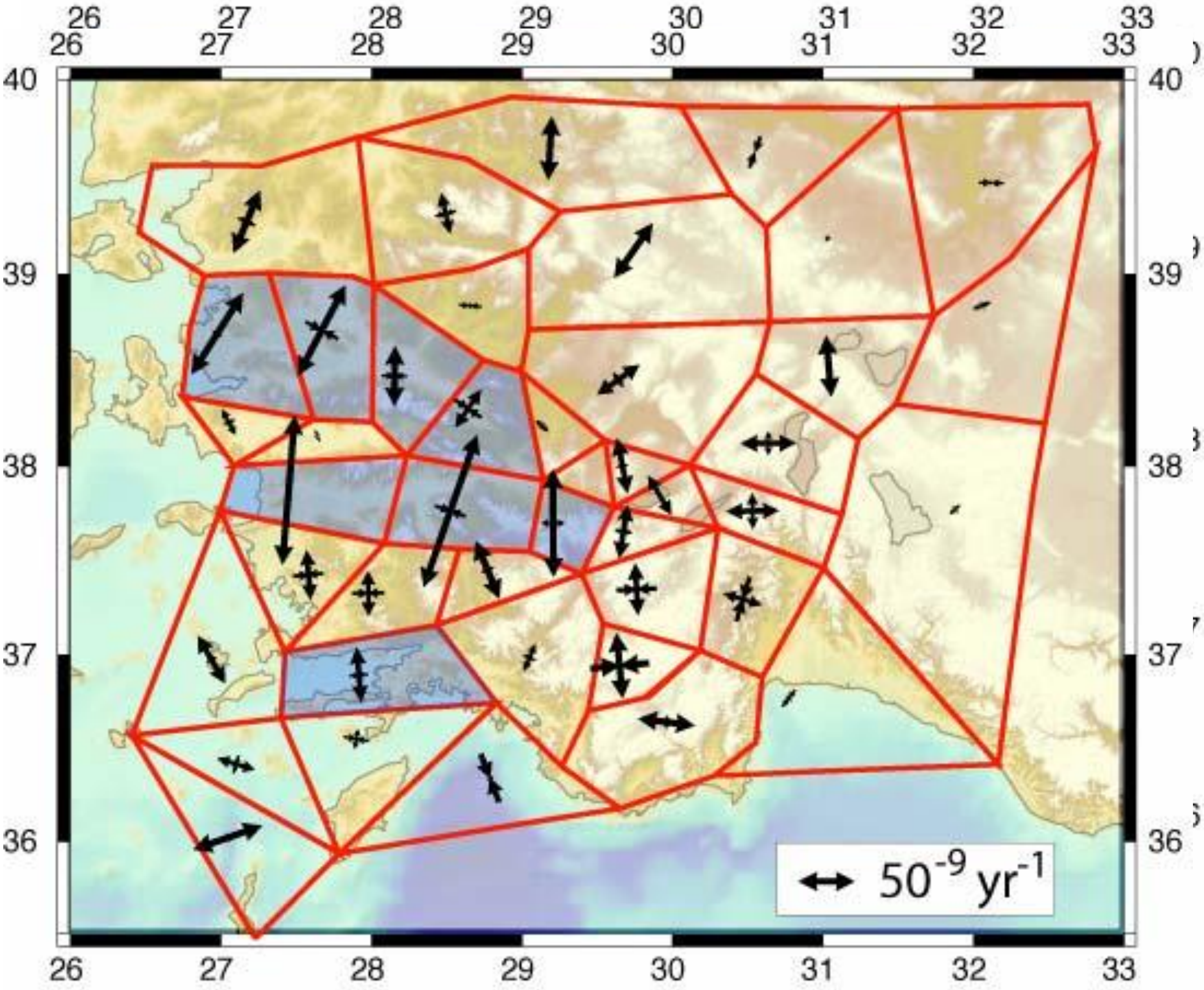
RESIDUAL VELOCITIES WRT CENTRAL ANATOLIA



