SURFACE EXPRESSION OF DEEP STRUCTURES OF THE CARPATHIAN BEND ZONE, ROMANIA

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University of Bucharest

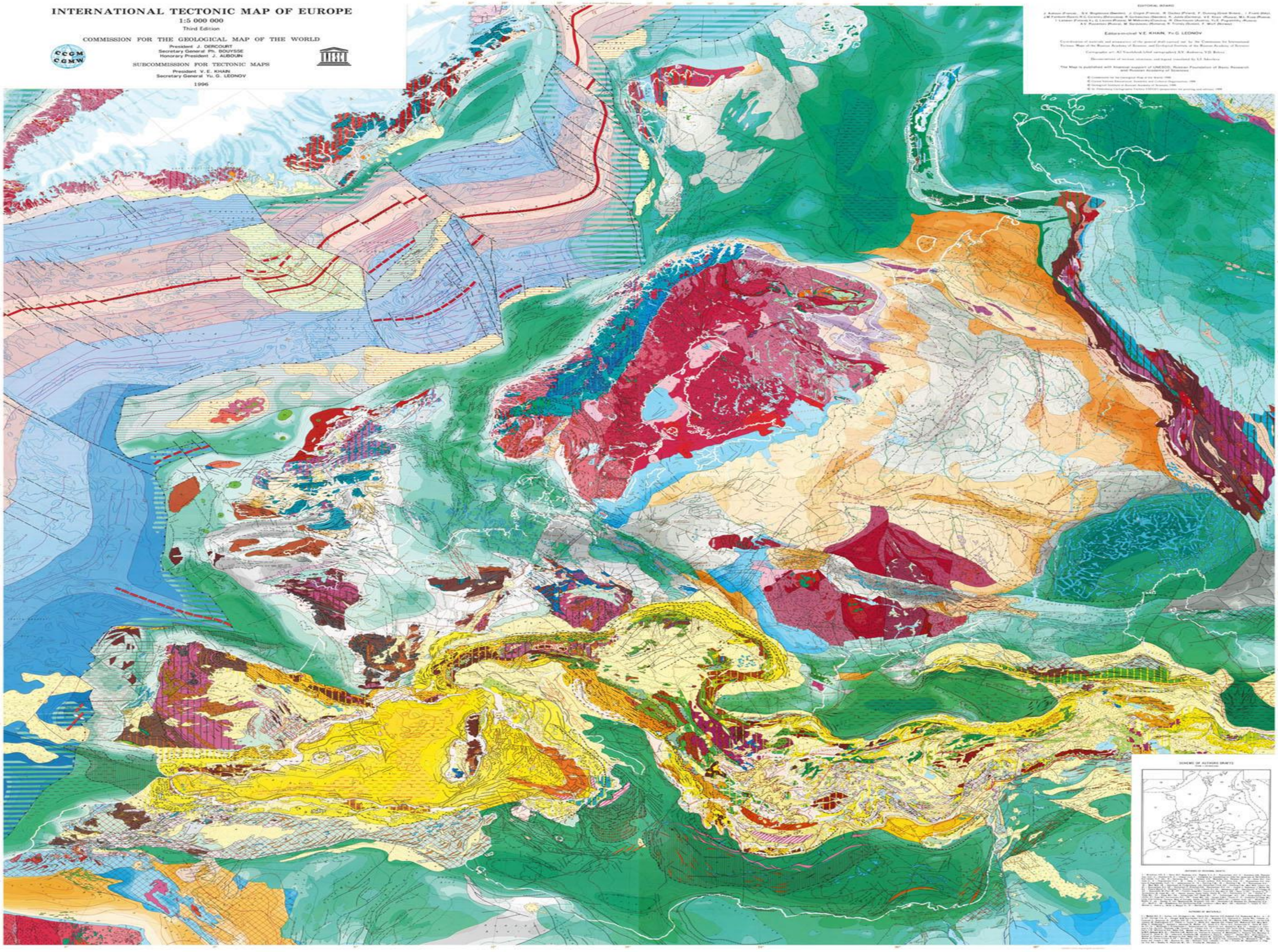
Gbely, Slovakia, 17 October 2019

dedicated to

Loránd Eötvös de Vásárosnamény

TALK OUTLINE

- INTRODUCTION
- TECTONIC FRAMEWORK AND BASIC GEOPHYSICAL INFORMATION
- CLASSIC GEOPHYSICAL INVESTIGATIONS
- SEISMIC ATTENUATION
- SEISMIC TOMOGRAPHY
- GPS
- REGIONAL GEODYNAMIC MODEL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Third Edition
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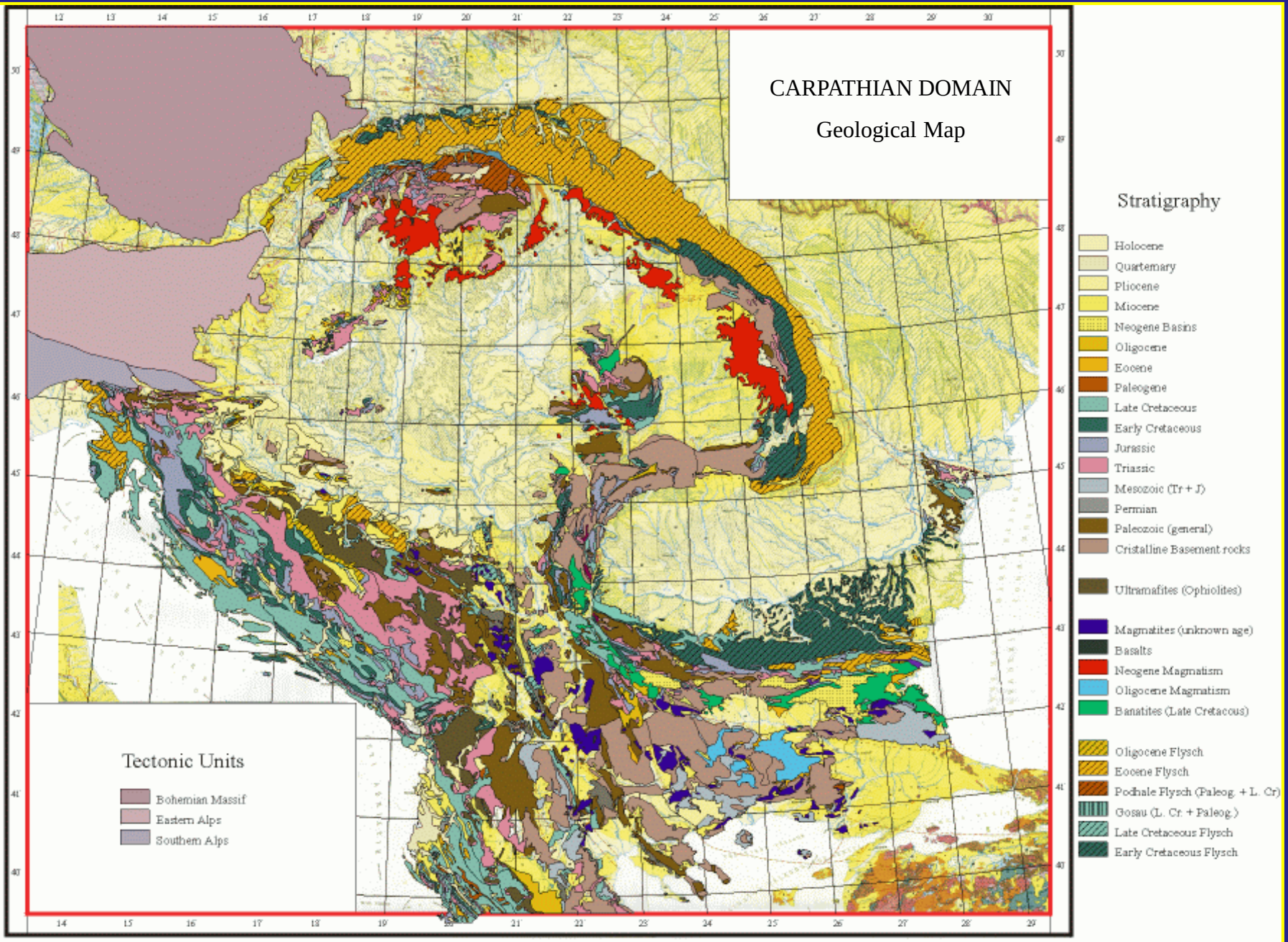
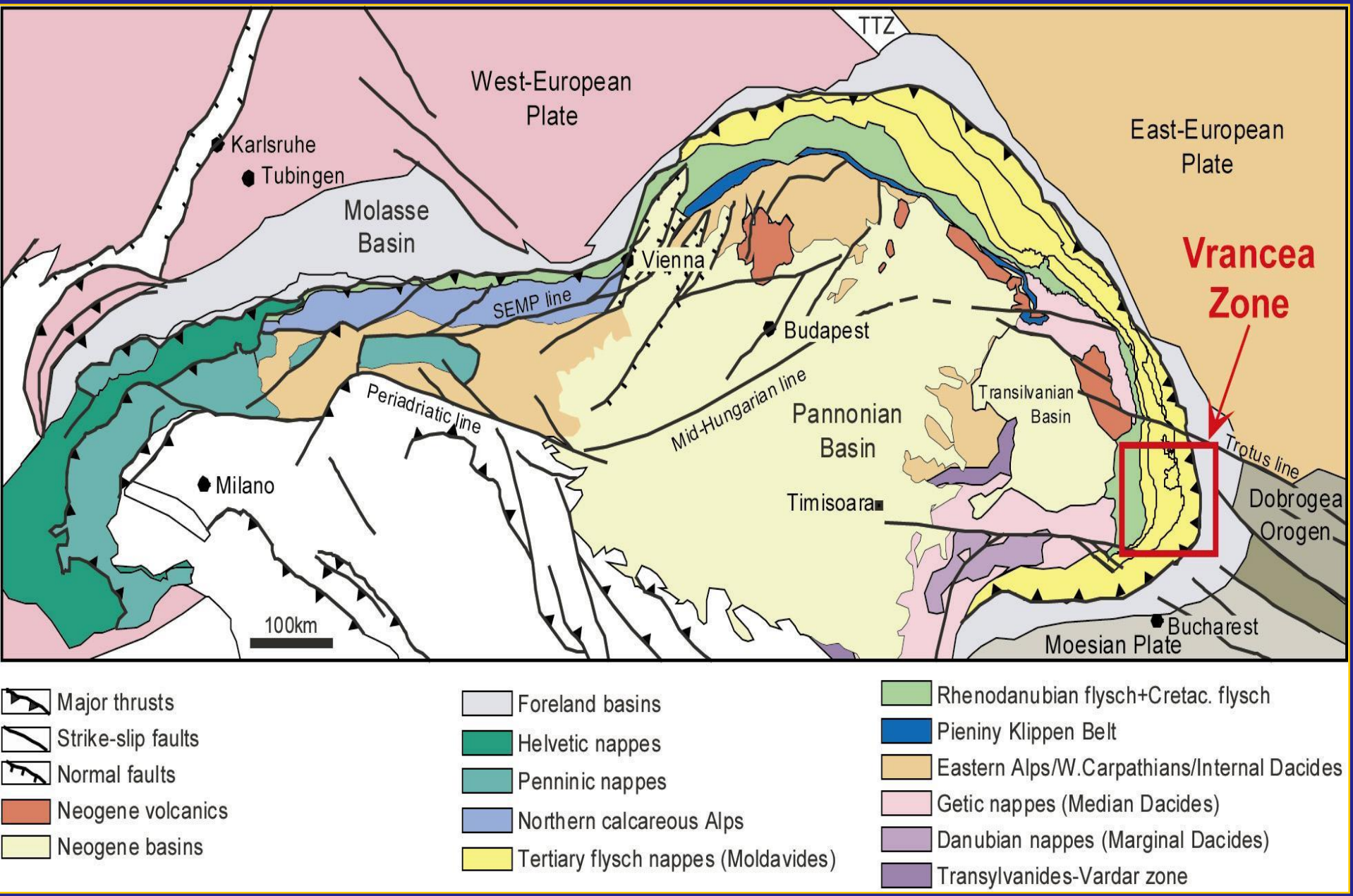
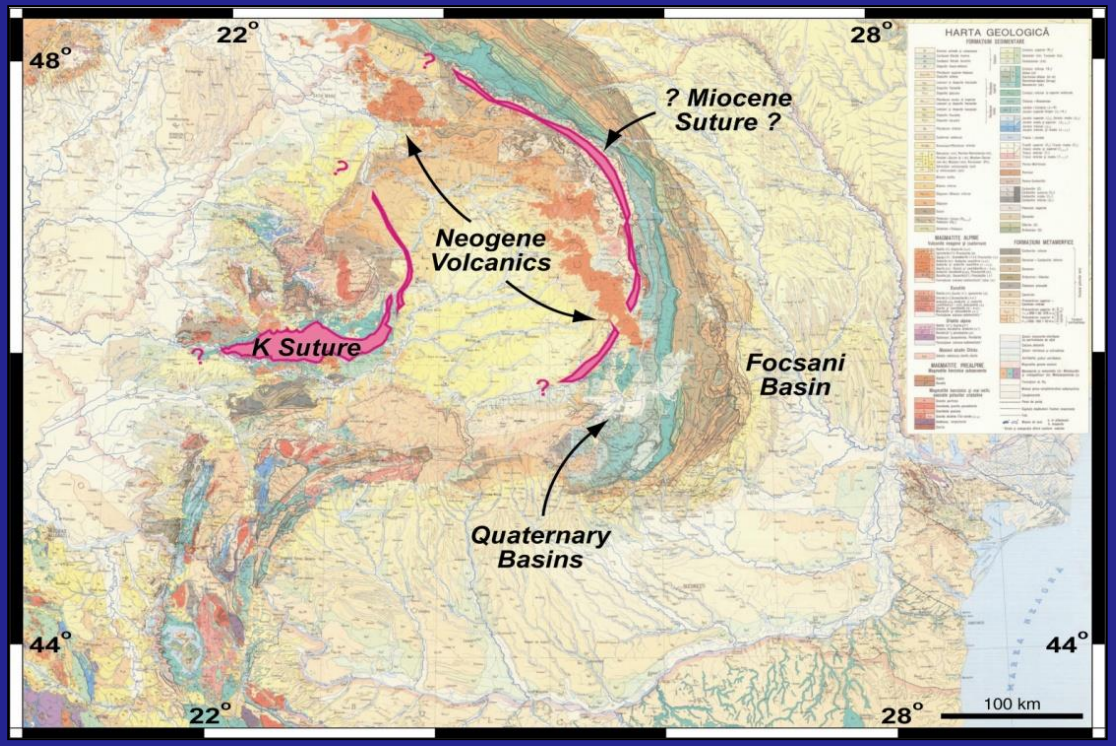
TECTONIC FRAMEWORK AND BASIC GEOPHYSICAL INFORMATION




TTZ
West-European Plate
East-European Plate
Karlsruhe
Tubingen
Molasse Basin
Vienna
SEMP line
Budapest
Vrancea Zone
Periadriatic line
Mid-Hungarian line
Pannonian Basin
Transilvanian Basin
Trotus line
Dobrogea Orogen
Milano
Timisoara
100km
Bucharest
Moesian Plate
Major thrusts
Strike-slip faults
Normal faults
Neogene volcanics
Neogene basins
Foreland basins
Helvetic nappes
Penninic nappes
Northern calcareous Alps
Tertiary flysch nappes (Moldavides)
Rhenodanubian flysch+Cretac. flysch
Pieniny Klippen Belt
Eastern Alps/W.Carpathians/Internal Dacides
Getic nappes (Median Dacides)
Danubian nappes (Marginal Dacides)
Transylvanides-Vardar zone



NEOGENE VOLCANISM

- Age progression (14 My NW, <1 My SE)
- Calc-alkaline composition
- Altered composition
- Very young alcali-basaltic (0.4 My) in Persani Mts.)

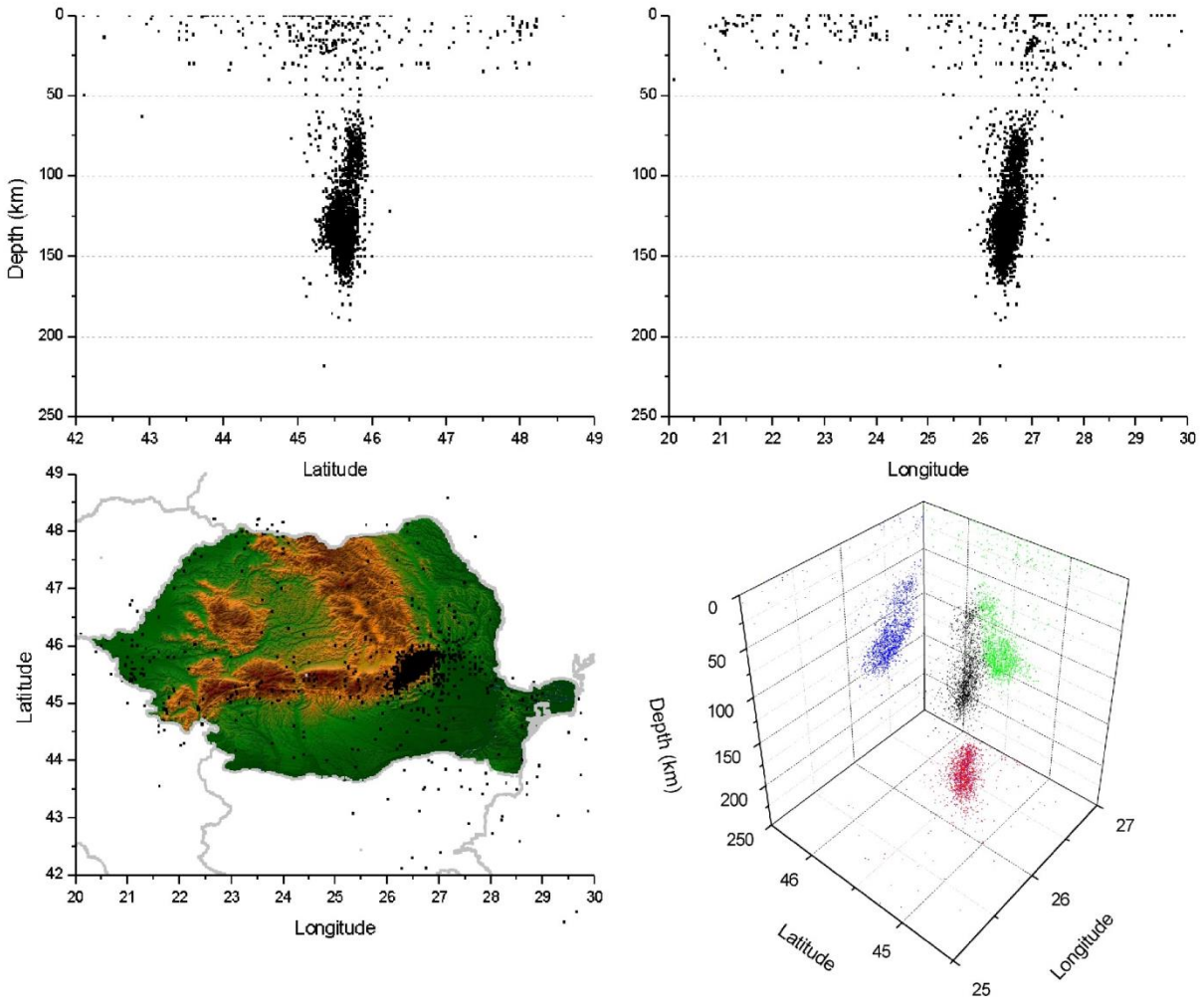
FOCSANI BASIN

- Very think sediments, >18 km
- Very complicate tectonics, so geometry still questionable

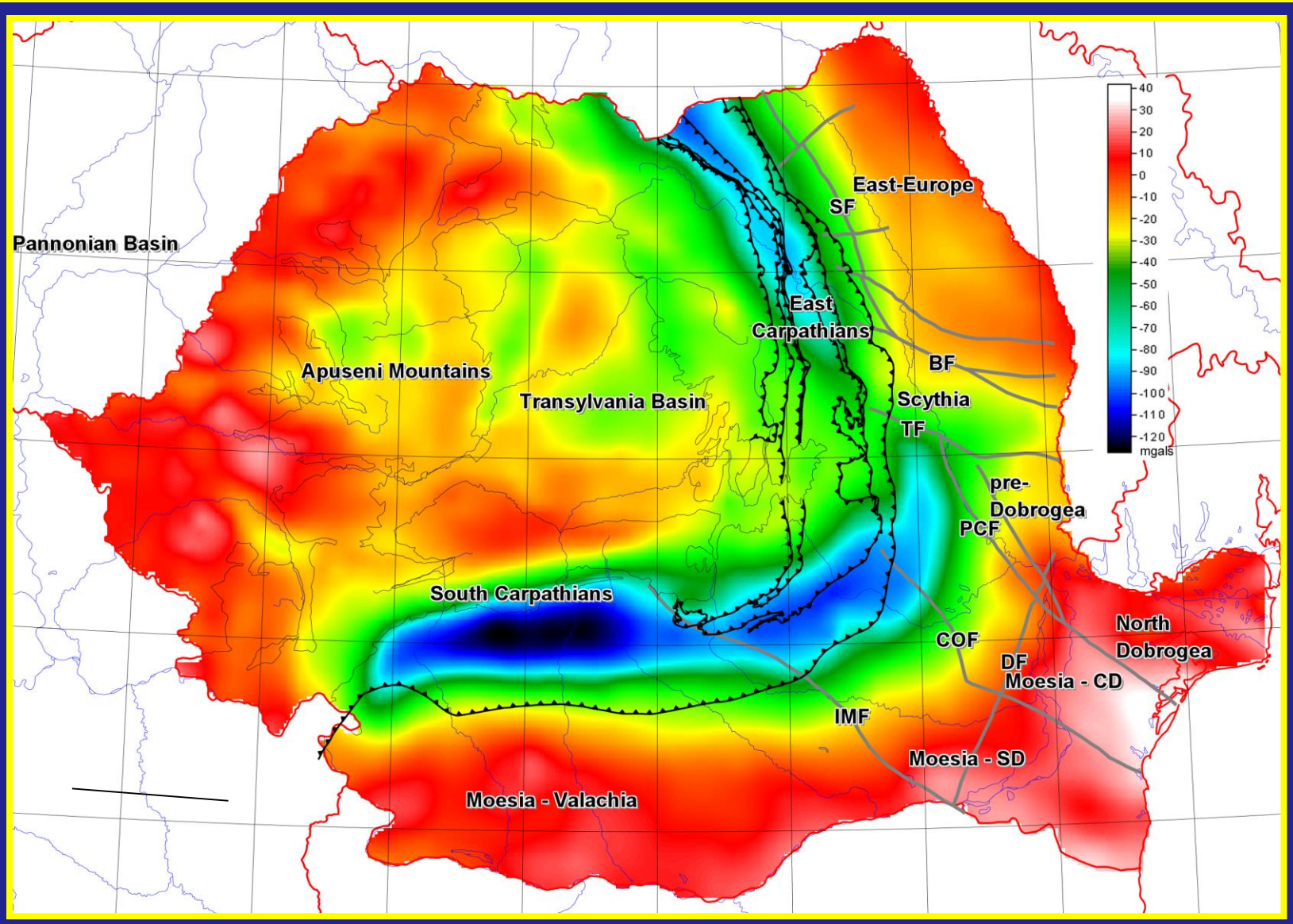
WHY VRANCEA ?

10 November	1940	150-180 km	Mw=7.7
4 March	1977	90-110 km	Mw=7.5
30 August	1986	130-150 km	Mw=7.2
30 May	1990	70- 90 km	Mw=6.9

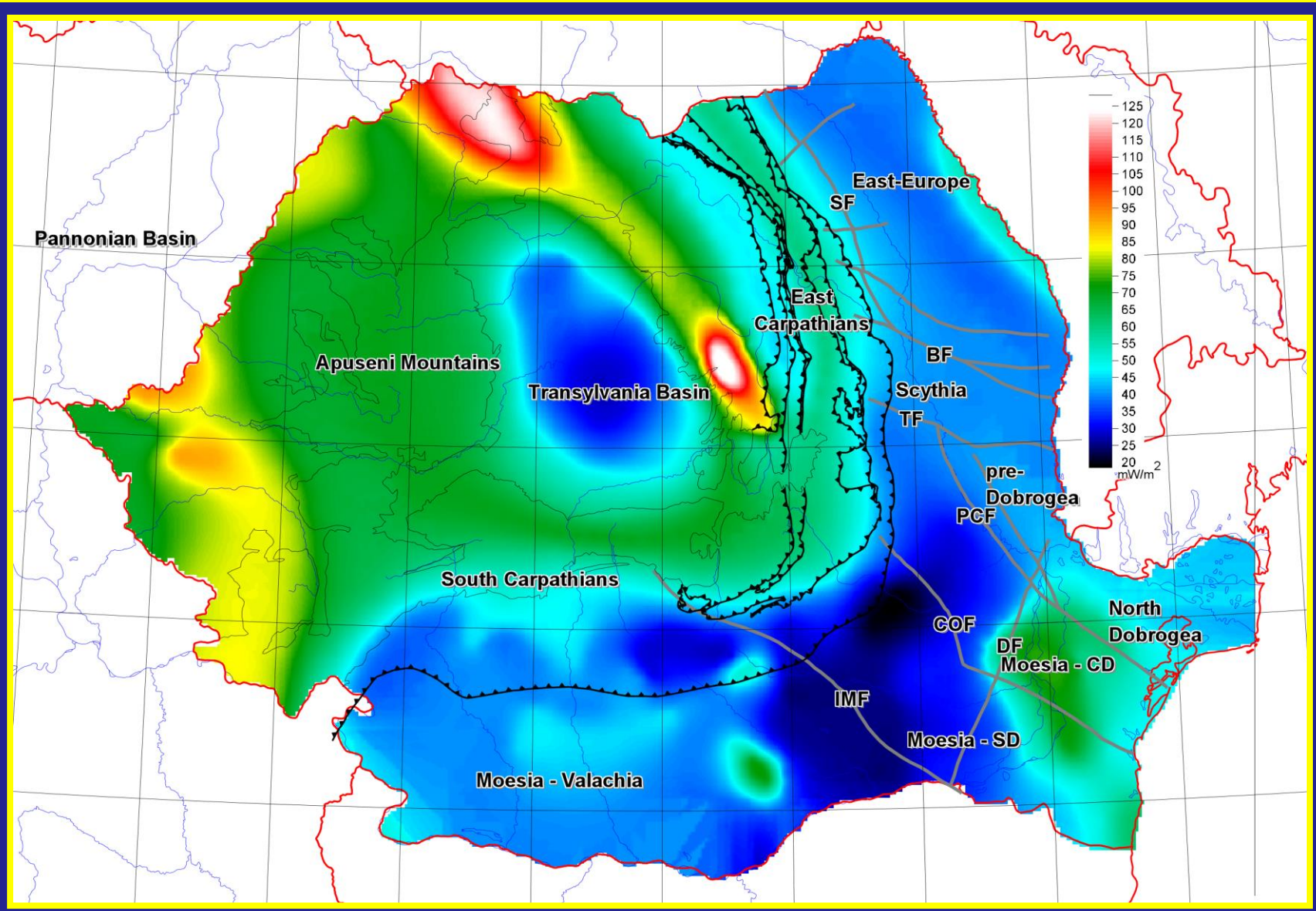
WHY VRANCEA ?


