SeismoTech
Geophysical Solutions

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PASSIVE SEISMIC TOMOGRAPHY

A Passive Concept….Actively Evolving

Active Uses of Passive Seismic Data

IRIS/GSH Workshop

June 3, Houston

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Passive Seismic-Definition

"The study of microearthquakes –natural or induced–, in order to provide information about the subsurface in large exploration areas or reservoir scale problems"

Main Passive Seismic applications:

- **Local Earthquake tomography (LET or PST)**
- **Regional or Global Earthquake tomography**
- **Reservoir or Hydraulic Fracturing Monitoring**
- **Low Frequency Passive Seismic**
- **Seismic Interferometry**

Passive Seismic-History

<u>Passive Seismic or Local Earthquake Tomography:</u>

- **Introduced to seismology and geophysics in the mid-70s and applied to investigations worldwide for regional, structural and seismo-tectonic purposes**

- **Hydrocarbon Sector:**

  1995: First global attempt to apply Passive Seismic for Anadarko in Peru

  1998: LandTech Enterprises introduces itself with a successful Passive Seismic project for Enterprise Oil in NW Greece

  2001: Official presentation of the results in Amsterdam (EAGE conference)

  2003: AAPG Explorer presents an extended article on PST

Passive Seismic-History

Passive seismic is based on the basic principle that all the little creaks and groans in the earth are actually seismic sources. It is “3-D seismic imaging … without the use of artificial surface sources.”

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AAPG EXPLORER

Passive Seismic

Thing?

some time for an array of applications, including:

✓ Monitoring mine fractures for safety purposes.

✓ Nuclear blast detection.

✓ Determining excavation stability in nuclear waste repositories.

✓ Geothermal reservoir performance.

✓ Probably the most highly publicized application of the technology was on the moon during the Apollo space program, where detectors measured the surface impact of meteorites and man-made objects to evaluate lunar crustal structure.

Passive seismic has maintained a somewhat shadowy presence in the E&P industry. In fact, it has been evaluated by various companies for select applications for more than a decade without creating any significant stir.

It's a fairly simple concept, based on

oil or gas reservoir.

"Passive seismic is 3-D seismic imaging of the target geology without the use of artificial surface sources," said Peter Duncan, president, MicroSeismic Inc. "Locally occurring micro-earthquakes and induced seismic emissions from E&P activity are used instead.

"It uses multi-component seismic receivers to take advantage of shear wave energy generated by the micro earthquakes," he continued, "thereby delivering a shear wave (Vs) velocity distribution estimate of the subsurface in addition to the conventional compressional (Vp) image."

In contrast, the man-made sources used in 3-D reflection seismic methods do not produce large shear waves. The result, according to Duncan: These conventional methods do not adequately

Passive seismic technology has the potential to solve a number of industry problems.

Consider, for instance, the continuing inefficiency and expense of land-based conventional 3-D activity. It never got up to speed economically with its marine counterpart for several reasons, including:

✓ It is labor intensive: Large crews must set and retrieve geophones manually, with miles of cable laid out on ground.

✓ Surface access is needed for vibrator buggies or shot hole rigs – and this can be expensive and messy.

✓ Permitting, remediation and other environmental concerns = $$$$.

In comparison, look at what passive seismic brings to the table:

See **Passive Seismic**, page 10

It looks like this: Schematic of a sonde currently deployed downhole on a long-term monitoring project in the Middle East.

Graphic courtesy of Input/Output

Passive Seismic Tomography – Why???

PASSIVE ?

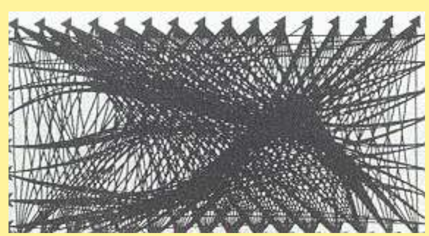
Does not involve controlled or forced sources

SEISMIC ?

Utilises earthquakes

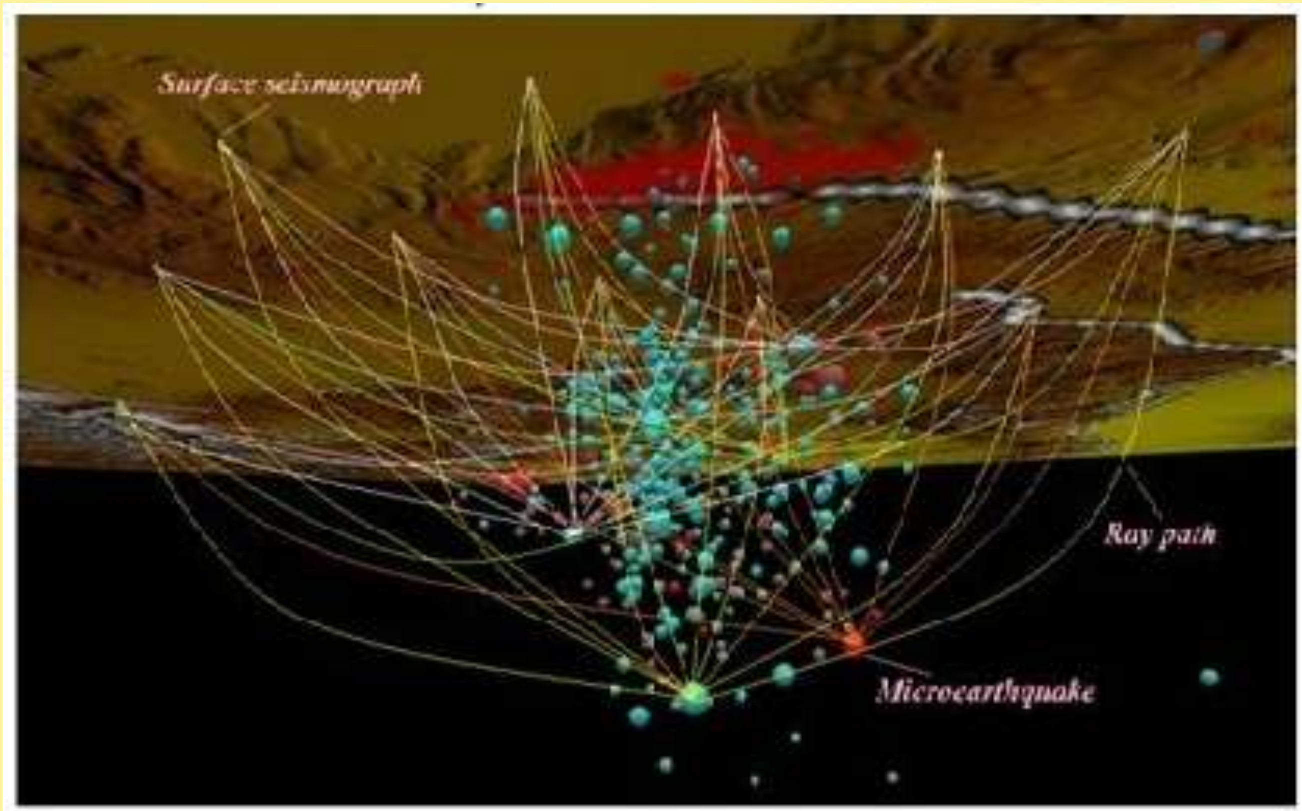
NOT ambient noise!

