VRANCEA SOURCE INVESTIGATION: MILESTONES SINCE 1977 TO THE PRESENT

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SUMMARY

- **Progress on earthquake monitoring**
- **Seismotectonics and seismicity patterns**
- **Seismic tomography**
- **Seismic source**
- **Geotectonic modelling**
- **Conclusions**

World-wide seismic networks

The World-Wide Standardized Seismograph Network (WWSSN)
developed in 1960’s - one of the most important advances in observational seismology.
Since installation until the mid-1990s it provided plenty of digital data, extremely useful for studying source and seismic wave propagation processes.

The GDSN and GEOSCOPE networks
Broadband instruments began to be widely deployed in the late 1980s and early 1990s.

National seismic network

Seismic survey in Romania was poorly developed in 1977, under reorganization, with outdated and improper equipment. For this reason, it was difficult for the Romanian seismologists to evaluate soon after the event the fundamental parameters: location and magnitude.

The seismic network in 1977: 8 seismic stations (Bacau, Bucuresti, Campulung, Focsani, Iasi, Muntele Rosu, Timisoara, Vrincioaia)

USA and PNUD – UNESCO support: ~ 2 million $
1978: DD-1 equipment (3 components) from China
1980: a new seismic network consisting of 10 stations with Teledyne-Geotech S-13 sensors, telemetred to Magurele through radio lines and 20 accelerographs from Kinemetrics.

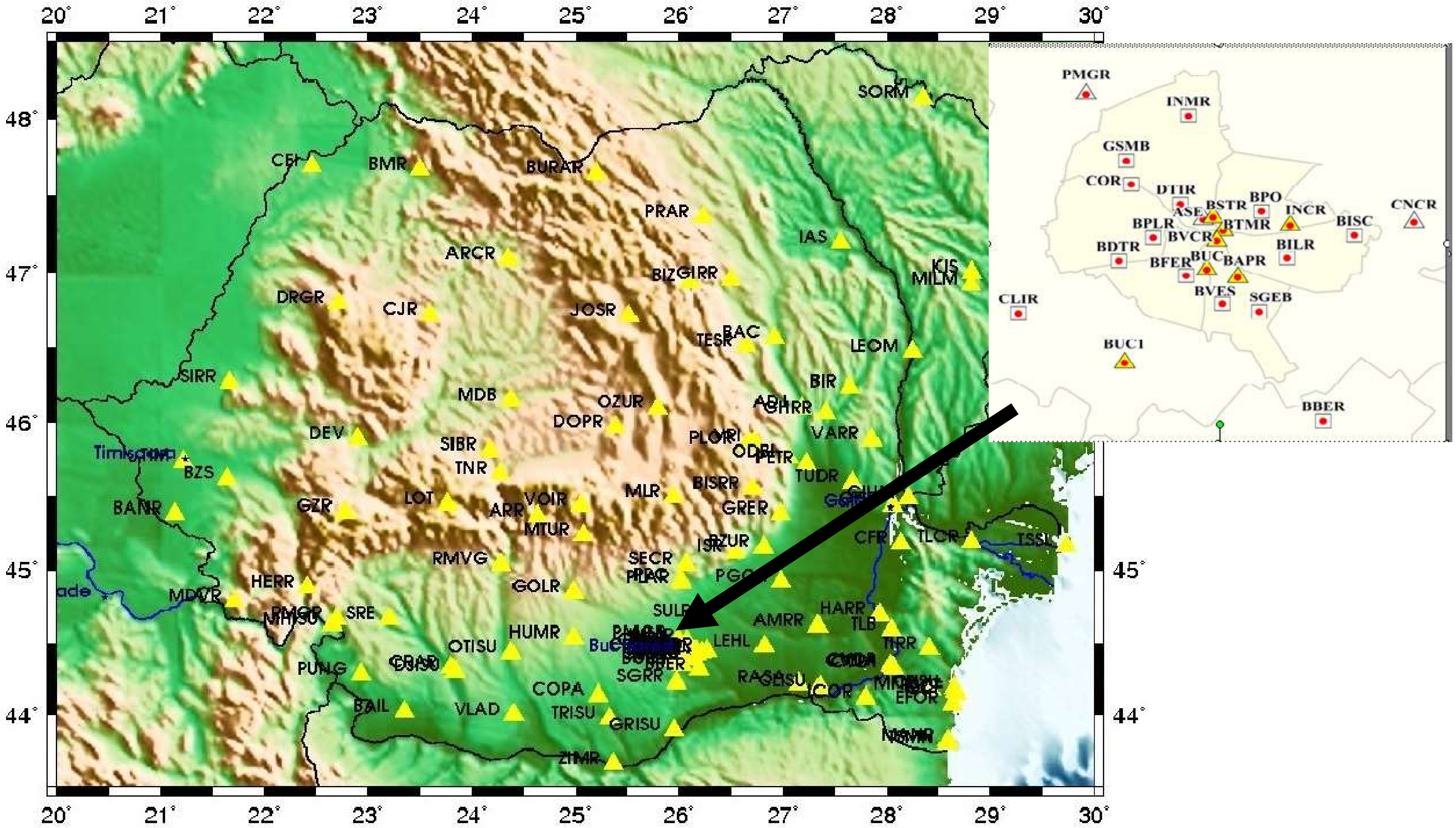
National seismic network

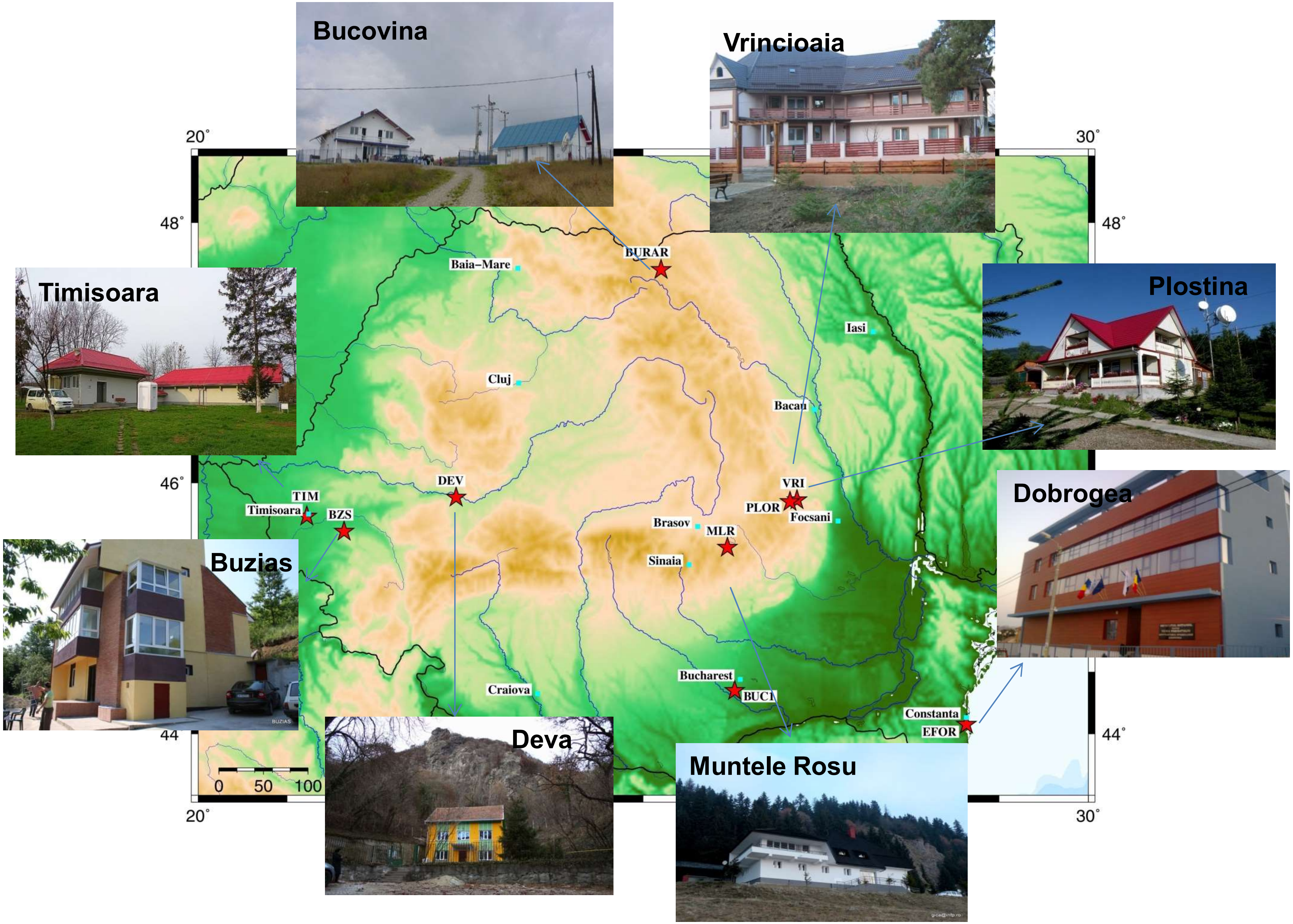
Starting with 1994, the Muntele Rosu observatory was provided with high-performance equipment by the Government of Germany and was included in **GEOFON network**. The Data Centre in Magurele became an automated system for digital acquisition and on-line processing, supplying rapid localization and magnitude (***Oncescu et al., 1996***).

A network of digital accelerometers (29 free-field stations with three components - Kinematics K2, GPS receivers for time synchronization) was installed in 1995–1997 in cooperation with Germany **(Collaborative Research Center 461: “Strong Earthquakes: A Challenge for Geosciences and Civil Engineering”, Univ. din Karlsruhe)**.

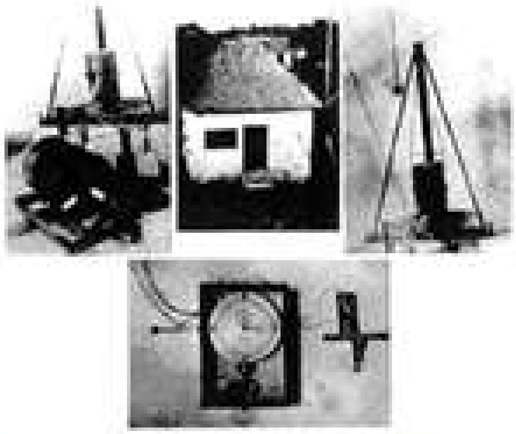
2002: **Romania – SUA cooperation (AFTAC)**: BURAR seismic array - 10 seismic sensors (9 SP + 1 BB) in boreholes (30-50 m), distributed on a (5x5) km^2 area.

Seismic network today



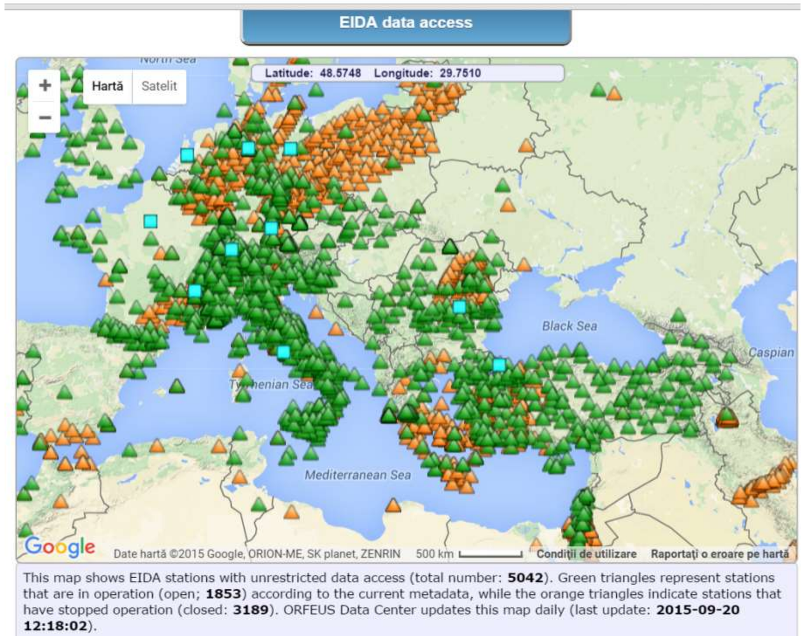

Bucovina
Vrincioaia
Timisoara
Plostina
Dobrogea
Buzias
Deva
Muntele Rosu
20°
30°
48°
46°
44°
BURAR
Baia–Mare
Iasi
Cluj
Bacau
VRI
PLOR
Focsani
DEV
TIM
Timisoara
BZS
Brasov
MLR
Sinaia
Bucharest
BUCI
Craiova
Constanta
EFOR
0
50
100

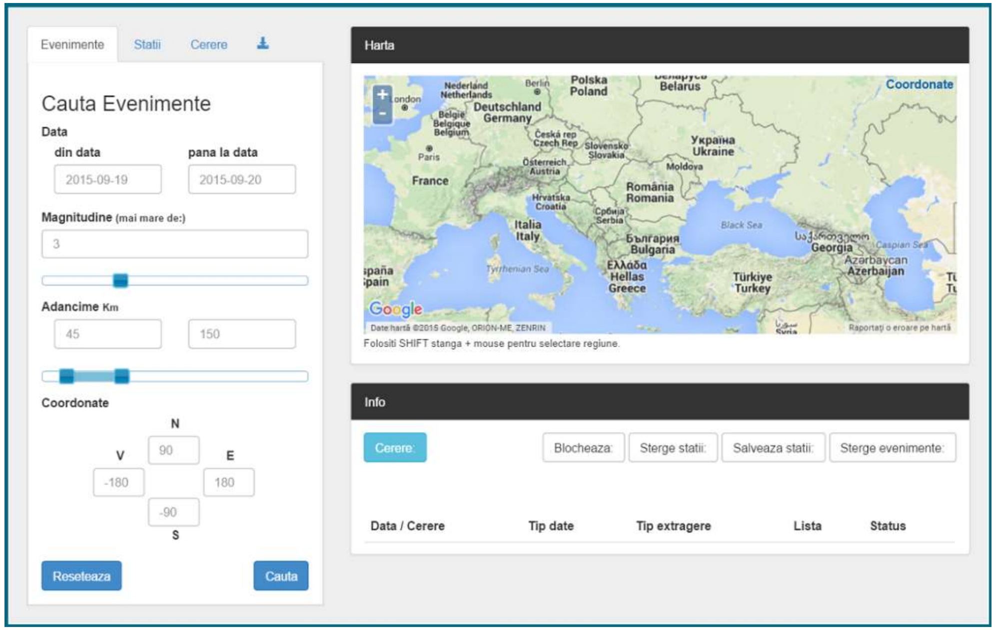
Statia Vrincioaia – in anii 70



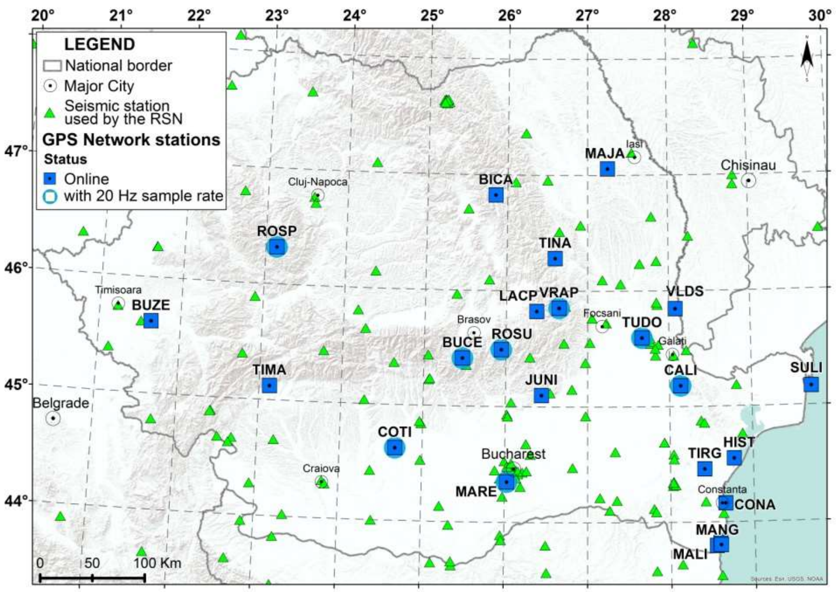
Observatorul seismologic "Radu Cornelius" de la Vrincioaia - in prezent

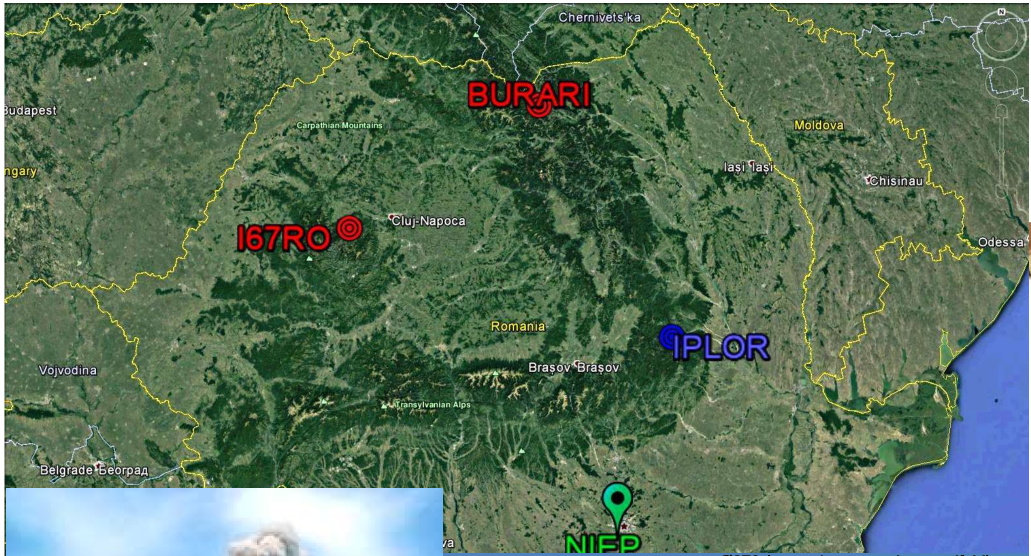
2016: NIEP becomes EIDA (European Integrated Data Archive) node for East Europe, supplying real-time data and services