Depth (km)
0
50
100
150
200
250
42
43
44
45
46
47
48
49
Latitude
20
21
22
23
24
25
26
27
28
29
30
Longitude
Latitude
Longitude
Depth (km)
Latitude
Longitude

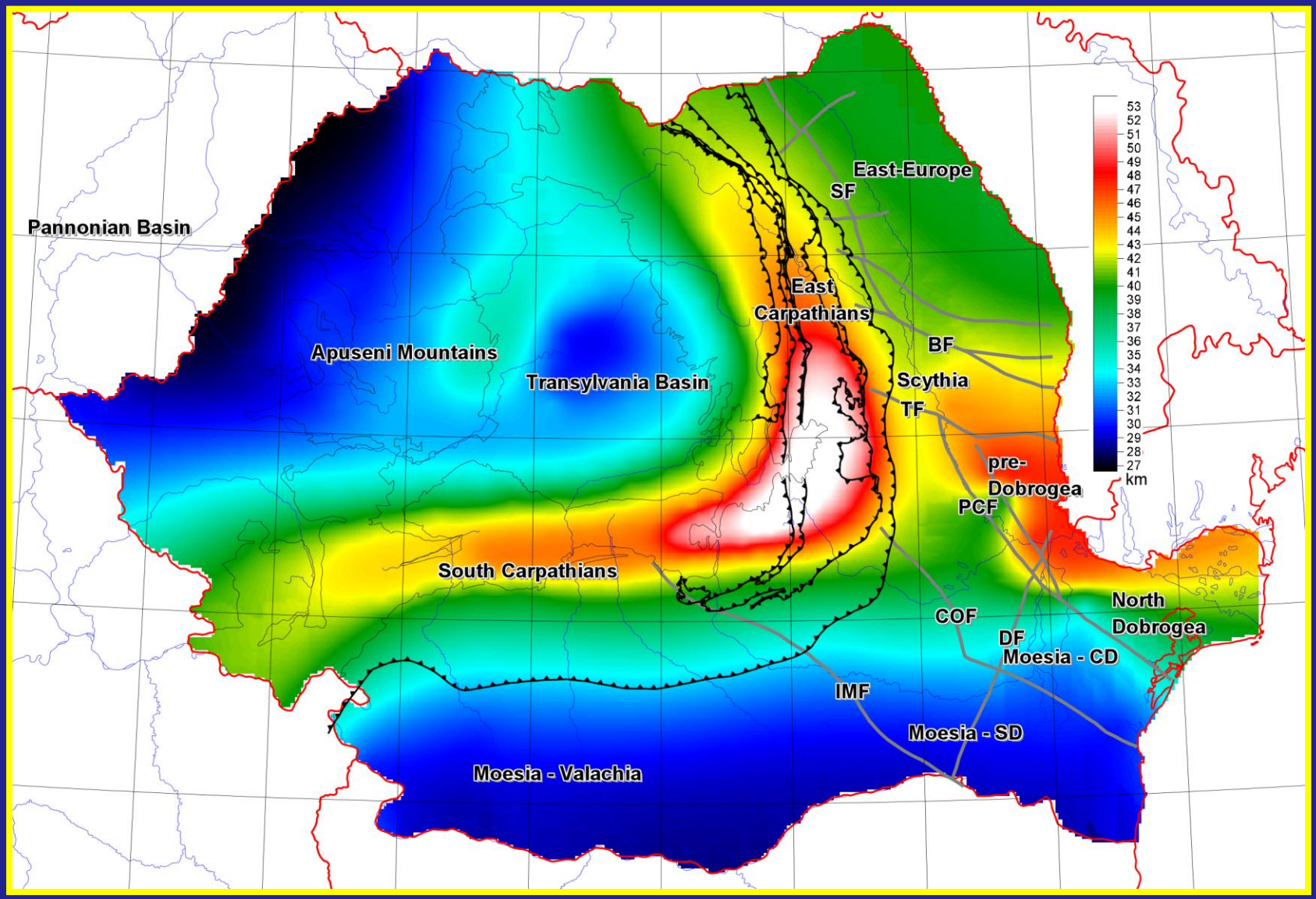
GRAVITY – BOUGUER MAP



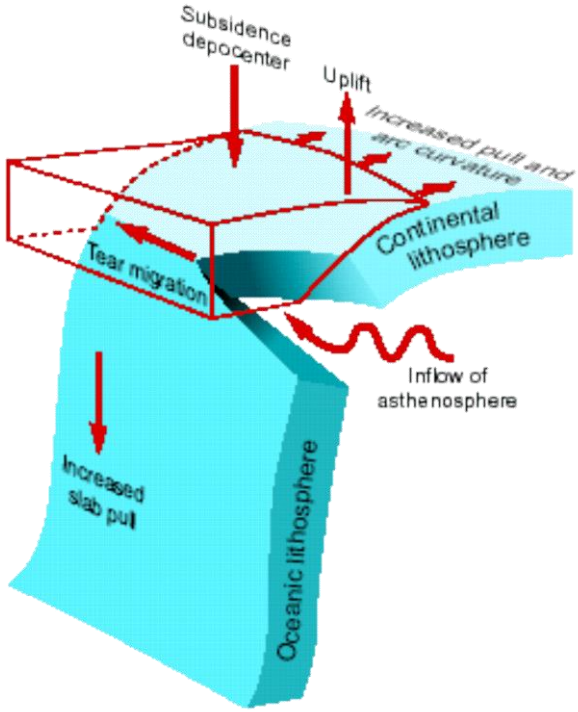
HEAT FLOW

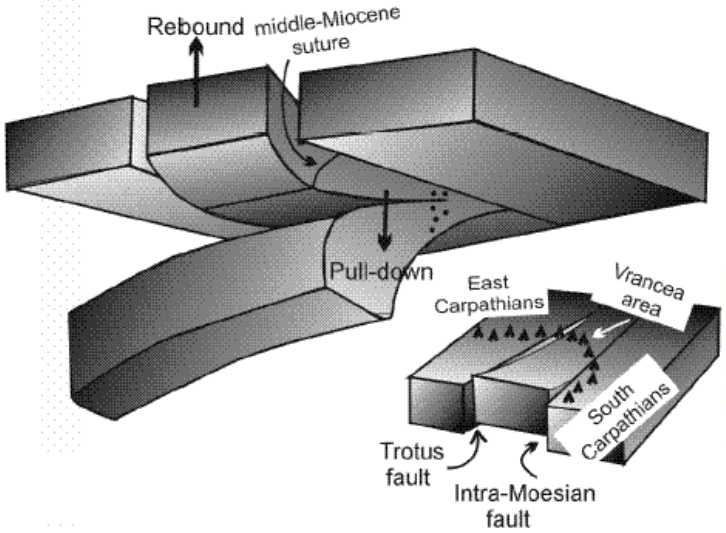

Pannonian Basin
East-Europe
SF
East
Carpathians
Apuseni Mountains
Transylvania Basin
BF
Scythia
TF
pre-
Dobrogea
PCF
South Carpathians
COF
North
Dobrogea
DF
Moesia - CD
IMF
Moesia - SD
Moesia - Valachia
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
mW/m2

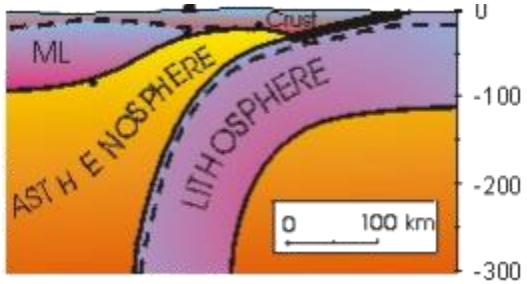
MOHO DEPTH


Pannonian Basin
Apuseni Mountains
Transylvania Basin
East Carpathians
East-Europe
SF
BF
Scythia
TF
pre-Dobrogea
PCF
South Carpathians
COF
North Dobrogea
DF
Moesia - CD
IMF
Moesia - SD
Moesia - Valachia
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
35
34
33
32
31
30
29
28
27
km

GEOPHYSICAL MODELS







Slab Detachment
(Wortel & Spakman, Science 2000)

- ***Small lateral motions***
- ***Uplift in the Vrancea area, subsidence east and north of the Vrancea zone***

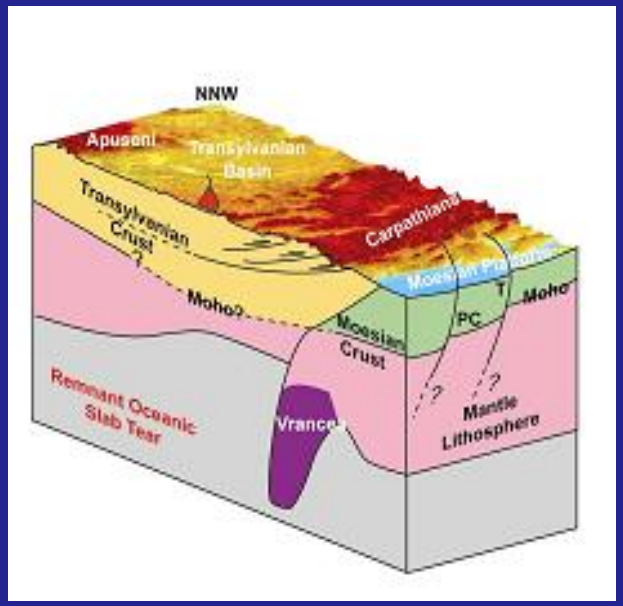
Partial Slab Delamination
(Gvirtzman, Geology 2002)

Slab Roll-Back

- ***Lateral motions dominant***
- ***Some subsidence east and west of the Vrancea Zone***
- ***Uplift caused by the lithospheric bulge farther east***

GEOPHYSICAL MODELS

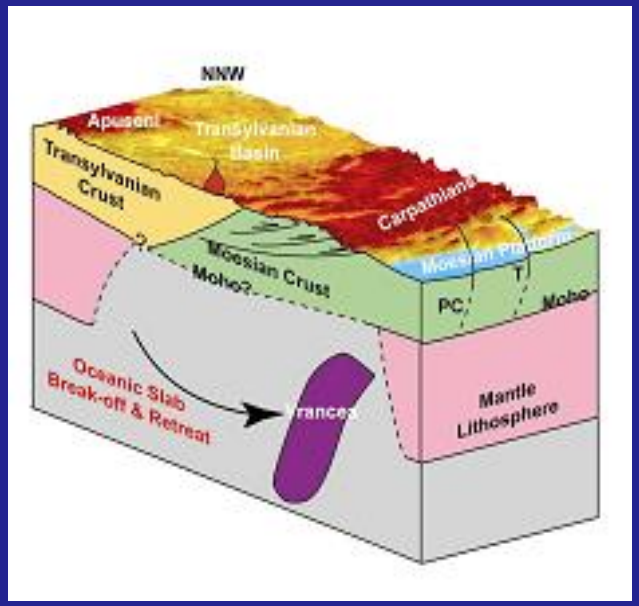
Subduction in place



Supported by:

Dipping reflectors in crust, offsets in Moho

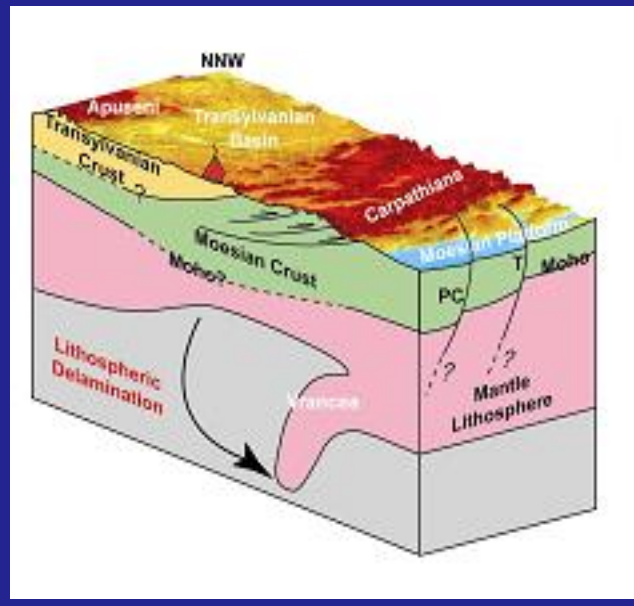
Slab break-off and retreat



Ruled out by:

Coupling between crust and mantle, no offsets along Moho

Continental lithosphere Delamination



Supported by:

Sub-horizontal reflectors in crust, sub-horizontal Moho, offsets in Moho

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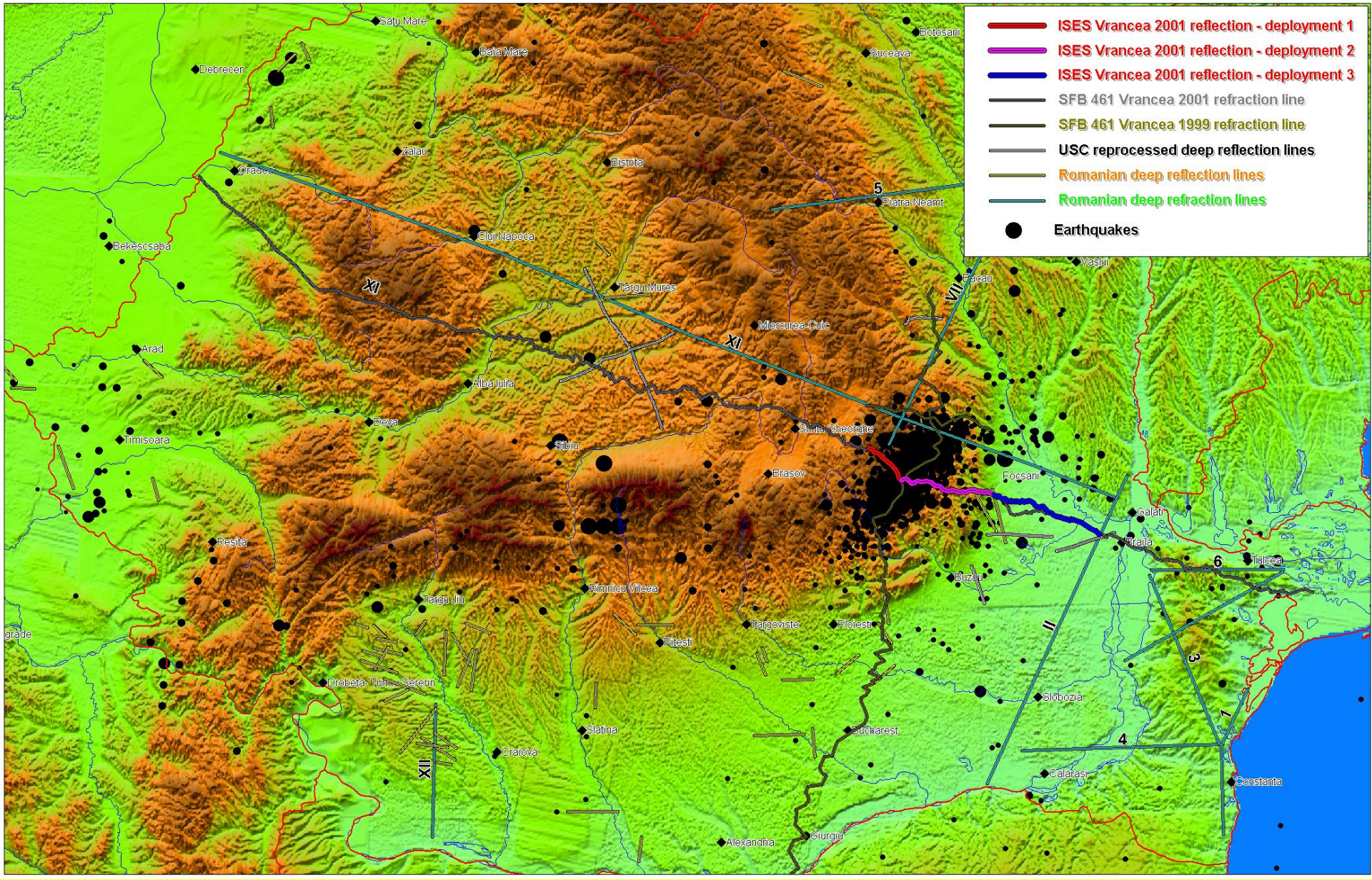
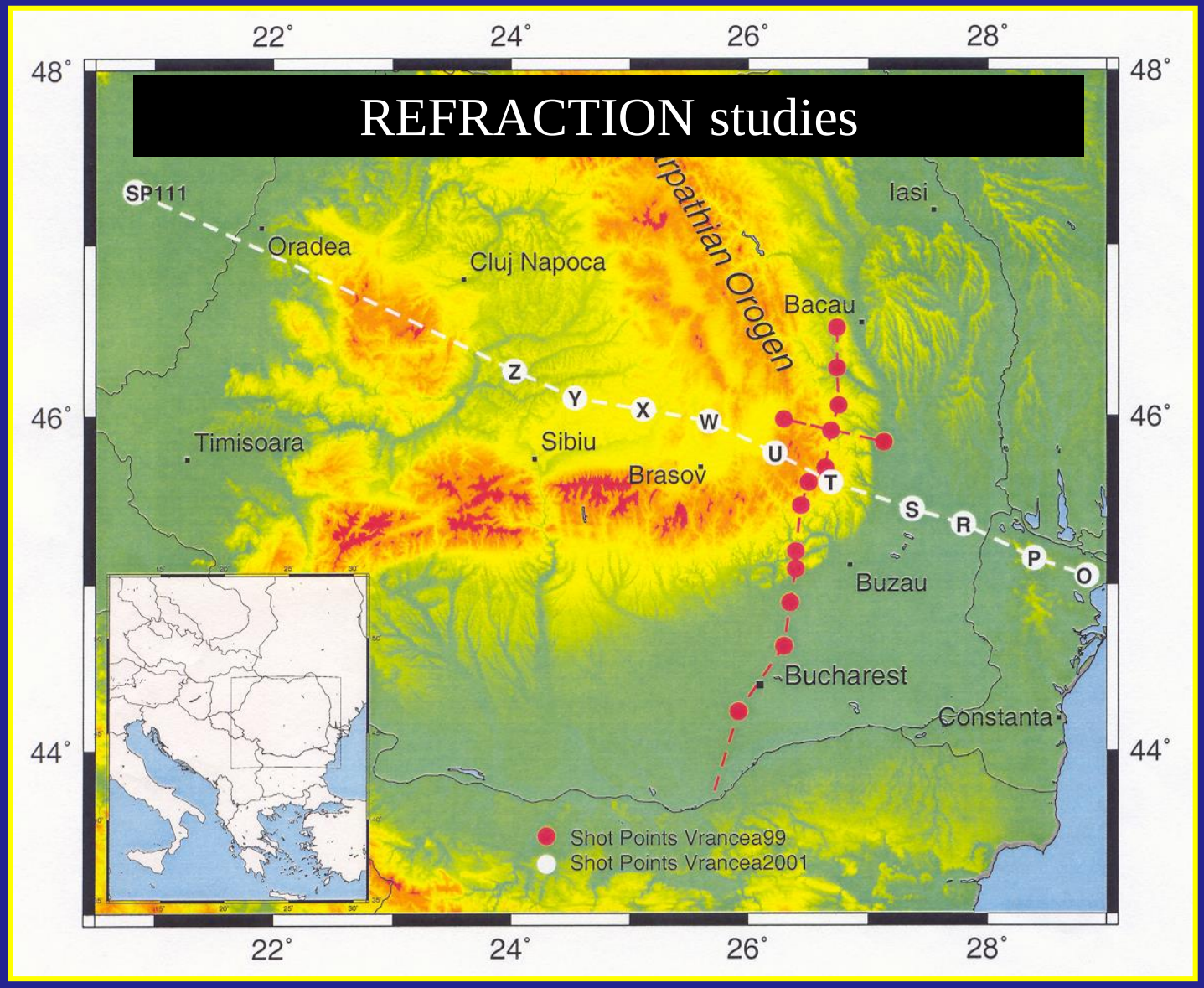
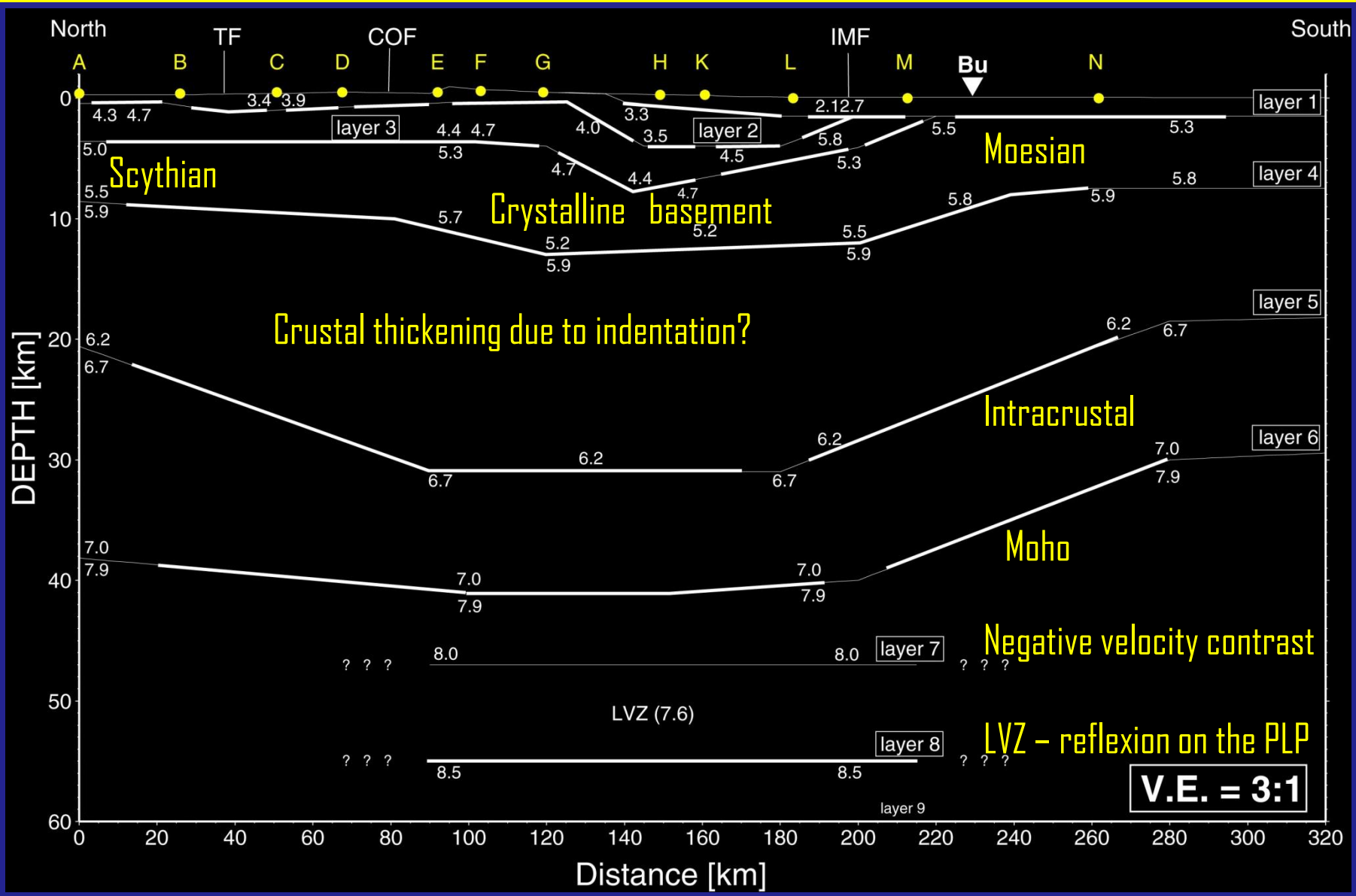
- SEISMIC TOMOGRAPHY
- GPS
- REGIONAL GEODYNAMIC MODEL