TOMOGRAPHY ?



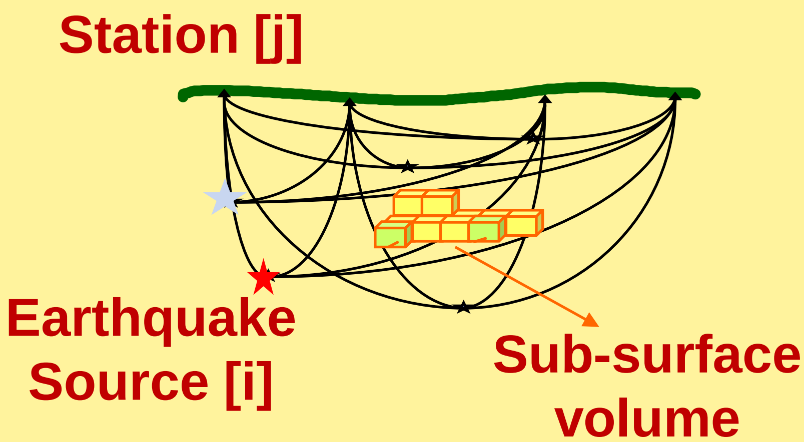
Seismic waves are X-raying the sub-surface volume

Passive Seismic Tomography – Why???



Seismic sources are within or below the target!

Passive Seismic Tomography – Basic Principle



$\tau_{ij} = \tau_i + T_{ijs}(x_i, y_i, z_i, u(s), x_j, y_j, z_j)$,

τ_i is the origin time of the i-th earthquake

x_i, y_i, z_i hypocenter coordinates

x_j, y_j, z_j receiver coordinates

$$T_{ij} = \int_{source}^{receiver} u\,ds$$

The arrival-time residuals $r_{ij} = t_{ij}^{obs} - t_{ij}^{cal}$ can be written as a linear system of equations:

$$r_{ij} = \sum_{k=1}^{3} \frac{\partial T_{ij}}{\partial x_k} \Delta x_k + \Delta \tau_i + \sum_{l=1}^{L} \frac{\partial T_{ij}}{\partial m_l} \Delta m_l$$

where Δx_k and Δm_l are the perturbations to the hypocenter parameters and the velocity perturbations, respectively.

The partial derivatives in the previously-mentioned equation can be calculated, given the velocity model and the raypath from the earthquake to the seismic station. The partial derivatives with respect to the hypocenter parameters are given by the equation (Lee and Stewart, 1981; Thurber, 1983):

$$\frac{\partial T_{ij}}{\partial x_k} = -\frac{1}{V}\left(\frac{dx_k}{ds}\right)_{source}$$

Passive Seismic Tomography – Deliverables

Main Deliverables

- 3D P-wave velocity cube (structural information)
- 3D Vp/Vs cube (lithological information)
- 3D Qp factor (rock properties)
- Accurate seismic event locations (related to active faults)
- Focal Mechanisms – Stress/Moment Tensors (fault characterization)

Passive Seismic Tomography – Advantages

Advantages

- Insensitive to penetration problems due to high velocity layers close to the surface or HLH velocity effects that are common in thrust-belt zones, basaltic environments etc.(in opposition to conventional seismic)
- Easily applicable in areas with accessibility limitations
- Environmentally friendly
- Cost Effective (especially for large exploration areas)
- Directly interpretable results

Passive Seismic Tomography – Benefits

Benefits

- Structural & lithological information for unexplored areas
- Stress/fault information
- Aid in well placement
- Improvement of poor quality conventional seismic data
- Correlation with other available data