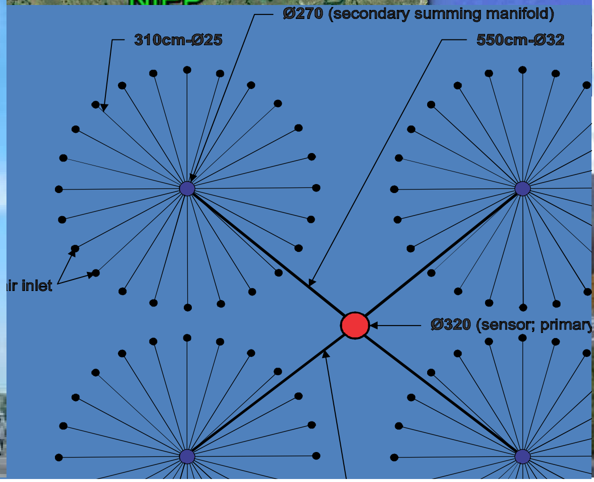


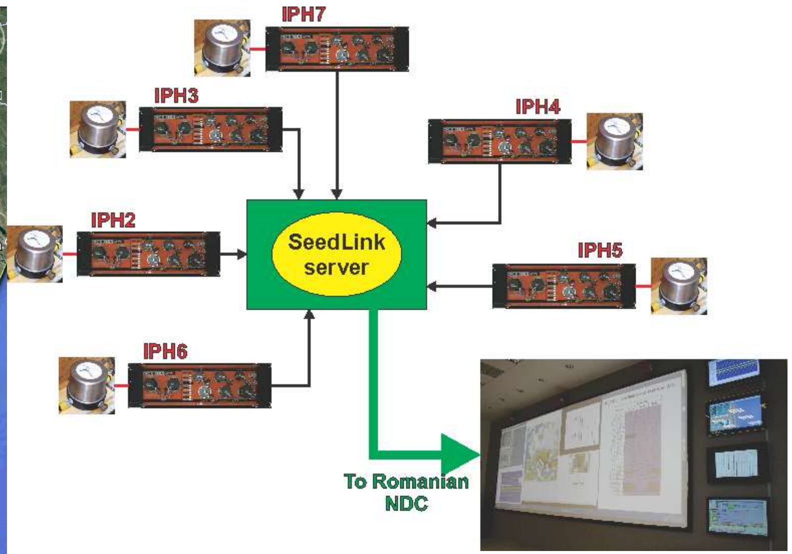


GNSS network



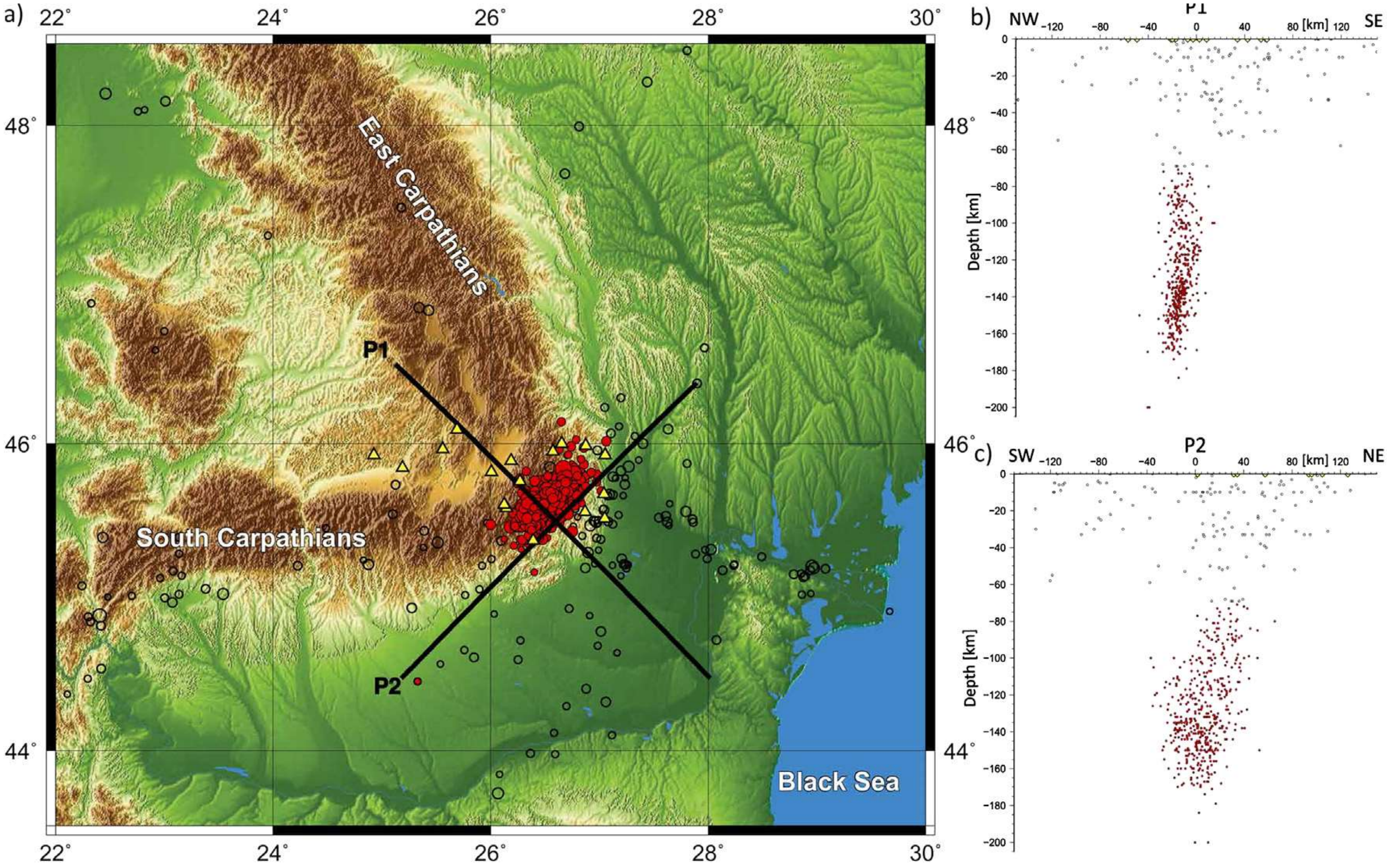






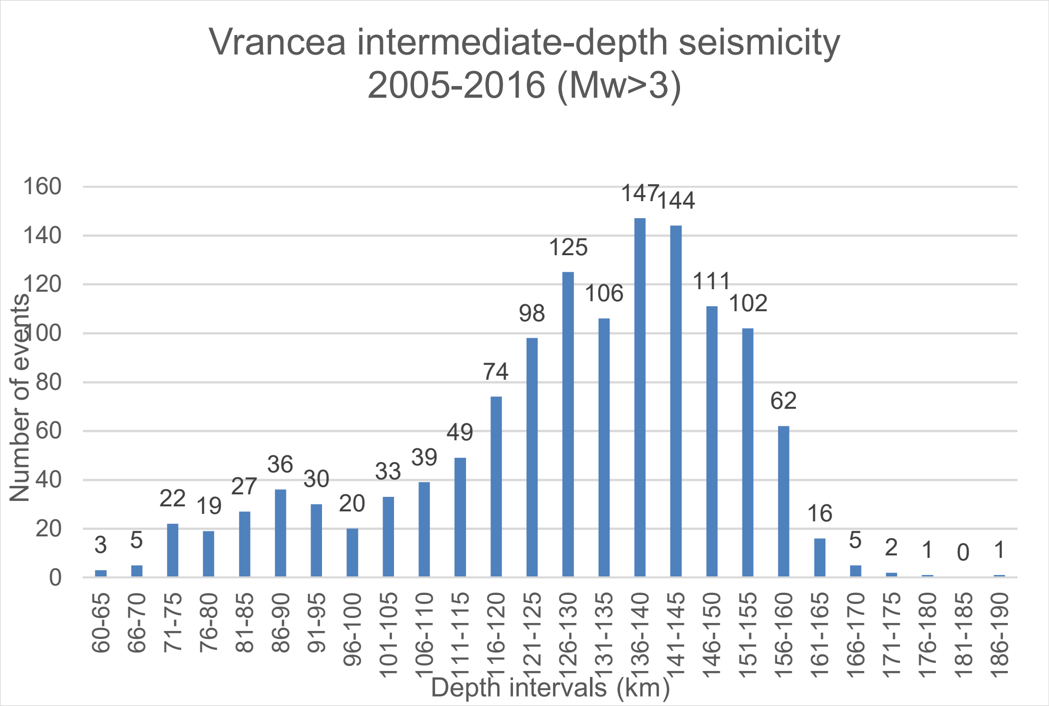
Example of an acoustic event (explosion at Bulgarian ammo facilities) detected with Ploştina infrasonic array (IPLOR)

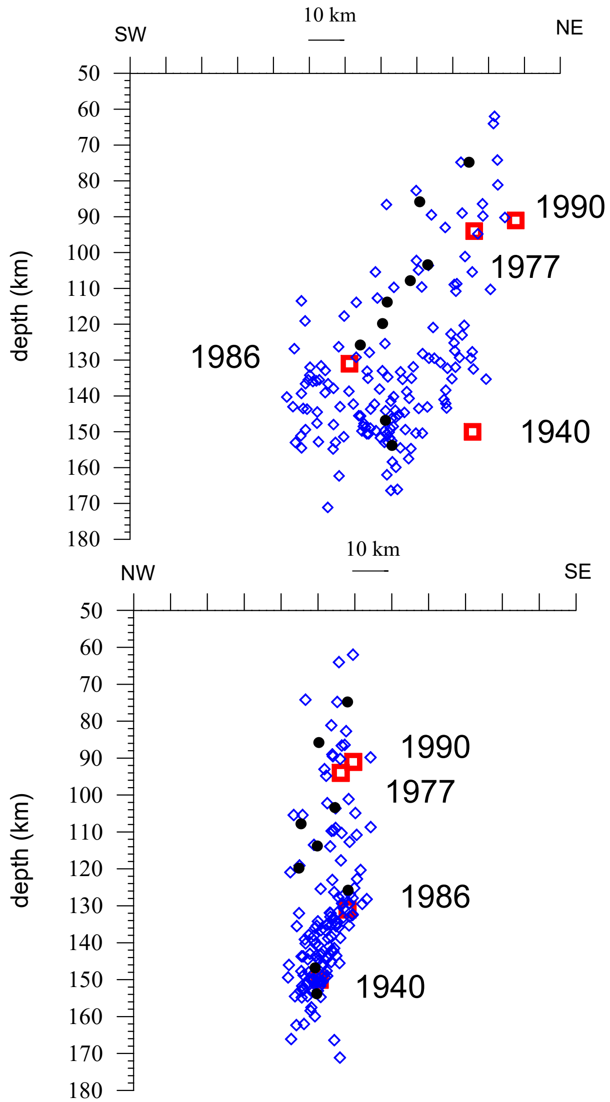
SEISMICITY



Bokelmann and Rodler (2014)

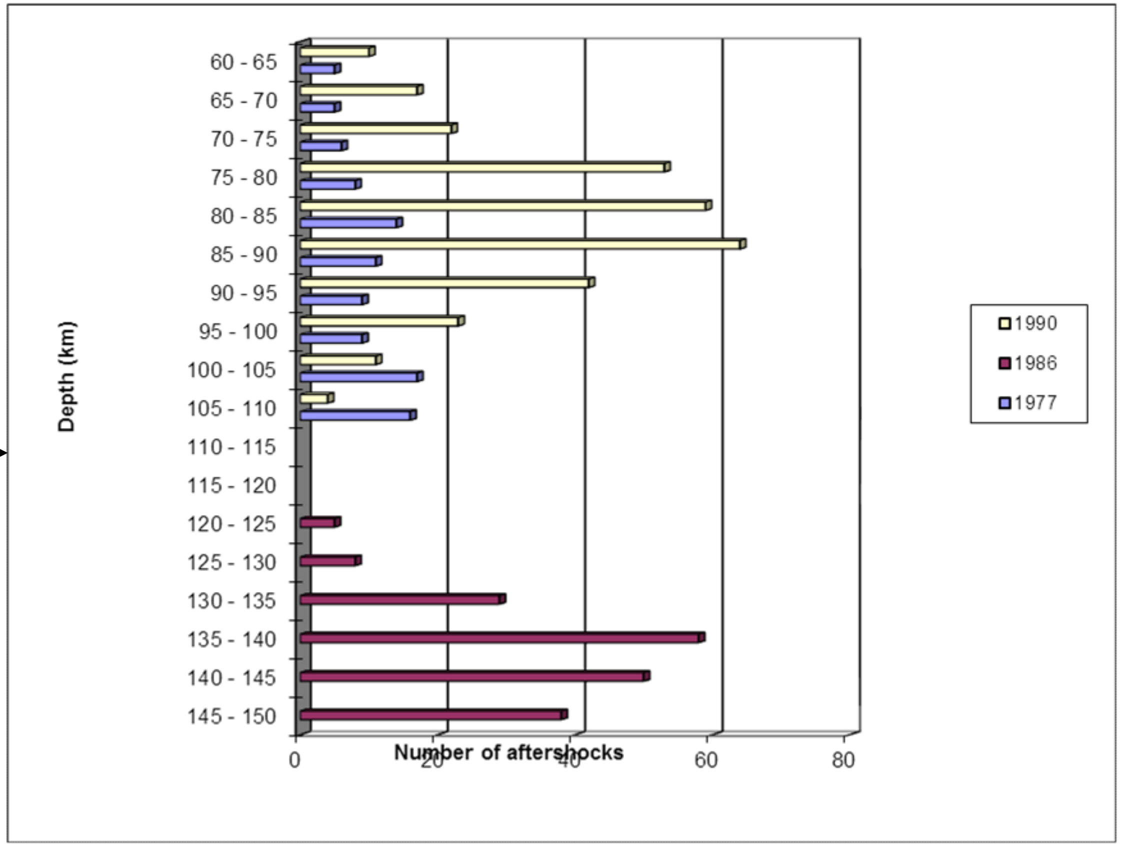
DEPTH DISTRIBUTION





DEPTH DISTRIBUTION

Barrier?



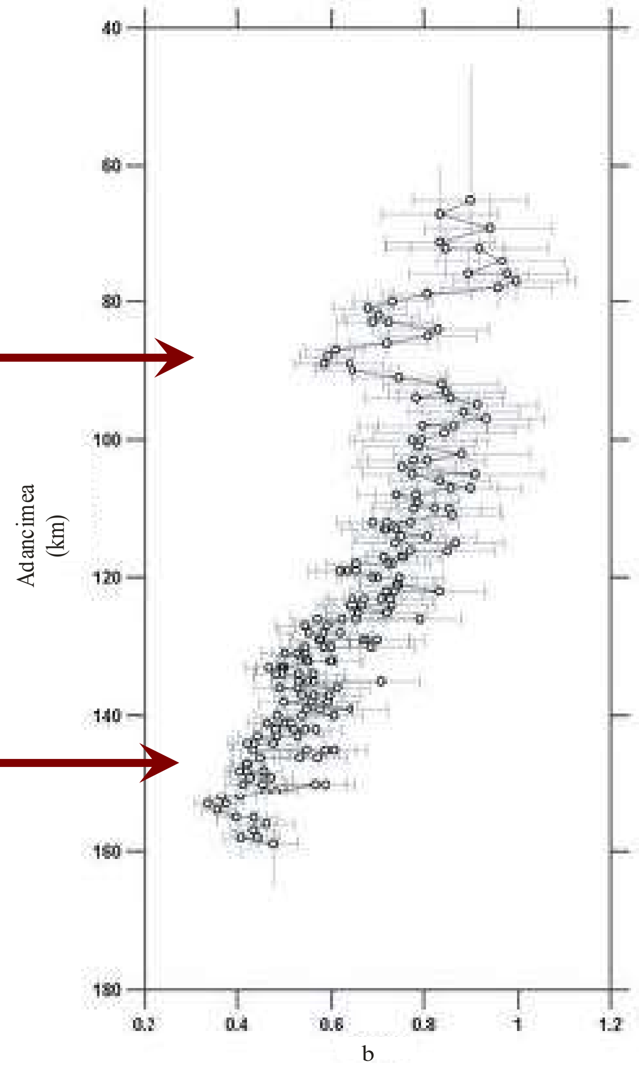
DEPTH DISTRIBUTION

Depth variation of the b-slope
1995 – 2006 catalogue

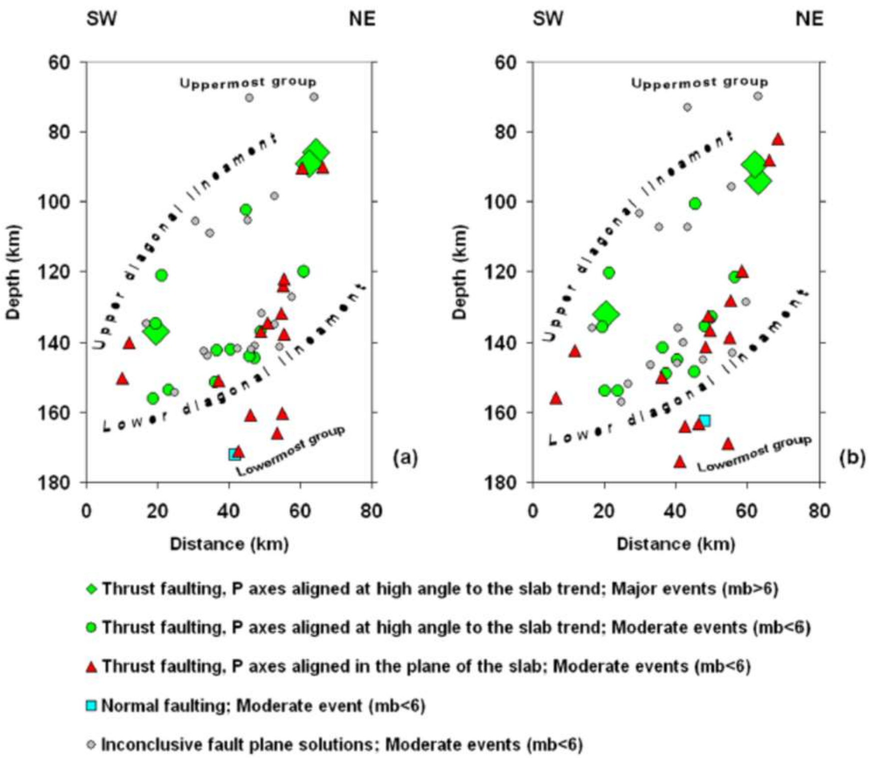
Low b values indicate zones with high stress