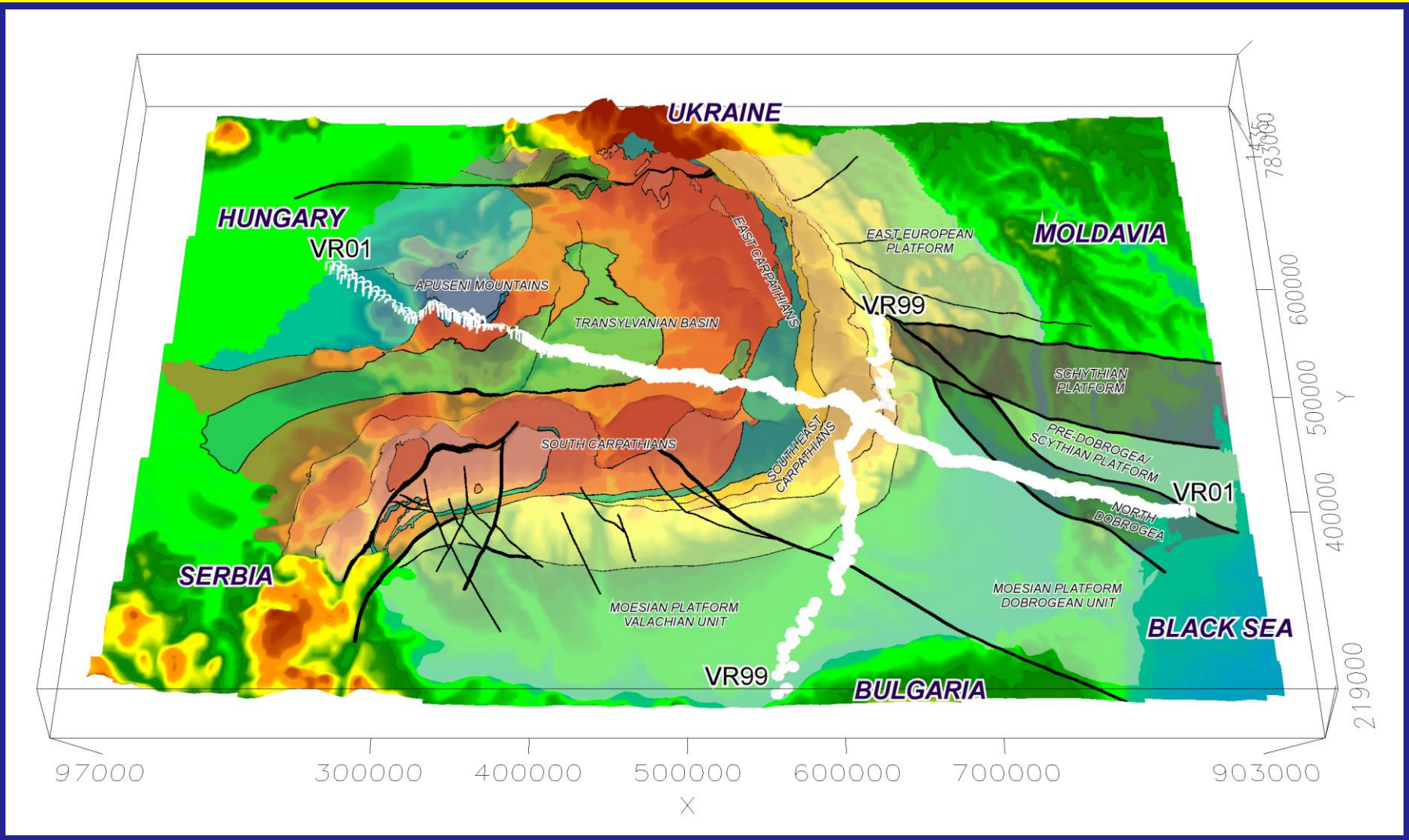

ISES Vrancea 2001 reflection - deployment 1
ISES Vrancea 2001 reflection - deployment 2
ISES Vrancea 2001 reflection - deployment 3
SFB 461 Vrancea 2001 refraction line
SFB 461 Vrancea 1999 refraction line
USC reprocessed deep reflection lines
Romanian deep reflection lines
Romanian deep refraction lines
Earthquakes
Satu Mare
Debrecen
Baia Mare
Botosani
Suceava
Zalau
Bistrita
Oradea
Piatra Neamt
Bekescsaba
Cluj-Napoca
Vaslui
Targu Mures
Bacau
Mercurea-Ciuc
Arad
Alba Iulia
Deva
Timisoara
Sibiu
Focsani
Brasov
Galati
Braila
Resita
Tulcea
Buzau
Targu Jiu
Ramnicu Valcea
Targoviste
Ploiesti
Pitesti
Drobeta-Turnu Severin
Slobozia
Slatina
Bucharest
Craiova
Calarasi
Constanta
Alexandria
Giurgiu
5
6
4
VII
XI
XII
II
3
1

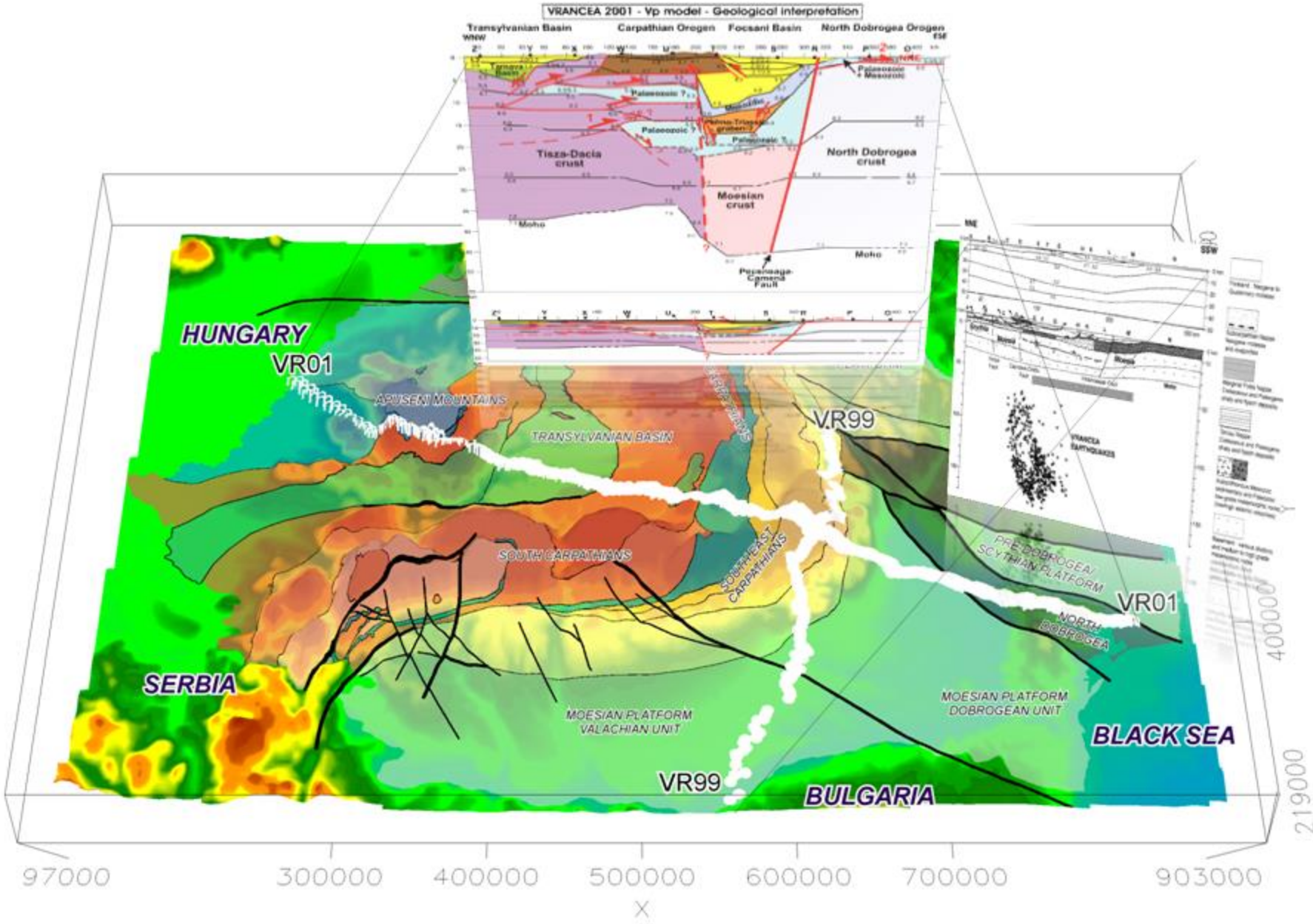

REFRACTION studies
22˚
24˚
26˚
28˚
48˚
46˚
44˚
SP111
Oradea
Cluj Napoca
Iasi
Bacau
Timisoara
Sibiu
Brasov
Buzau
Bucharest
Constanta
Z
Y
X
W
U
T
S
R
P
O
Shot Points Vrancea99
Shot Points Vrancea2001

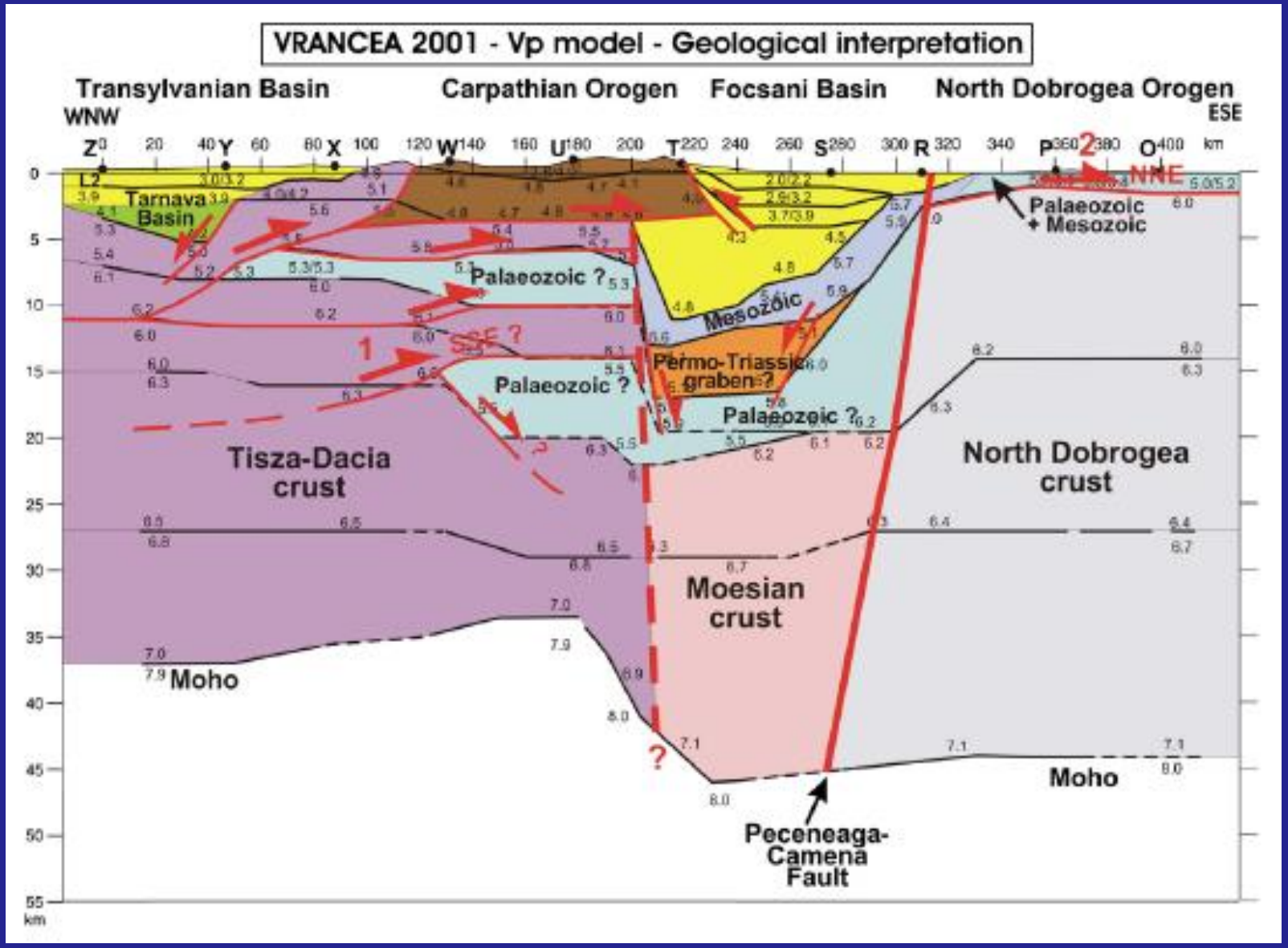
2D VELOCITY – DEPTH MODEL



2D VELOCITY – DEPTH MODEL

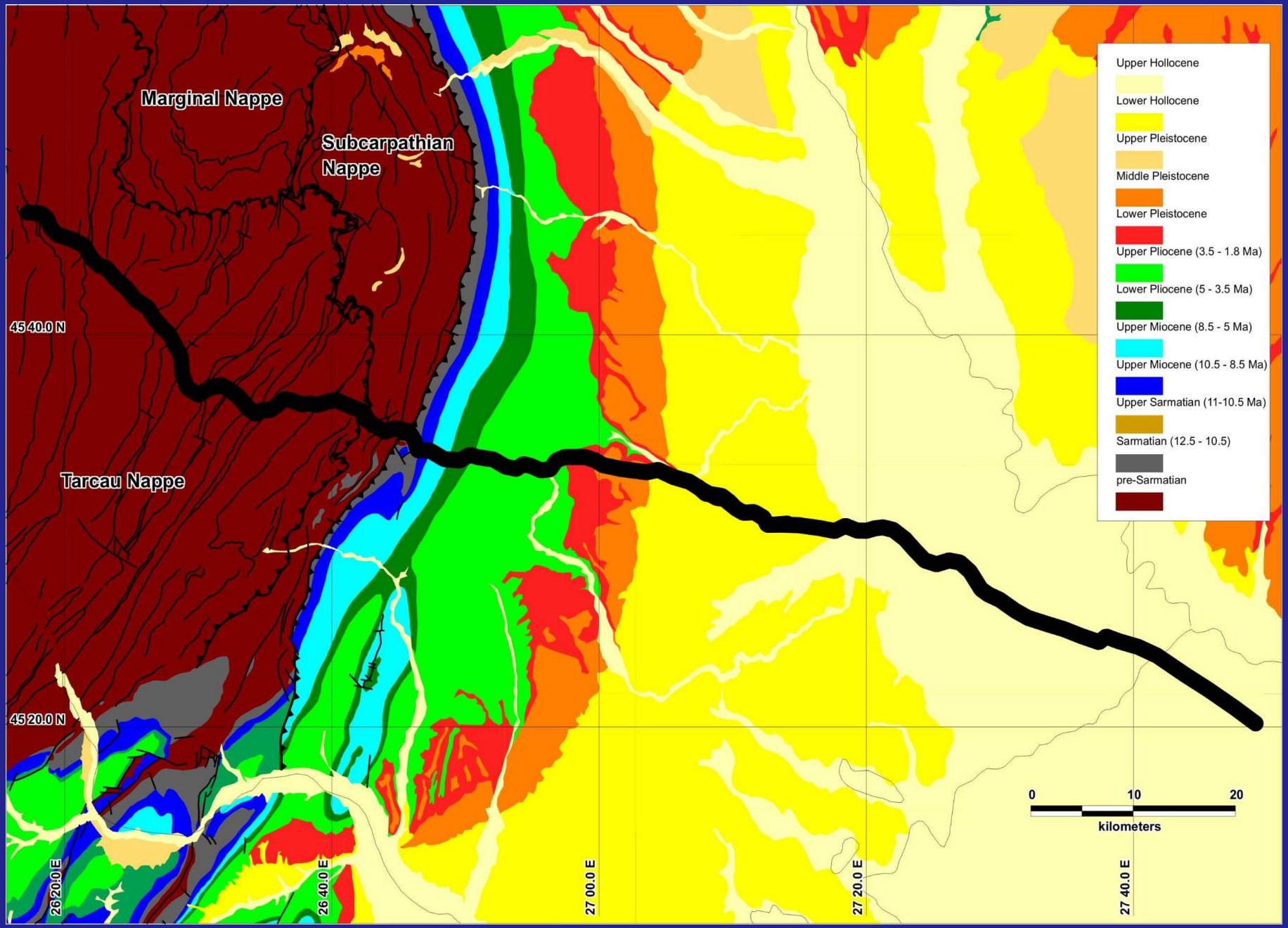



VRANCEA 2001 - Vp model - Geological interpretation
Transylvanian Basin
Carpathian Orogen
Focsani Basin
North Dobrogea Orogen
WNW
ESE
Tisza-Dacia crust
Moesian crust
North Dobrogea crust
Moho
Peceneaga-Camena Fault
HUNGARY
VR01
APUSENI MOUNTAINS
TRANSYLVANIAN BASIN
VR99
SOUTH CARPATHIANS
SOUTHEAST CARPATHIANS
PRE-DOBROGEAN SCYTHIAN PLATFORM
NORTH DOBROGEA
SERBIA
MOESIAN PLATFORM VALACHIAN UNIT
MOESIAN PLATFORM DOBROGEAN UNIT
BLACK SEA
BULGARIA
97000
300000
400000
500000
600000
700000
903000
X
400000
219000



Hauser et al., 2007, Tectonophysics

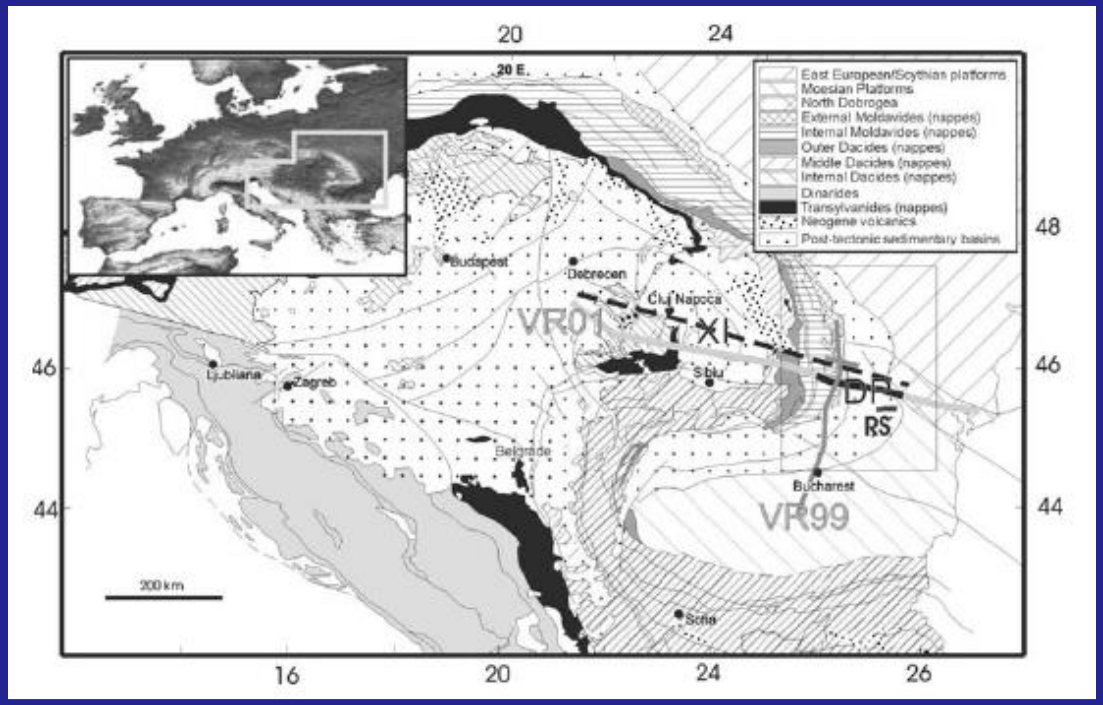
REFLECTION – DACIA PLAN



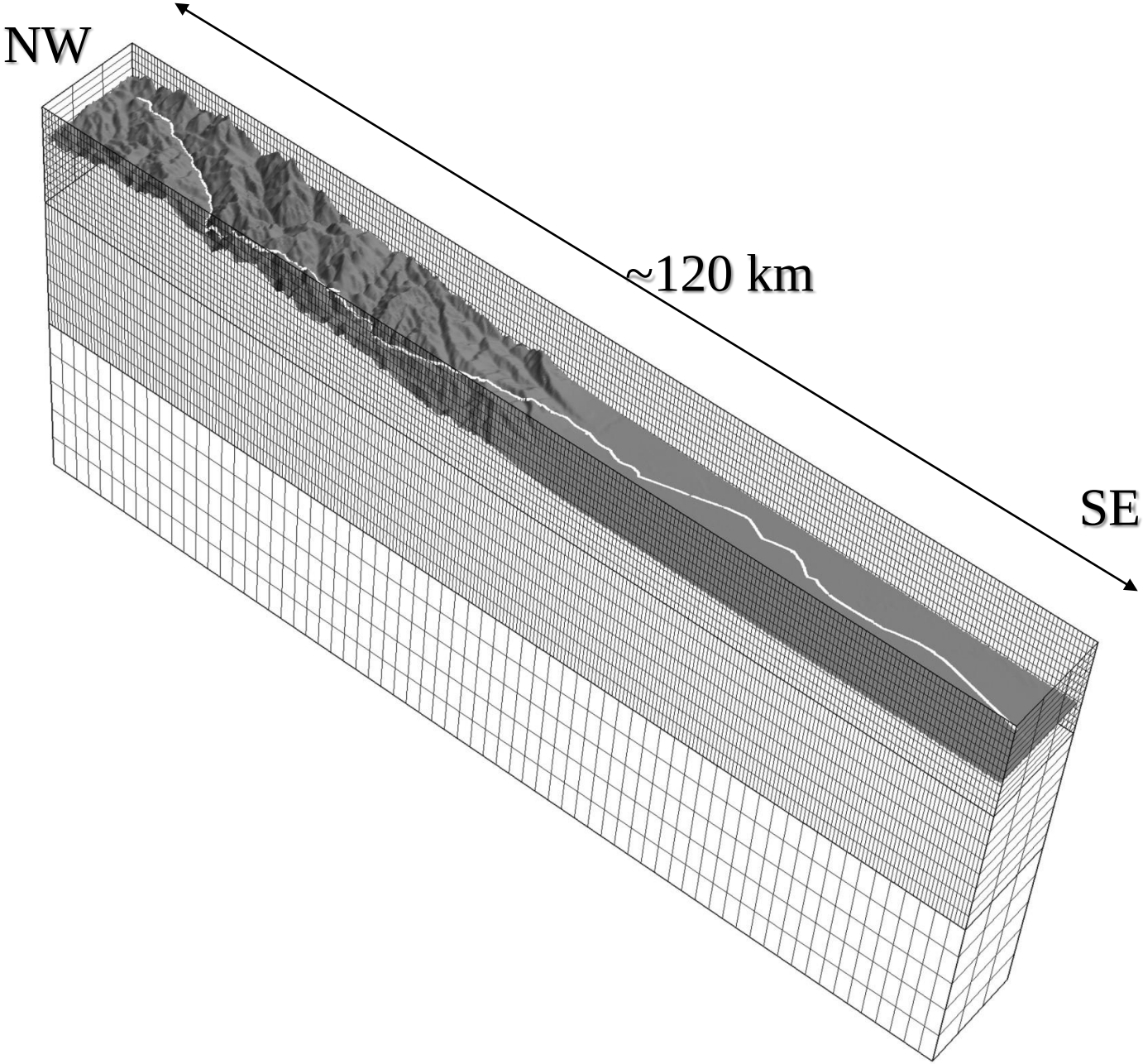
Danube **A**nd **C**arpathian **I**ntegrated **A**ction on **P**rocesses in the **L**ithosphere **A**nd **N**eotectonics (**DACIA-PLAN**)

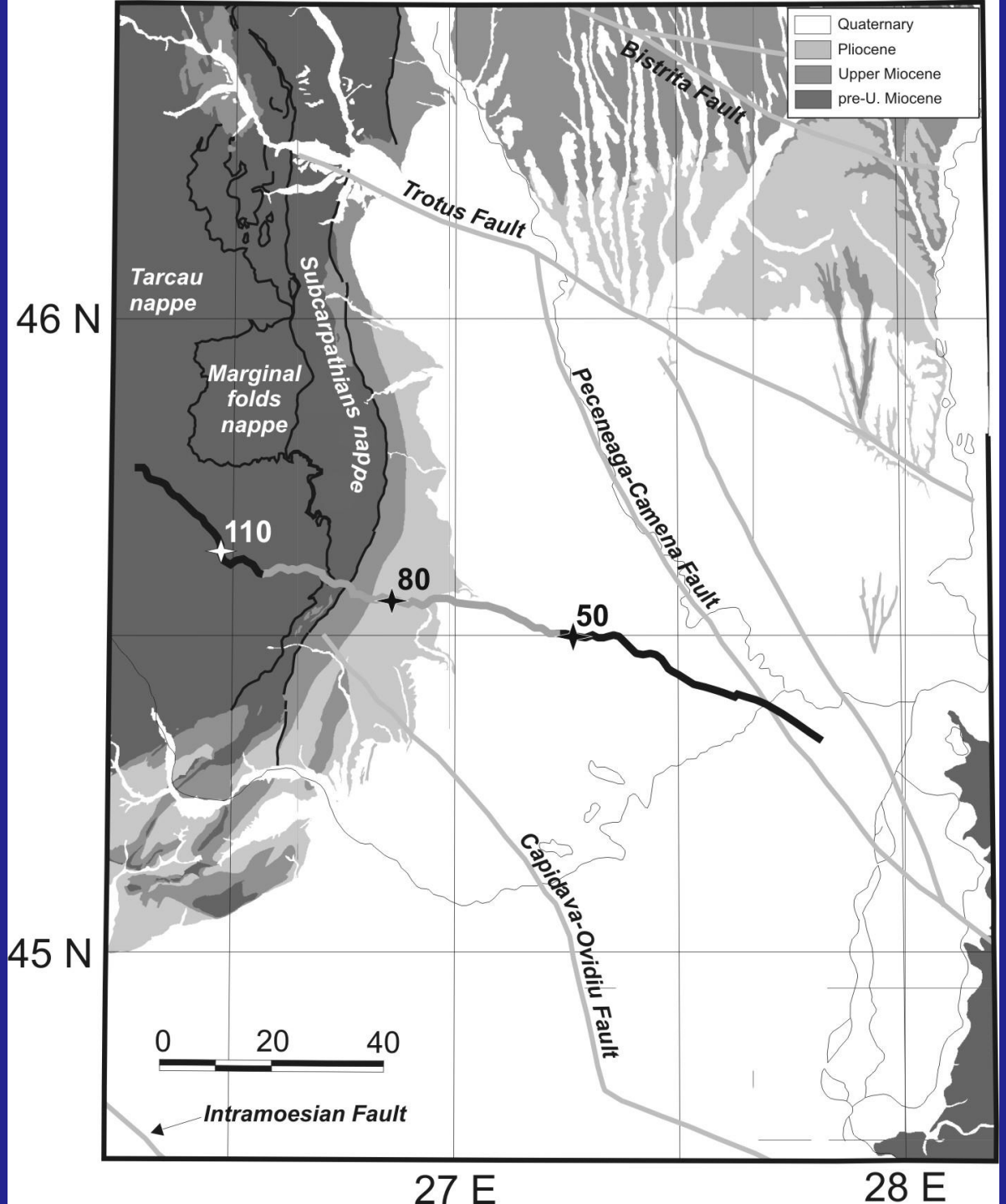
Goal of the project:
Obtaining new information on the deep structure of the external Carpathians nappe system and the architecture of the Tertiary/Quaternary basins developed within and adjacent to the Vrancea zone, including the Focsani Basin