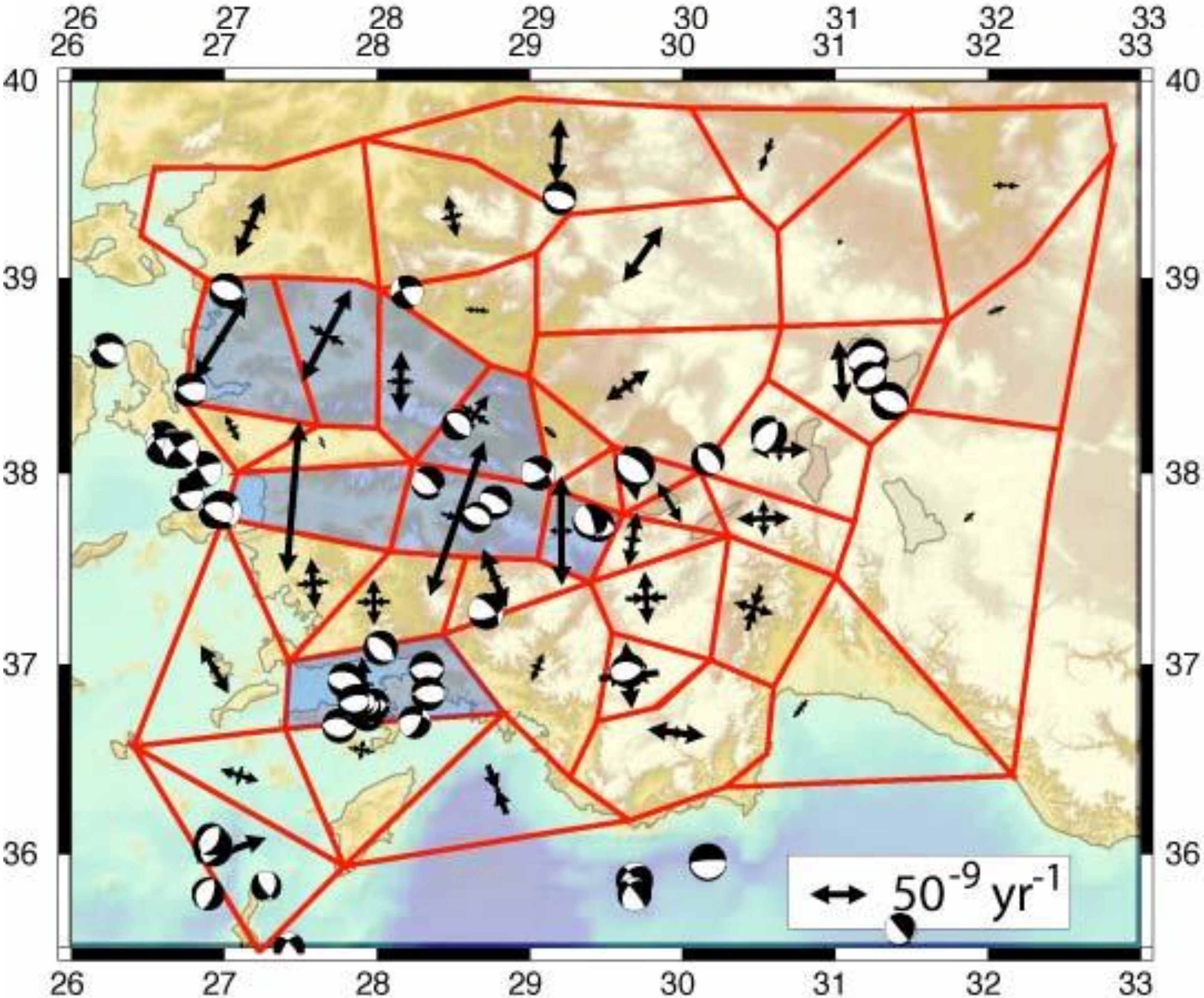
STRAIN ANALYSIS



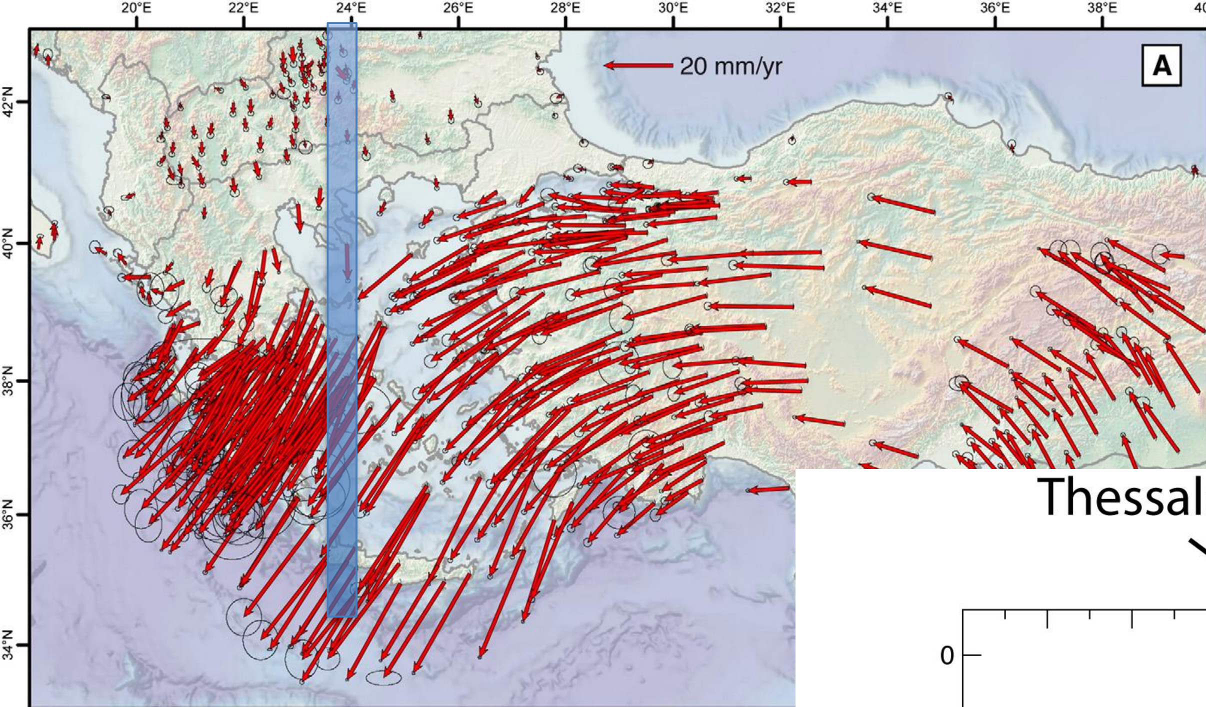
STRAIN ANALYSIS: RESULTATS



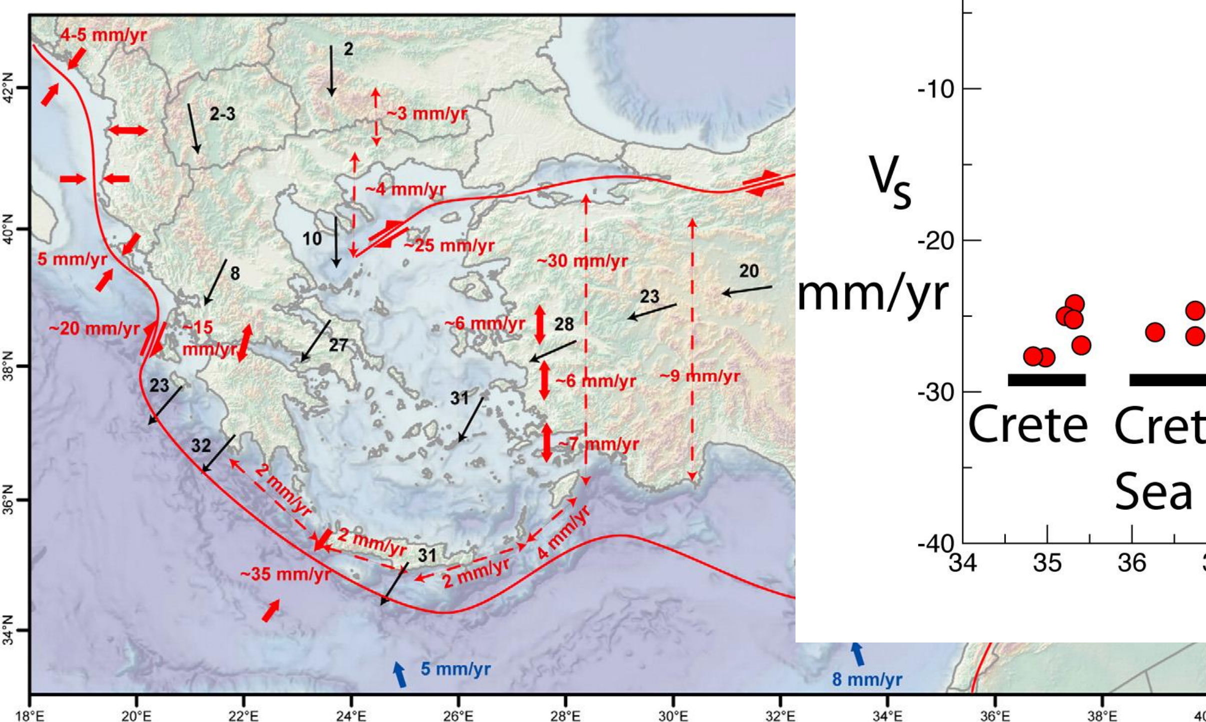
STRAIN VS FOCAL MECHANISM



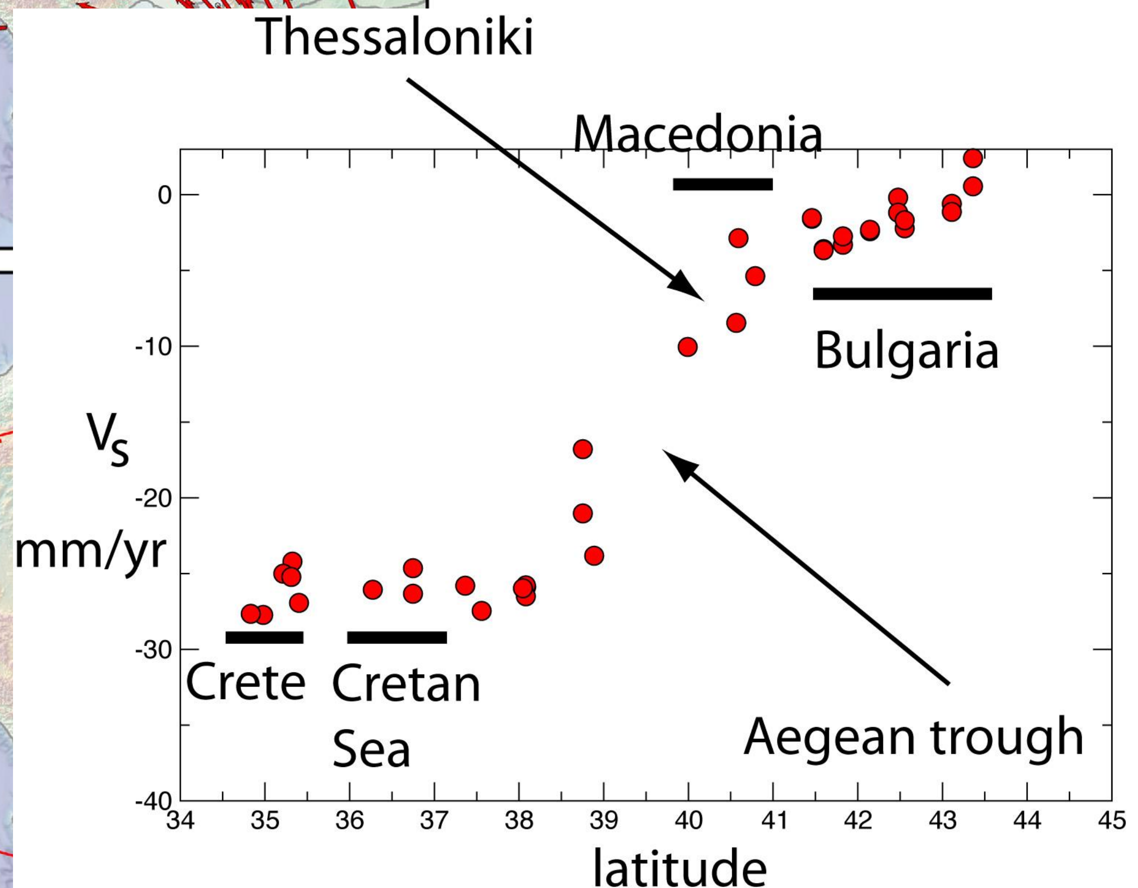
THE AEGEAN



A
20 mm/yr



4-5 mm/yr
~3 mm/yr
~4 mm/yr
~25 mm/yr
~30 mm/yr
5 mm/yr
~20 mm/yr
~15 mm/yr
~6 mm/yr
~9 mm/yr
~7 mm/yr
2 mm/yr
4 mm/yr
~35 mm/yr
5 mm/yr
8 mm/yr



Thessaloniki
Macedonia
Bulgaria
V_S
mm/yr
Crete
Cretan Sea
Aegean trough
latitude

CONCLUSIONS

- The Mediterranean is a puzzle made of continental, oceanic pieces
- Some piece might be almost rigid, some others are deforming
- The missing pieces of the puzzle are still mostly in northern Africa
- So far, results have shown a great diversity of deformation styles
- The link to the underlying dynamics has still to be made
- Vertical motion might be a key-element that our simple semi-kinematics models are unable to account in a unified model