Contents

Passive Seismic Tomography – Land Equipment

SR-24 Portable Seismograph

S-100 Borehole Seismic Sensor

24bit, very low power consumption

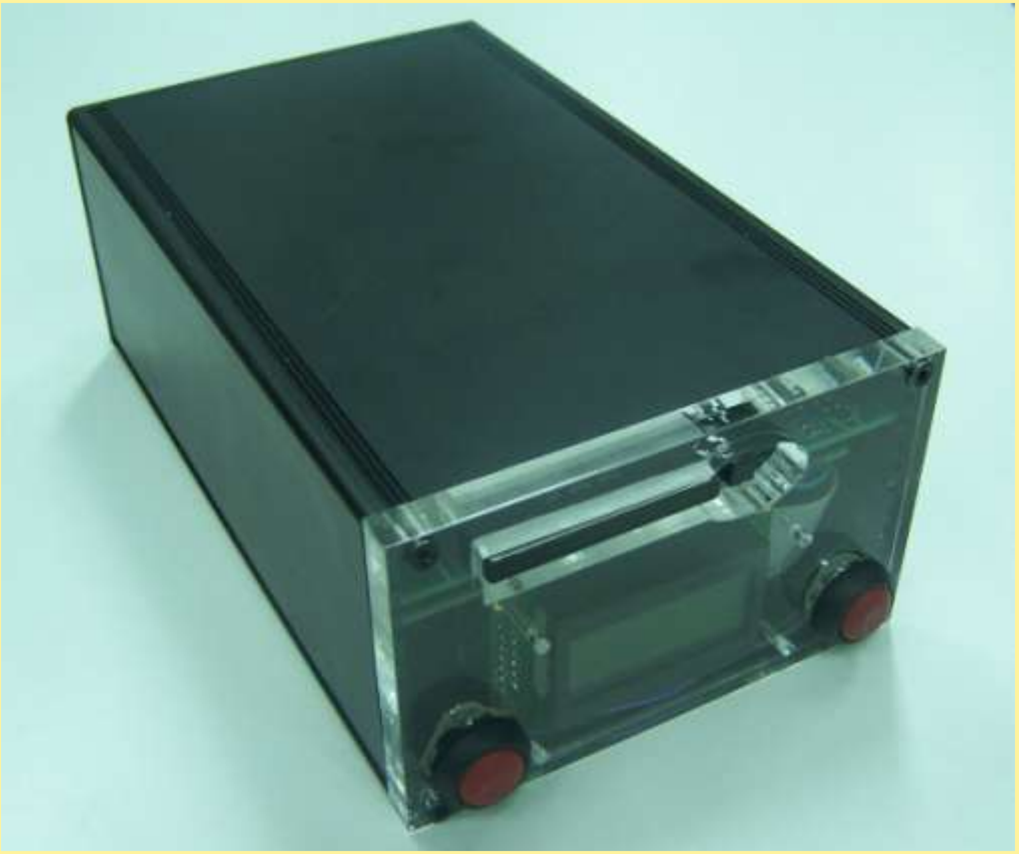
Sampling rate: 1-1000 samples/sec

3C seismic shallow borehole seismic sensor

Bandwidth 0.2 – 100Hz

Land Equipment – Latest Developments

X1 Portable Seismograph



General Specifications

- **24 or 32 bit,**
- **Sampling Rate: 1-4000 sps**
- **3-6 channels**
- **Ultra low power consumption: 0.56 W**
- **52 days using a single car battery**
- **Data storage: 52 days @ 100 sps (4GB FC)**
- **Dimensions: 16 x 10 x 7 cm**
- **Weight: 460 gr**
- **Operation Temperature: -20 – 70 C**
- **Differential Input**
- **On Site Event Detection and P & S phase picking**
- **Various Telemetry Options**

Land Equipment – Latest Developments

S200 Shallow Borehole Sensor

General Specifications

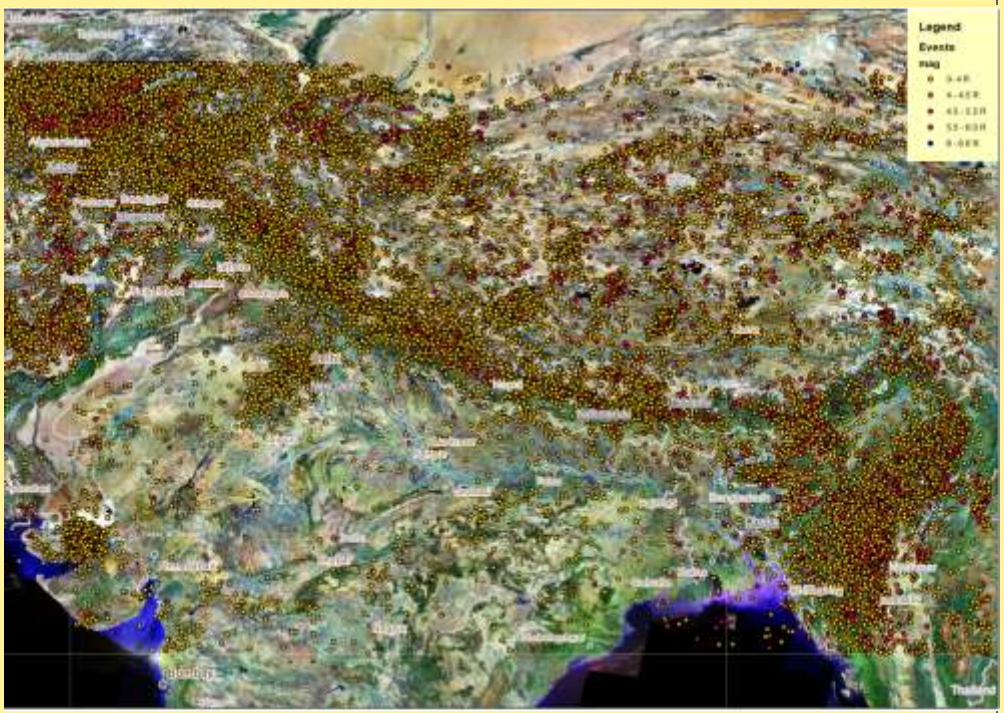
- 3 Components
- Bandwidth : 0.2 – 100 Hz
- 2-4 geophones per component
- Automatic Signal Amplification
- Operation Temperature: -20 – 70 C
- Ideal for Surface Frac monitoring Applications