Data acquisition parameters:
- receiver spacing: 100 m
- receiver type: 1D Reftek 125 s
- source spacing: 1 km
- source type: dynamite
- record length: 90 s



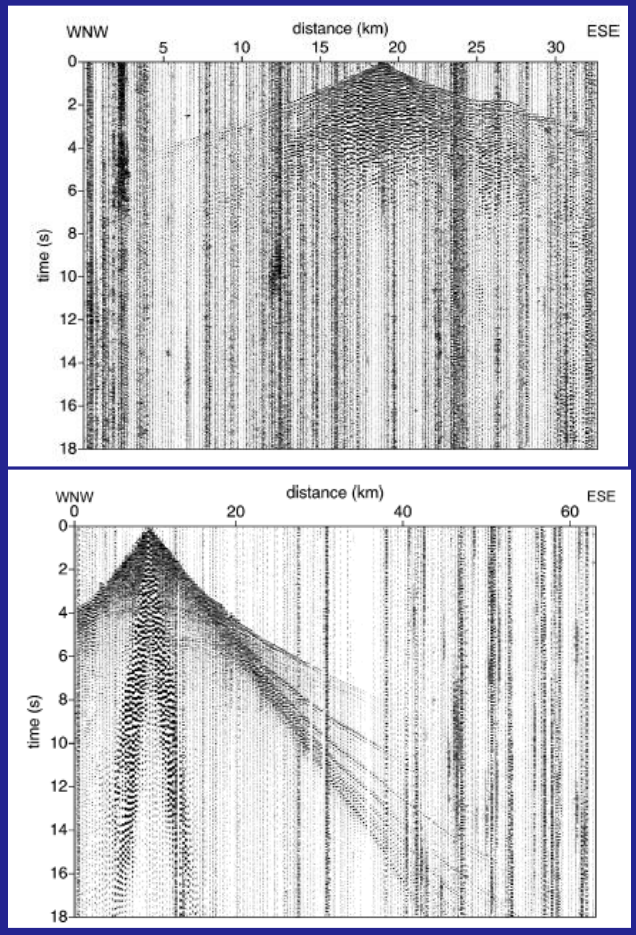
Tectonic map of the Carpathians/Dinarides/Pannonians basin system in south-eastern Europe showing the position of deep refraction and reflection seismic profiles (modified after Sandulescu, 1984)


NW
~120 km
SE

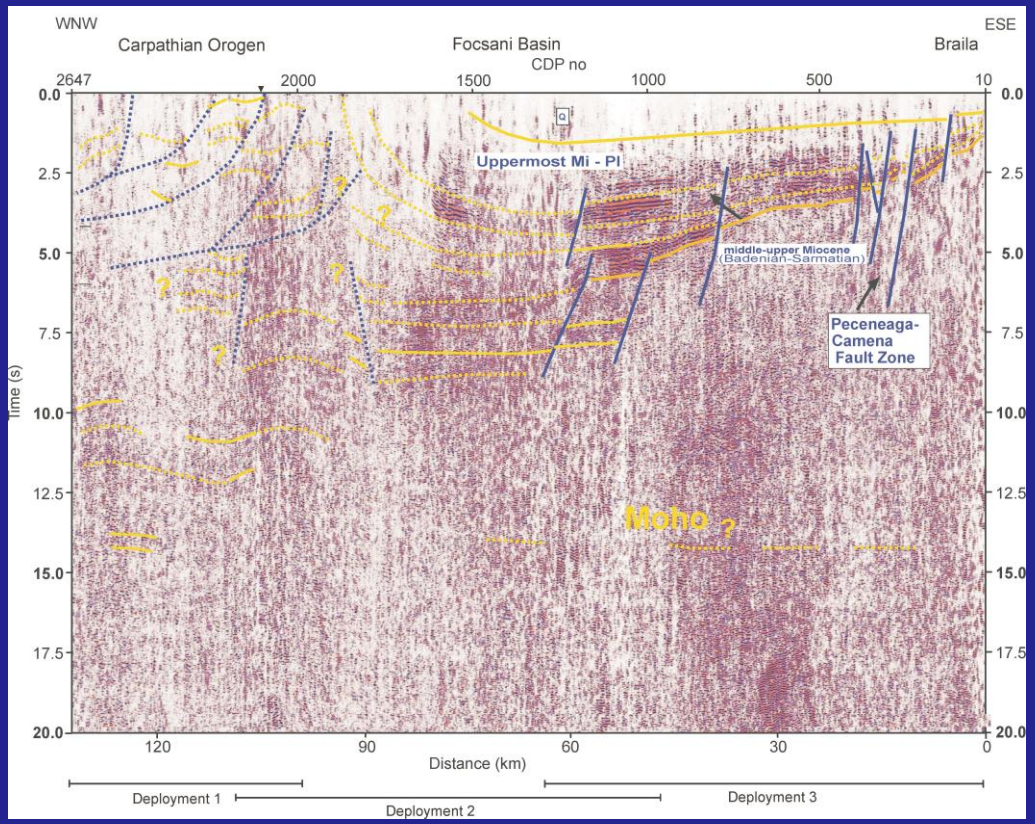

Quaternary
Pliocene
Upper Miocene
pre-U. Miocene
Bistrita Fault
Trotus Fault
Tarcau nappe
Subcarpathians nappe
Marginal folds nappe
Peceneaga-Camena Fault
110
80
50
Capidava-Ovidiu Fault
0
20
40
Intramoesian Fault
46 N
45 N
27 E
28 E

Danube And Carpathian Integrated Action on Processes in the Lithosphere And Neotectonics (DACIA-PLAN)

Processing of DACIA-PLAN data



Examples of records from the mountainous area (up) and Focsani Basin (down)

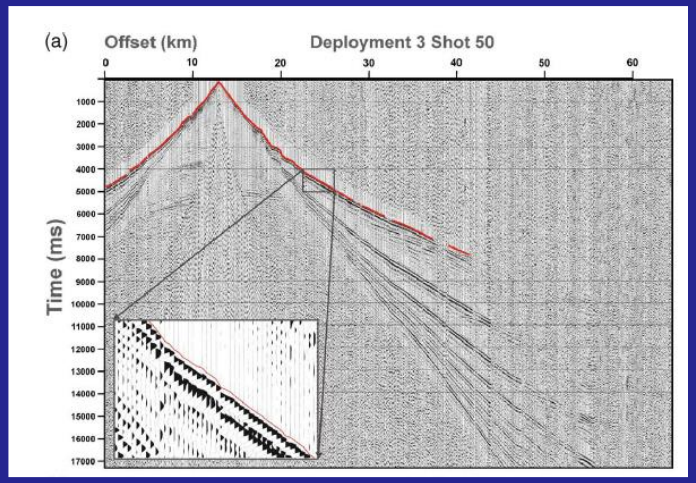


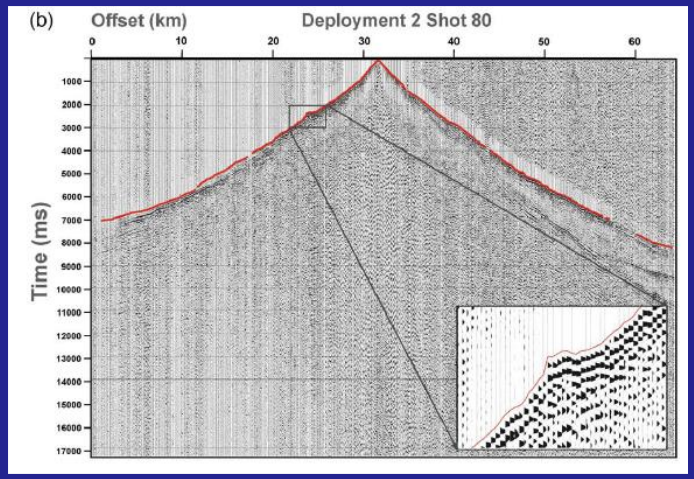
Interpreted seismic section for DACIA-PLAN
Panea et al., Tectonophysics, 2005

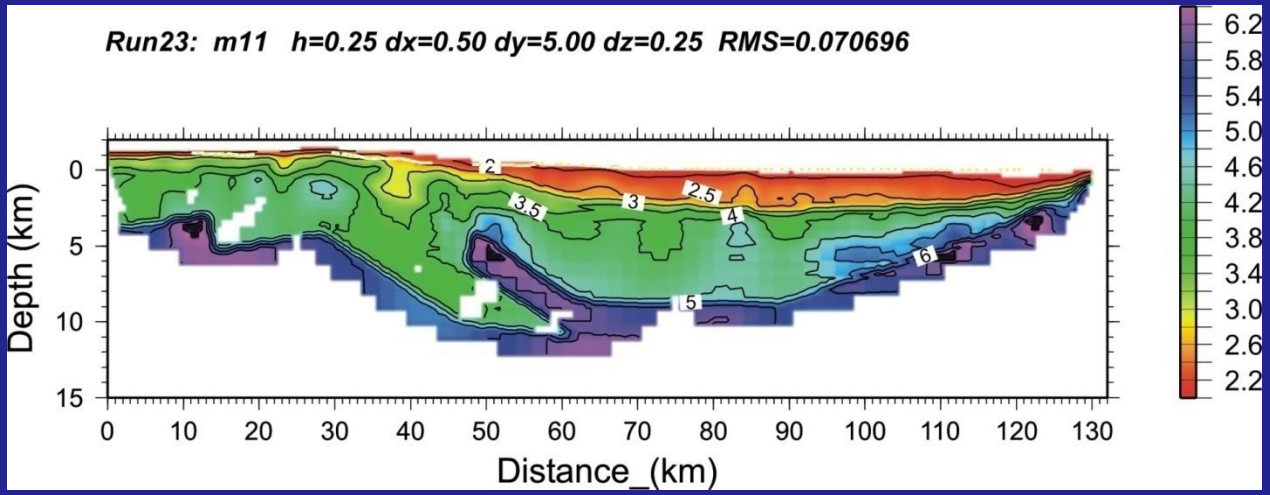
Danube **A**nd **C**arpathian **I**ntegrated **A**ction on **P**rocesses in the **L**ithosphere **A**nd **N**eotectonics (**DACIA-PLAN**)

Determine the P-wave velocity model along the DACIA-PLAN profile after the inversion of the first-arrival travel-times

Examples of records with picked first-arrival travel-times over (a) the Focsani Basin and (b) mountainous area

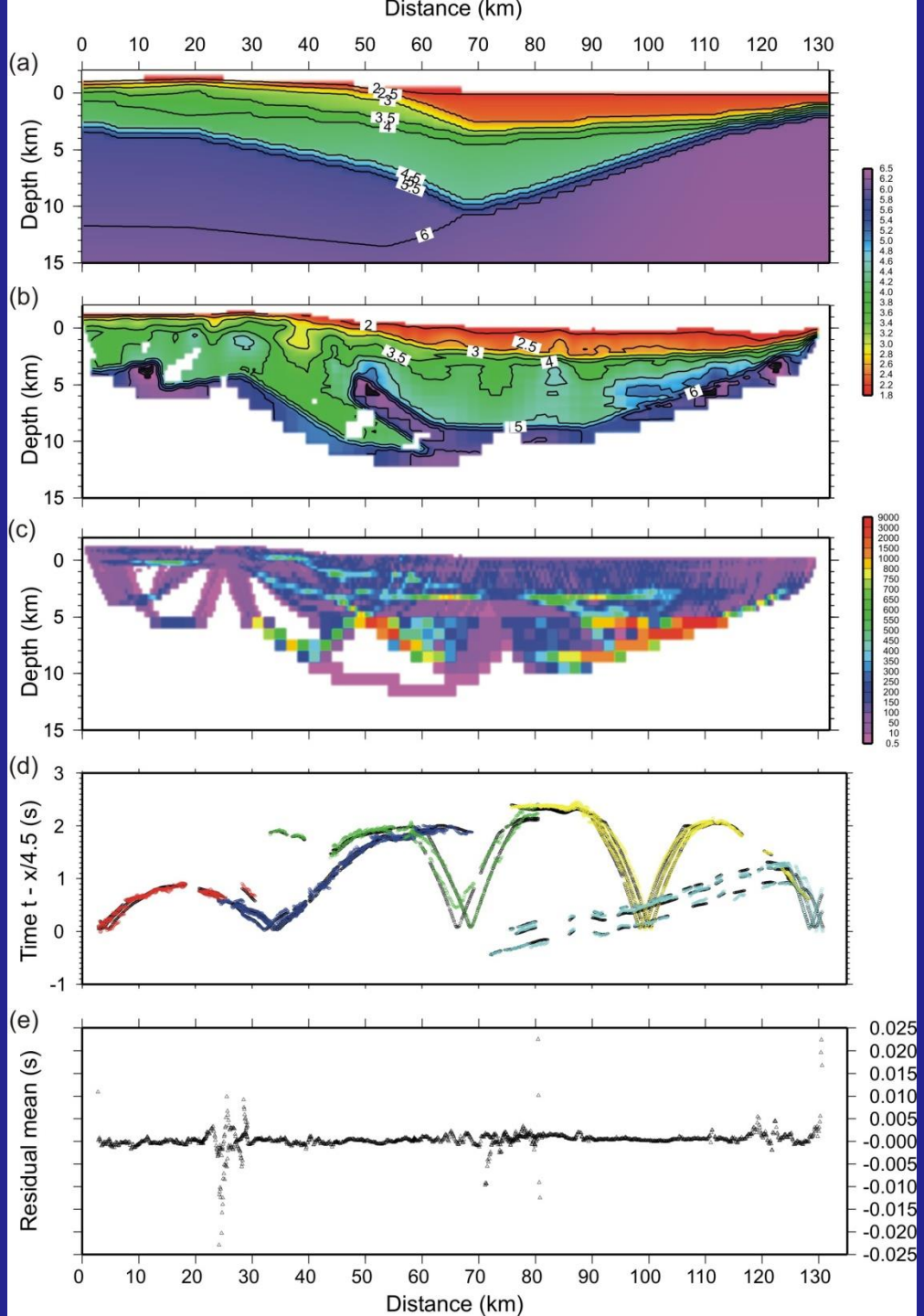






Velocity model obtained after the inversion of the first-arrival travel-times (interpolation between isovelocity lines)

Bocin et al., Tectonophysics, 2005



initial model

final model

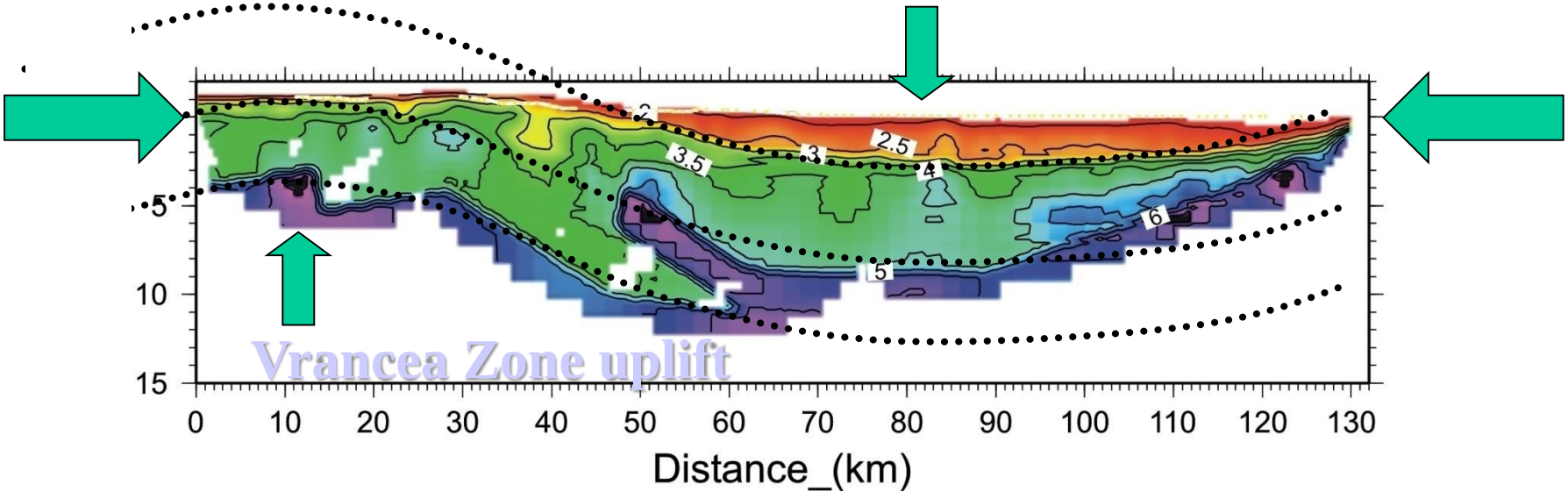
cell hit rate

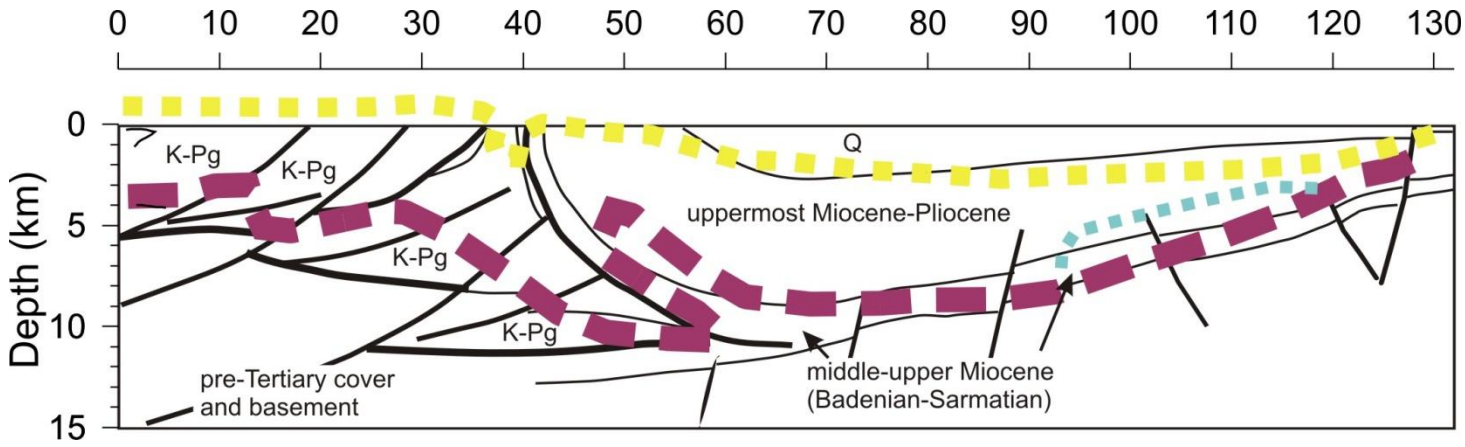
~46000 travel times

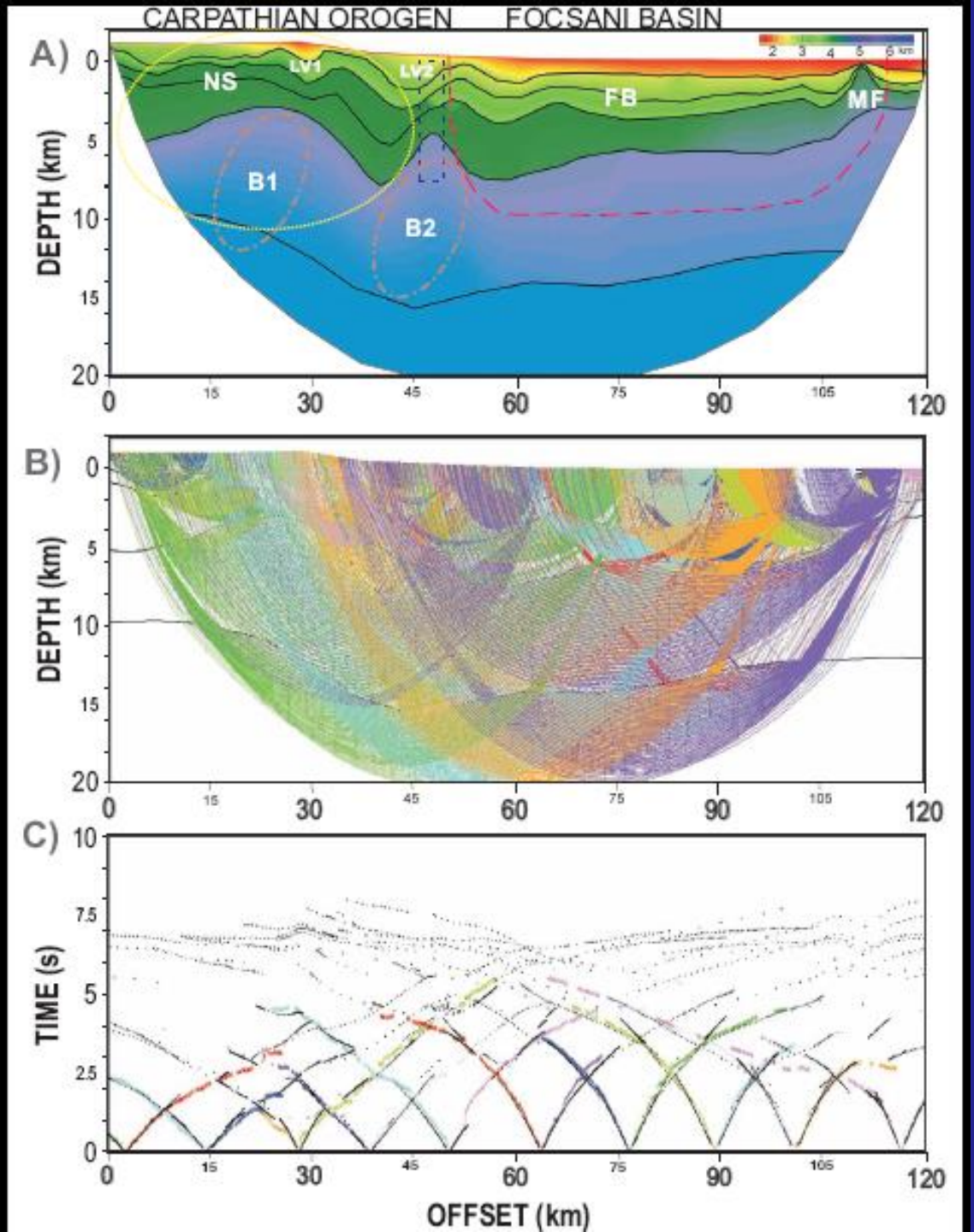
selected misfits

residuals

Focsani Basin subsidence





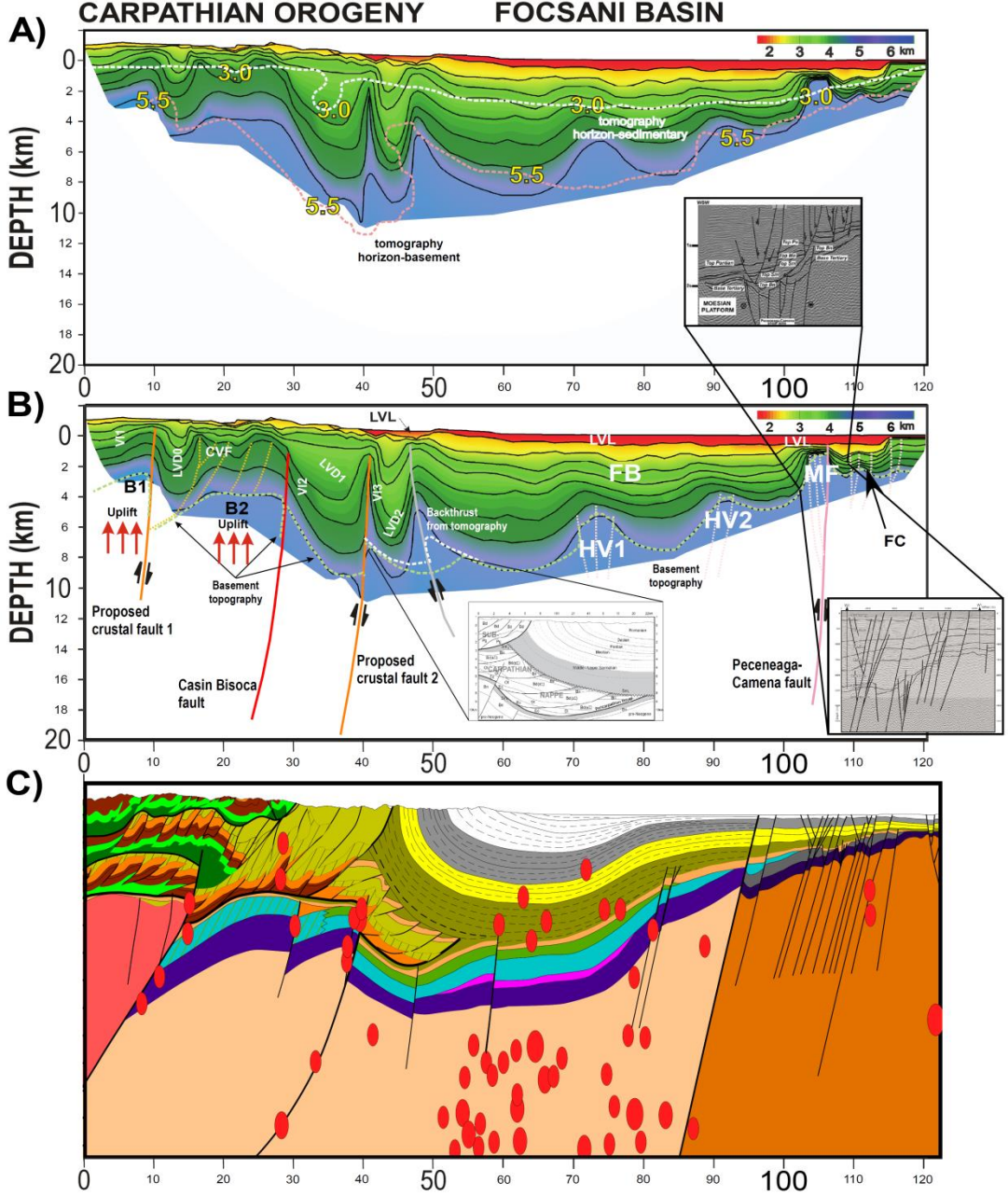


Velocity model from ray-tracing (which used all possible phases)