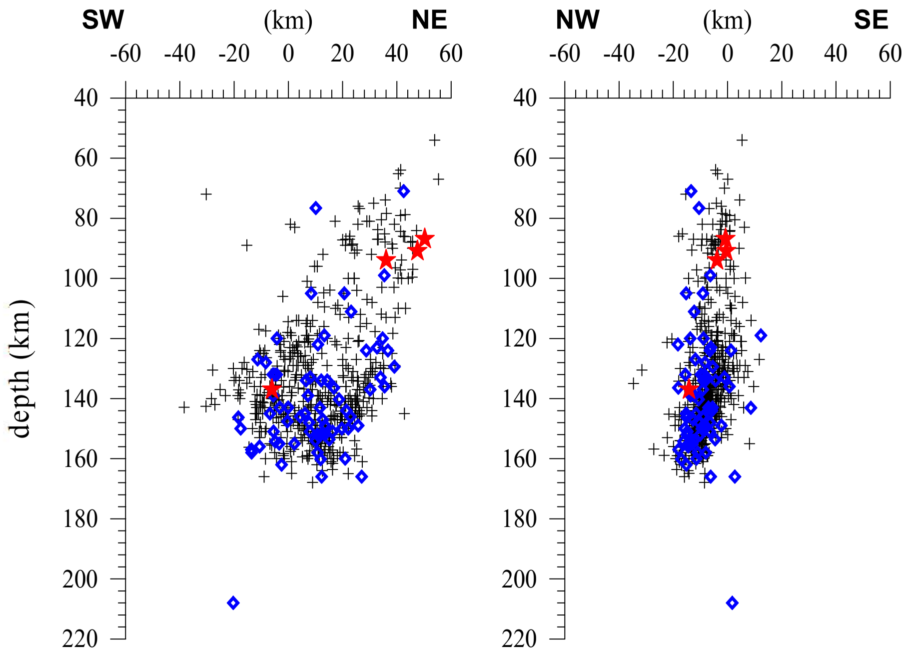
1977
1990
2004

1940
1986



SEISMICITY PATTERNS

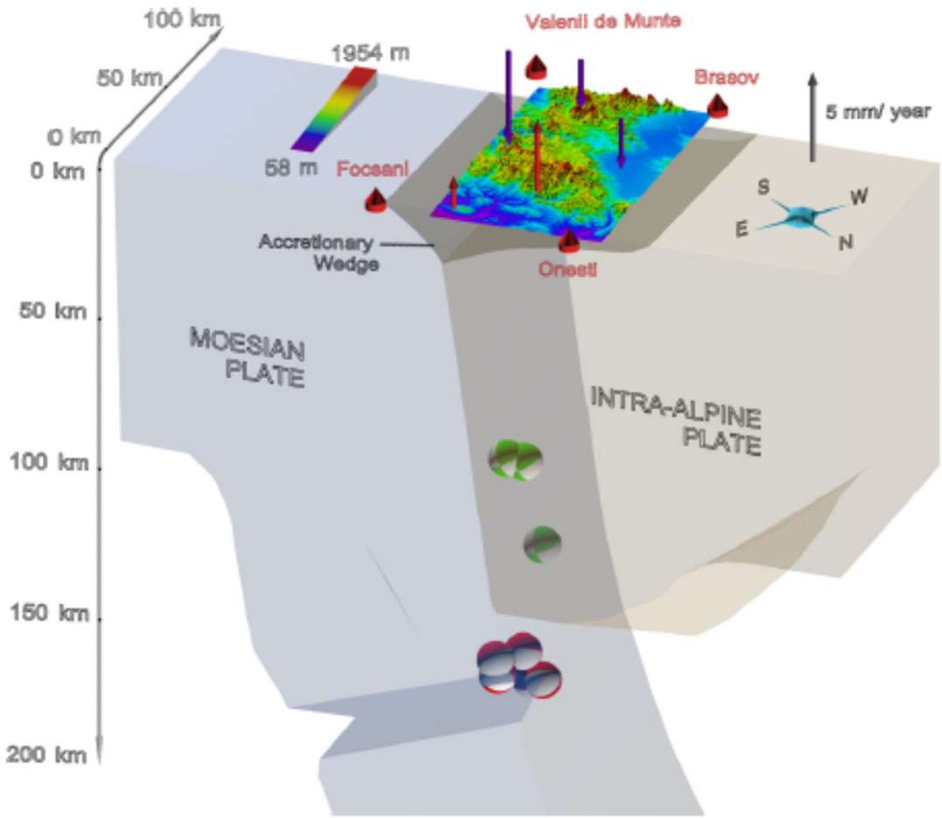




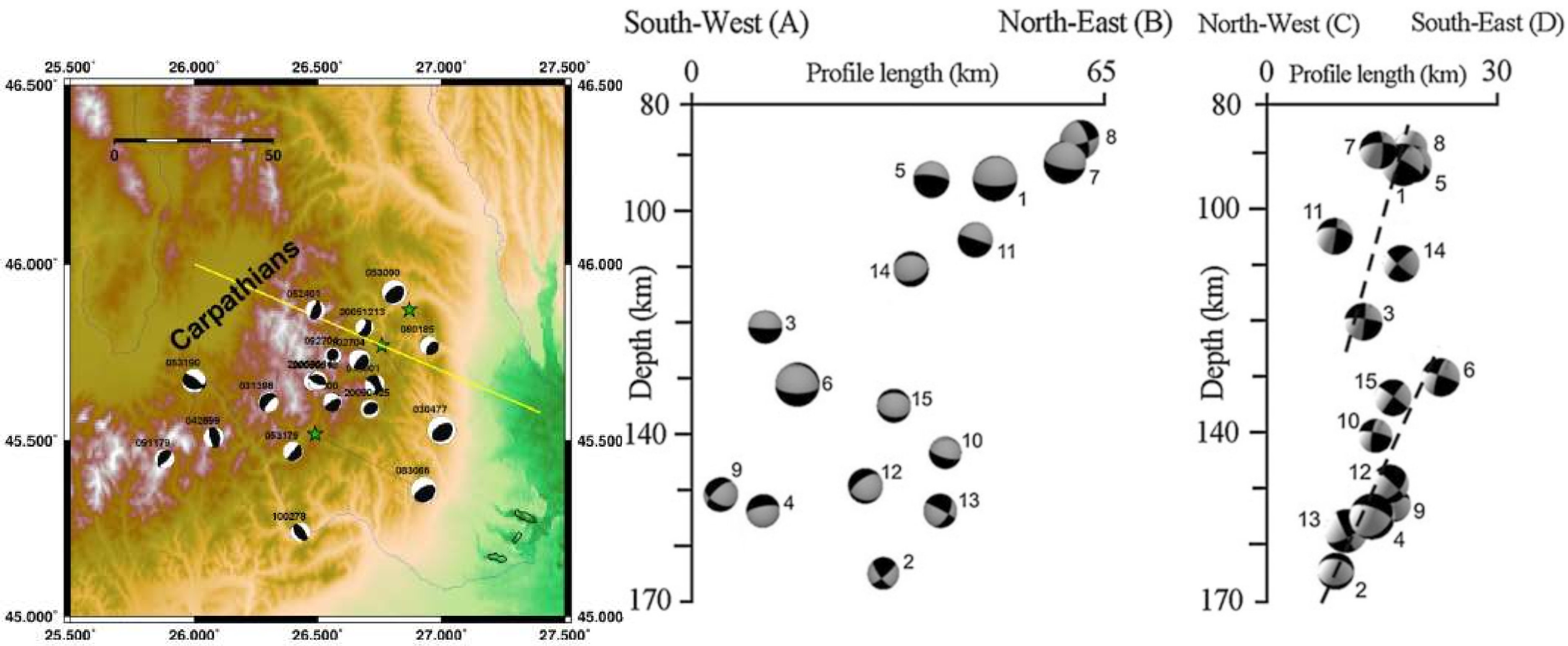
Radulian et al. (2012)

Mitrofan et al. (2016)

SEISMICITY PATTERNS



Mitrofan et al. (2016)



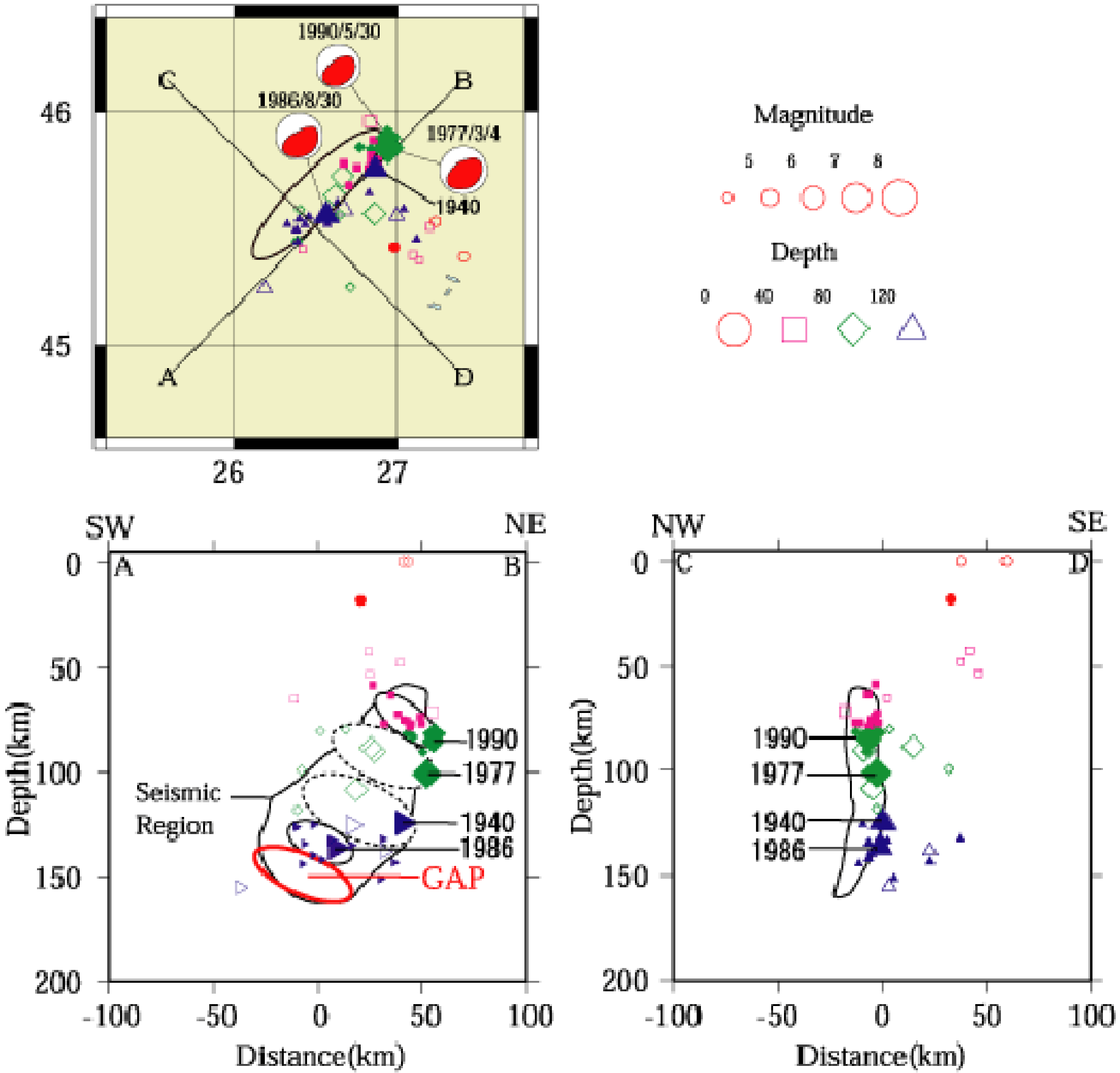
CMT solutions for Vrancea earthquakes Mw > 4.8
http://www.globalcmt.org/

Extension along nodal planes dipping toward West. Two possible major weakness planes inside the lithospheric body generating earthquakes.

Radulian (2014)

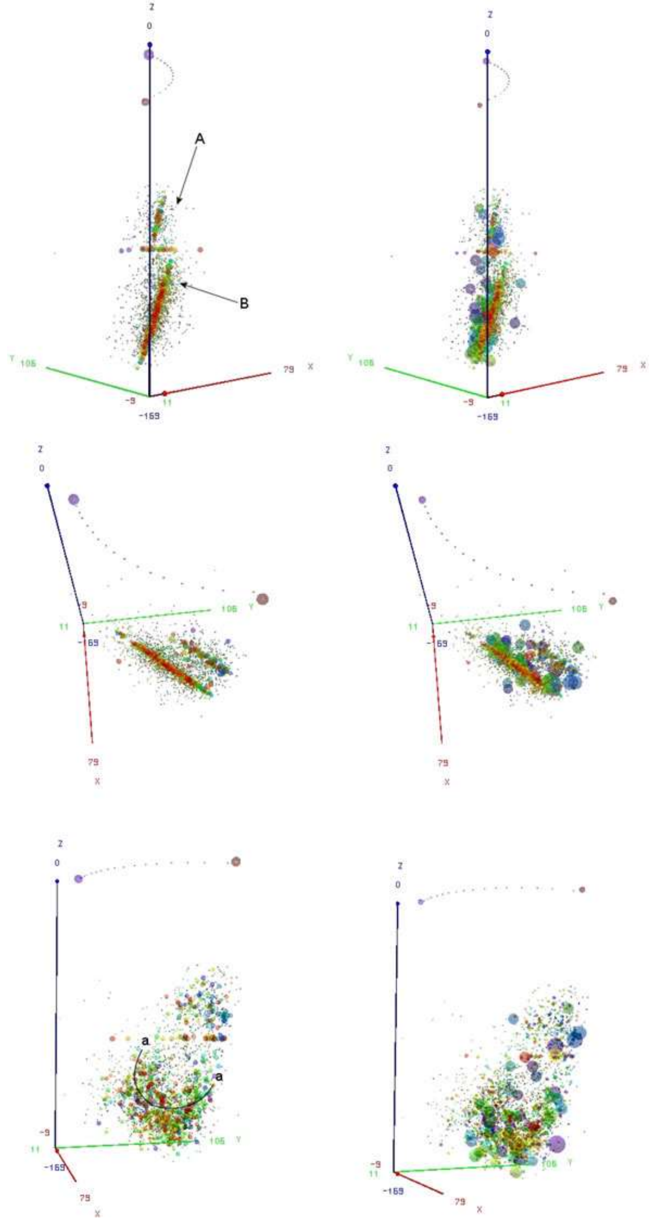
SEISMICITY PATTERNS

Hurukawa and Imoto (2010) model: repetitive migration of stress release starting from the bottom active segment (140 – 170 km) propagating to the middle active segment (110 – 140 km) and finishing in the upper active segment (80 – 110 km). This migration phenomenon repeats each century.