Passive Seismic Tomography – Project stages

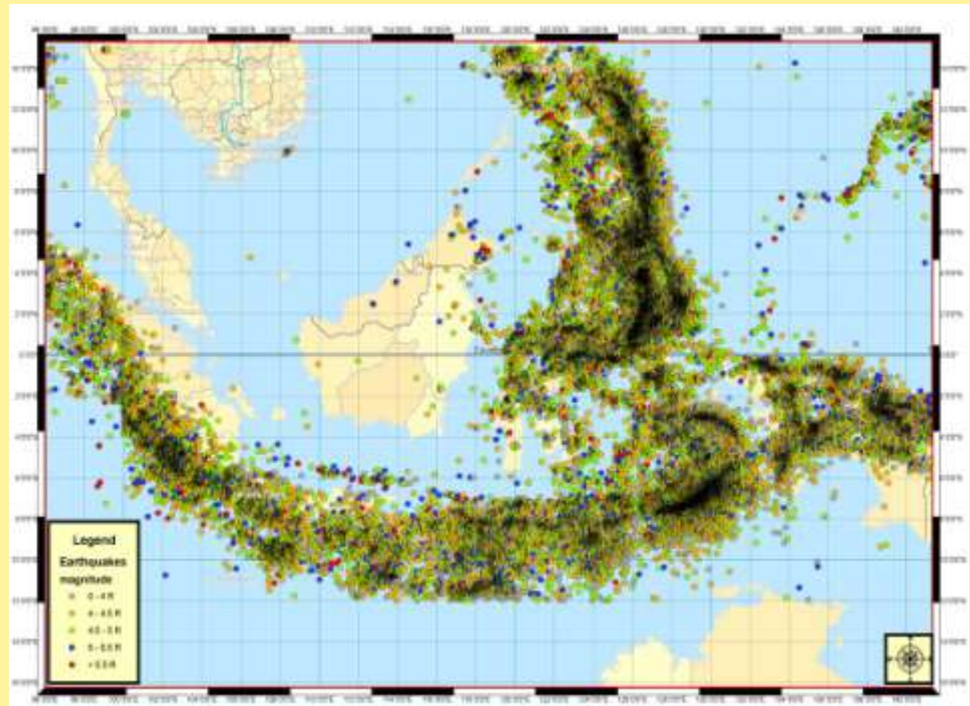
- **Feasibility study**:
  Seismicity level of the area estimated through available datasets & desktop seismic network design. If necessary, check seismicity level by installing a sparse seismic network for 1-2 months.
- **Seismic Network Installation**
- **Acquisition and data processing**
- **3D Tomographic inversion & QC of results**
- **Interpretation/Correlation with available data**

Passive Seismic Tomography – Feasibility

India Seismicity



Indonesia Seismicity



Feasibility – Latest Developments

Feasibility Procedure

- Seismicity Assessment for the Area of Interest
- PST Sensitivity Tests (Checkerboard) for Different Recording Periods and Network Layouts (Case Studies)
- PST Modeling According to Provided Geological Model (2D to 3D model) for Different Recording Periods and Network Layouts (Case Studies)
- Feasibility Study Results Evaluation