Ray coverage with different colors for different rays

Missfit

Bocin et al., 2009



Tomography velocity model

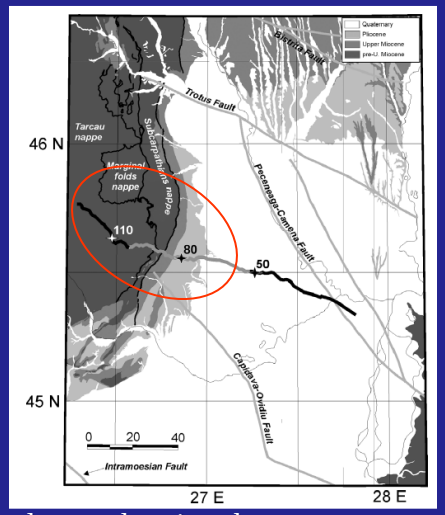
Ray tracing velocity model

Geological cross section across the thin skinned nappes of the south-eastern Carpathians and the foreland basin

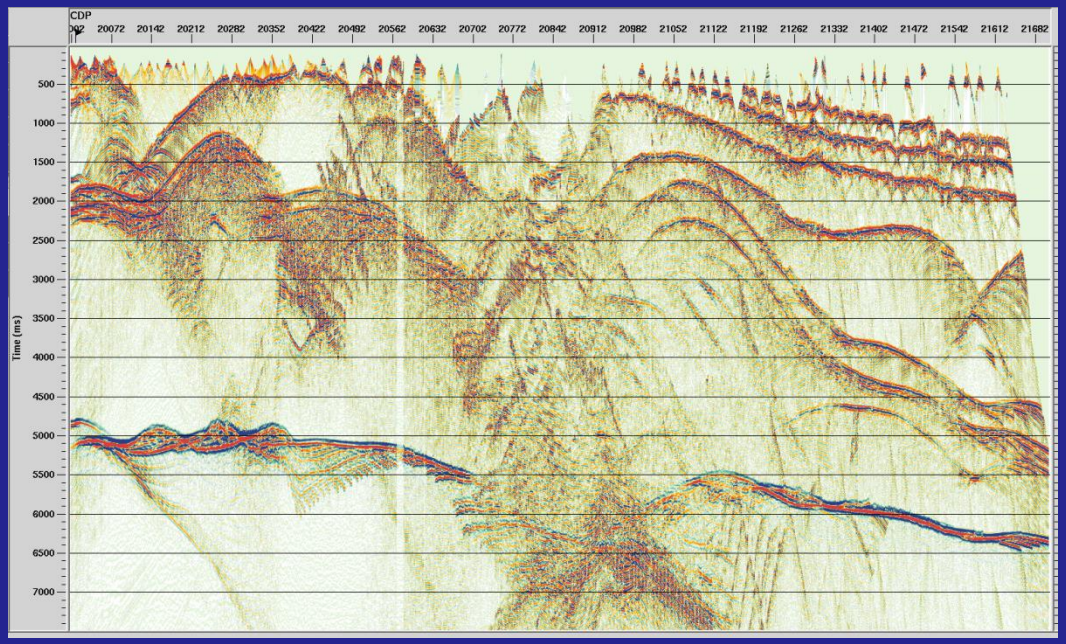
Bocin et al., 2009

Danube **A**nd **C**arpathian **I**ntegrated **A**ction on **P**rocesses in the **L**ithosphere **A**nd **N**eotectonics (**DACIA-PLAN**)

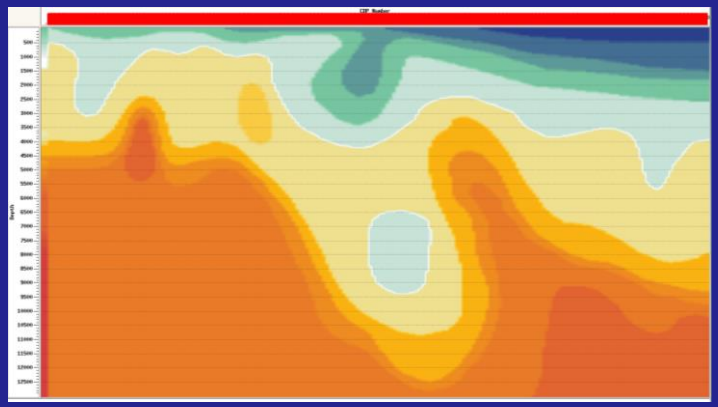
Use the finite-difference modeling to obtain a seismic image over the south-eastern Carpathians



Geological map showing the segment of DACIA-PLAN involved in modeling (red line)



Un-migrated section obtained after the processing of modeled data



Interval velocities in depth used in finite-difference modeling

Summary/conclusions

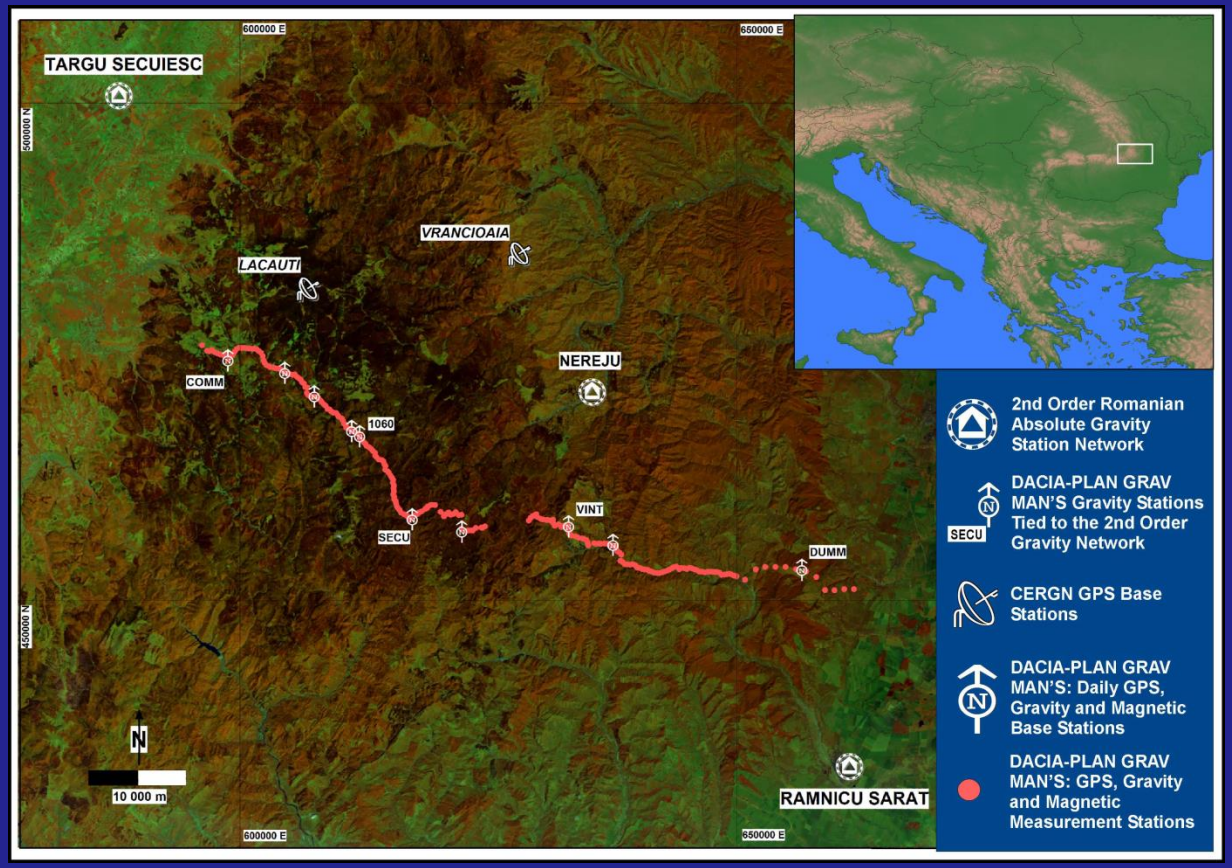
- **pre-Tertiary basement in the Vrancea Zone is involved in Carpathian thrusting and is significantly shallower (<5 km) than previously thought, with post-thrusting basement uplift**

- **a thick rift-like sedimentary basin "opening" to the west underlies the external Carpathian nappes, in a depth range (10-25 km) coincident with crustal depth Vrancea Zone hypocentres**

- **continental crust of European affinity extends at least as far west as the external Carpathian nappes, the contact with the (Moesian) crustal segment to the west; the crustal-scale strike-slip boundary implies emplacement prior to and structural control on Alpine-Carpathian tectonics and present-day seismicity**

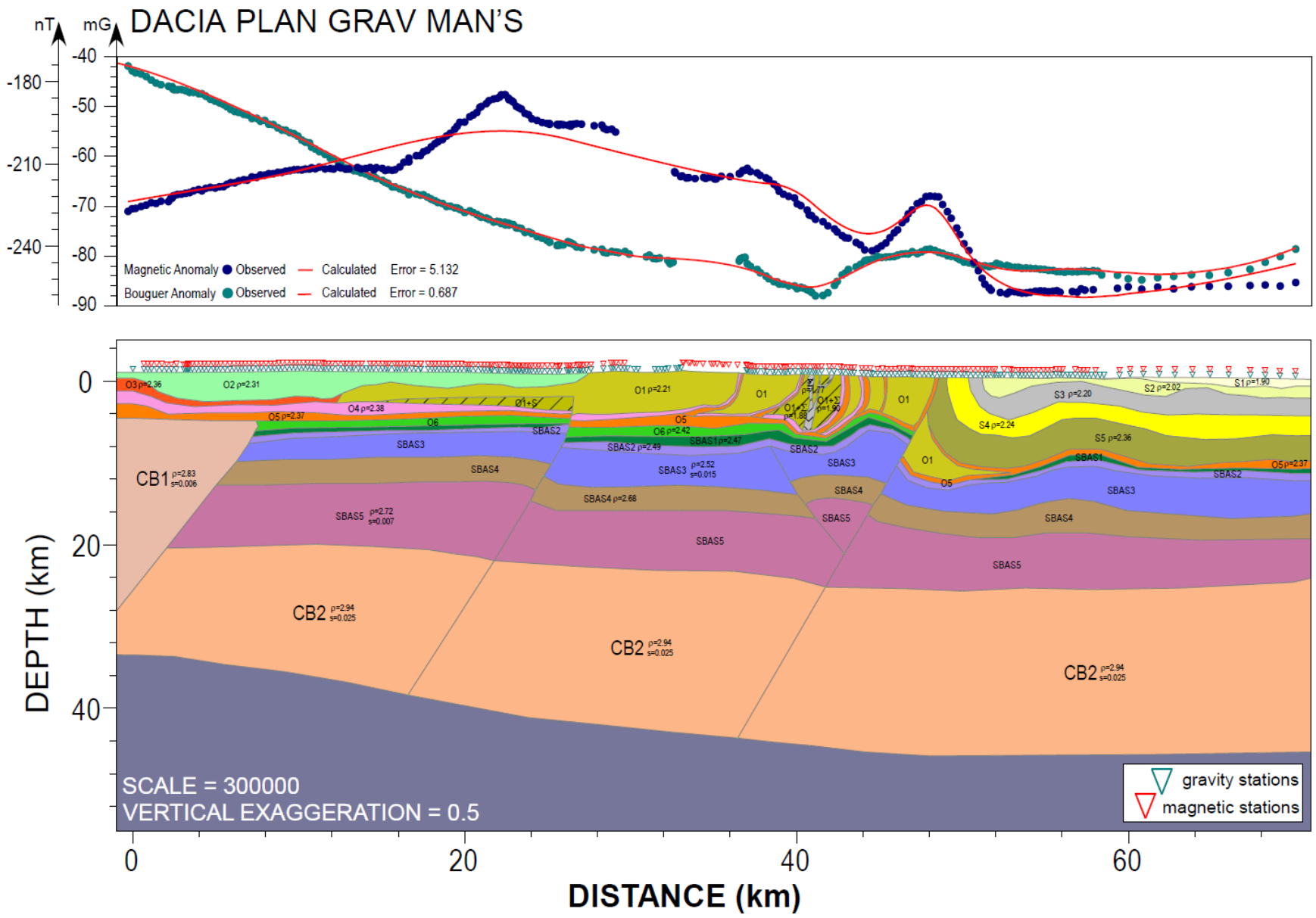
Vrancea Zone

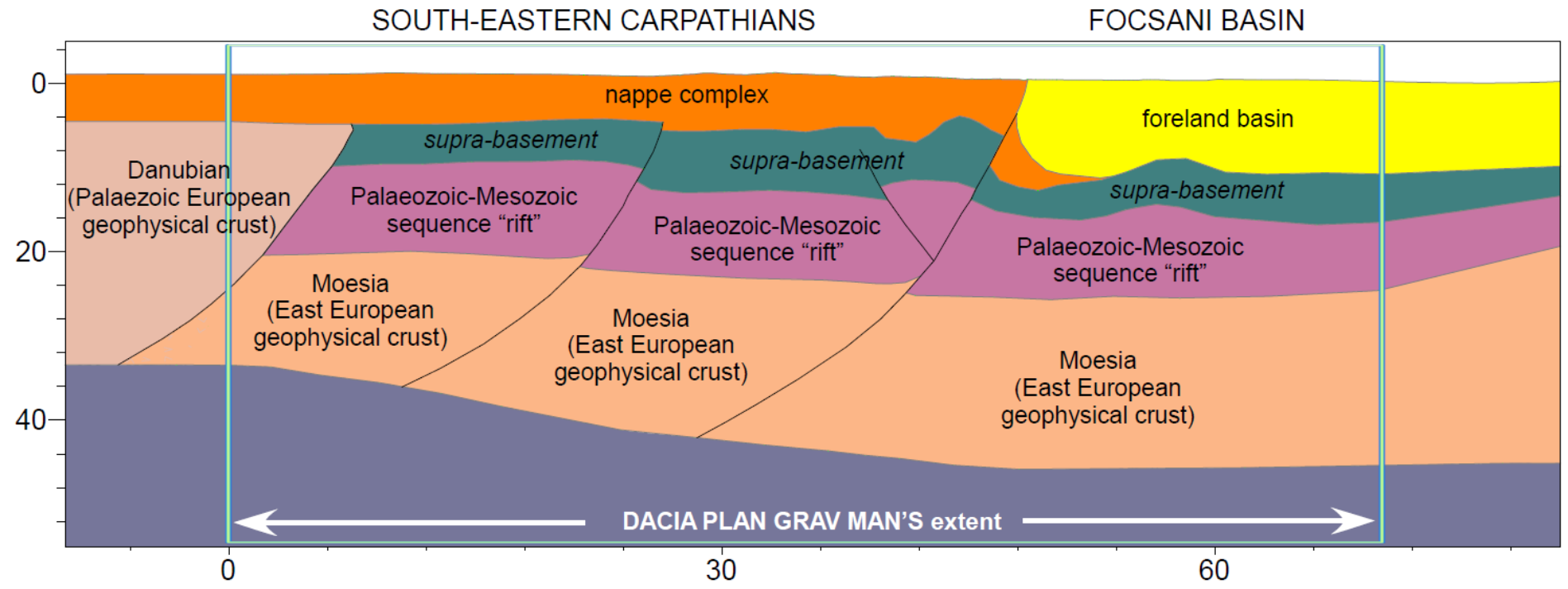
Magnetic/gravity models (preliminary)

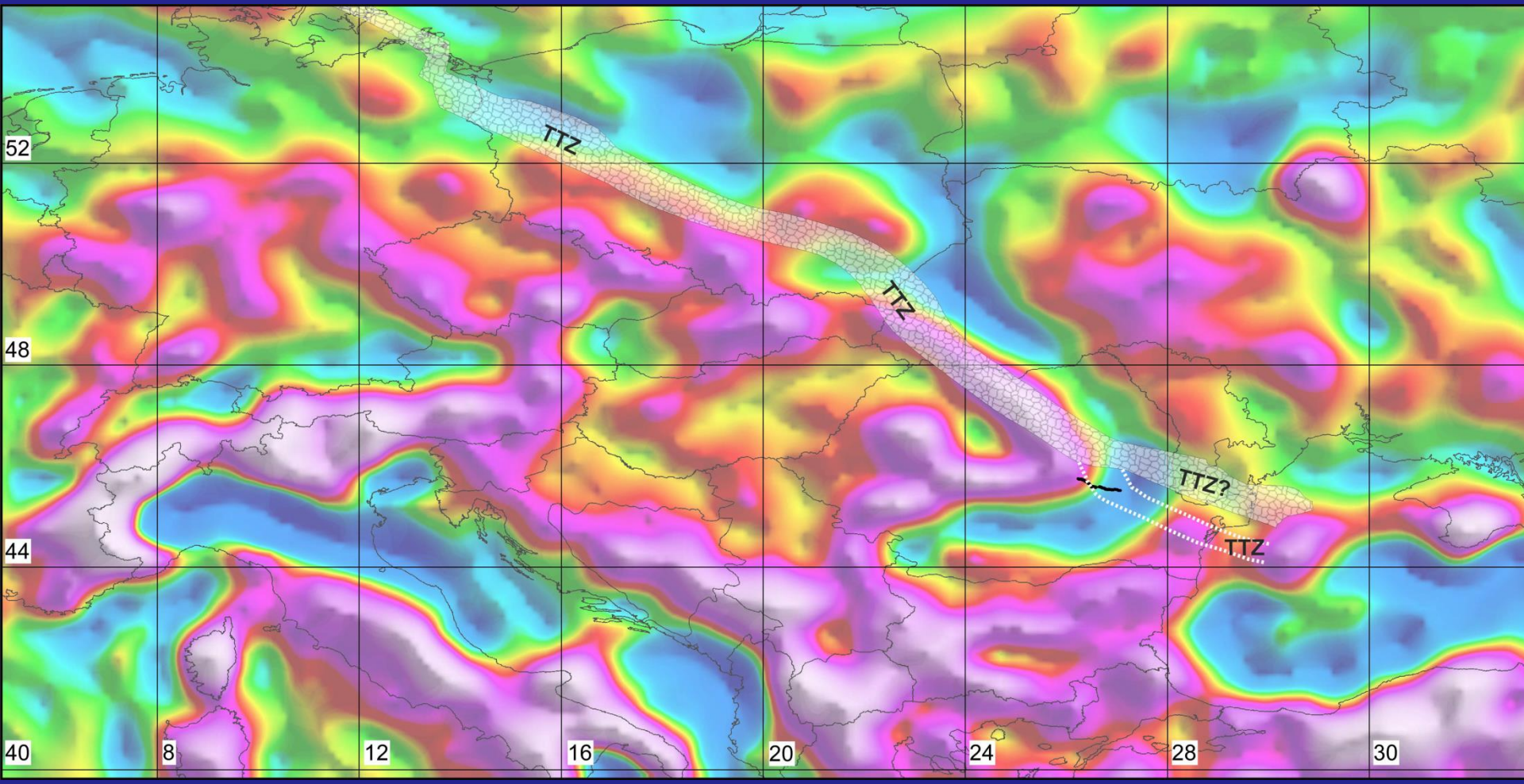


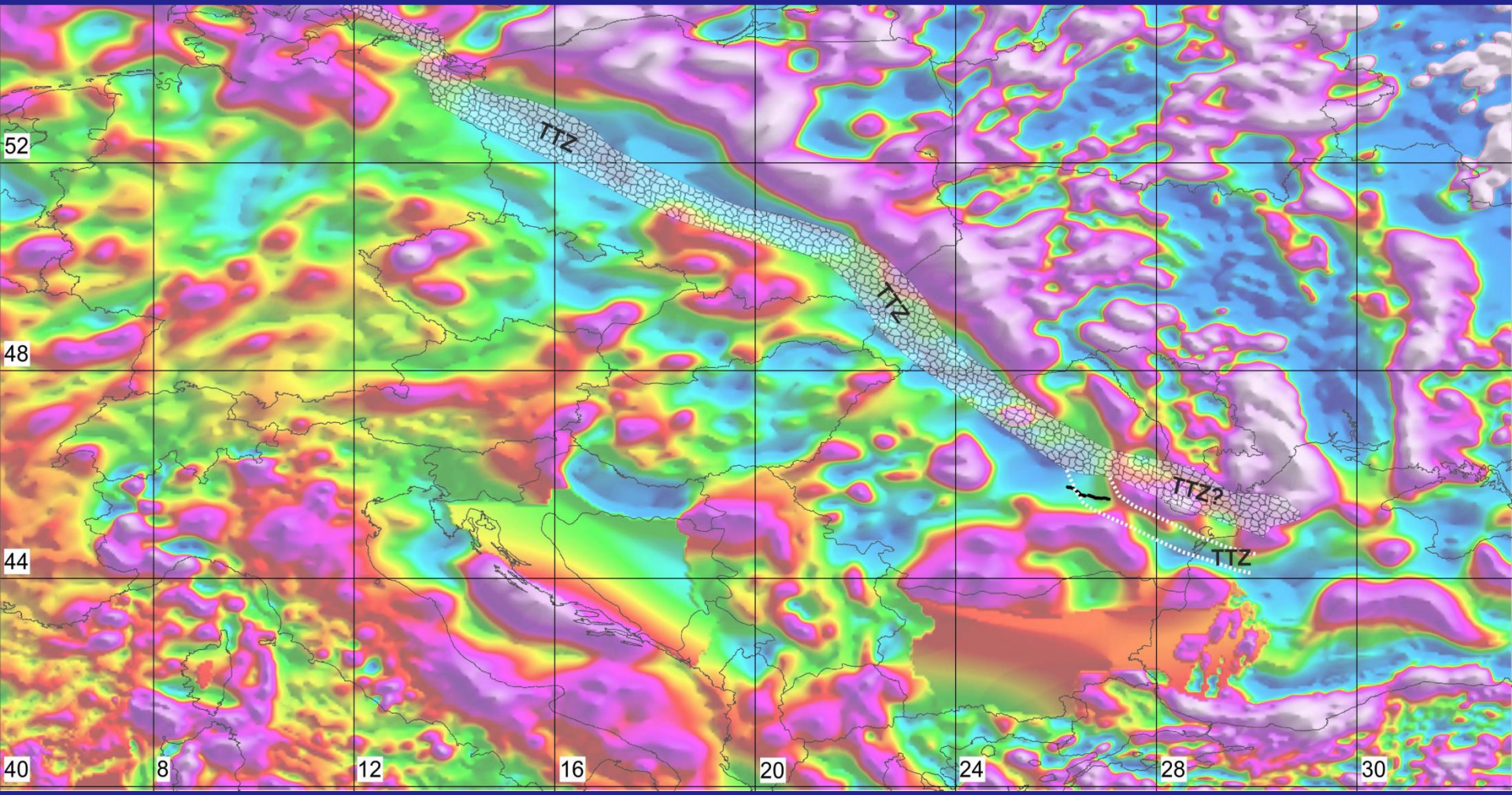
- velocity model (refraction)
  - structural model
  - geology
- reflection seismic
- Euler deconvolution