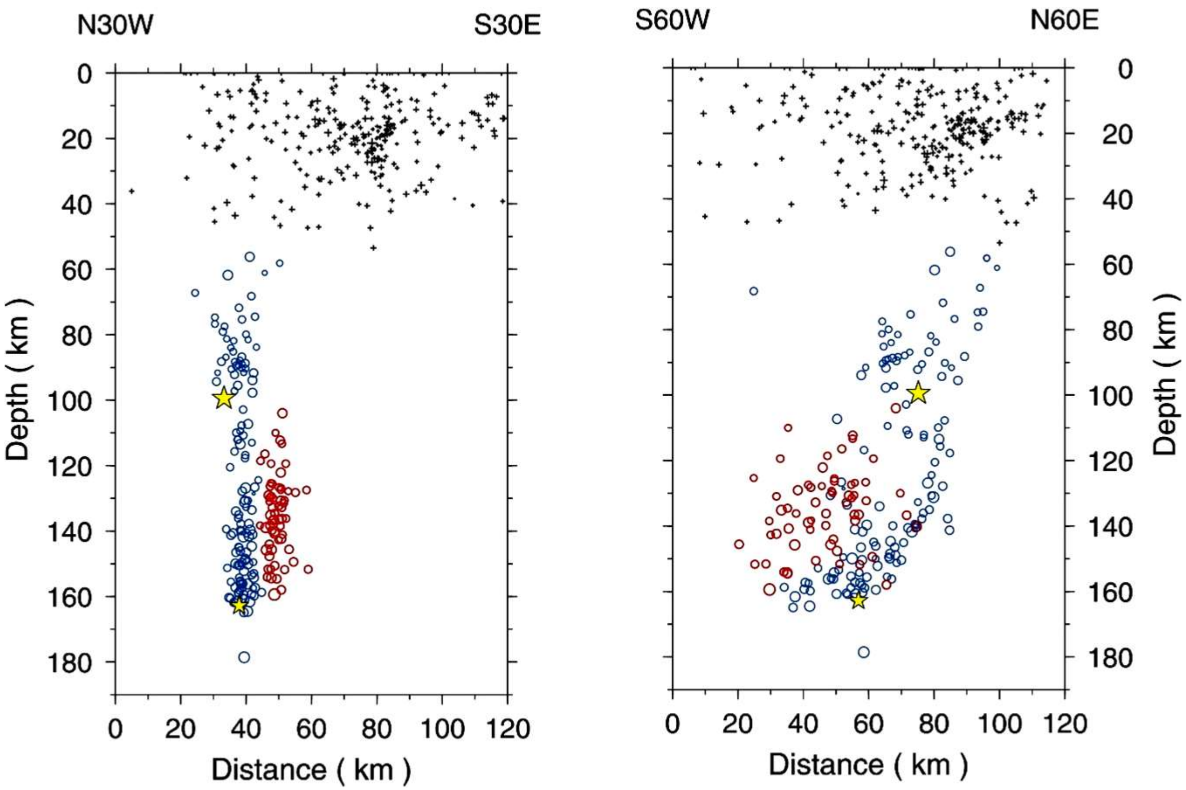


Carbunar and Radulian (2011)

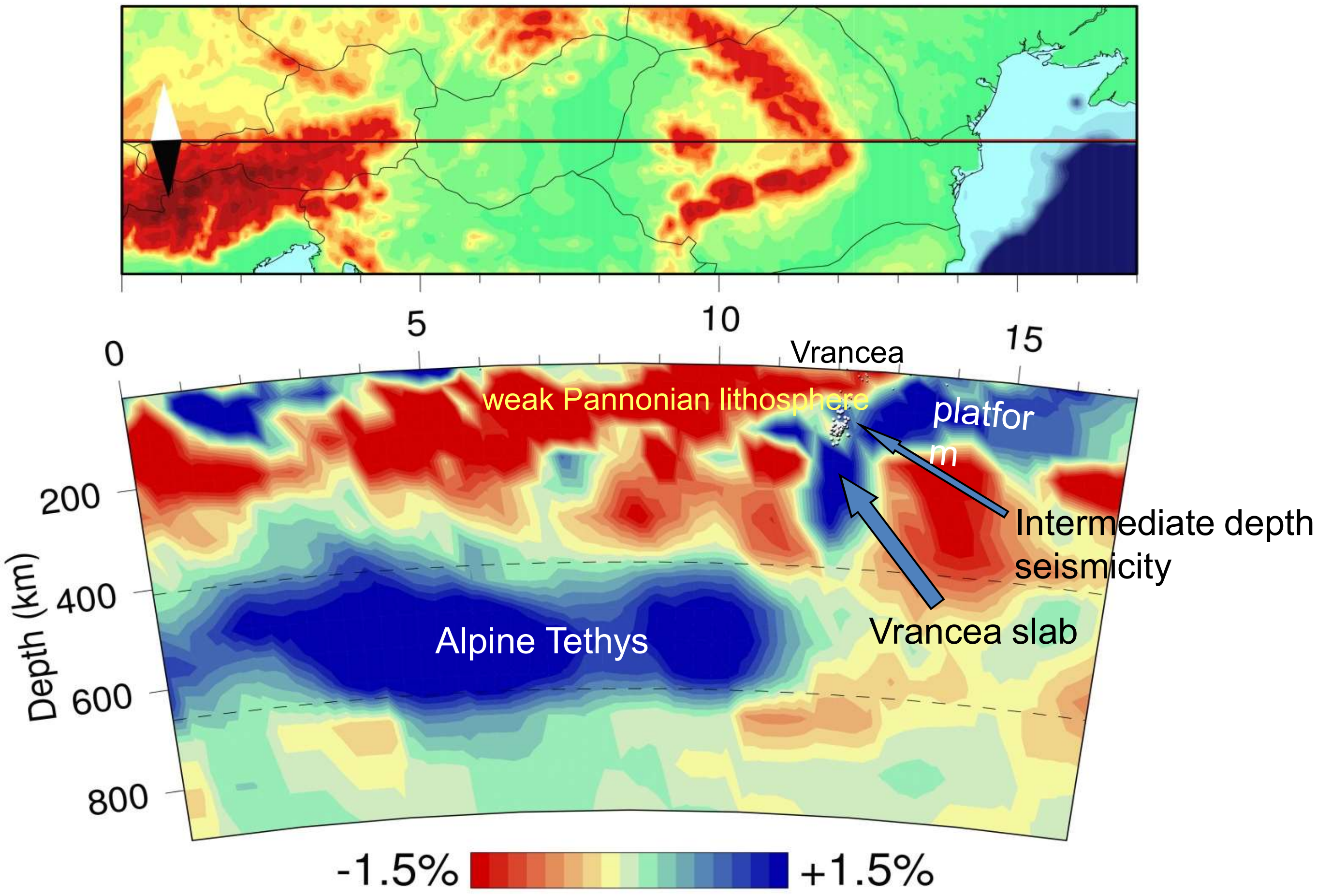
DOUBLE SEISMIC ZONE?



Bonjer et al. (2005)

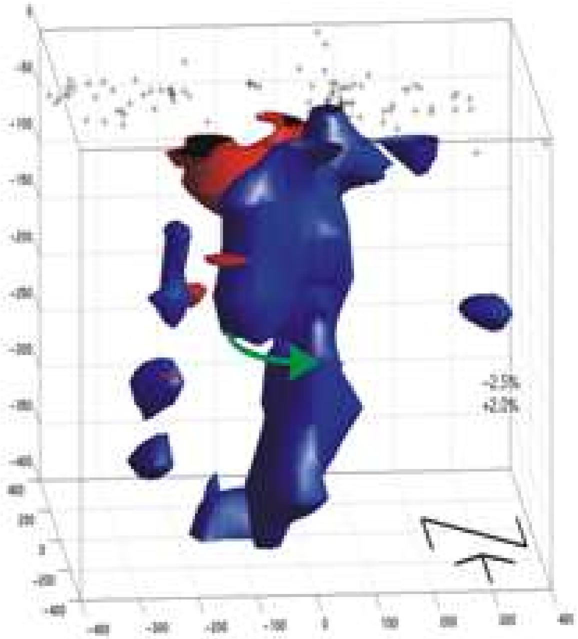


SEISMIC TOMOGRAPHY

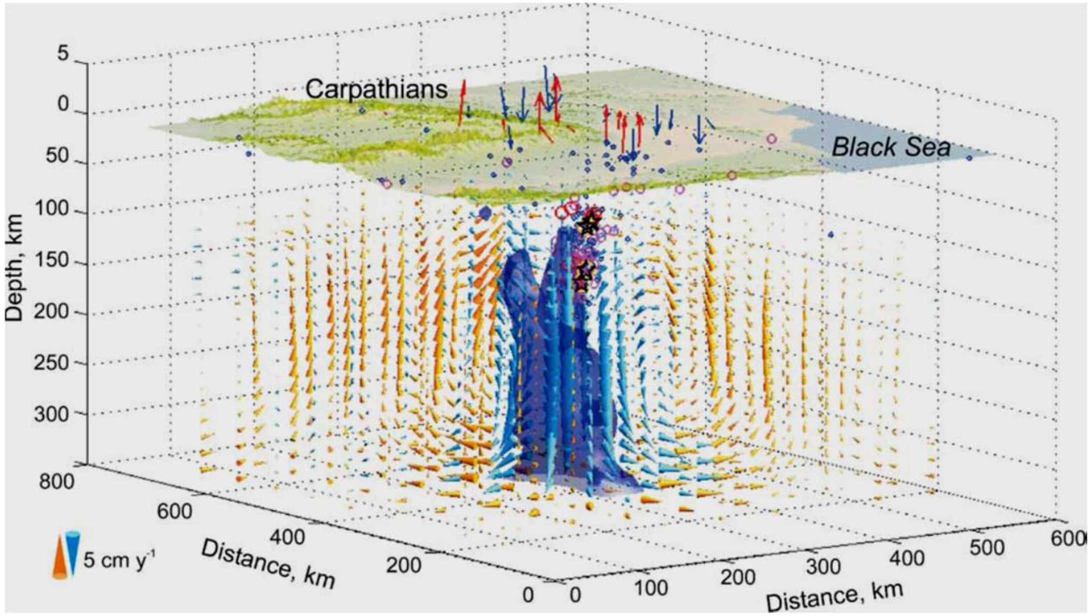


Bijwaard and Spakman (2000)*; *Wortel and Spakman (2000)

CALIXTO EXPERIMENT

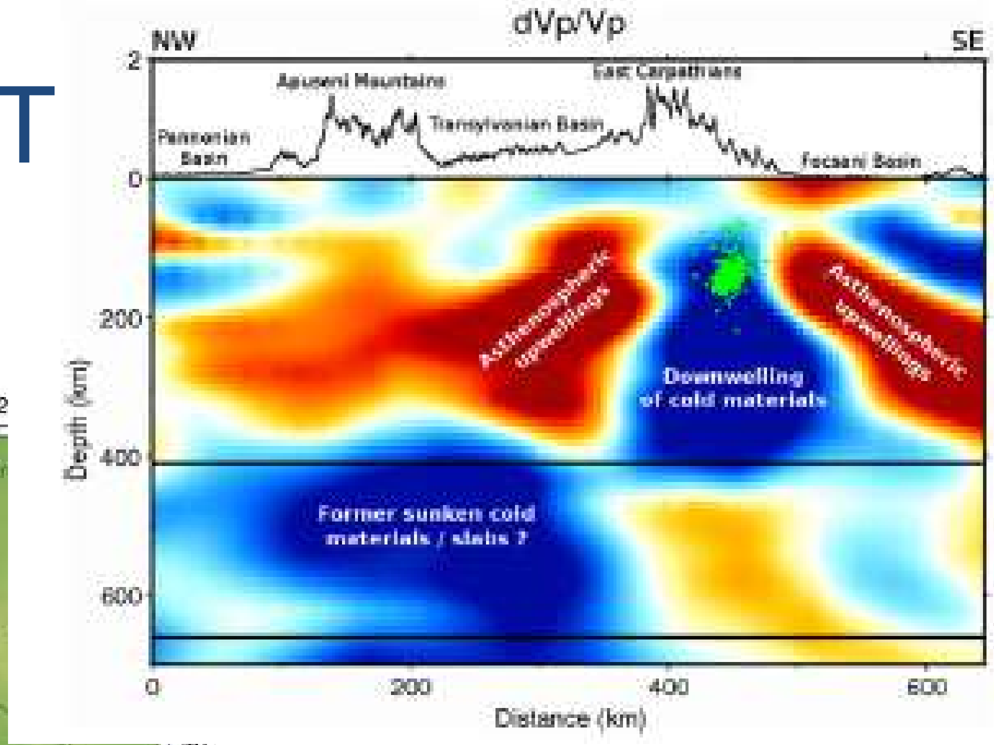


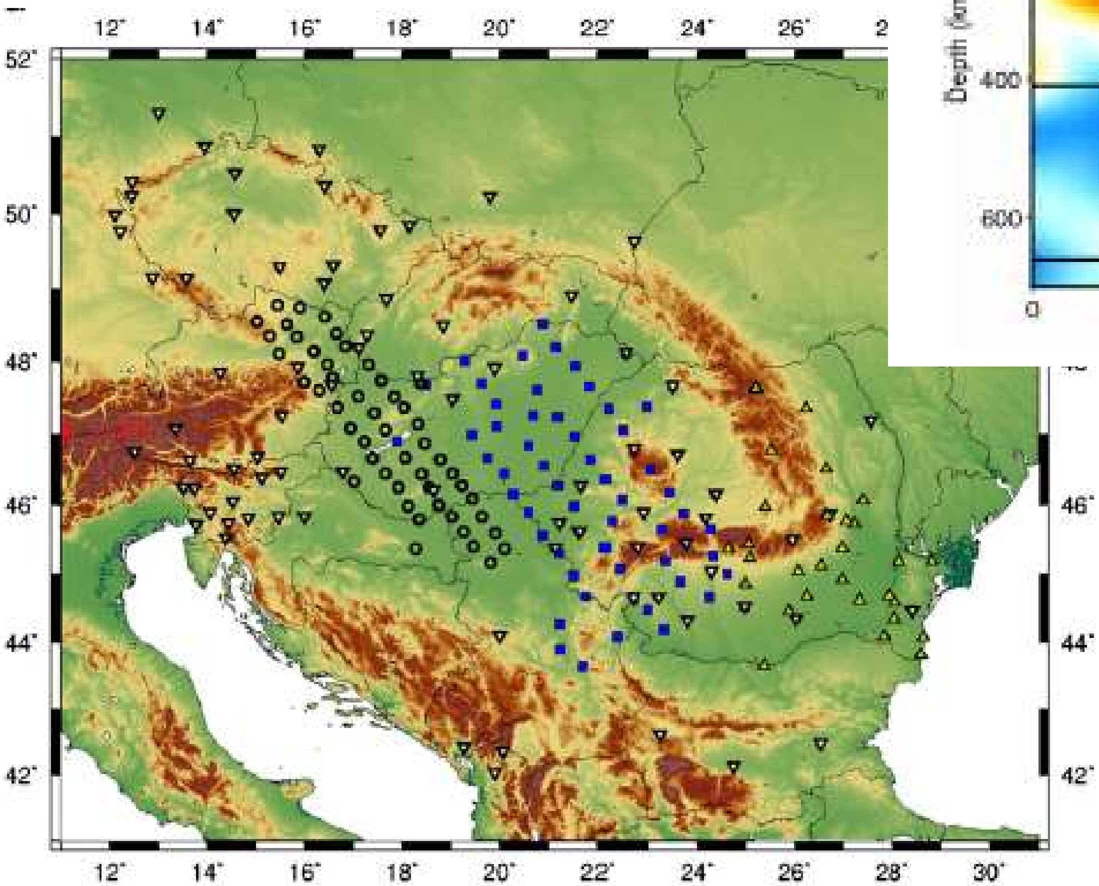
Martin et al. (2006)



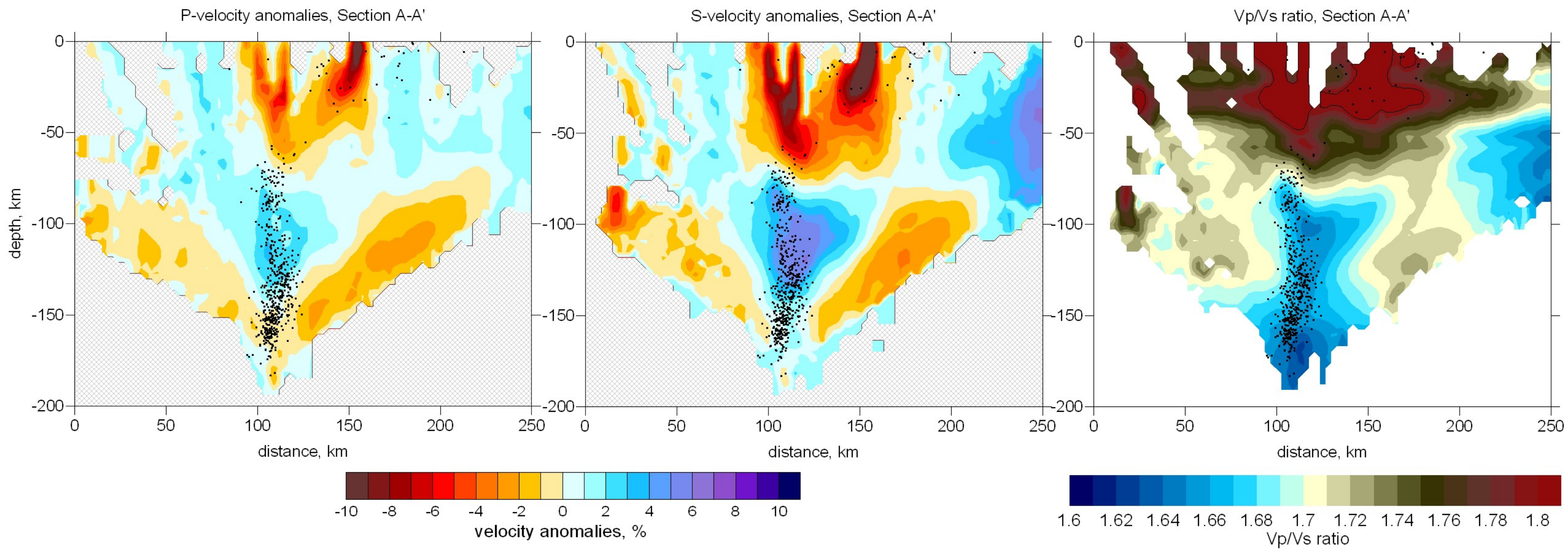
Ismail-Zadeh et al. (2005)