Passive Seismic Tomography – Land Network Installation




Passive Seismic Tomography – Acquisition

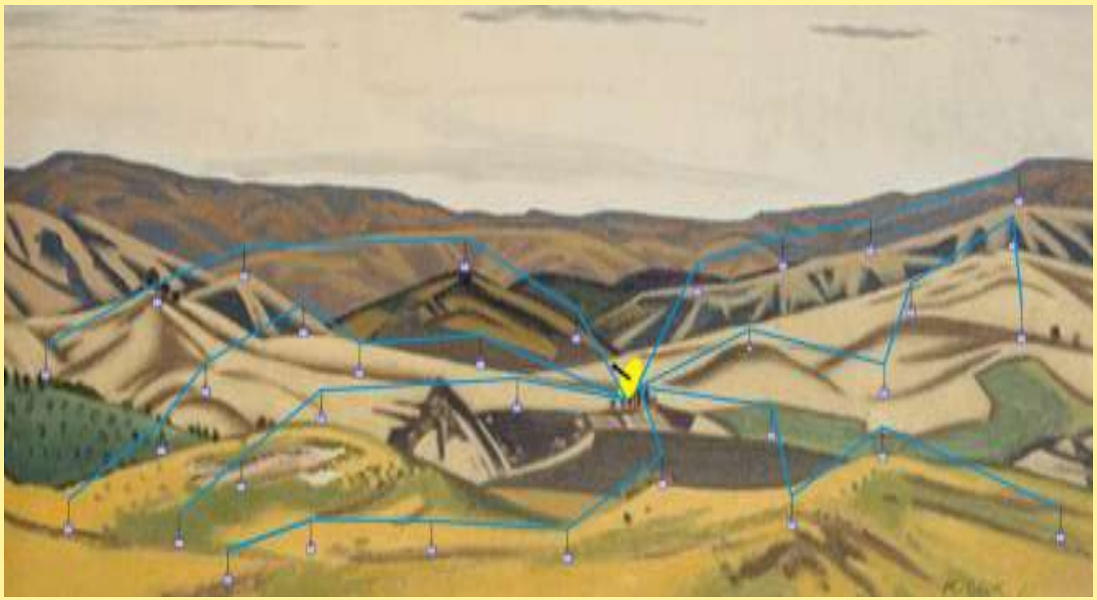
Difficult operational conditions



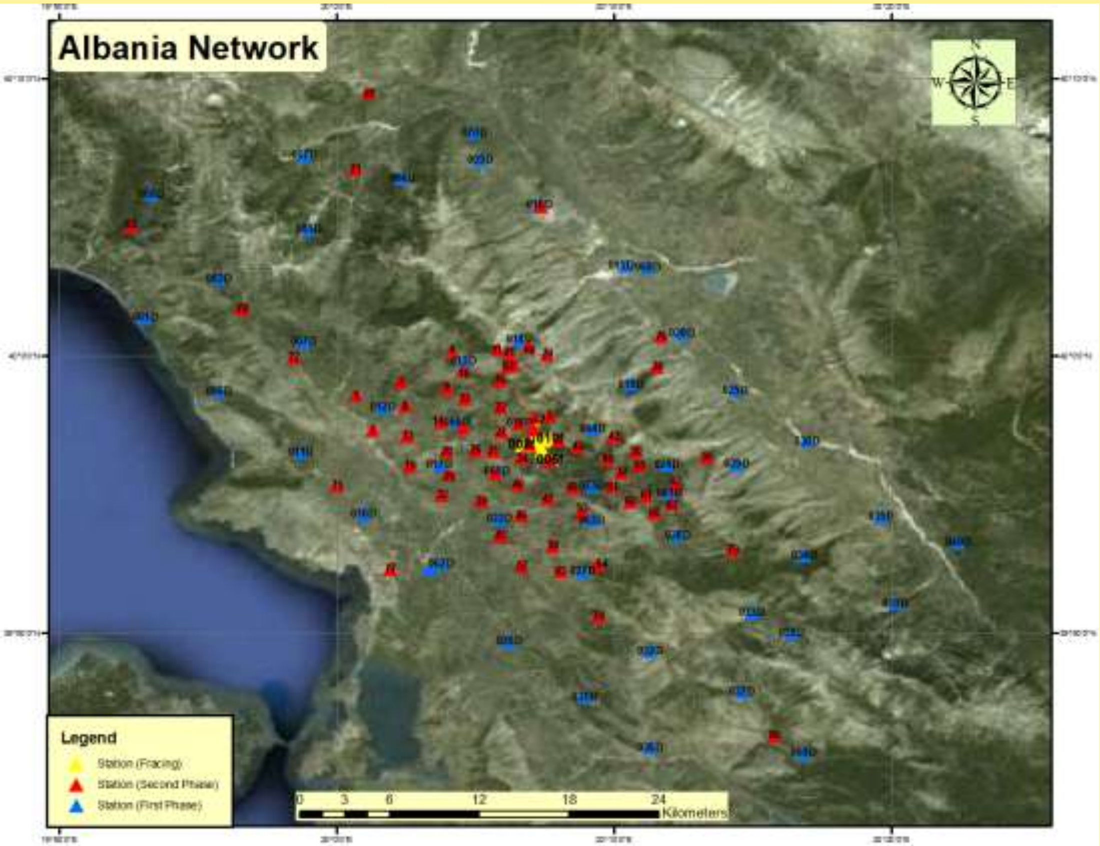


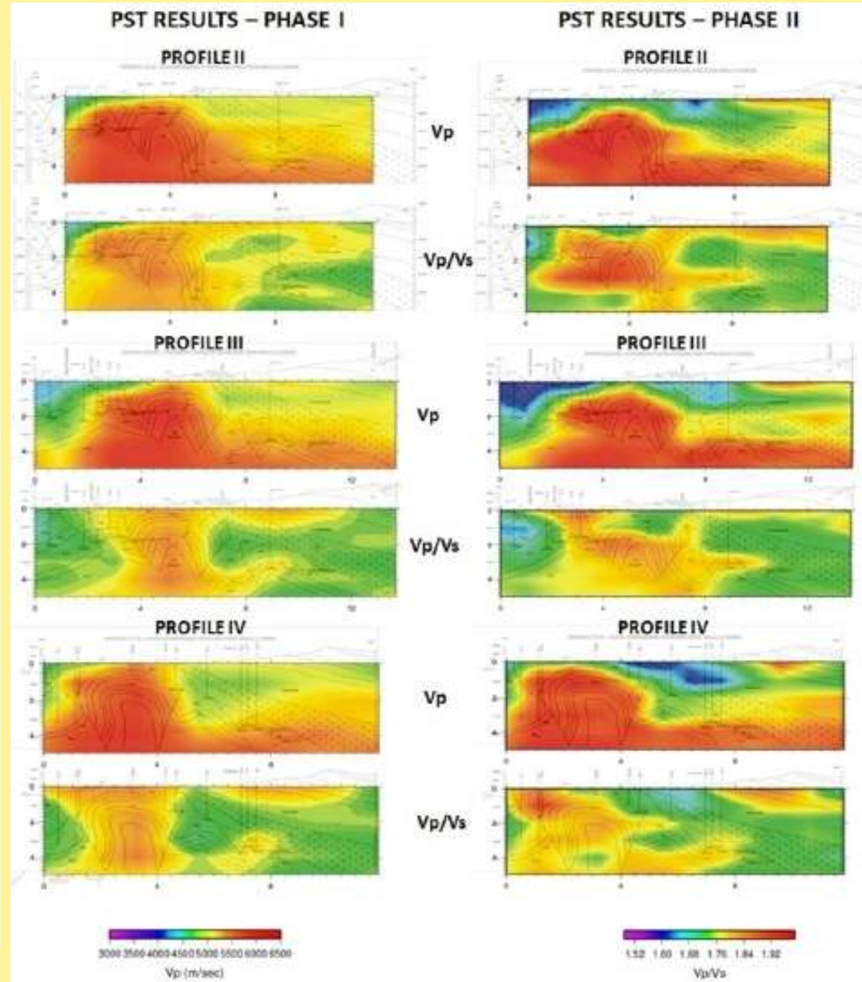

Data Acquisition- Latest Developments

Data Transfer- Telemetry Options (WiFi, GSM-3G, Wi-fly Satelite)