- change of crystalline basement affinity

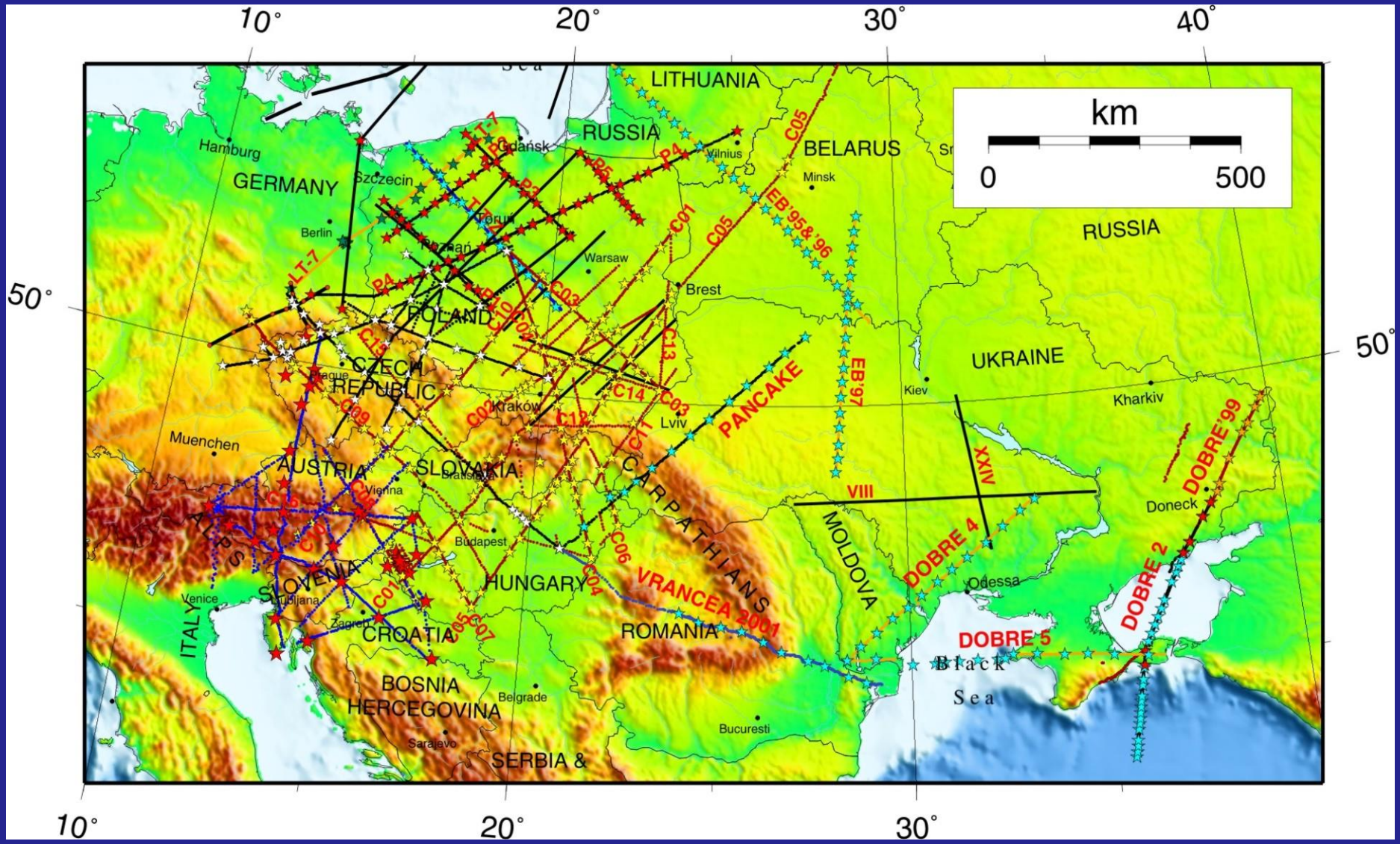

DACIA PLAN GRAV MAN'S
nT
mG
-180
-210
-240
-40
-50
-60
-70
-80
-90
Magnetic Anomaly Observed Calculated Error = 5.132
Bouguer Anomaly Observed Calculated Error = 0.687
DEPTH (km)
0
20
40
CB1 ρ=2.83 s=0.006
CB2 ρ=2.94 s=0.025
SBAS1 ρ=2.47
SBAS2 ρ=2.49
SBAS3 ρ=2.52 s=0.015
SBAS4 ρ=2.68
SBAS5 ρ=2.72 s=0.007
O1 ρ=2.21
O2 ρ=2.31
O3 ρ=2.36
O4 ρ=2.38
O5 ρ=2.37
O6 ρ=2.42
S1 ρ=1.90
S2 ρ=2.02
S3 ρ=2.20
S4 ρ=2.24
S5 ρ=2.36
SCALE = 300000
VERTICAL EXAGGERATION = 0.5
gravity stations
magnetic stations
0
20
40
60
DISTANCE (km)

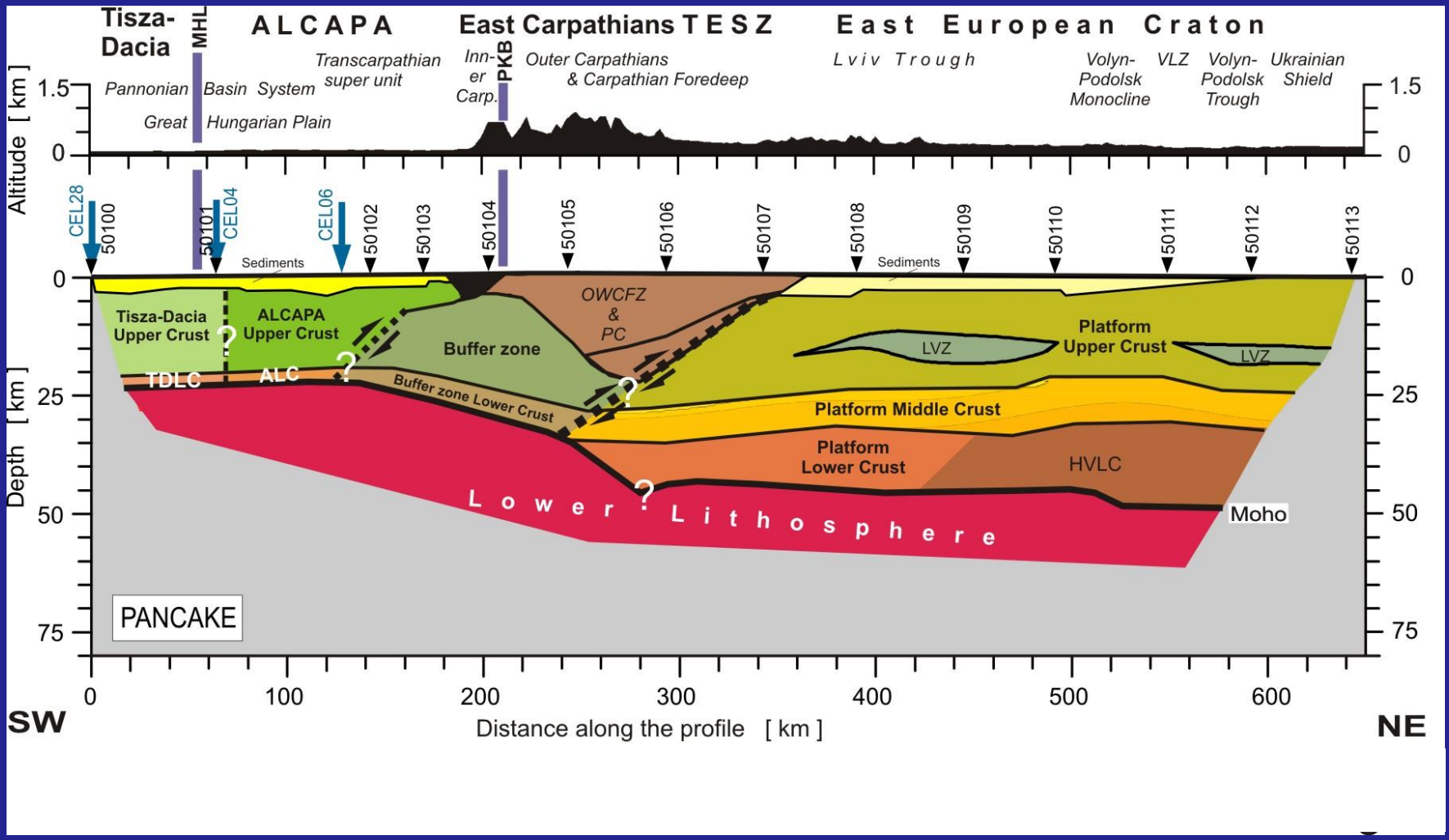

SOUTH-EASTERN CARPATHIANS
FOCSANI BASIN
0
20
40
nappe complex
foreland basin
supra-basement
supra-basement
supra-basement
Danubian
(Palaezoic European
geophysical crust)
Palaeozoic-Mesozoic
sequence "rift"
Palaeozoic-Mesozoic
sequence "rift"
Palaeozoic-Mesozoic
sequence "rift"
Moesia
(East European
geophysical crust)
Moesia
(East European
geophysical crust)
Moesia
(East European
geophysical crust)
DACIA PLAN GRAV MAN'S extent
0
30
60


TTZ
TTZ
TTZ?
TTZ
52
48
44
40
8
12
16
20
24
28
30


TTZ
TTZ
TTZ?
TTZ
52
48
44
40
8
12
16
20
24
28
30

Central European WARR (Wide-Angle Refraction and Reflection) profiles since ~1990





Simplified sketch of the crustal structure along the PANCAKE profile developed by forward ray tracing, with tectonic interpretation (Starostenko et al., 2013)

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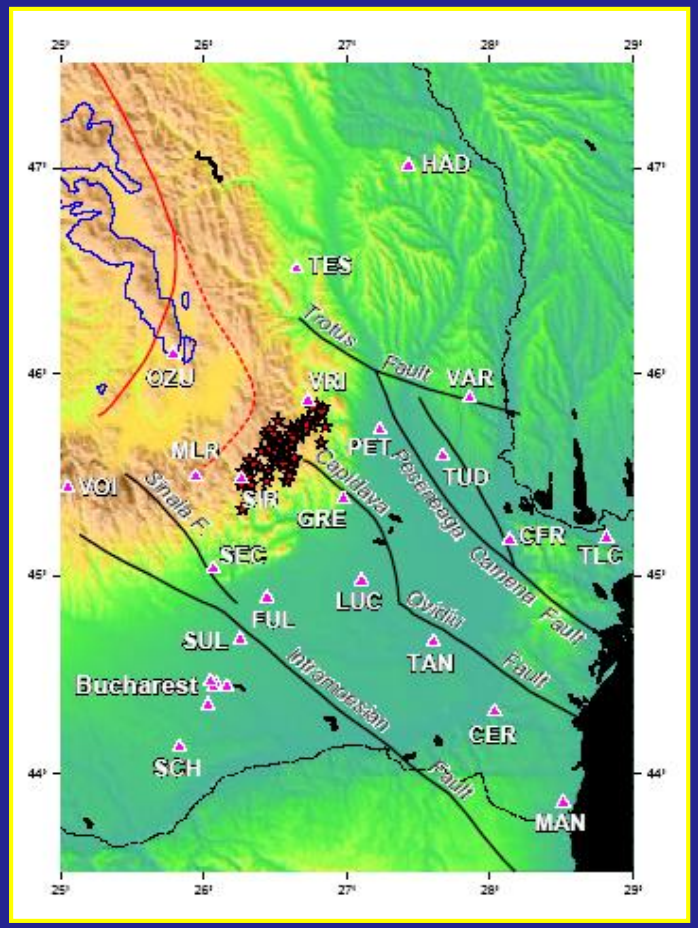
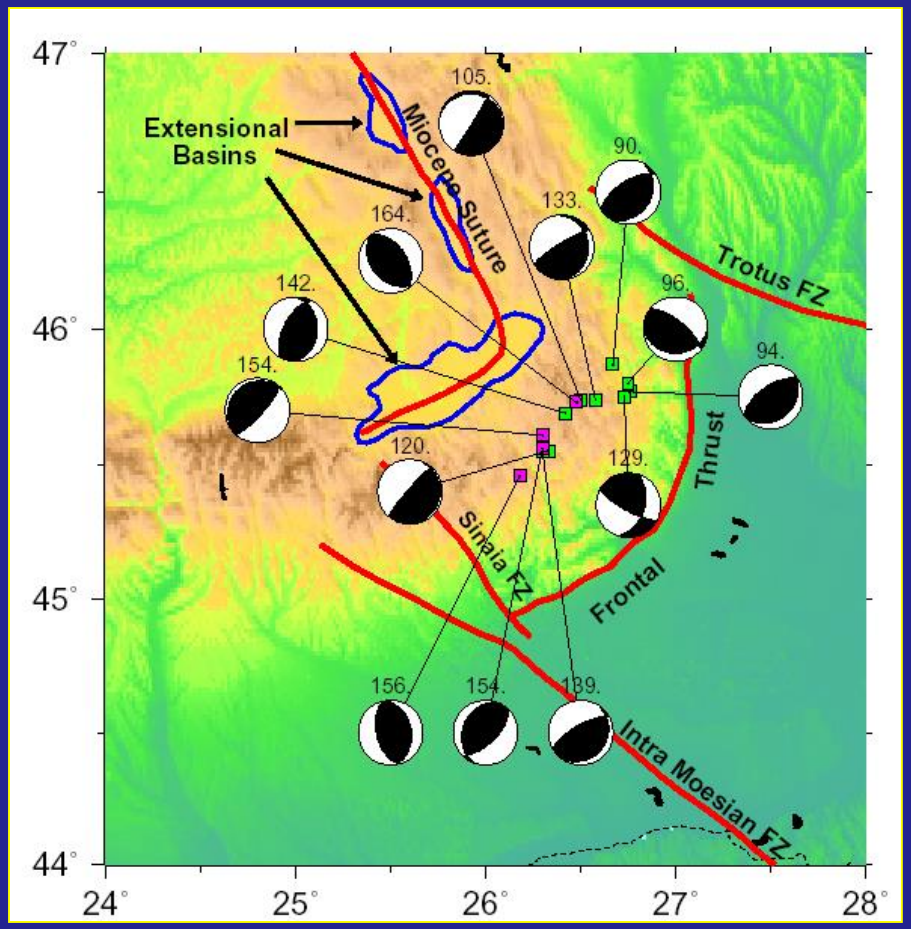
SEISMIC ATTENUATION



Stars: 51 Vracea Zone earthquakes (plus 2 outside Zone) that were focused innitialy Recorded by 10 or more stations of the Romanian National Seismic Network between May 1999 and Nov.2001. Representative of seismicity of Vrancea. More events will be available during the proposed work and will be used also. Time period includes events recorded by temporary CALIXTO network

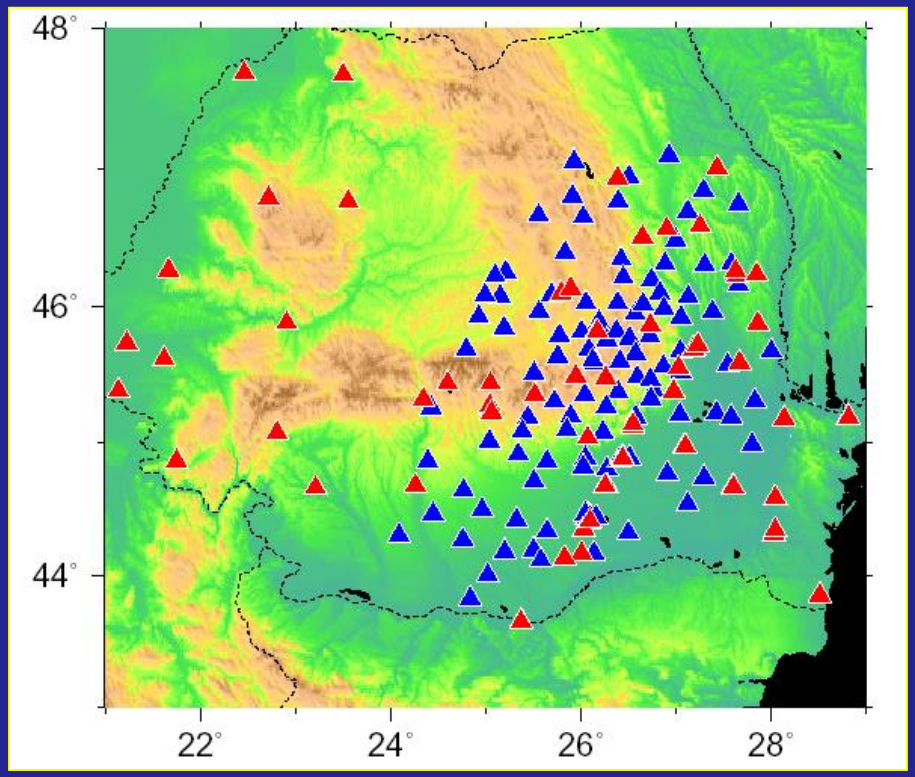
SEISMIC ATTENUATION



Harvard CMT focal mechanisms (1977-2001) for events within the study area. Centroid depths (km) are numbers next to beach balls.

These and other mechanisms for Vrancea earthquakes clearly indicate sinking into mantle (steeply plunging T axes) of tabular body striking around NE-SW and dipping steeply NW or vertical (Hauser et al., 2001). Variability of mechanism P axes is marked, although they plunge shallowly. Mechanisms for several events at NE and SE edges of Vrancea seismcity could mark boundaries of the ‘slab’, and the body itself may be segmented into slivers by steep or vertical NW-SE striking faults.

SEISMIC ATTENUATION



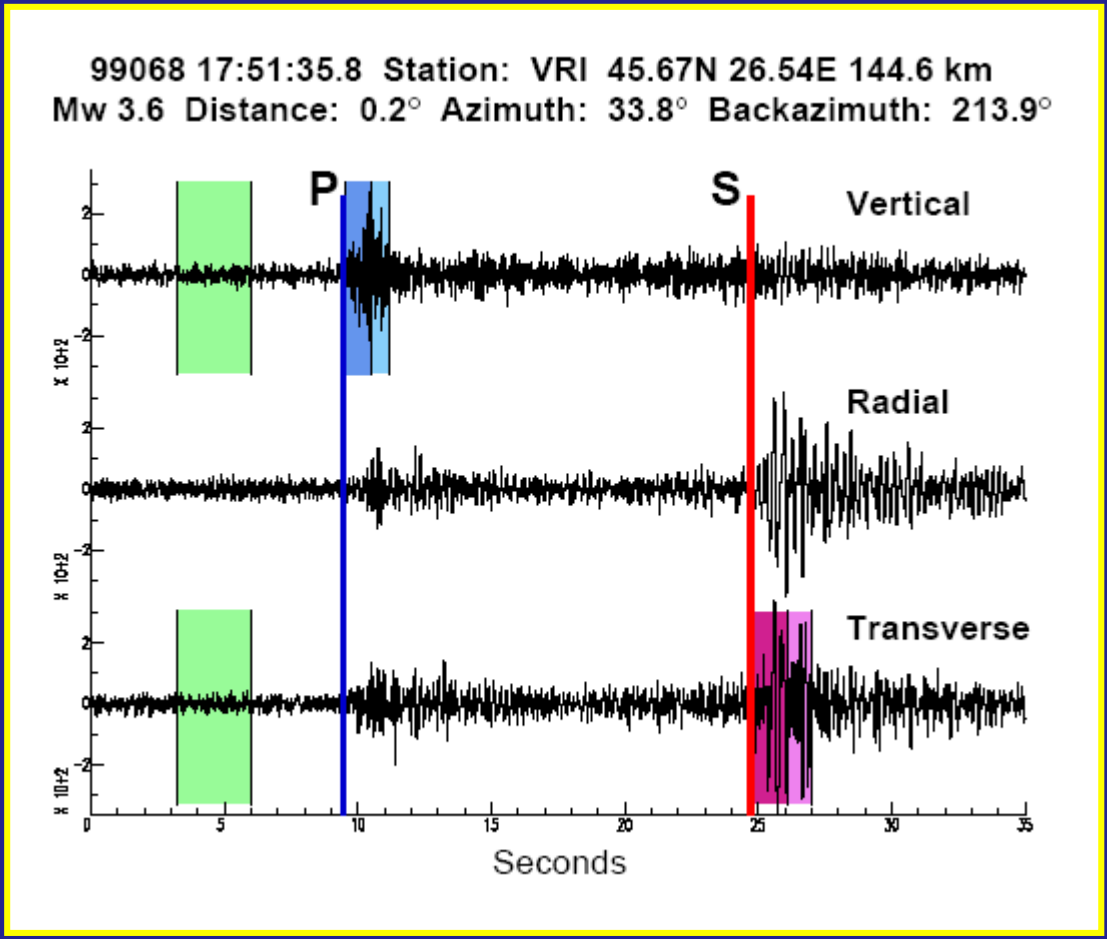
Stations used in the proposed Q studies.

Purple triangles are stations of the Romanian National Seismic Network and the joint German- Romanian K2 Network.

Blue triangles are stations of the CALIXTO temporary seismic deployment (one year).

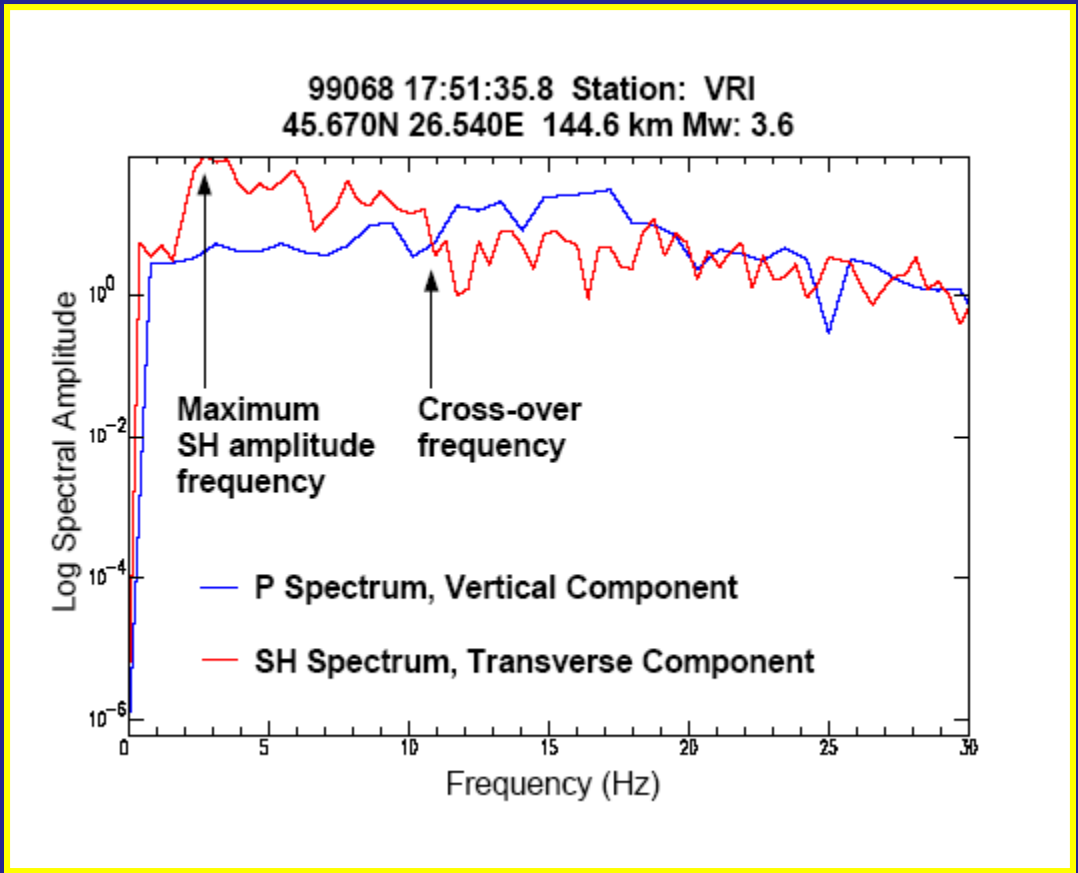
Excellent station coverage over the Carpathian bend zone and surroundings.

SEISMIC ATTENUATION



Typical seismogram recorded at VRI. P and S waves clearly recorded with good signal/noise.

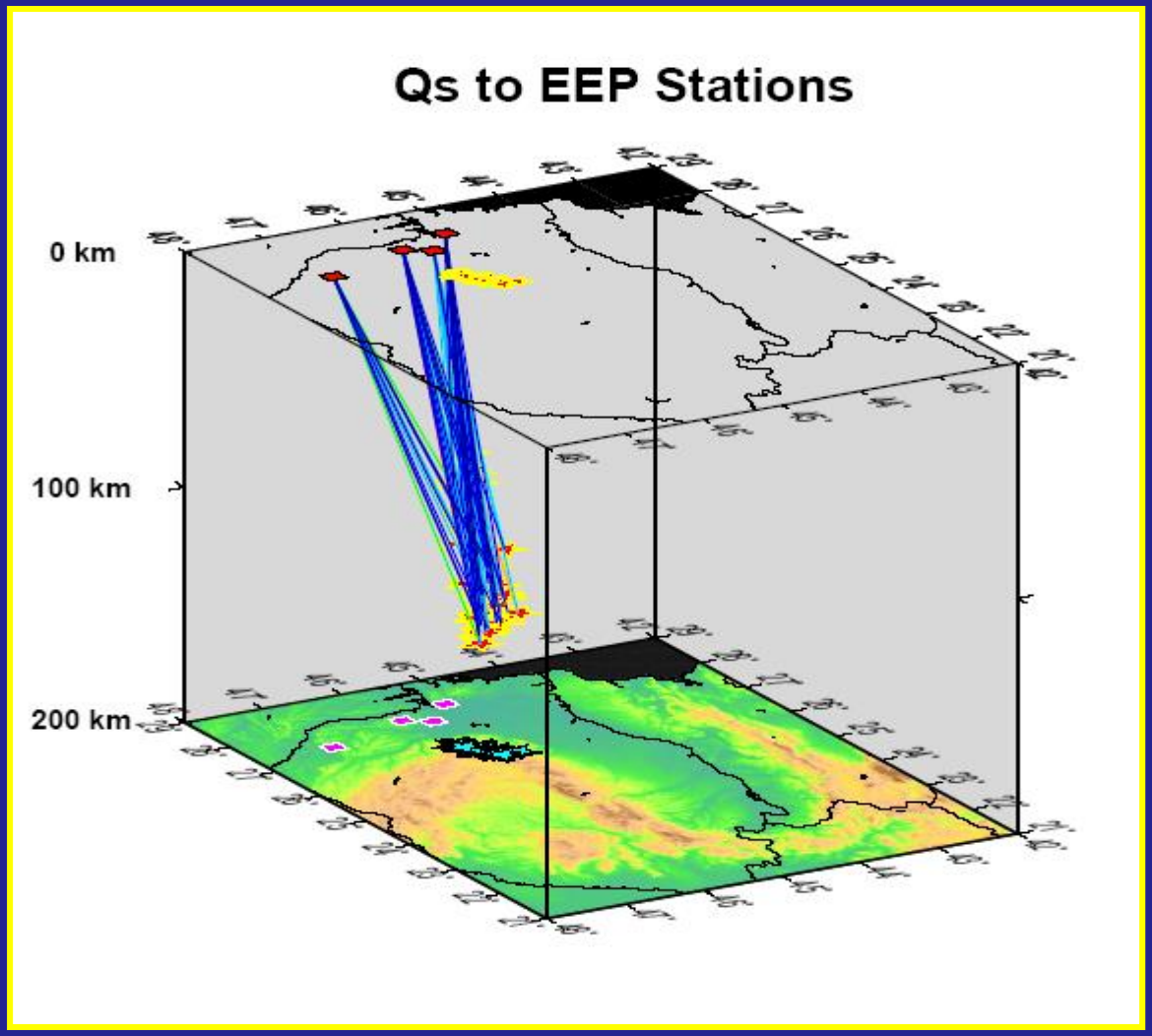
SEISMIC ATTENUATION



Log spectral amplitude of P and S waves plotted vs frequency

The cross over frequency of the S amplitude spectrum with respect to the P spectrum = a limit of estimation of spectral slope in the calculation of t* and Qs.