SCP EXPERIMENT



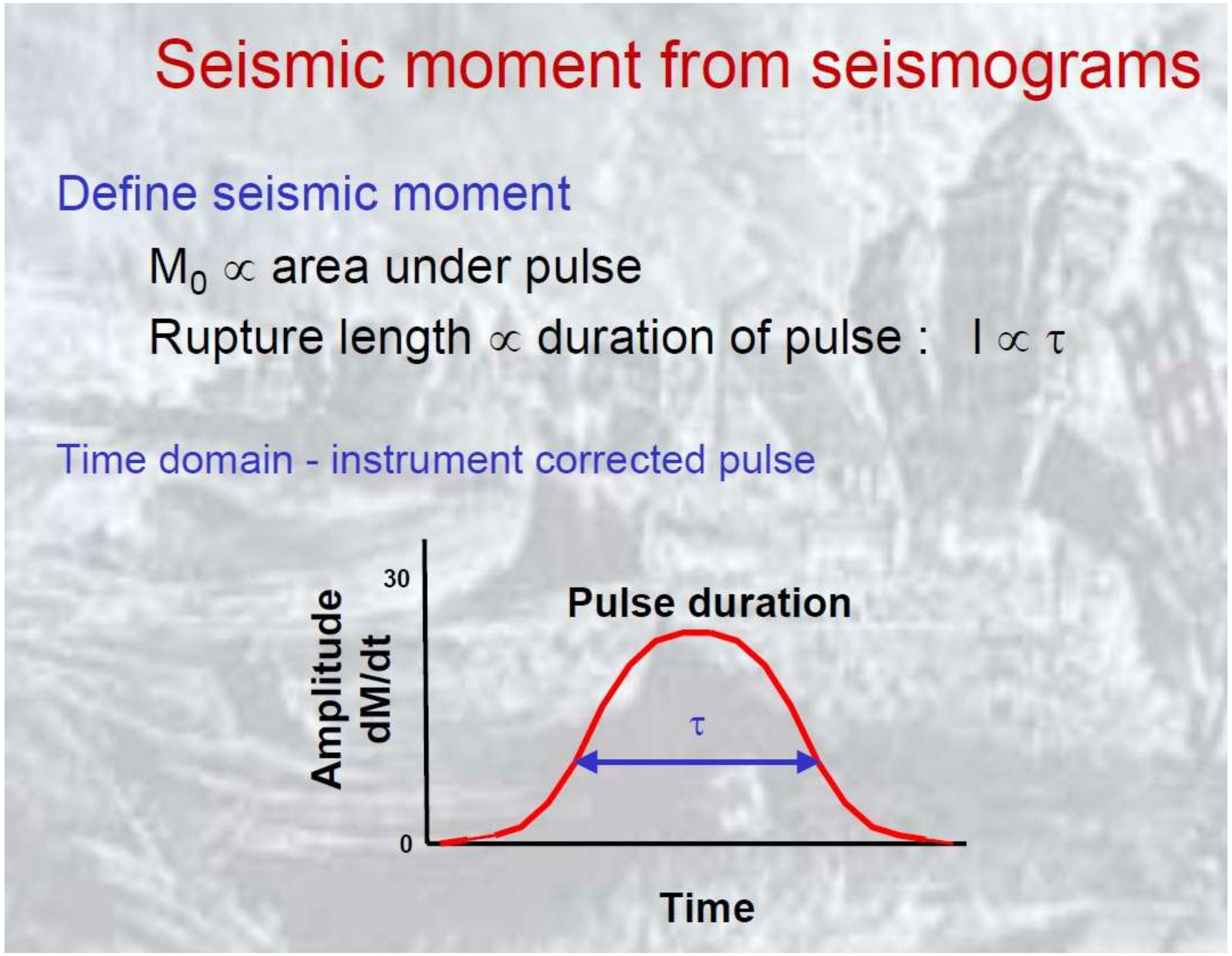


Ren et al. (2012)



Koulakov et al. (2010)

SEISMIC SOURCE



SEISMIC SOURCE

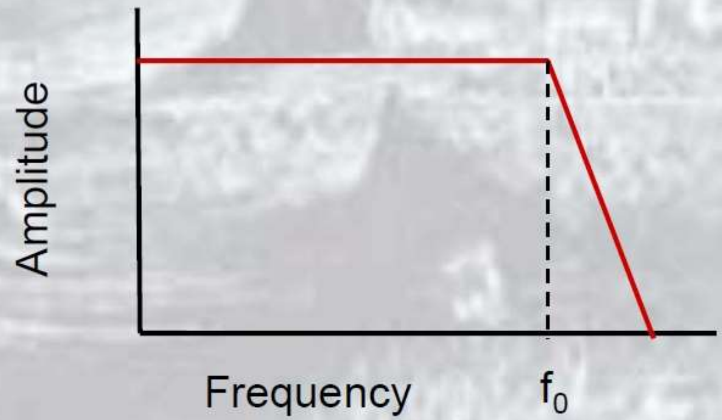
Seismic moment from seismograms

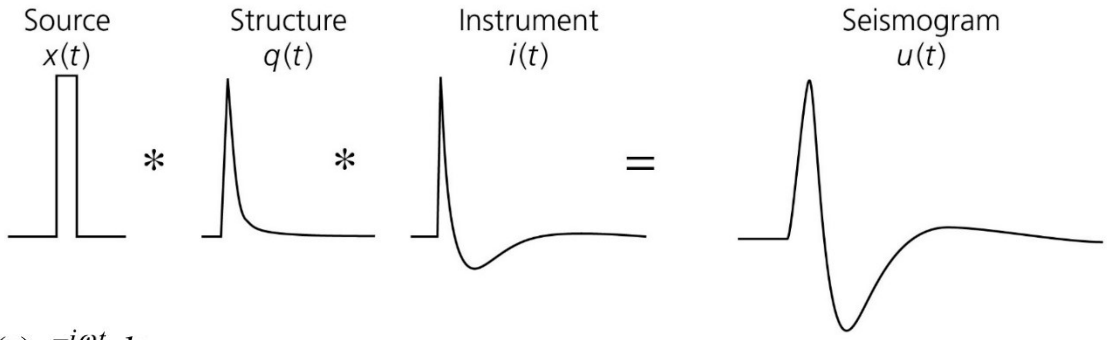
Define seismic moment

$M_0 \propto A_0$

Rupture length $\propto$ 1/ frequency: $l \propto 1 / f_0$

Frequency domain





$$u(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} U(\omega)e^{i\omega t}d\omega \qquad U(\omega) = \int_{-\infty}^{\infty} u(t)e^{-i\omega t}dt$$

$$s(t) = w(t) * r(t) = \int_{-\infty}^{\infty} w(t-\tau)r(\tau)d\tau$$

$$u(t) = x(t) * e(t) * q(t) * i(t)$$

$$U(\omega) = X(\omega)\ E(\omega)\ Q(\omega)\ I(\omega)$$

- A useful way to estimate the source time function is based on the so-called Green's function:

$$g(t) = e(t) * q(t)$$

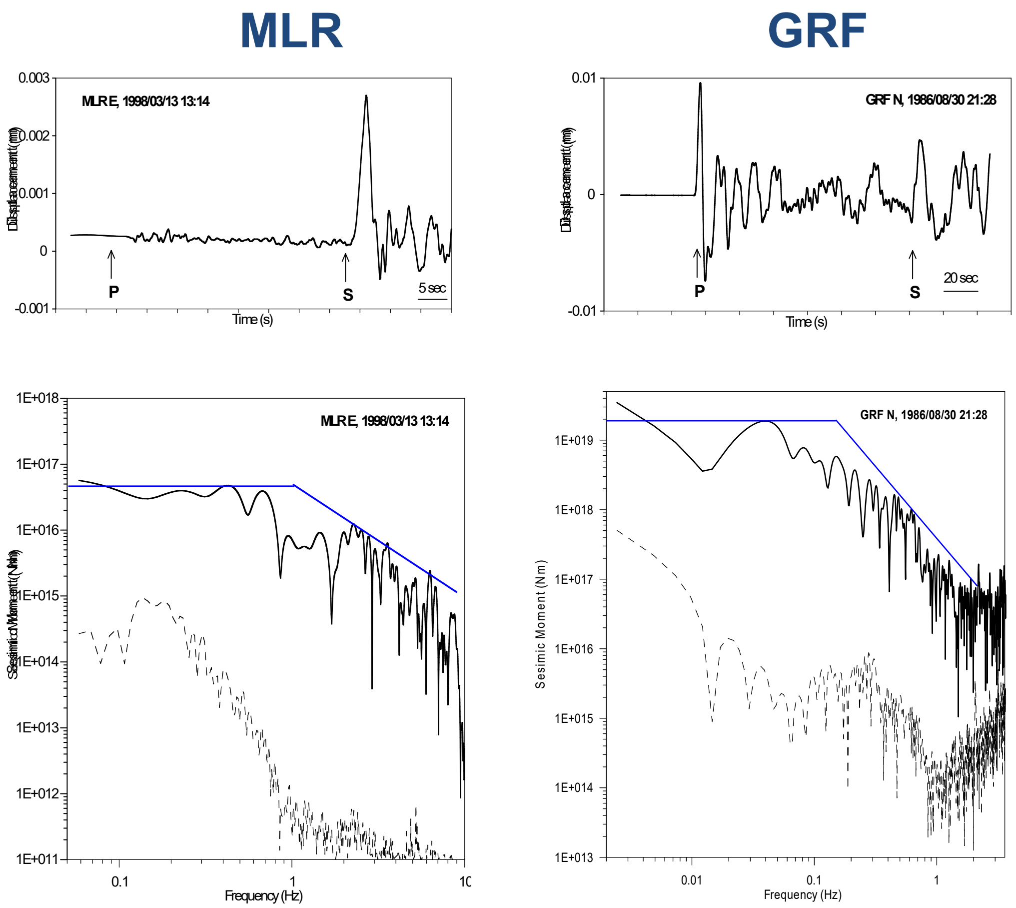
  which combines the elastic and anelastic effects of propagation from the source to the receiver.
- Essentially, the Green's function describes the signal that would arrive at the seismometer if the source time function were a delta function.
- The source time function of an earthquake can be found by deconvolving the Green's function and seismometer response from the seismogram $u(t)$:

$$X(\omega) = \frac{U(\omega)}{G(\omega)I(\omega)}$$

THE AUSTRALIAN NATIONAL UNIVERSITY

SEISMIC SOURCE

- Examples of waveforms and spectra of Vrancea intermediate-depth earthquakes recorded at local distance - Muntele Rosu (***MLR***), and regional distance - Grafenberg (***GRF***).
- The signal (*P*-wave) and noise spectra are plotted together.

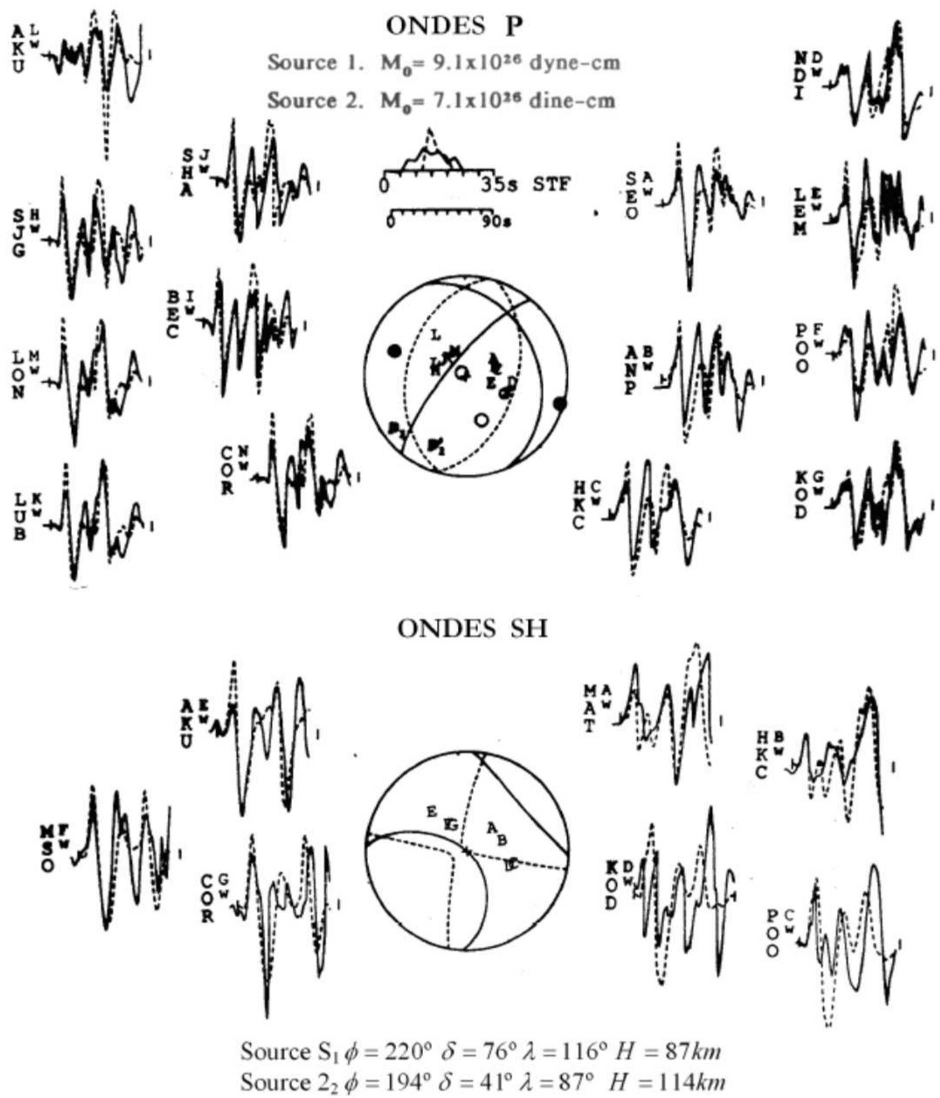


1999/09/13, $M_w = 4.7$ 1986/08/30, $Mw = 7.1$

Gusev et al. (2002)

1977 EVENT

- ***Müller et al. (1978)*** – focal mechanism using first P polarities from WWSSN stations; complexe source with 4 shocks
- ***Hartzell (1978)***: seismic moment from surface waves: 1.2 x 10^{21} Nm
- ***Fuchs et al. (1979)***: aftershocks analysis and rupture plane estimation (2000 km^2)
- ***Rakers and Müller (1982)*** - focal mechanism using first P polarities from WWSSN stations + Romanian and Russian stations; complexe source with 3 shocks
- ***Tavera (1990)***: waveform inversion for WWSSN recordings; complexe source with 2 shocks and ~ 20 s duration



Tavera (1990)

1977 EVENT

Aftershock activity

Installing of a supplementary network of mobile seismic stations in the Vrancea region provided by the Government of Germany.
The analysis of aftershocks of the 1977 event carried out by ***Fuchs et al. (1979)*** on the basis of permanent as well as temporary stations allowed a better constraint of the aftershock surface extent in the 70 – 130 km depth interval with many aftershocks located between 80 and 110 km.
This aftershock area coincides well with the area obtained by ***Hurukawa et al. (2008)*** using a modified joint hypocentre method. Also, it fits the horizontal extension of about 50-60 km towards SW from hypocentre as estimated by waveform analyses (***Müller et al., 1978***; ***Fuchs et al., 1979***; ***Hartzell, 1979***; ***Raker and Müller, 1982***; ***Iosif et al., 1983***).

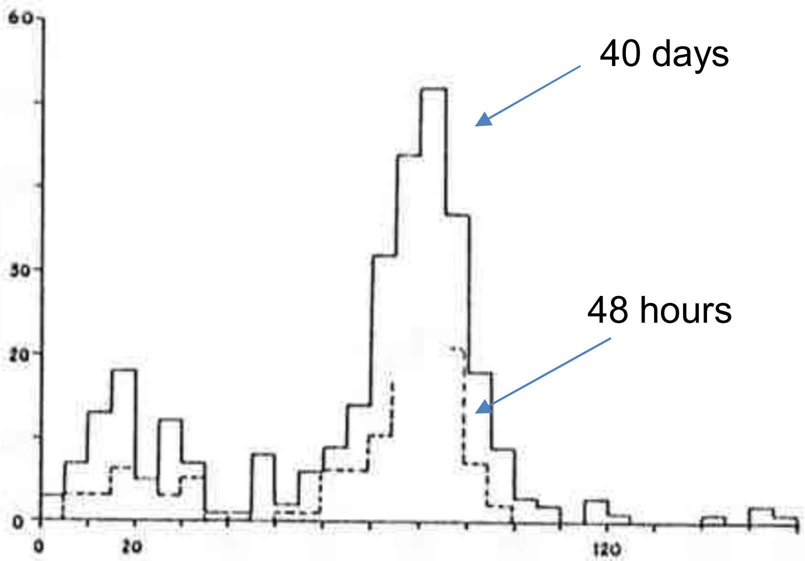
1986 EVENT

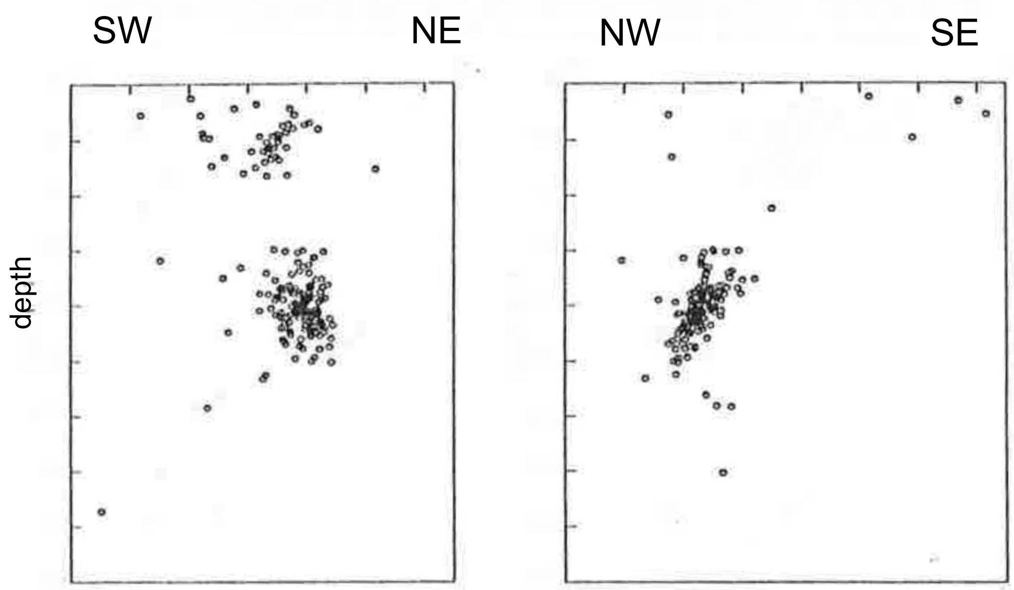
- ***Radu and Oncescu (1987)*** – focal mechanism using first P polarities from WWSSN stations
- ***Deschamps et al. (1986)***: focal mechanism P-wave modelling (WWSSN data)
- ***Monfret et al. (1990)***: focal mechanism from P and Rayleigh waves (WWSSN + GDSN). Lateral heterogeneities around hypocentre explaining the variation of wave amplitudes radiated close to the fault plane
- ***Trifu and Oncescu (1987)*** – aftershock analysis (Romanian local network)
- ***Oncescu (1989)***: estimates of seismic energy, corner frequency, stress drop, slip and rupture duration, fracture energy (11 accelerograph recordings). Asperity role.
- ***Tavera (1990)***: waveform inversion for WWSSN recordings

1990 EVENT

Trifu et al. (1992): aftershock activity.