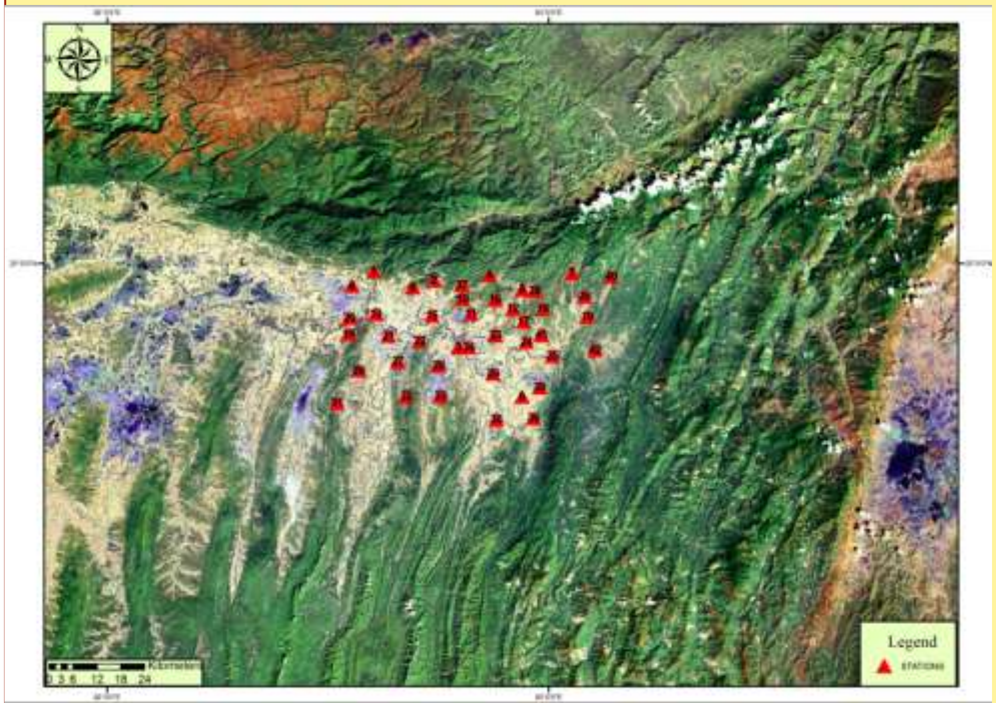
Acquisition-Seismic Network Design (Albania)
Effect on PST results



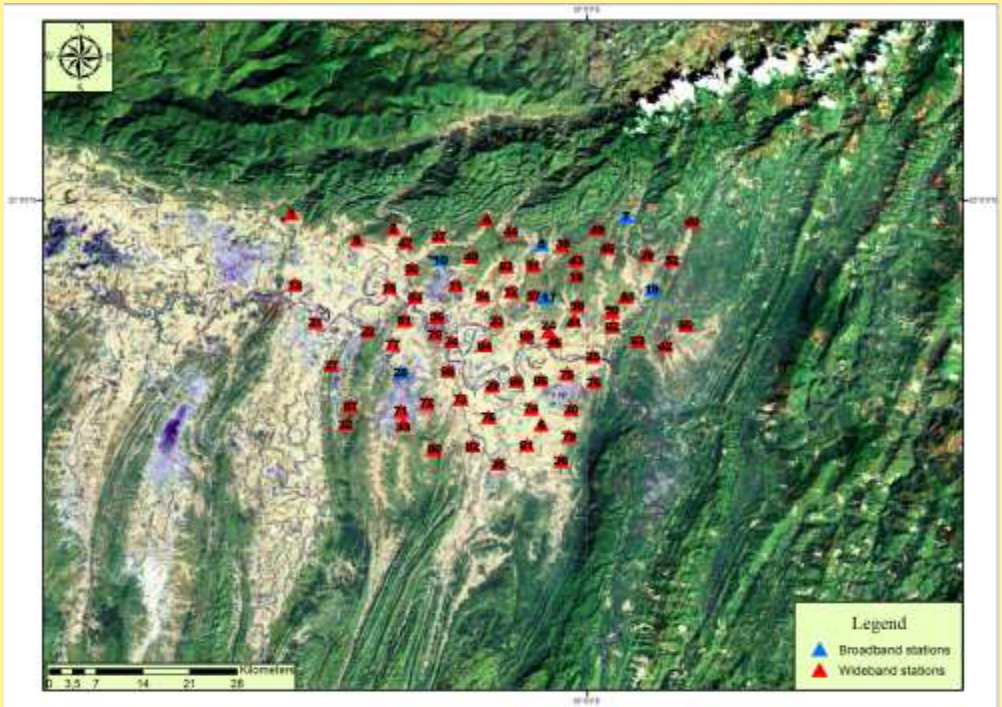


Acquisition-Seismic Network Design (India)