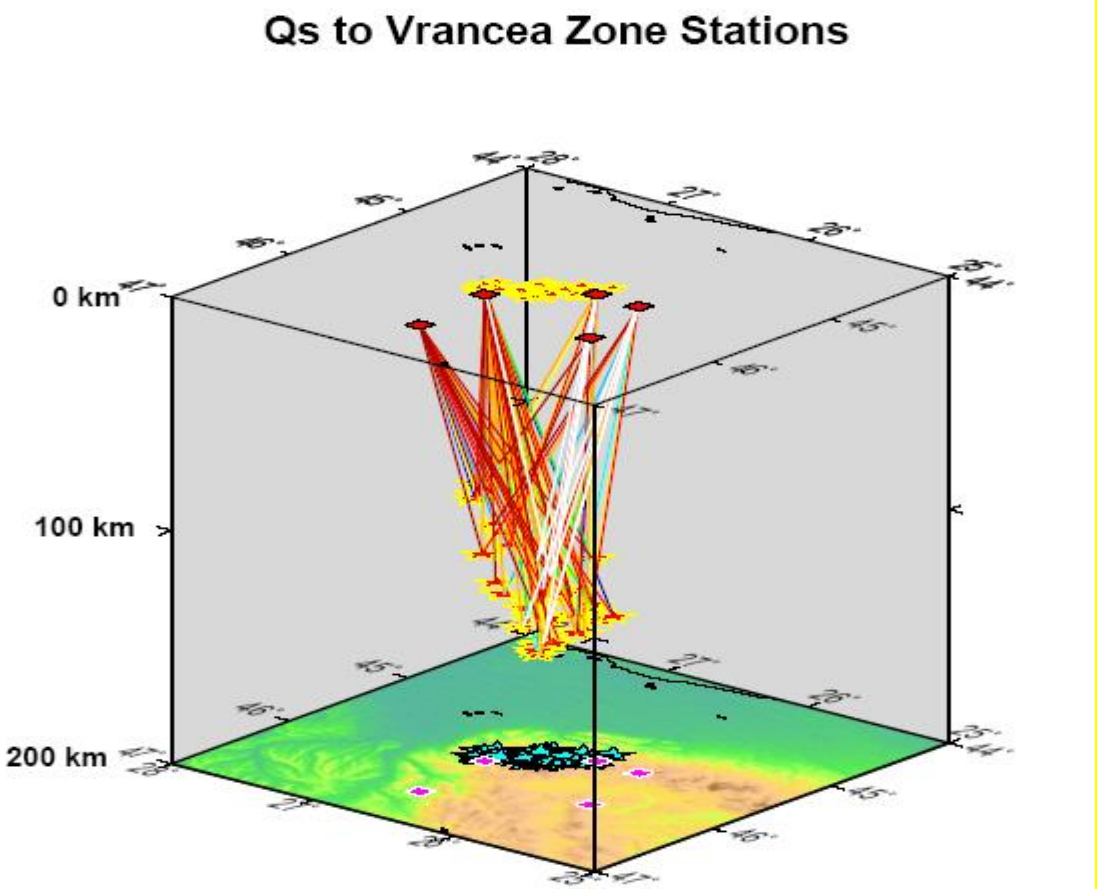
SEISMIC ATTENUATION



Ray paths from Vrancea zone earthquakes to four stations on two portions of the stable East European Platform, color coded according to the Qs estimates for the event-station pairs. Blue colors are for Qs greater than 500, cyan for 350-500, green for 300-350, yellow for 250-300, orange for 200-250 and red for less than 200. White is for the complete S wave blocking. Note that paths to EEP stations are **consistently low attenuation (high Qs)**, consistent with the cratonic nature of the EEP, both the Moldavian portion north of the Trotus Fault, and the Schythian Platform portion to the south.

Red Q<200 Orange 200<Q< 250 Yellow 250<Q< 300 White = complete S wave blocking
Green 300<Q<350 Cyan 350<Q<500 Blue 500<Q

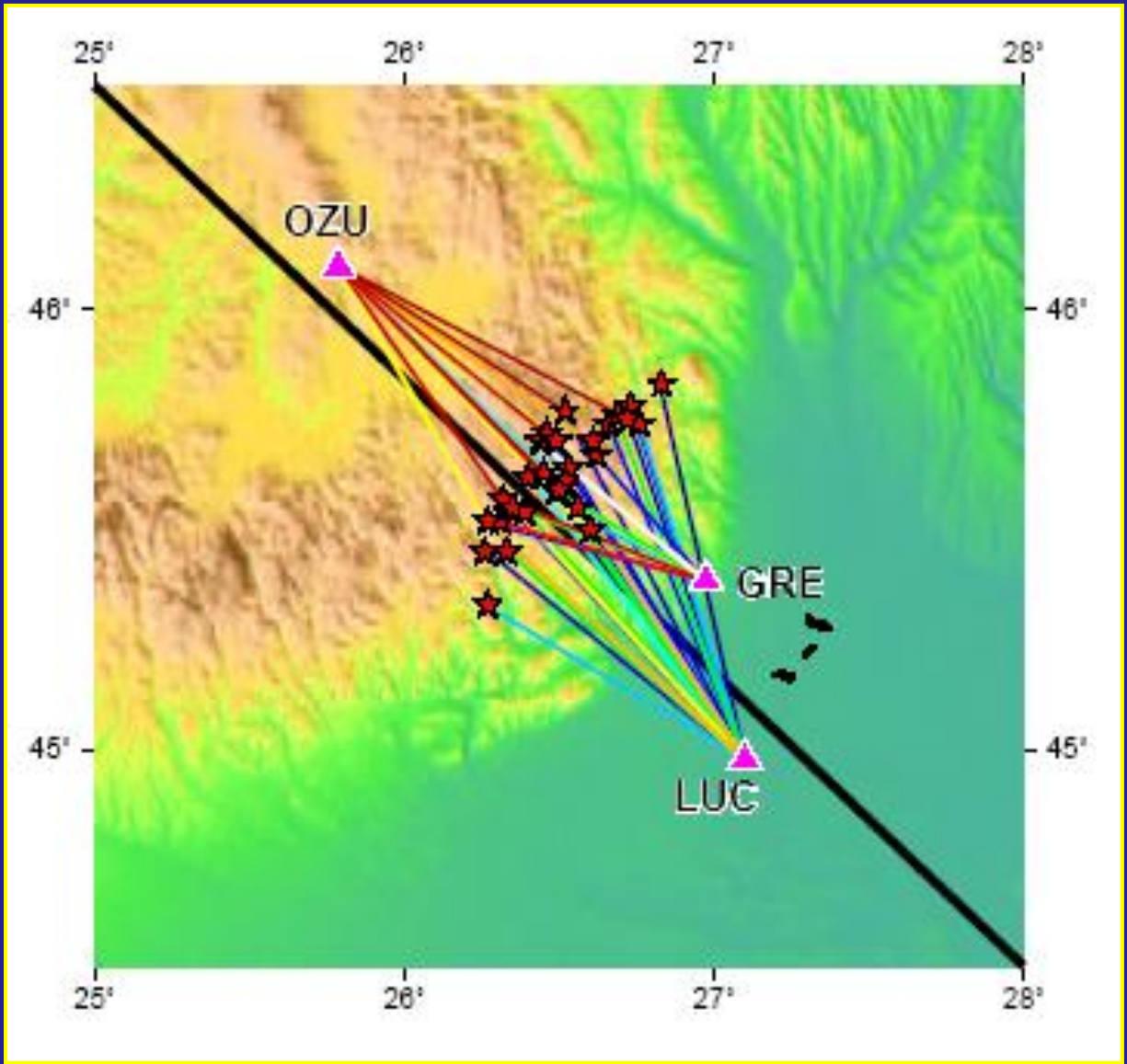
SEISMIC ATTENUATION



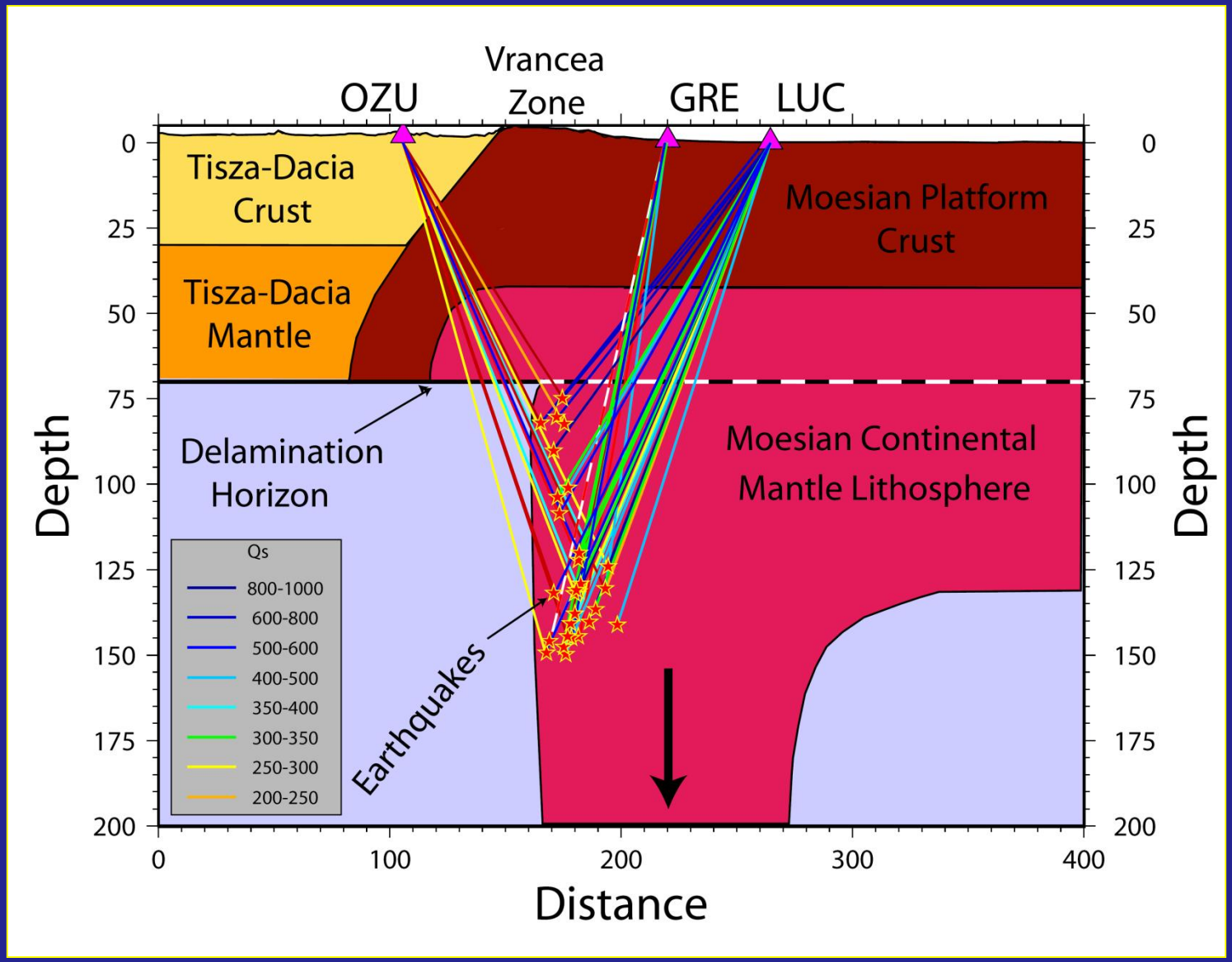
Ray paths from Vrancea zone earthquakes to five stations in the Vrancea zone region, the Carpathian chains or the Transylvanian basin, color coded according to the Qs estimates for the event-station pairs. Note that paths to these stations are **consistently high attenuation (low Qs)**, and note particularly the high frequency of S wave blockage to the stations in the Southern Carpathians and Transylvanian basin. These stations are closest to the most recent volcanic activity in the Carpathian region. High attenuation at these stations confirms the long-term belief, on the basis of surface geology, that the inner Carpathian region could be a back-arc.

Red Q<200 Orange 200<Q< 250 Yellow 250<Q< 300 White = complete S wave blocking
Green 300<Q<350 Cyan 350<Q<500 Blue 500<Q

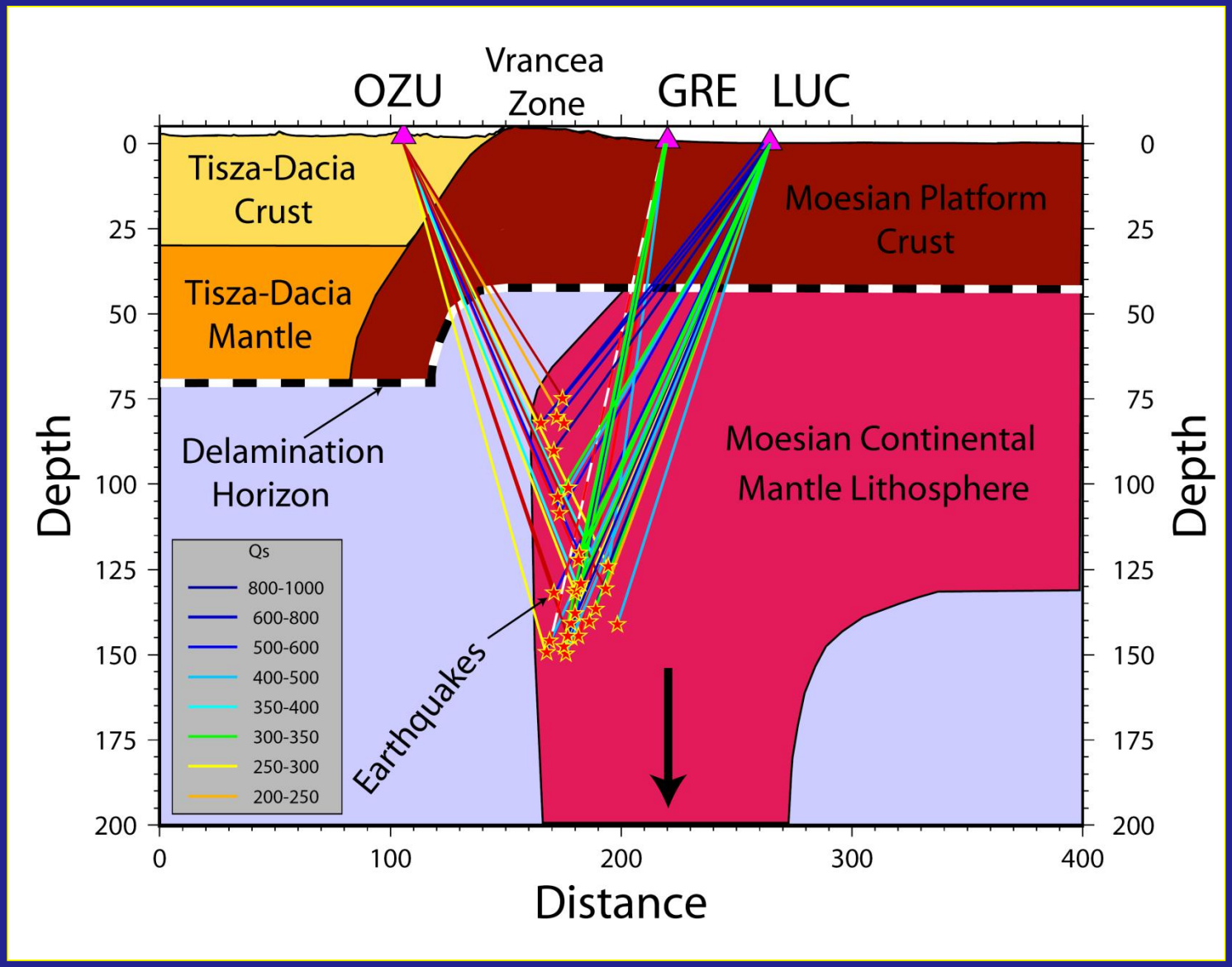
SEISMIC ATTENUATION



SEISMIC ATTENUATION



SEISMIC ATTENUATION



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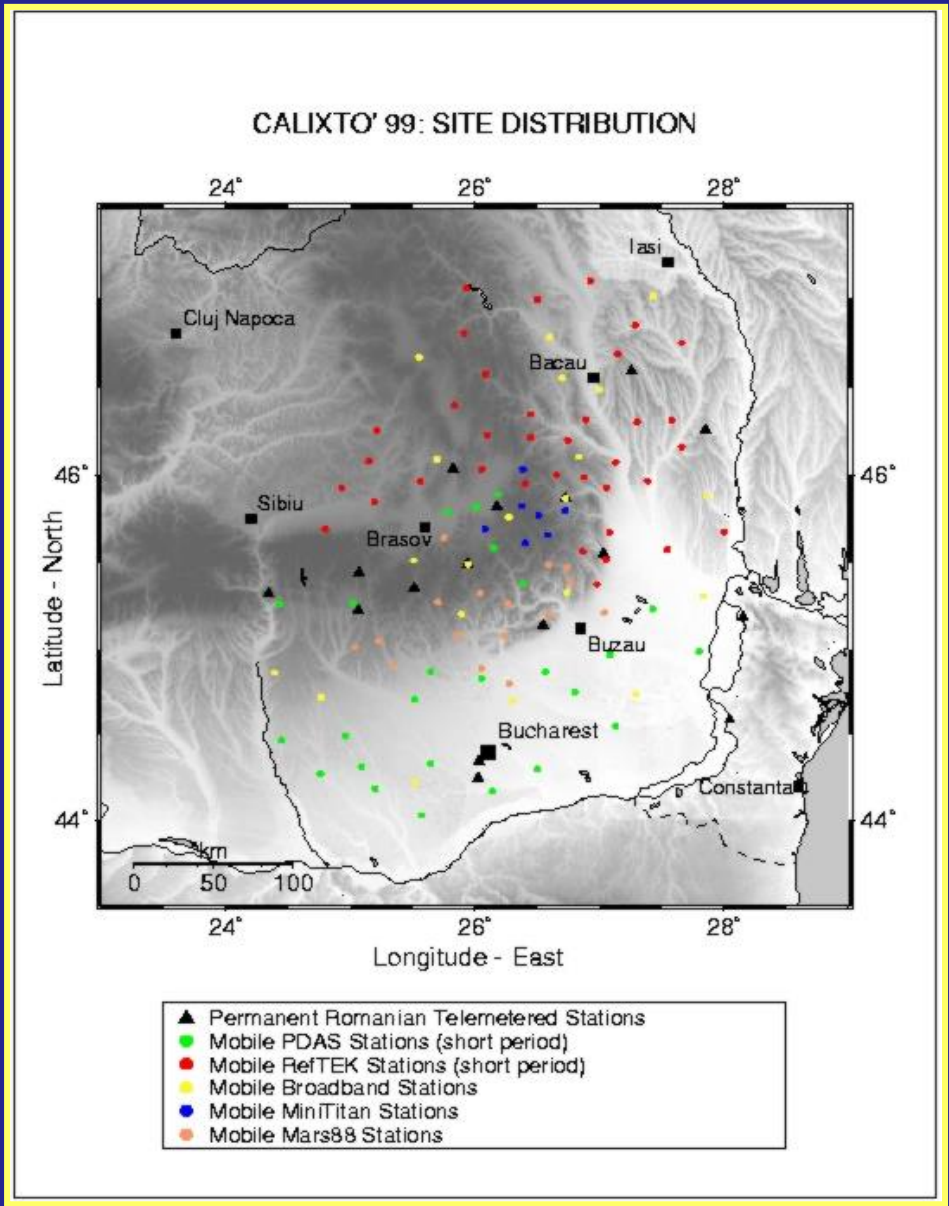
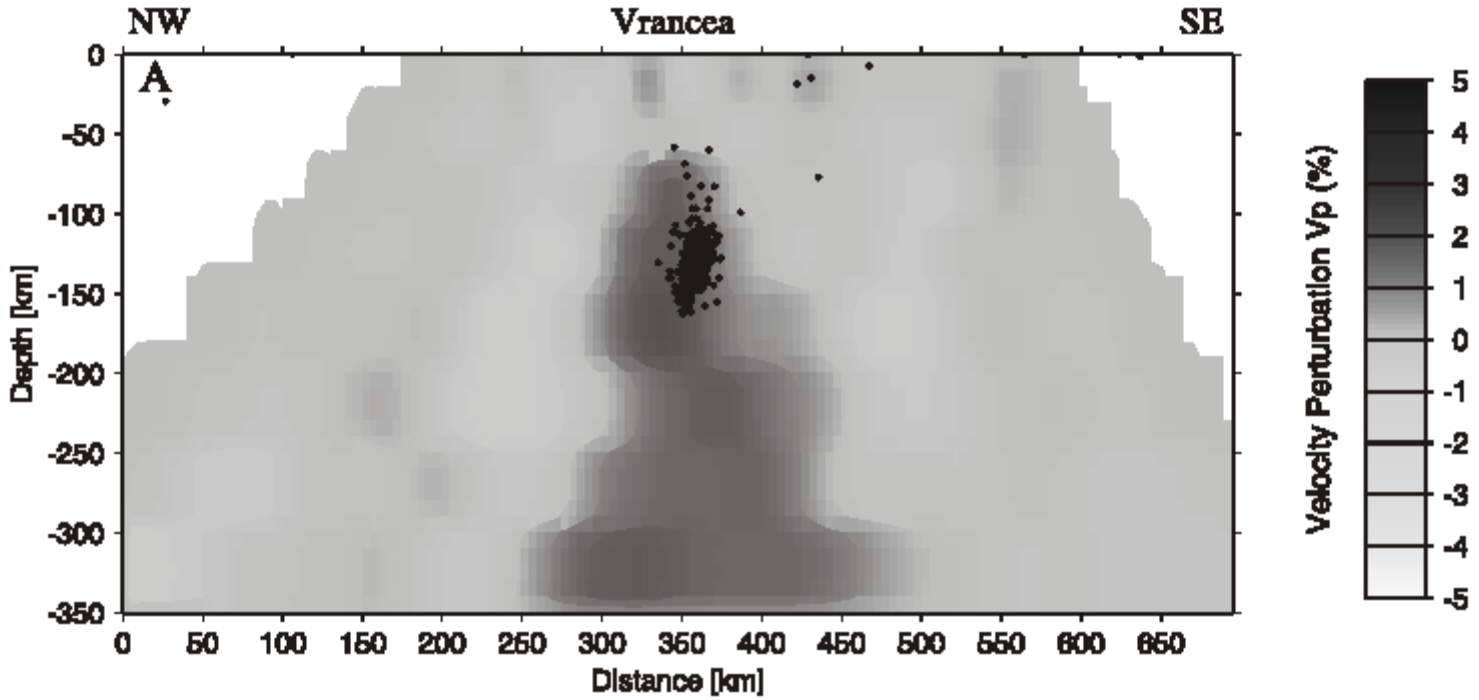
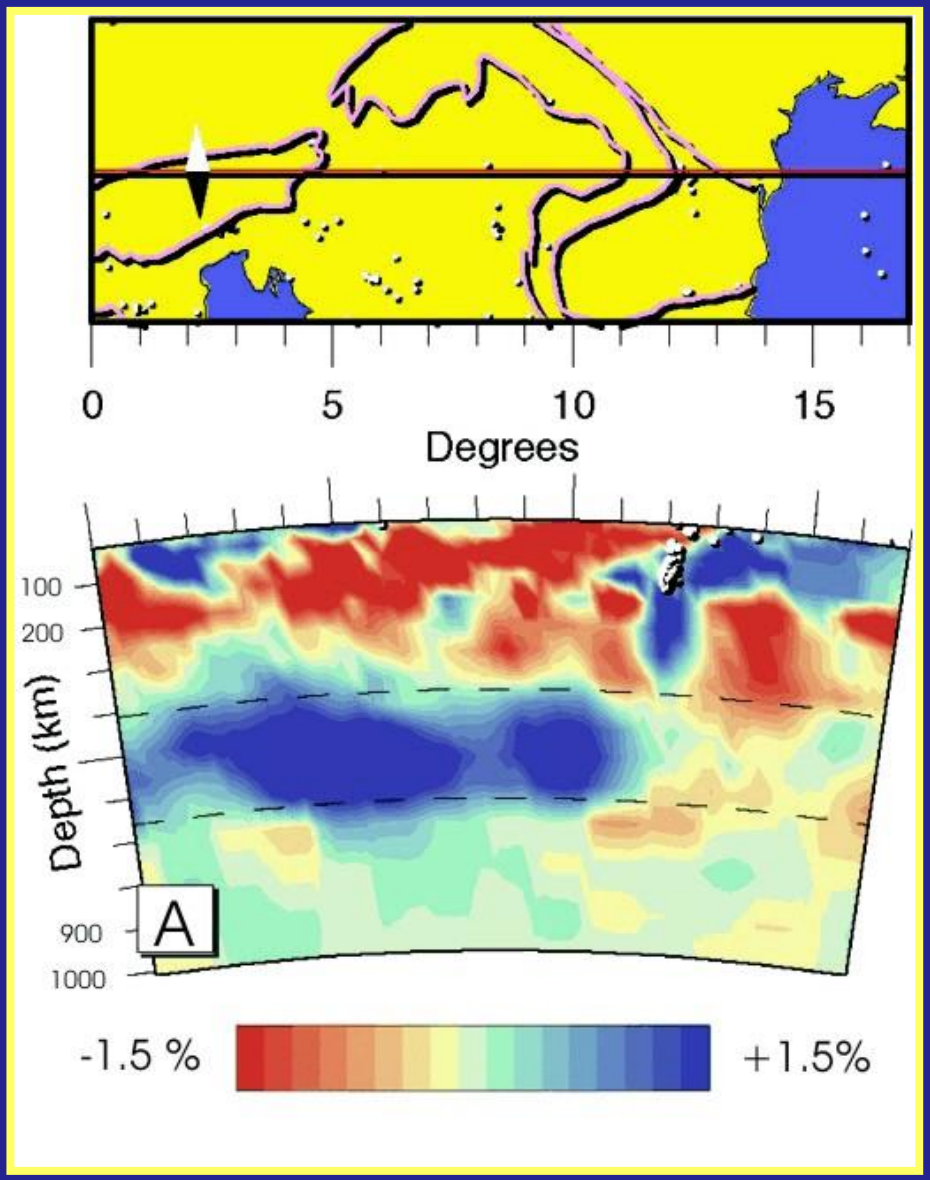
SEISMIC TOMOGRAPHY: CALIXTO