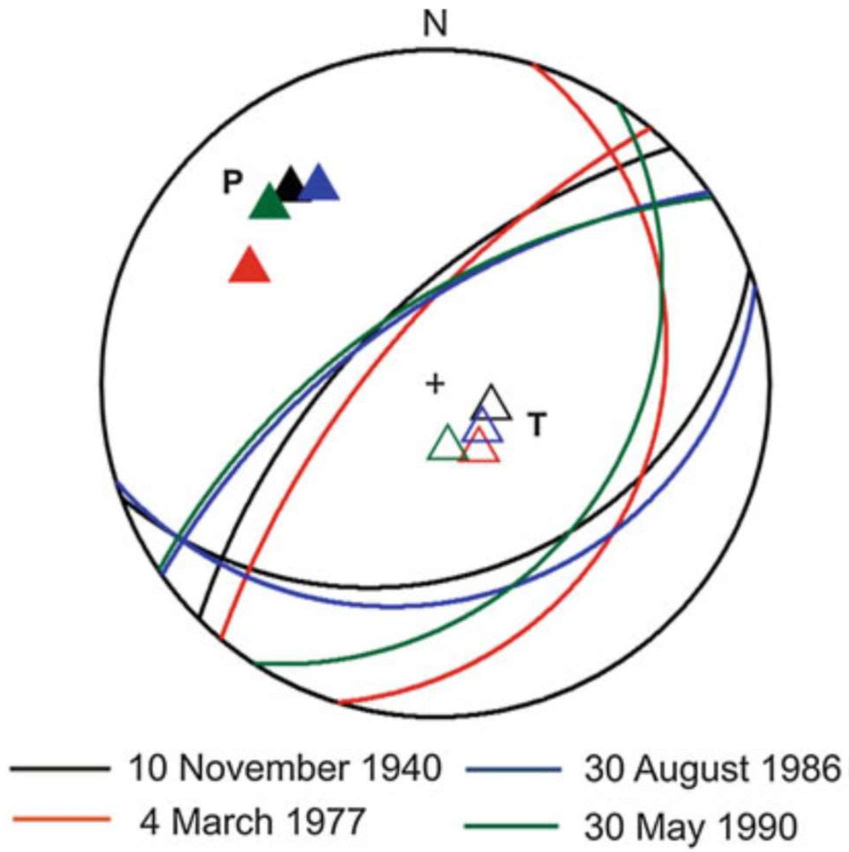
- Upward rupture propagation
- Seismicity deficit between crustal and mantle domains
- Triggering of crustal earthquakes
- Source area: 235 – 285 km^2
- Static stress drop: 8 – 11 MPa





Focal mechanism

The nodal plane identified as rupture plane for Vrancea major earthquakes coincides with the plane around which the seismicity is clustered.
A predominant geodynamic process is assumed intimately linked to the presence of one (or two) weakness plane crossing the lithospheric body.
We can advance the hypothesis: major Vrancea earthquakes are governed by the same geodynamic process .

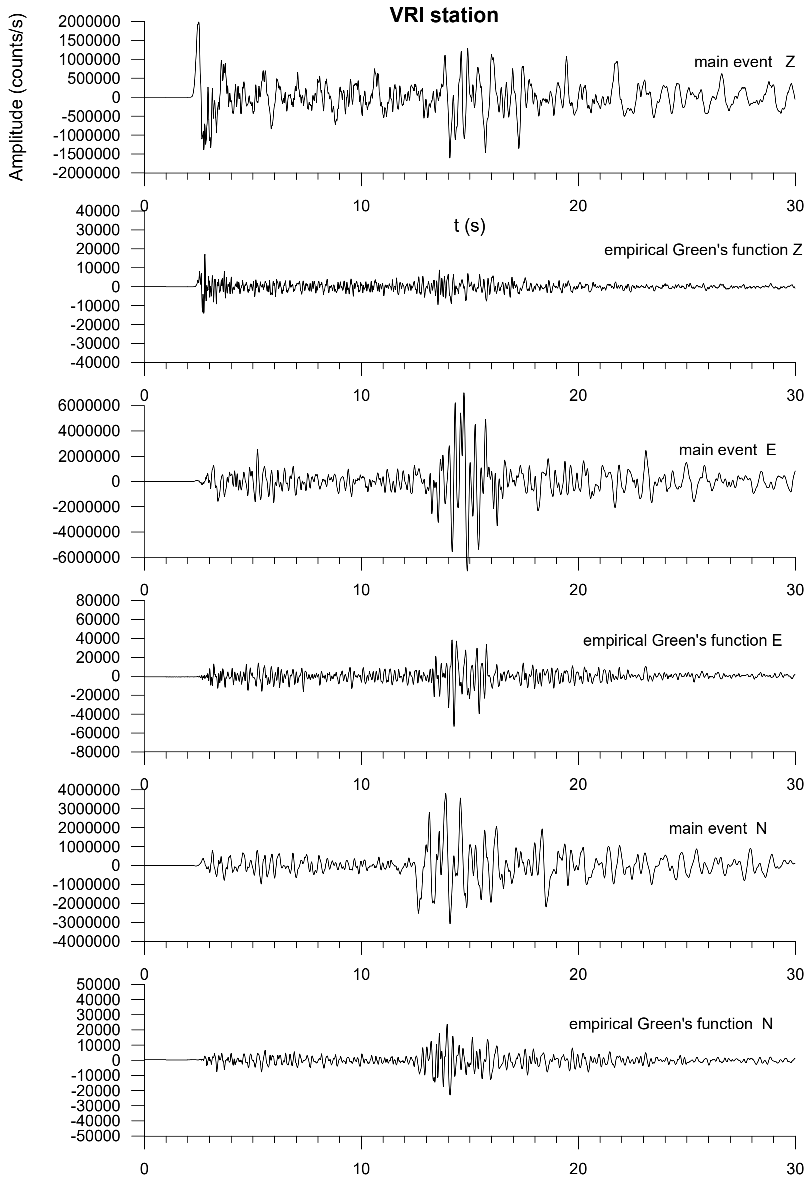


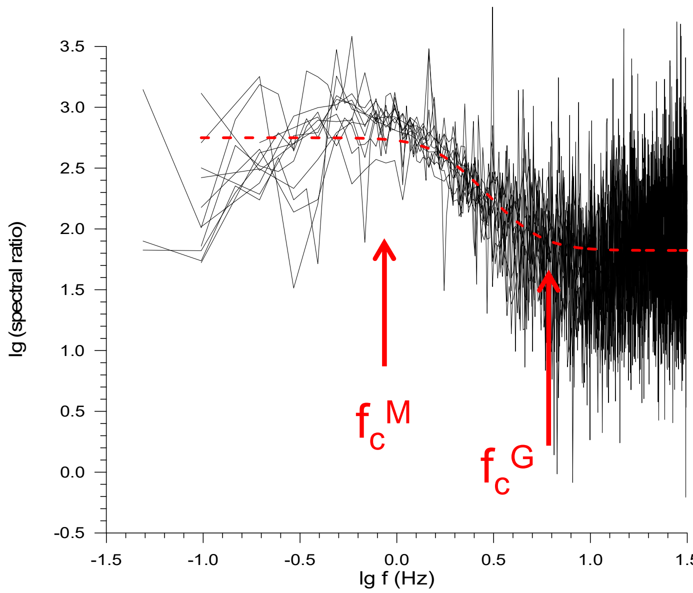
MAJOR VRANCEA SHOCKS

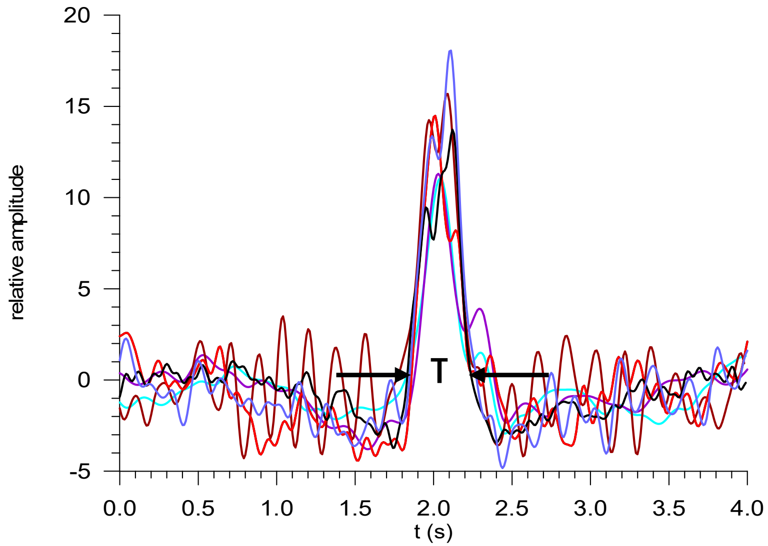
- Impact of waveform recordings availability at world-wide (WWSSN, GDSN, GEOSCOPE and IRIS), regional (Graefenberg array) and local (accelerograms) scales
- Predominant focal mechanism
- Preference for unilateral rupture: upwards (1977, 1990), downwards (1986)
- Significant lateral inhomogenities close to hypocentre
- Relative weak aftershock activity: M_{max} 4.7 (1977), M_{max} 5.1 (1986), M_{max} 4.3 (1990)
- Unusually high dynamic stress drops – rapid and effcient ruptures

Main: 25 April 2009, 17:18, $M_w = 5.2$

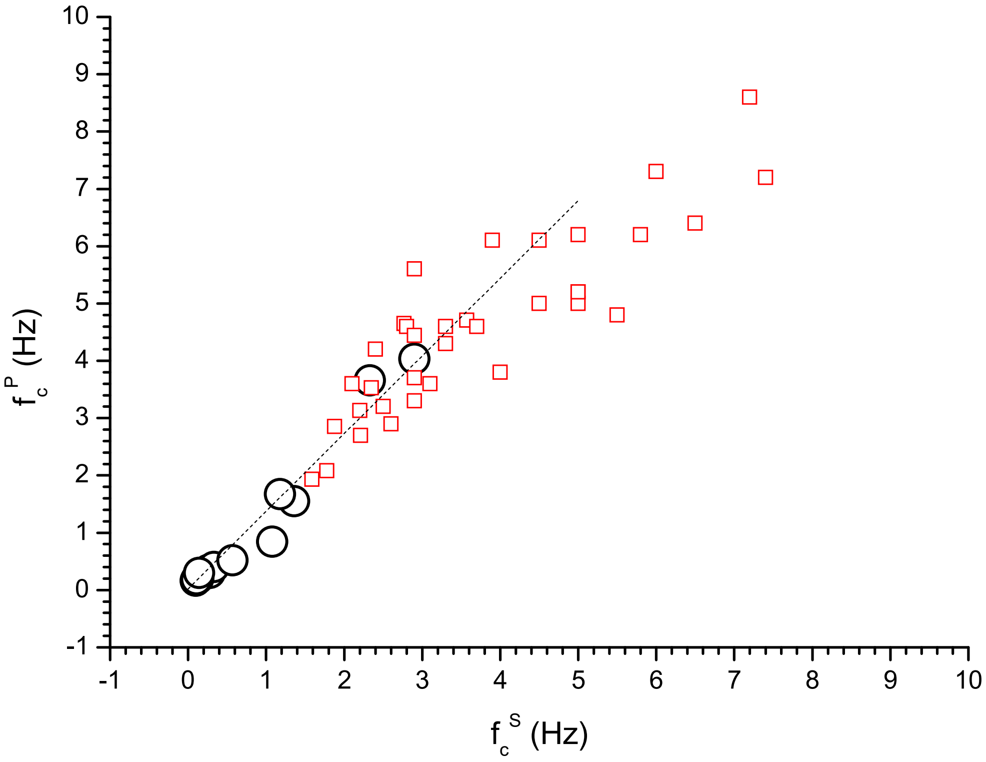
EGF: 26 April 2009, 23:19, $M_w = 3.8$







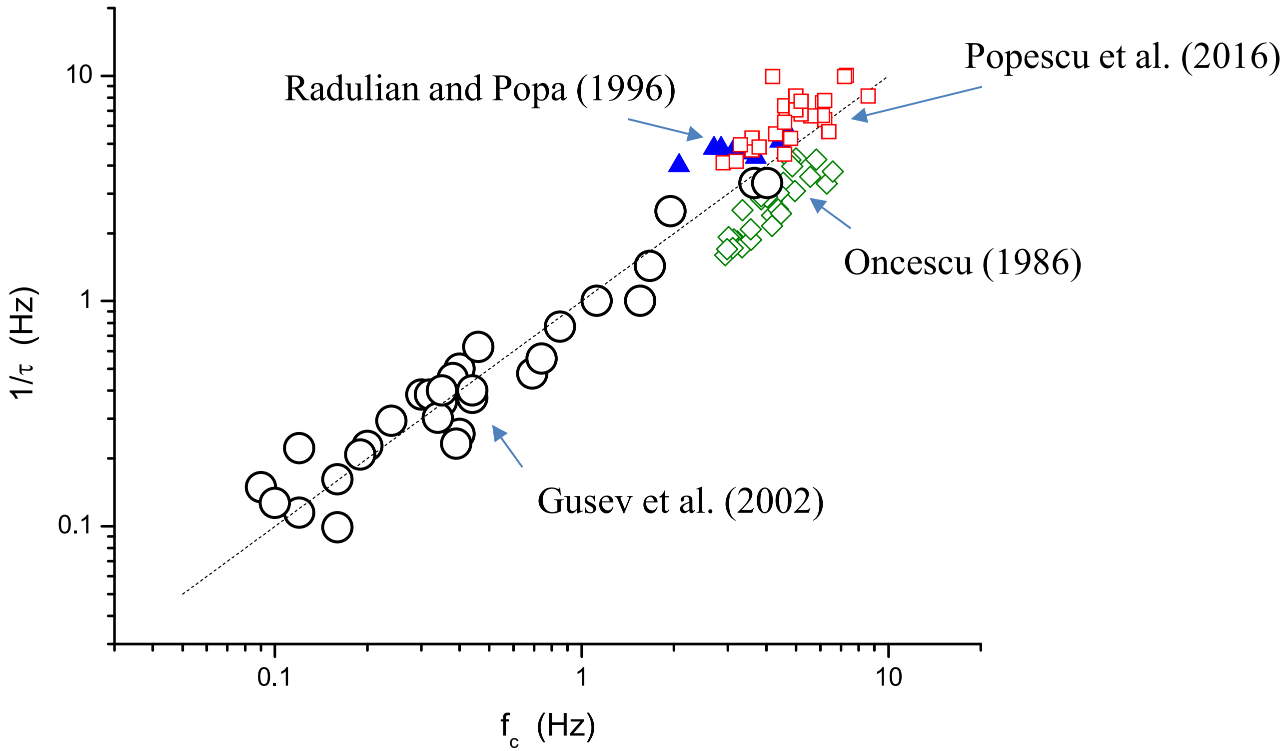
SOURCE SCALING



Corner frequency from P and S waves

$$f_c^P = 1.42\, f_c^S - 0.09$$

SOURCE SCALING

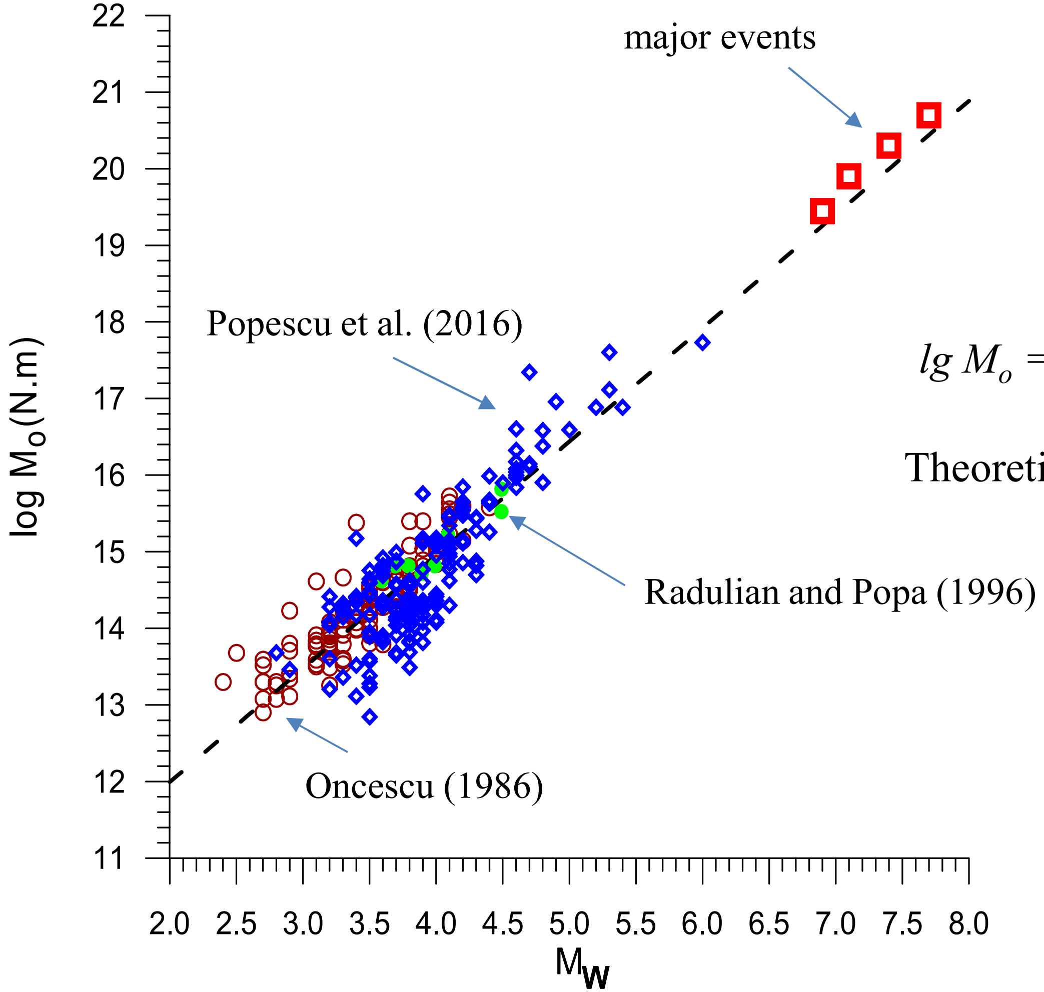


Source duration – corner frequency

A linear correlation with slope close to 1 (f_c~ $1/\tau$) is obtained in agreement with the scaling determined by Gusev et al. (2002) from spectral and time-domain analyses on wide-band digital records for 16 Vrancea earthquakes.

SOURCE SCALING

Seismic moment - magnitude

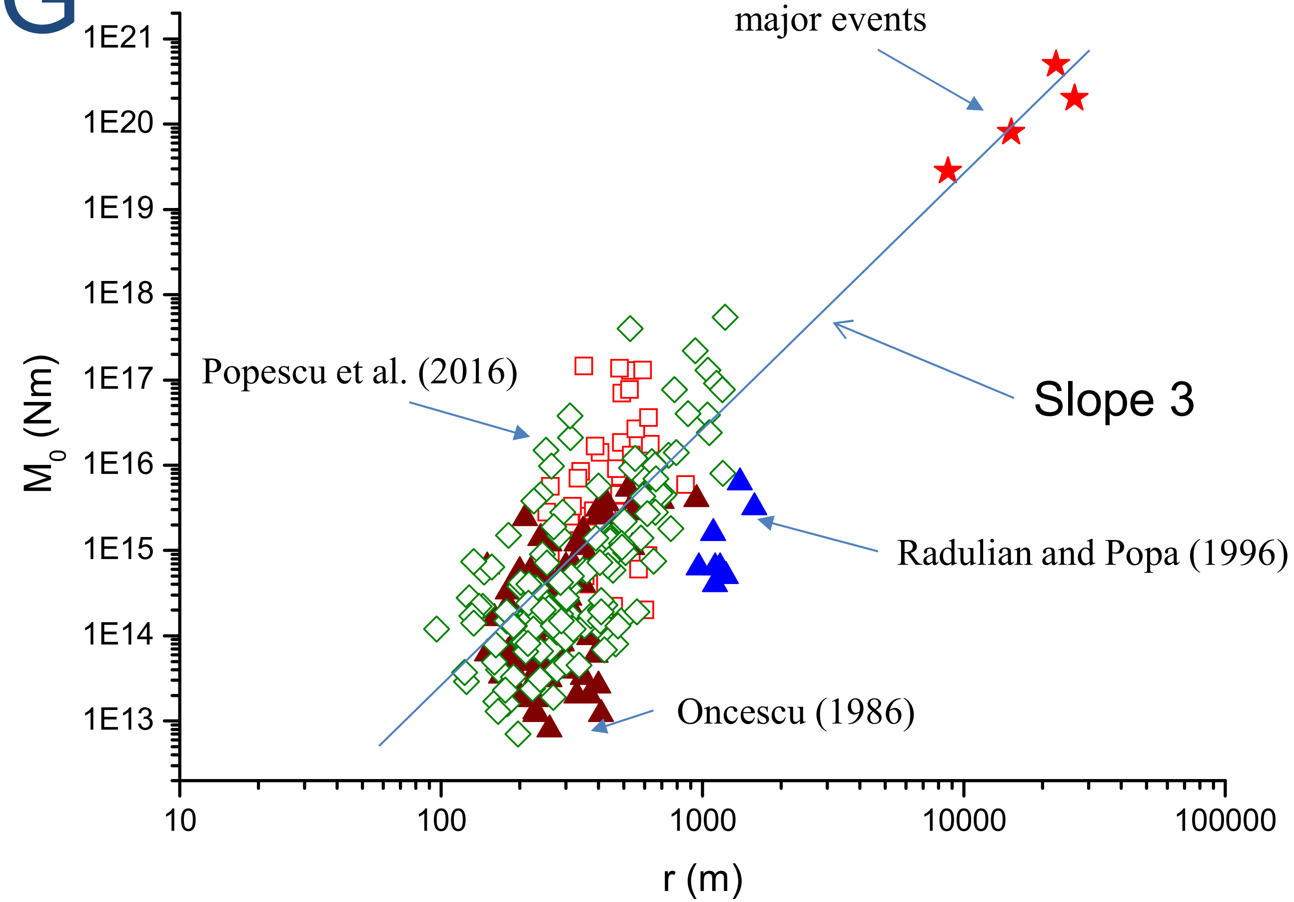


$$lg\ M_o = (1.48 \pm 0.04)\ M_w + (9.03 \pm 0.14)$$

Theoretical values: 1.5 slope, 9.045 intercept

SCALING

Seismic moment – source radius



$$M_0 = 4\pi\, \rho\, R\, v^3_{p,s}\, u_0 / F^{p,s}_{\theta,\varphi}$$

Keilis-Borok (1959)

$$r = c_m / (2\,\pi)\, v_{P,S} / (f_c^{P,S})$$

circular model (Brune, 1970; Madariaga, 1976)

SOURCE SCALING

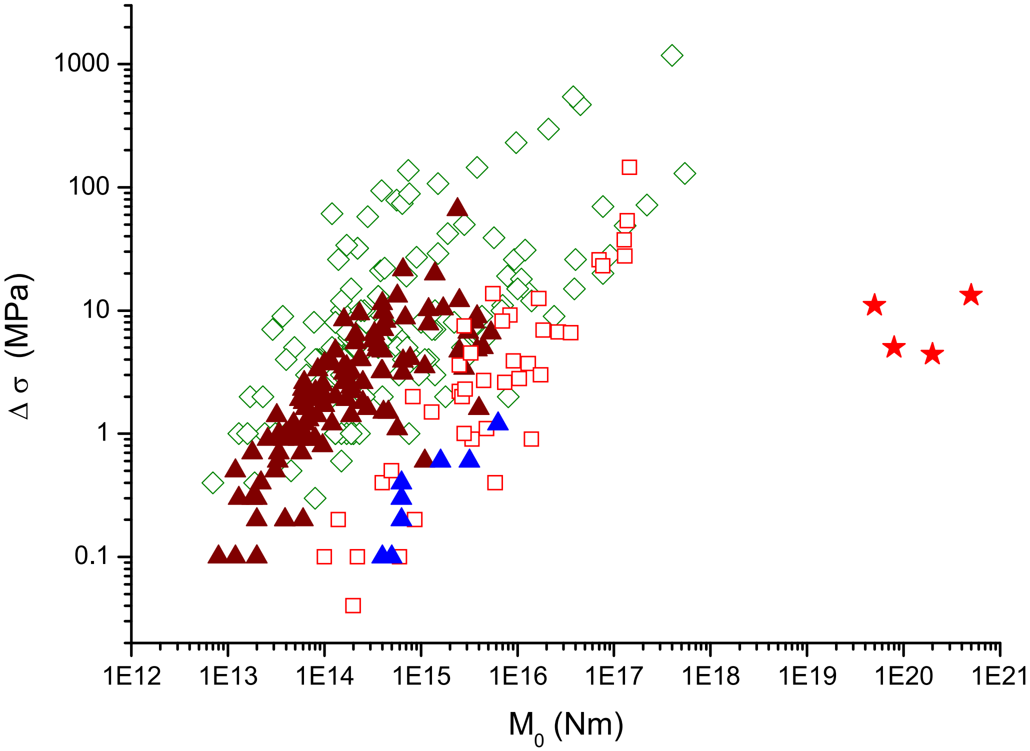
Stress drop - seismic moment

$$\Delta\sigma = \frac{7M_0}{16}\frac{f_c^3}{k^3\beta^3}$$

Eshelby (1957), Madariaga (1976)

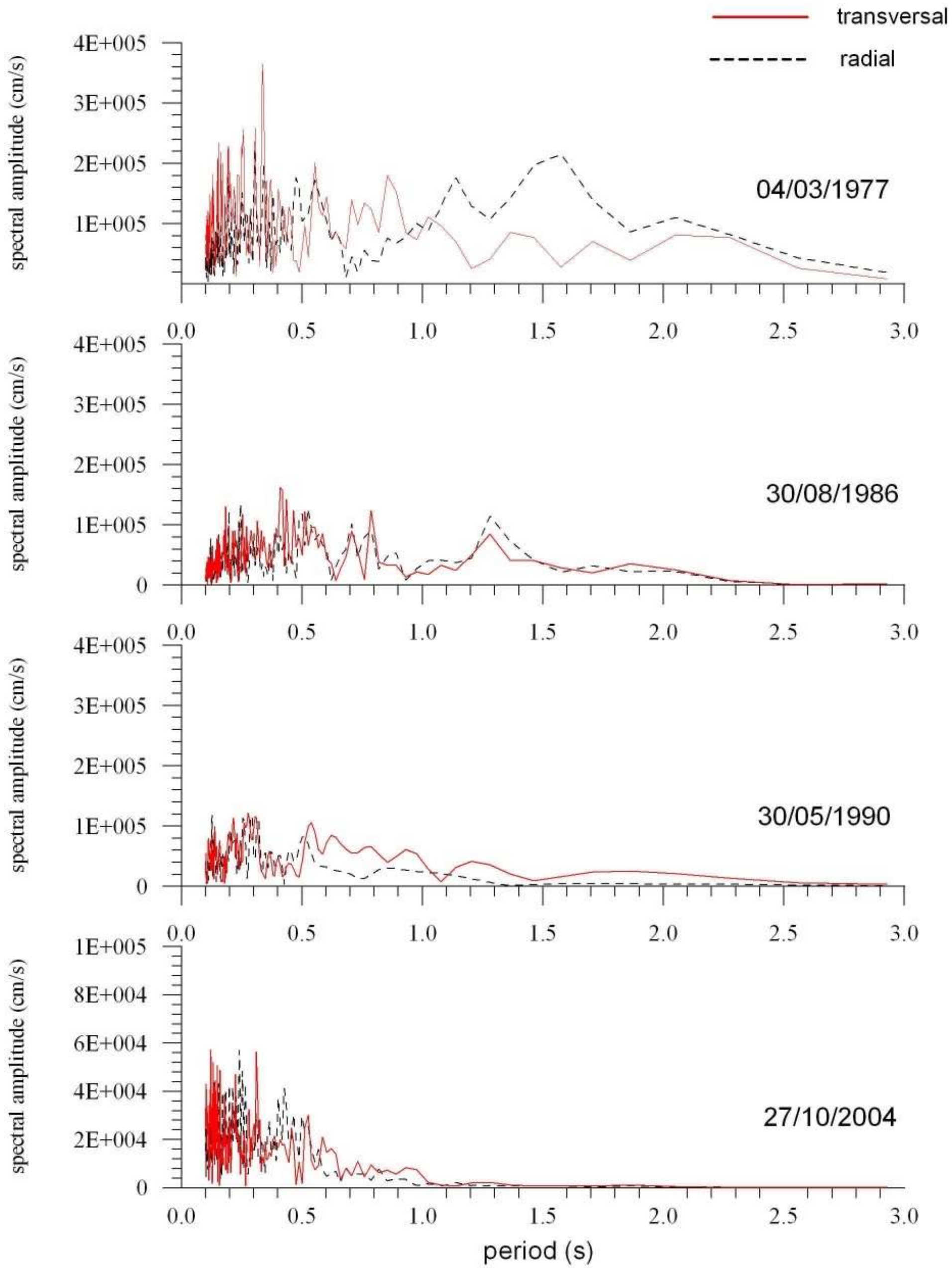
$$\Delta\sigma = 7M_0 /(16\ r^3)$$

Brune (1970)



The apparent stress drop increasing trend with increasing seismic moment for smaller events (up to magnitude 6) can be due to the limited frequency bandwidth of the instrument (e.g., Hardebeck and Aron, 2009; Ide and Beroza, 2001; Abercombie, 2015) and poor signal/noise ratio at high frequencies leading to an underestimation of the corner frequency for the smaller earthquakes.

SEISMIC SOURCE



GEOTECTONIC MODELLING

Key issue (still open):
The nature of the cold and dense material that is descending into the deeper mantle

Oceanic lithosphere: paleosubduction

or

Continental lithosphere: subduction or delamination

GEOTECTONIC MODELLING

Initial hypotheses

- Lithosphere descending to NW under the Carpathians arc:

Roman (1970), Isack and Molnar (1971), Bleahu et al. (1973), Radu (1974), Oncescu and Trifu (1986).

- Paleo-subduction (there is no visible plate boundary)
- The Miocene emplacement of the corresponding nappe pile has been the result of an approximately westward-directed oceanic subduction, which further evolved by continental collision, about 10 Ma ago.

GEOTECTONIC MODELLING

Detachment hypotheses

- ***Fuchs et al. (1979)***: complete detached slab
- ***Wortel et al. (1993)***; ***Csontos (1995)***; ***Mason et al. (1998)***; ***Seghedi et al. (1998)***; ***Linzer et al. (1998)***: break-off, detachment and roll-back of the oceanic slab
- ***Wortel and Spakman (2000)***; ***Sperner et al. (2001)***; ***Ismail-Zadeh et al. (2012)***: subducted plate has undergone lateral tearing along the Carpathians orogen strike.
- ***Sperner et al. (2001)***: slab still partially attached to the upper lithosphere
- ***Matenco et al. (1997)***: variant of detachment model with a back stepping of the subduction system: lateral migration of the plate boundary activity, possibly by slab detachment, from the EEP (northern Eastern Carpathian foreland) to the MP (southern Eastern Carpathian foreland)

GEOTECTONIC MODELLING

Detachment hypotheses

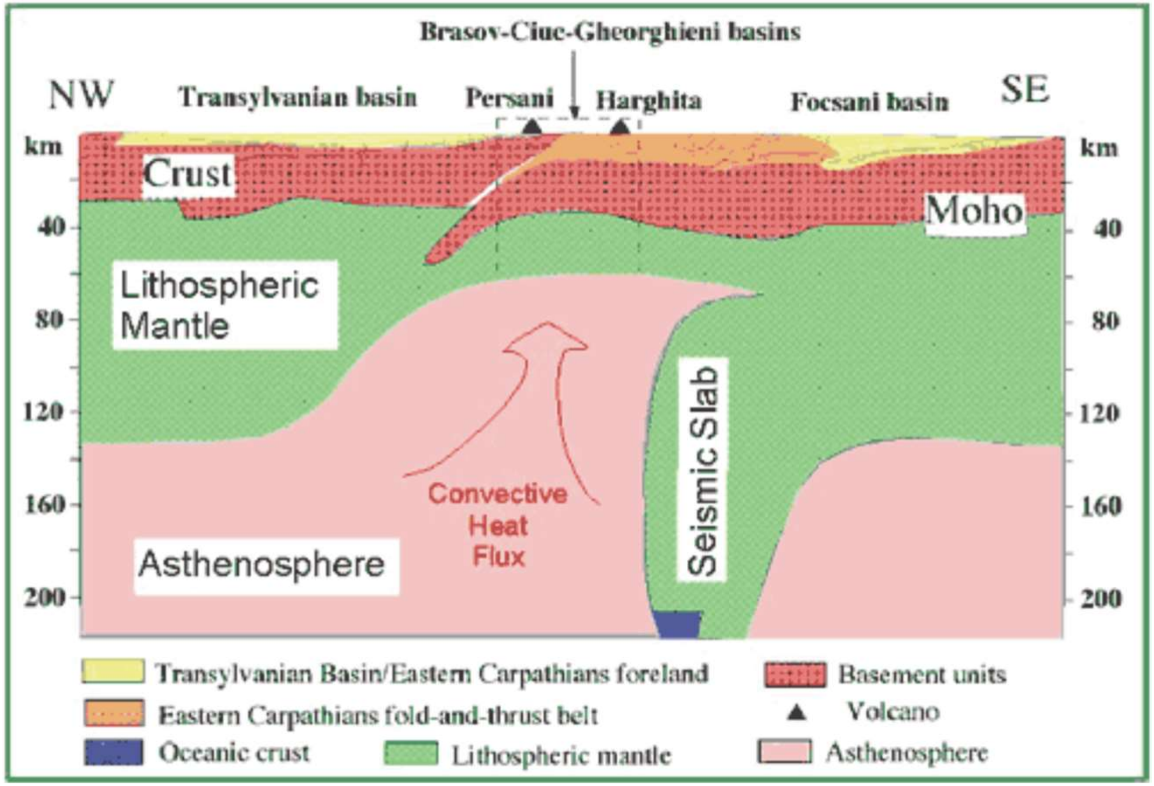
There has been recently some debate (e.g., Seghedi *et al.* 2011; Ismail-Zadeh *et al.* 2012) on the hypothesis of a slab detachment having propagated along the entire length of the Eastern Carpathians range; such a controversy still does not preclude the possibility that currently, lateral tearing could be developing just within a slab fragment preserved in Vrancea area (as suggested by Wortel & Spakman 2000; Hackney *et al.* 2002; Bonjer *et al.* 2008).

GEOTECTONIC MODELLING

Delamination hypotheses

Gîrbacea (1997); ***Gîrbacea and Frisch (1998)***; ***Chalot-Prat and Gîrbacea (2000)***: delamination of the lower part of the lithospheric mantle from the lower plate

The oceanic lithosphere subduction ended some time in the late Miocene, and since then a portion of East European or Moesian platform continental lithosphere has been delaminated along a horizontal mid-lithospheric interface and dripping down into the upper mantle.
The delaminated lithosphere migrated SE some 130 km into its present position beneath Vrancea (steepening the sinking lithosphere dip to near vertical).



GEOTECTONIC MODELLING

Delamination hypotheses

Pana and Erdmer (1996) and ***Pana and Morris (1999)***: there is no geological evidence for the presence of an oceanic crust in the Eastern Carpathians evolution since Miocene. The lithosphere descending in the mantle is likely a narrow continental crust or of transition.