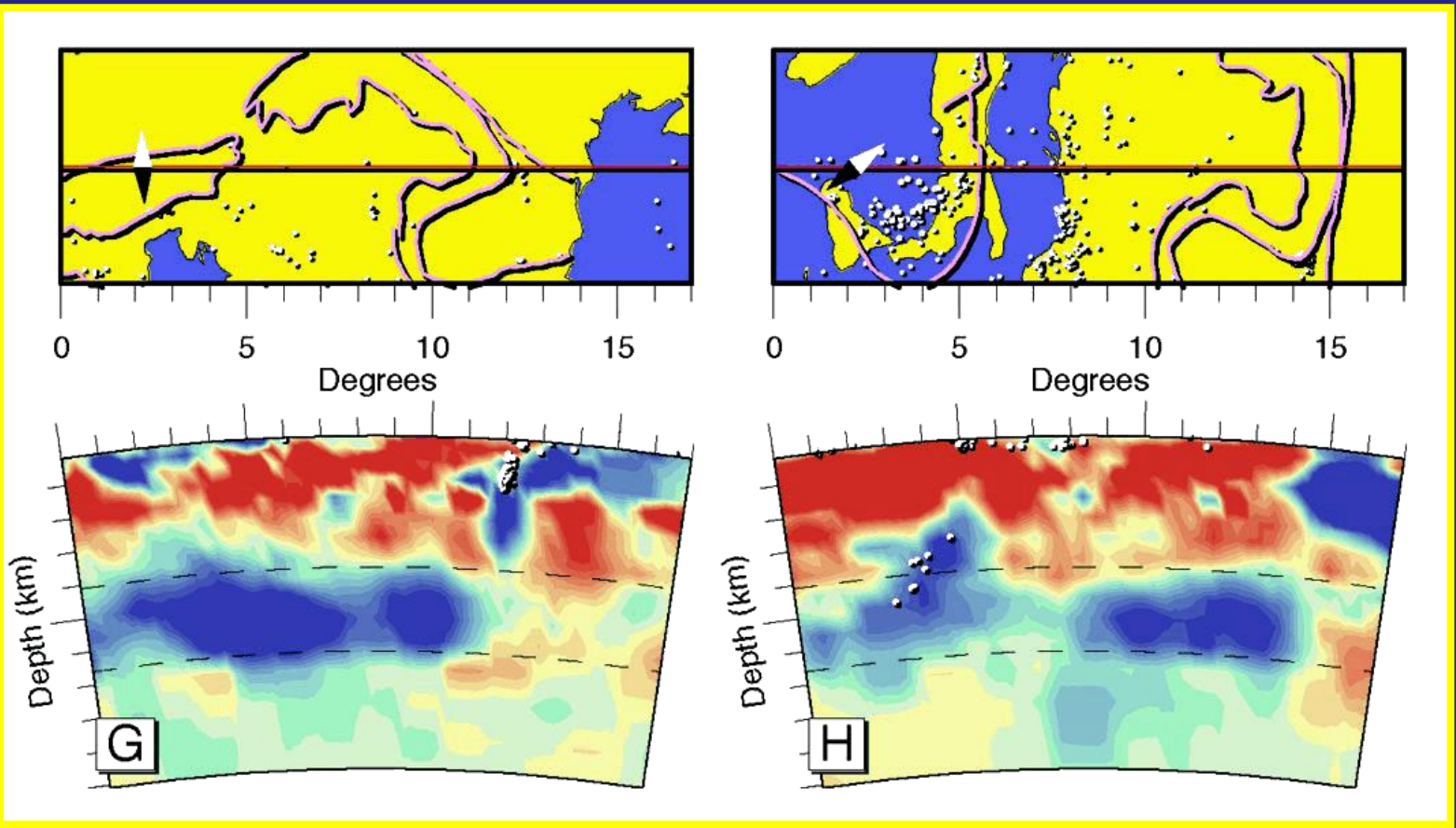
CALIXTO


NW
Vrancea
SE
A
0
-50
-100
-150
-200
-250
-300
-350
Depth [km]
0
50
100
150
200
250
300
350
400
450
500
550
600
650
Distance [km]
Velocity Perturbation Vp (%)
5
4
3
2
1
0
-1
-2
-3
-4
-5

REGIONAL STUDIES (Wortel and Spakman, 2000)



REGIONAL STUDIES (Wortel and Spakman, 2000)



- Almost vertical high-velocity body under Vrancea zone
- Cluster of earthquakes in the upper 150 km of this body
- Body attached to the upper lithosphere/crust ?

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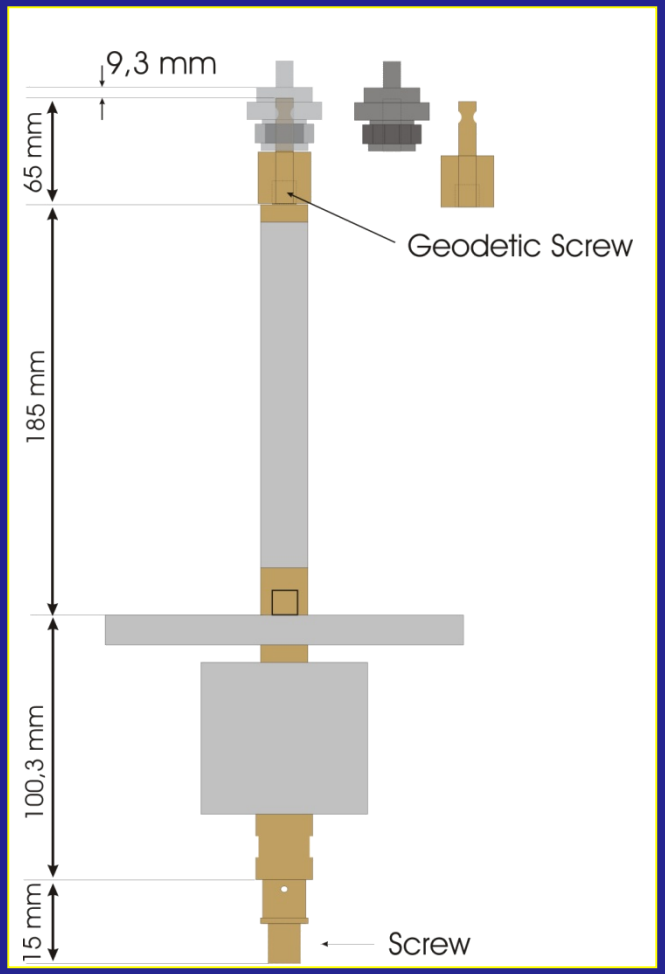
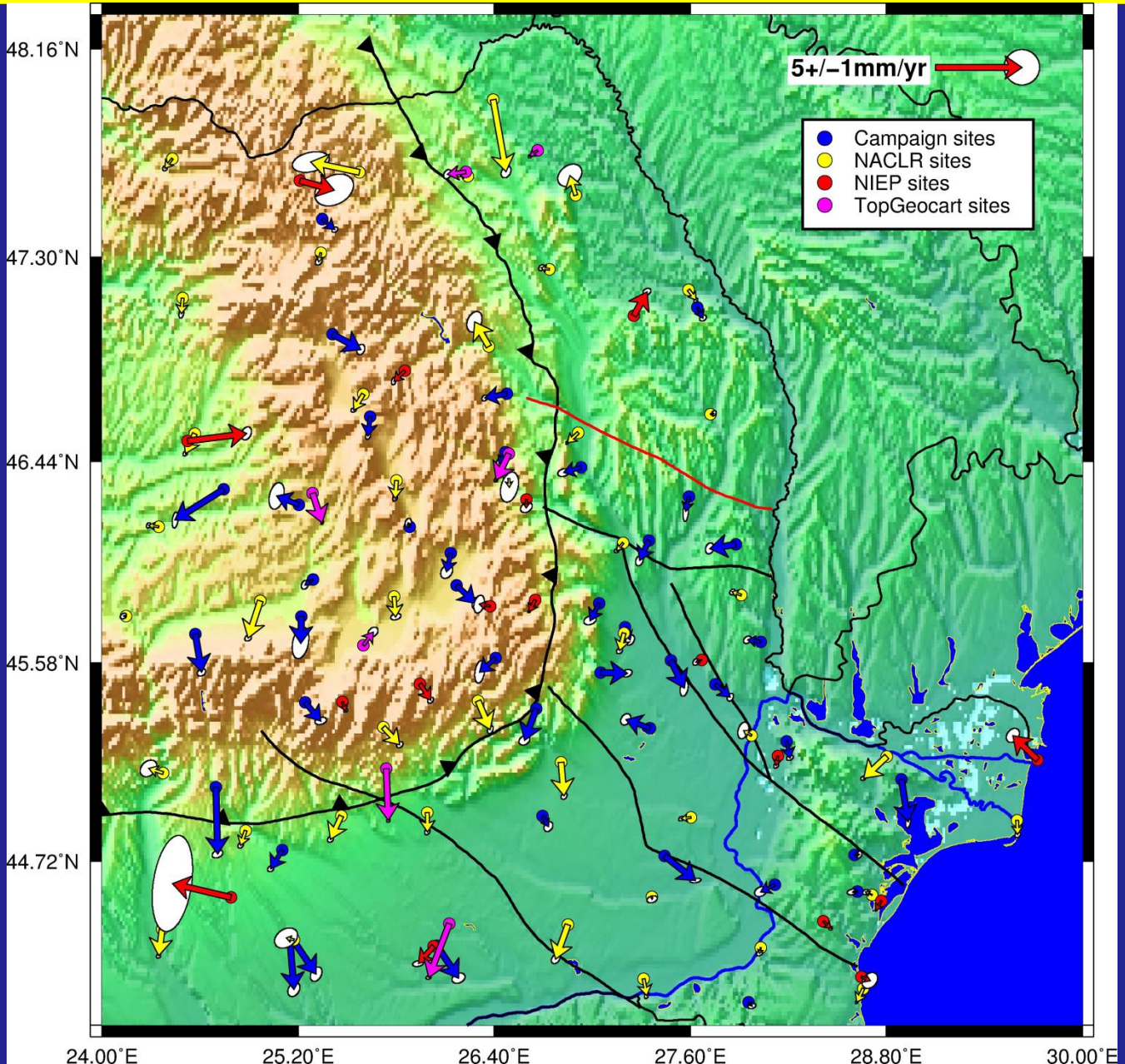
Campaign Measurements

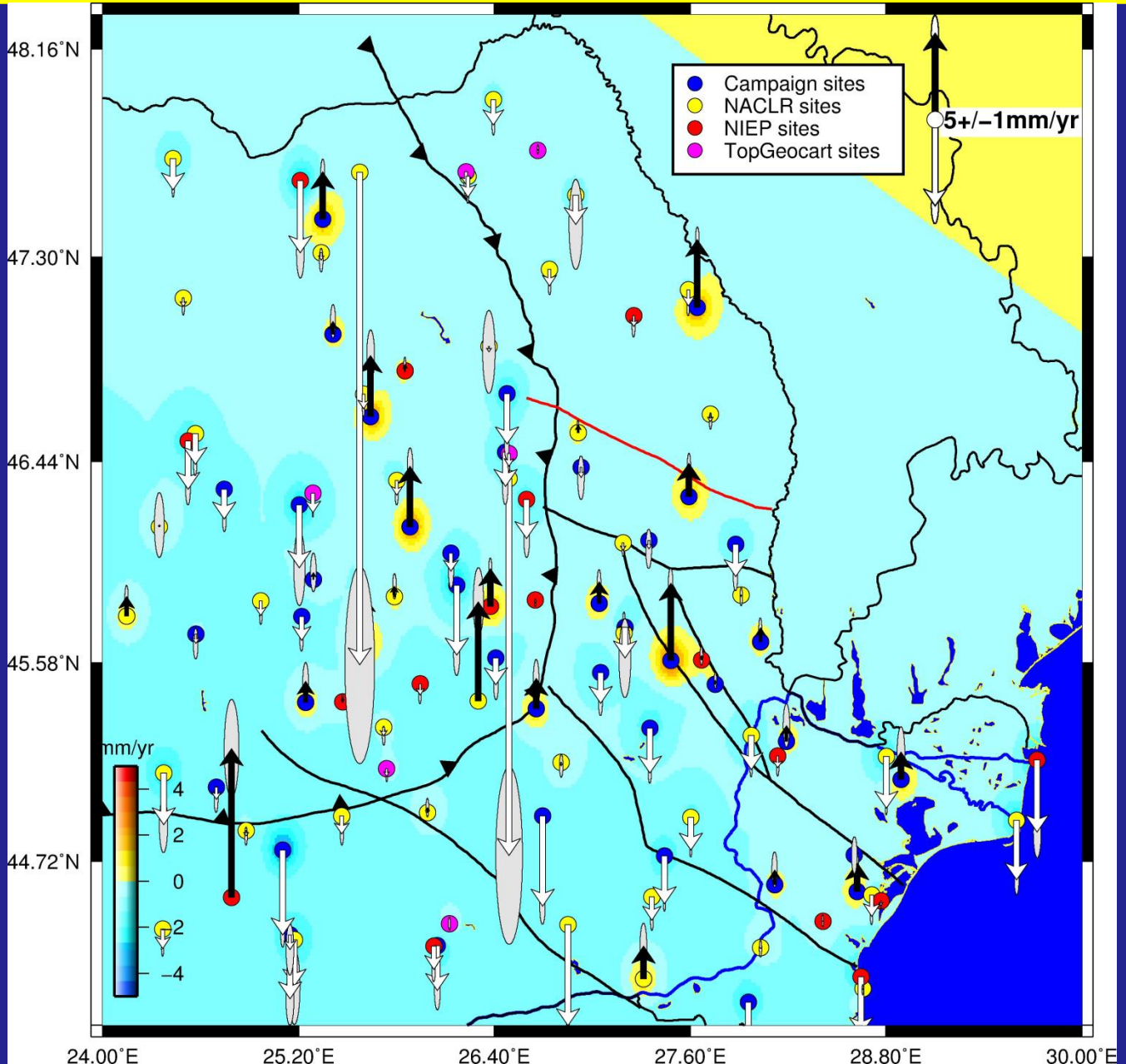


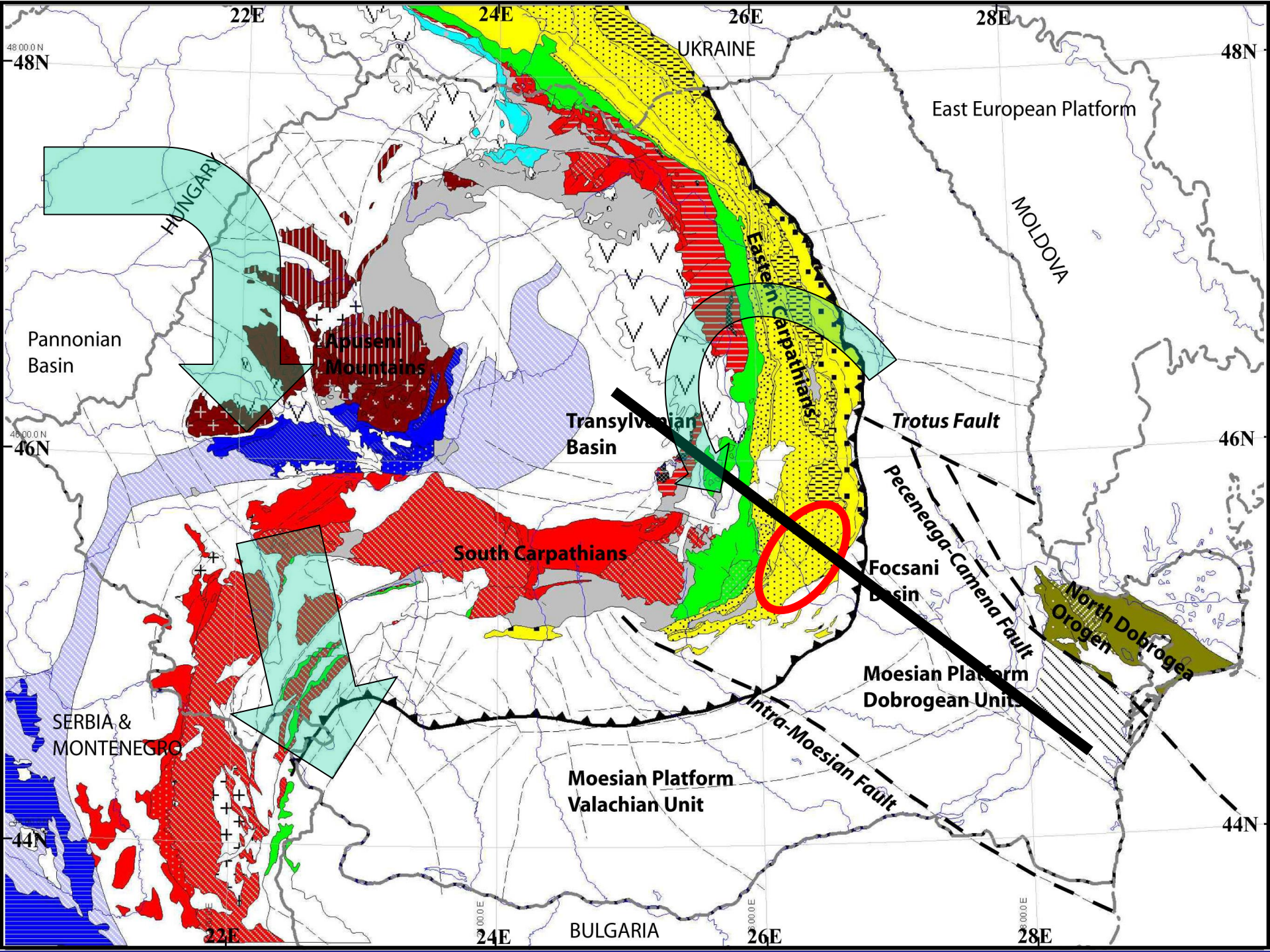
- Leica SR500 series (2002+)
- Performed in ‘short-term’ campaigns (2-4 weeks)
- Some points have history of > 7 years

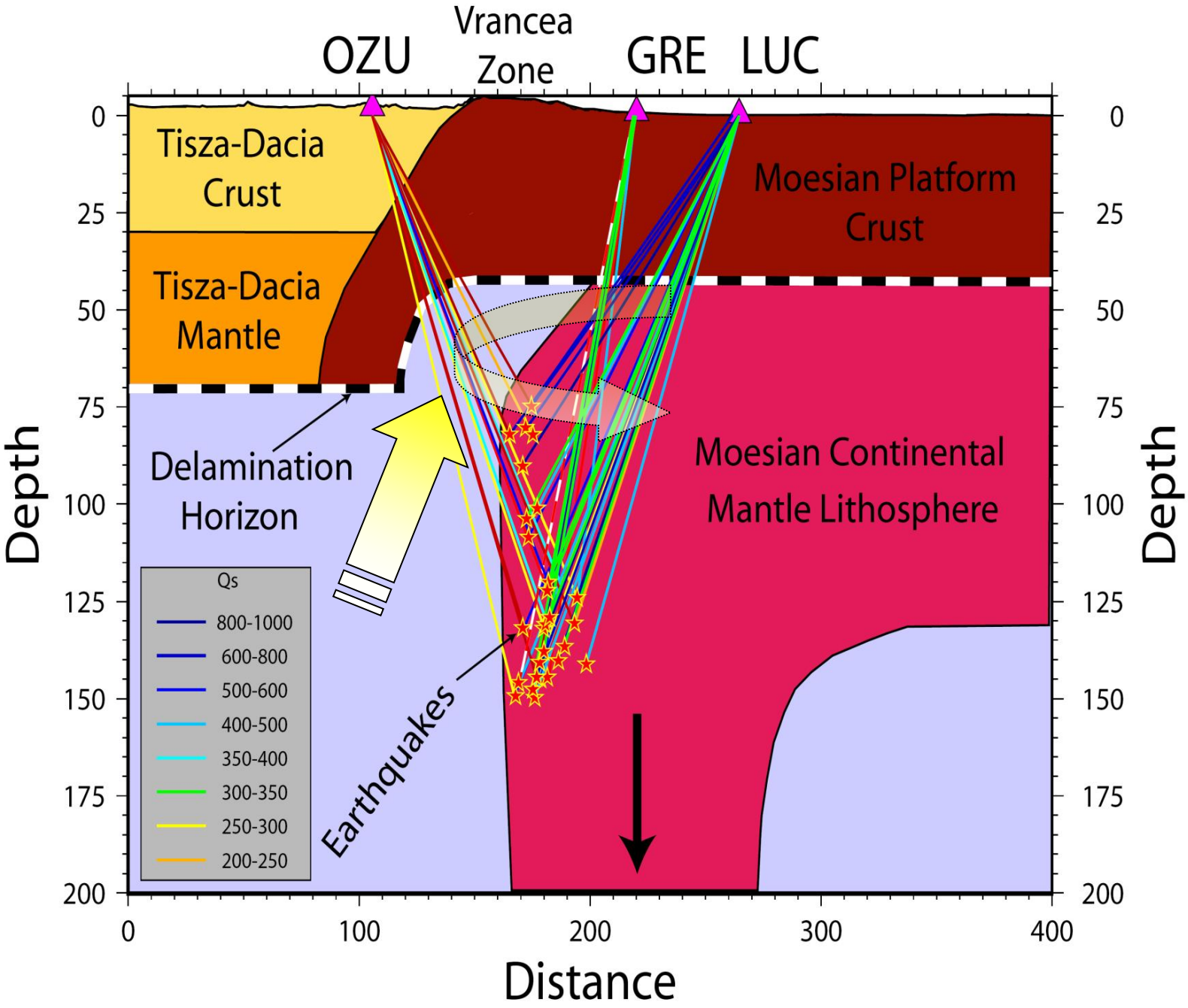
GPS – horizontal component, velocity vectors



GPS – vertical component, velocity vectors




22E
24E
26E
28E
48N
46N
44N
UKRAINE
East European Platform
MOLDOVA
HUNGARY
Pannonian Basin
Apuseni Mountains
Eastern Carpathians
Transylvanian Basin
Trotus Fault
Peceneaga-Camena Fault
South Carpathians
Focsani Basin
North Dobrogea Orogen
Moesian Platform Dobrogean Unit
Intra-Moesian Fault
SERBIA & MONTENEGRO
Moesian Platform Valachian Unit
BULGARIA


OZU
Vrancea Zone
GRE
LUC
Tisza-Dacia Crust
Tisza-Dacia Mantle
Moesian Platform Crust
Moesian Continental Mantle Lithosphere
Delamination Horizon
Earthquakes
Qs
800-1000
600-800
500-600
400-500
350-400
300-350
250-300
200-250
Depth
Depth
Distance
0
25
50
75
100
125
150
175
200
0
100
200
300
400

OVERALL CONCLUSIONS

Major variations of the lithosphere's structure led to

- strength decrease
- localization of strain in adjacent basins

Pannonian Basin = hottest -> weakest basin in continental Europe

Significant Q movements =>

- seismic hazards
- landscape and slope instability
- rapid evolution of drainage systems

OVERALL CONCLUSIONS

Orogenic patterns control:

- Neotectonic activity

- Location of natural hazards

Late stages of of post-orogenic evolutions are characterized by:

- structural inversions -> different vertical movements
- changes in
  - lithosphere dynamics
  - tectonic topography
  - landscape evolution
  - climate variations

FINAL

Key natural laboratory for the further developments of new generation of models for deep orogeny and its impact on surface processes by integrated, geoscientific approach (geotectonics, geophysics, satellite imagery and others), from **local** to **regional** and **to (semi)continental scale**.


THANK YOU !