Knapp et al. (2005) and ***Fillerup et al. (2010)***: interpretations on oceanic origin of the seismogenic body in Vrancea are not consistent with the geological constraints in the Eastern Carpathians and adjacent foreland. According to ***Knapp et al. (2005)***, the Neogene strata of the Eastern Carpathians are found much to the west, in the Transylvania Basin, while the geological structure in the Carpathians foredeep area, including Moho are sub-horizontally oriented toward east and above the Vrancea seismogenic zone.

GEOTECTONIC MODELLING

Oceanic lithosphere

Fuchs et al. (1979): oceanic lithosphere sinking steeply into the mantle

Wortel and Spakman (2000) and ***Sperner et al. (2001)***: oceanic slab detachment with the break-off point migrating to the SE towards Vrancea, where it has now reached the final break-off stage

Girbacea and Frisch (1998) and ***Gvirtzman (2002)***: lateral migration of an oceanic slab

Martin et al. (2006), ***Wenzel et al. (1998)***, ***Wortel and Spakman (2000)***: subduction and lateral tearing of a slab

GEOTECTONIC MODELLING

Oceanic lithosphere

Bokelmann and Rodler (2014): dispersion for rays that travel nearly vertically, roughly through the supposed position of the slab under Vrancea. All dispersion observations correspond to high frequencies, at 8 Hz, being delayed relative to 0.5 Hz by an average of 0.7 s in the sense of “normal dispersion”. A similar effect had been observed at subduction zones around the world where a thin low velocity layer on top of the slab acts as a waveguide for high frequencies but is too thin to be “recognized” by long wavelengths (Abers, 2005; Bokelmann et al., 2011; Martin et al., 2003). Observed dispersion is consistent with the presence of a subduction zone composed of oceanic lithosphere under the Eastern Carpathians

Bonjer et al. (2005), ***Radulian et al. (2007)***: suggested the existence of a double seismic zone in Vrancea. This is characteristic for oceanic subduction.

GEOTECTONIC MODELLING

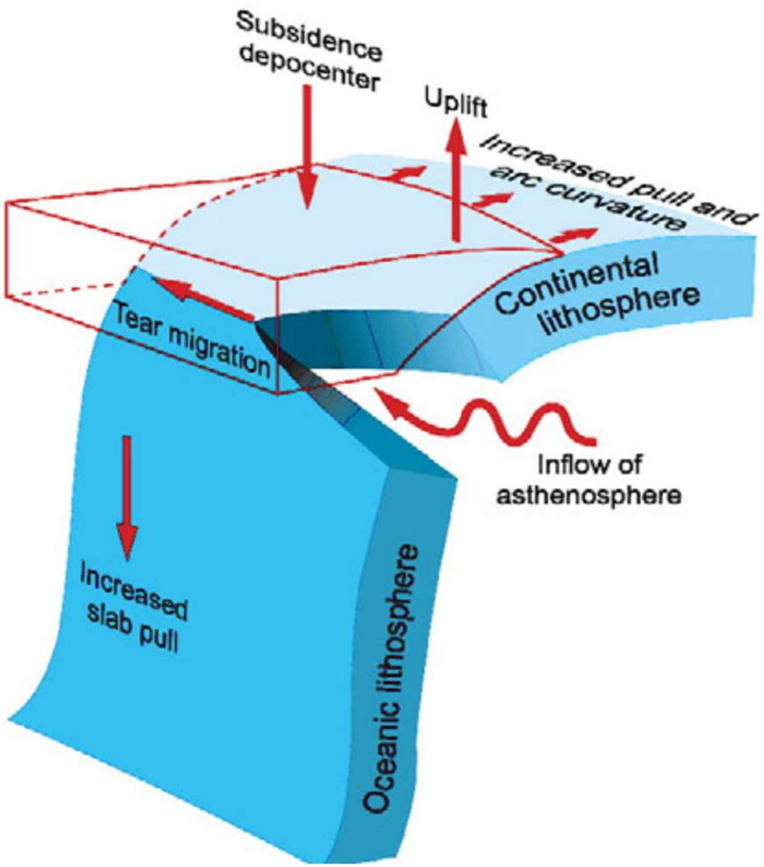
Continental lithosphere

Knapp et al. (2005): active delamination of continental lithosphere

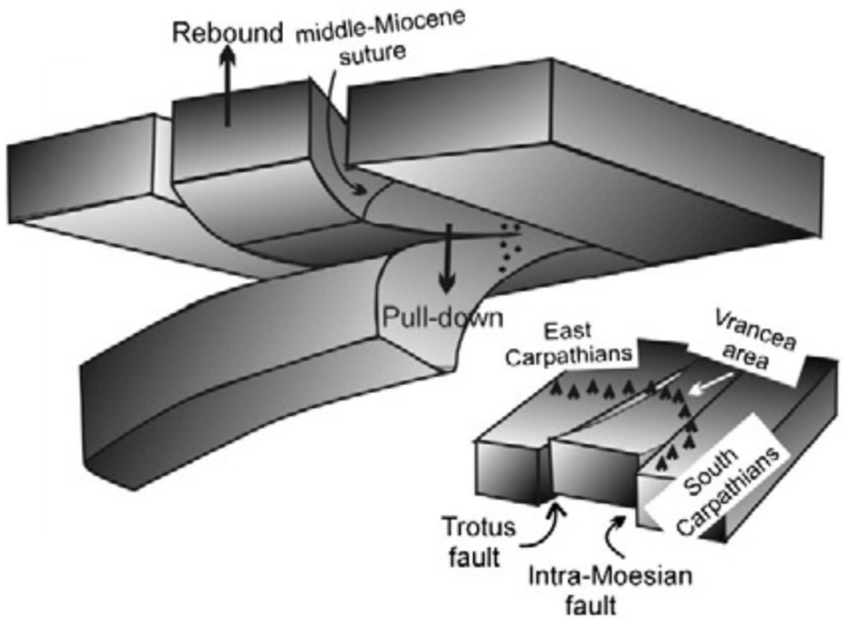
Lorinczi and Houseman (2009): strain-rate profile in the seismogenic volume caused by gravitational instability is consistent with predictions from numerical experiments for a downwelling of continental lithosphere rather than subducted oceanic lithosphere

Ren et al. (2012) have obtained a high-resolution P-wave velocity model of the upper mantle beneath the Carpathian–Pannonian Region. They found that the Vrancea structure is broadly consistent with models based on either delamination of mantle lithosphere or lithospheric gravitational instability

GEOTECTONIC MODELLING



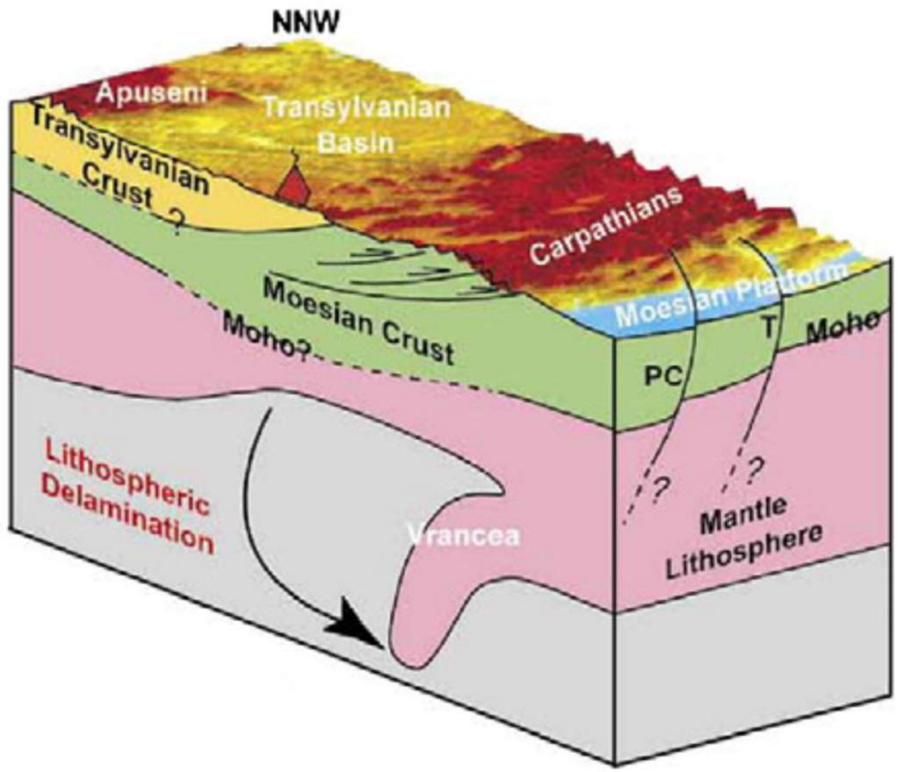
Wortel and Spakman (2000)



Girbacea and Frisch (1998)

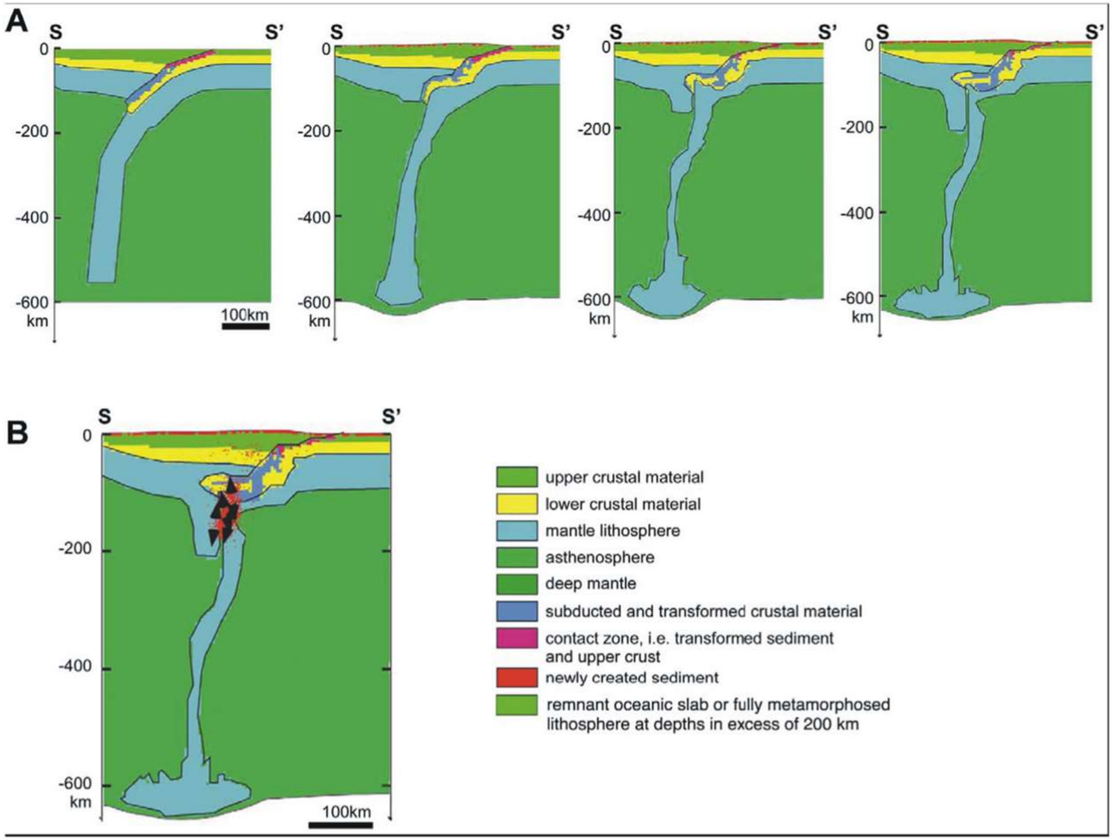
GEOTECTONIC MODELLING

The model proposed by ***Knapp et al. (2005)*** and ***Fillerup et al. (2010)*** assumes an active process of delamination of a continental lithosphere as a result of closure of an intra-continental basin and lithosphere thickening.
Thus, Vrancea region lies over a continental crust with no connection to a subduction of an oceanic fragment.



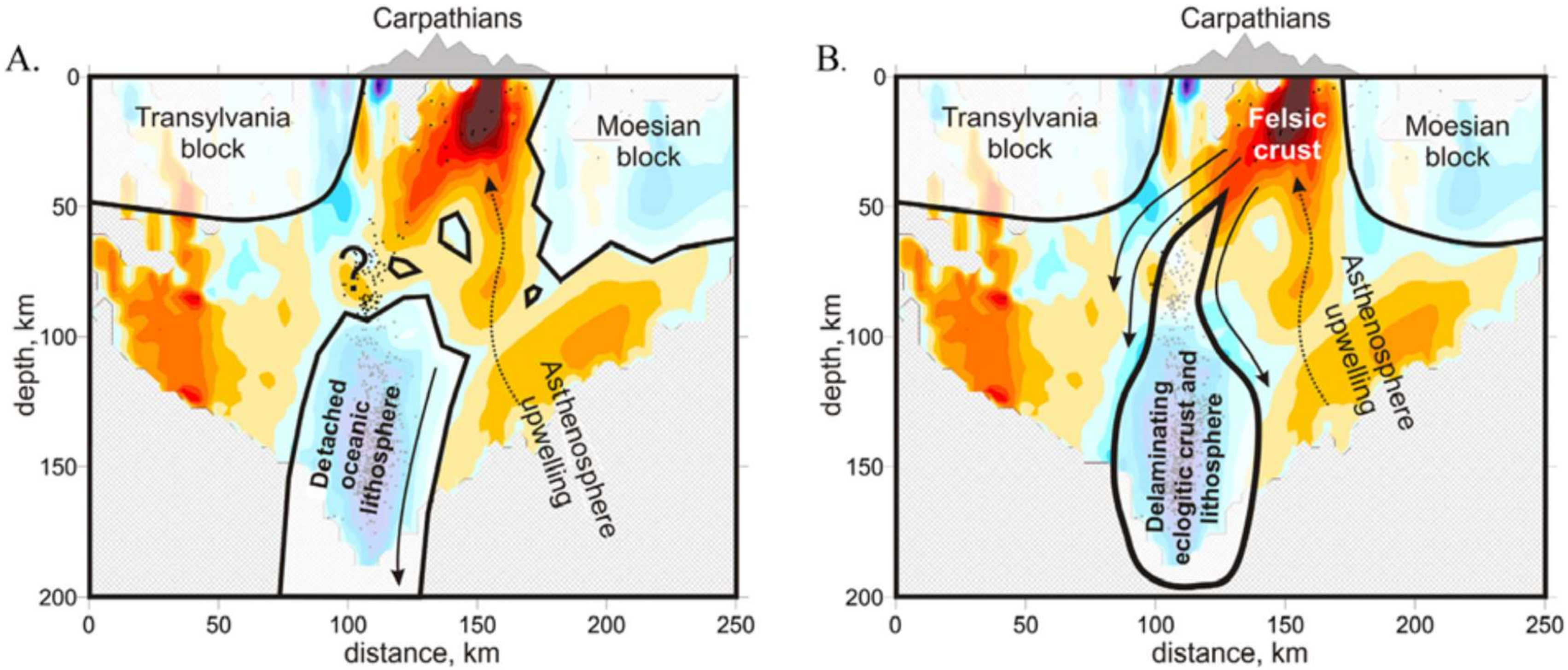
GEOTECTONIC MODELLING

Cloetingh et al. (2004): in regimes of slow convergence the subducting lithosphere has enough time to interact with mantle and to evolve to thermal restoration. Subduction along Carpathians is controlled by thermo-mechanical properties of pushed lithosphere and lateral variations in the contact zone. The model explains the build up of a deep basin with an unusual geometry of pronounced subsidence in front of the Carpathians Arc.



GEOTECTONIC MODELLING

Houseman and Gemmer (2007): model of continental lithosphere thinning under the Panonnian Basin and thickening under the Eastern Carpathians. The high-velocity body can be interpreted as a thickened part of the lithosphere under Carpathians which undergoes a descending process in manta due to gravitational instability (Rayleigh–Taylor instability). The model partially explains the results from local data tomography (***Koulakov et al., 2010***).



KEY QUESTIONS

- Nature of the material descending in the mantle:
  oceanic or continental?
- What is the cause of the mantle earthquakes?
- In case of detachment, where is the place (~ 50 km, ~ 100 km or ~ 160 km)
- Is there a causal relationships between the Vrancea strong events?
- Is the slab still attached to the lithosphere and is there a substantial amount of stress transferred to the crust?

CONCLUSIONS

- Seismic source understanding – driven by observation data improvements
- 1977 earthquake: turning point in investigating Vrancea seismogenic area from multiple points of view: knowledge, research infrastructure, management, policies and strategy

CONCLUSIONS

- Seismicity patterns could be indicative of a presently developing slab break-off in the Vrancea region

- The hypothesis discussed in ***Radulian (2014)*** about the Vrancea strong shocks nucleating repeatedly on just a few weakness surfaces which pre-existed within the slab.

- Possible migration/triggering effects in the generation of the Vrancea major shocks is discussed (***Hurukawa et al., 2008***; ***Ganas et al., 2010***) – however questionable (e.g., results from lithospheric block-and-fault dynamics modelling - ***Soloviev and Ismail-Zadeh***)

CONCLUSIONS

- All images obtained by seismic tomography, either from distant or local data, outline a high-velocity body. According to tomography results from teleseismic data (***Wortel and Spakman 2000***; ***Piromallo and Morelli 2003***; ***Martin et al. 2006***) this body extends as far as 350–370 km depth.

- None of the tomographic studies succeeded to unambiguously highlight the nature of the high-velocity body and the place where the conjectured slab is discontinuous

- Some consensus is emerging today on the Vrancea slab break-off model. However, the corresponding tearing depth is still questionable:
  - in the 40–70 km depth range (Mason *et al.,* 1998; Wenzel *et al.*, 2002); Bonjer *et al.,* 2008)
  - around 100 km depth (***Bokelmann and Rodler, 2014***)
  - in the 160-175 km depth (Mitrofan et al., 2016)
  - below 200 km depth (***Wortel and Spakman, 2000***; ***Martin et al., 2006***)