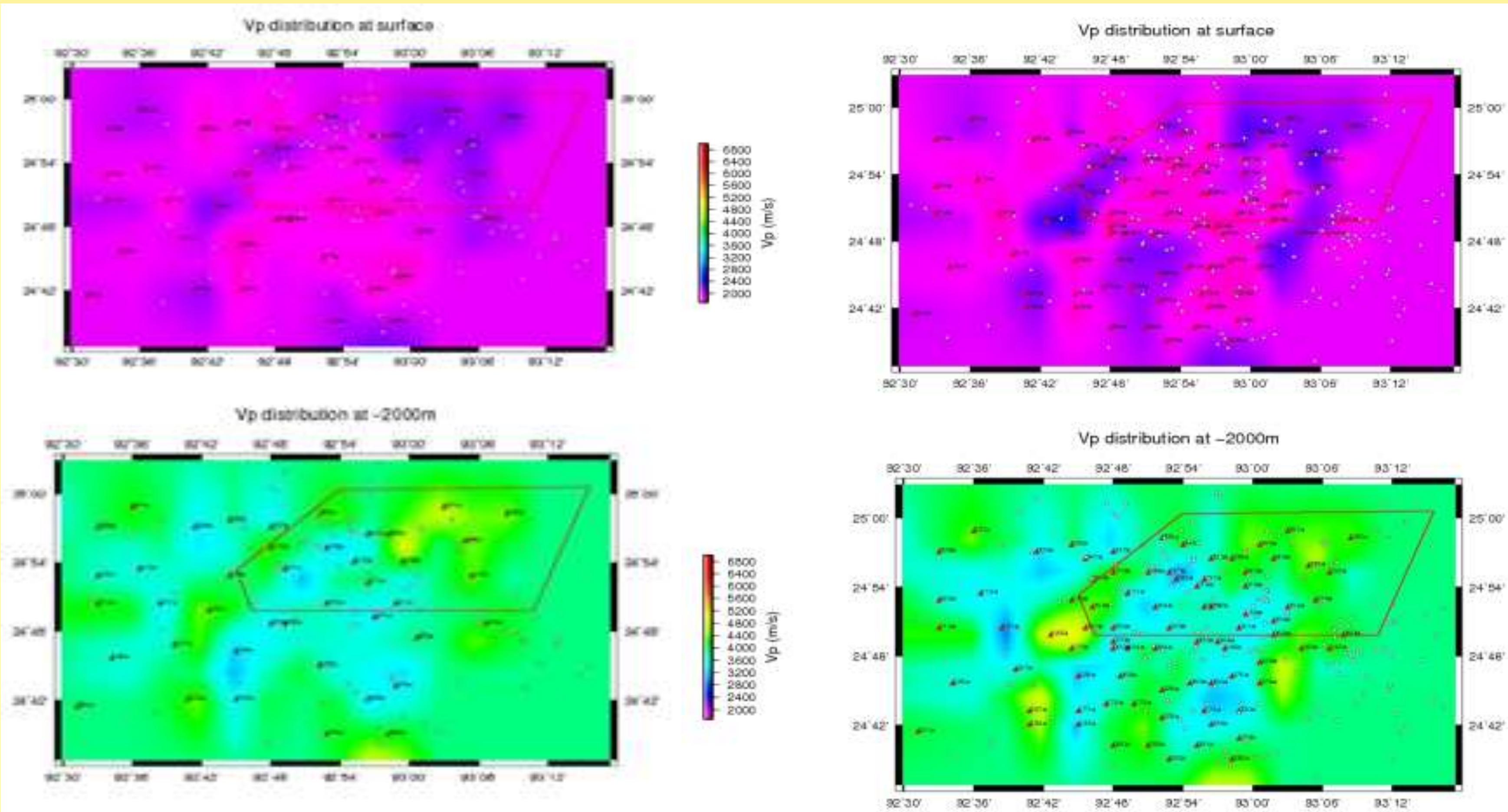
1st Phase



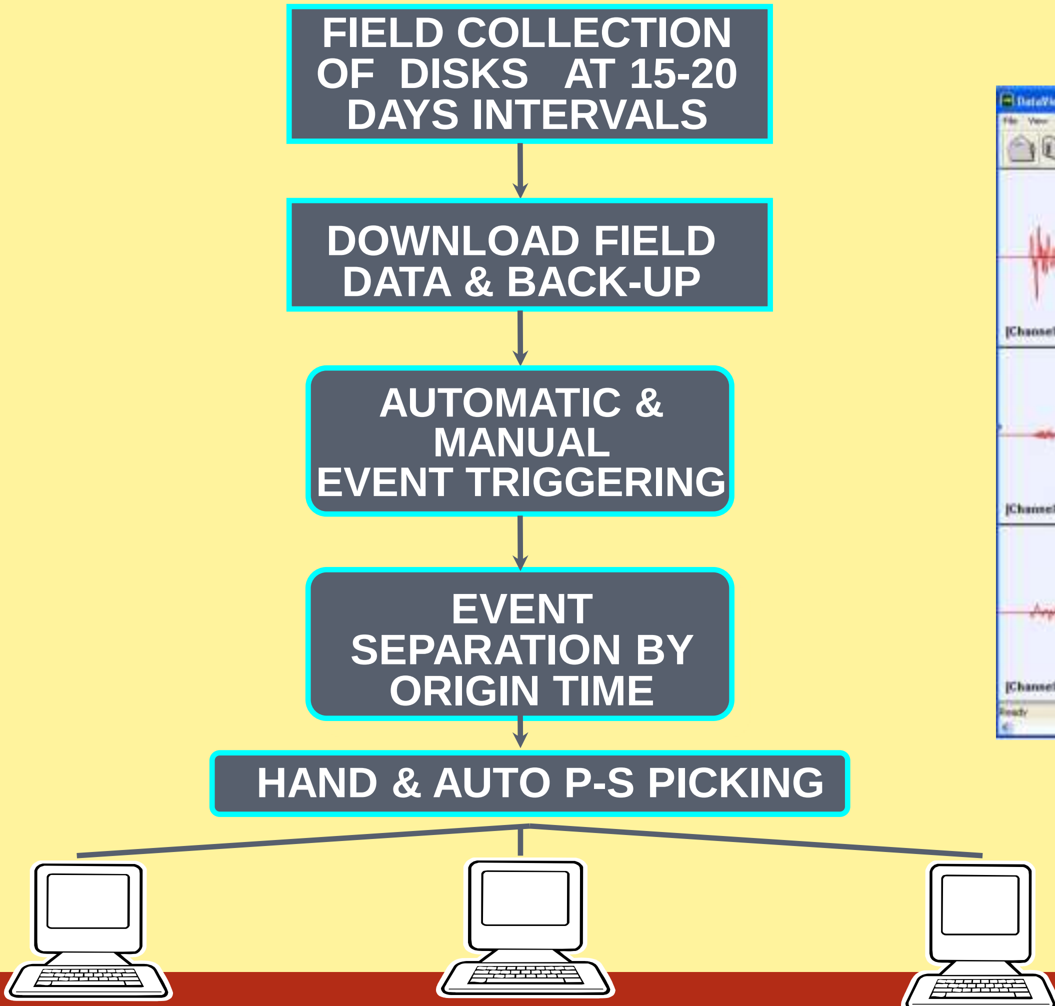
2nd Phase

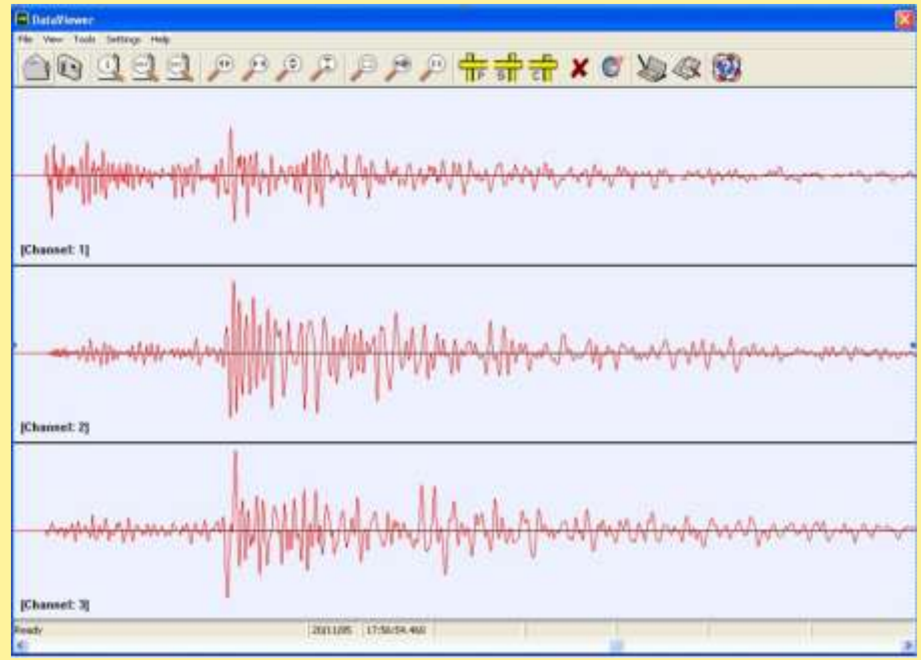


PST Results Comparison:
Same acquisition period-Different Station Number and Distribution



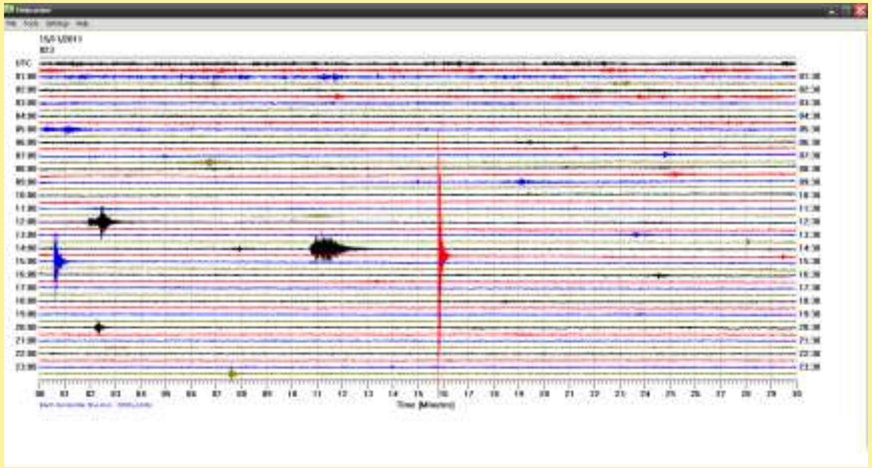
Passive Seismic Tomography – Acquisition/Processing



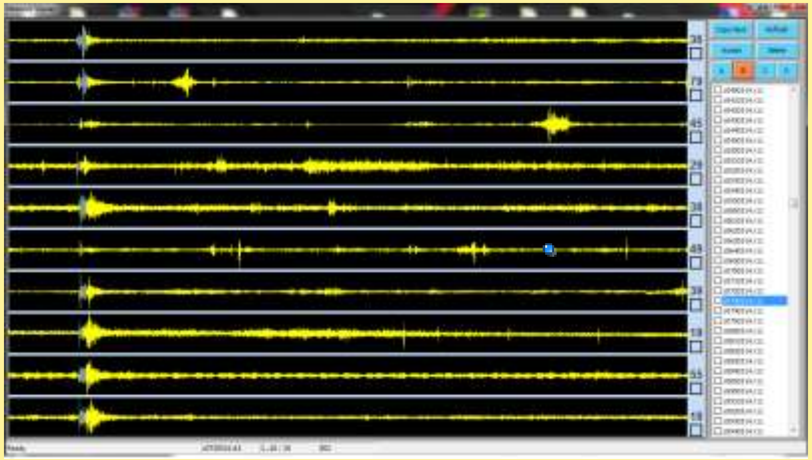


DataViewer

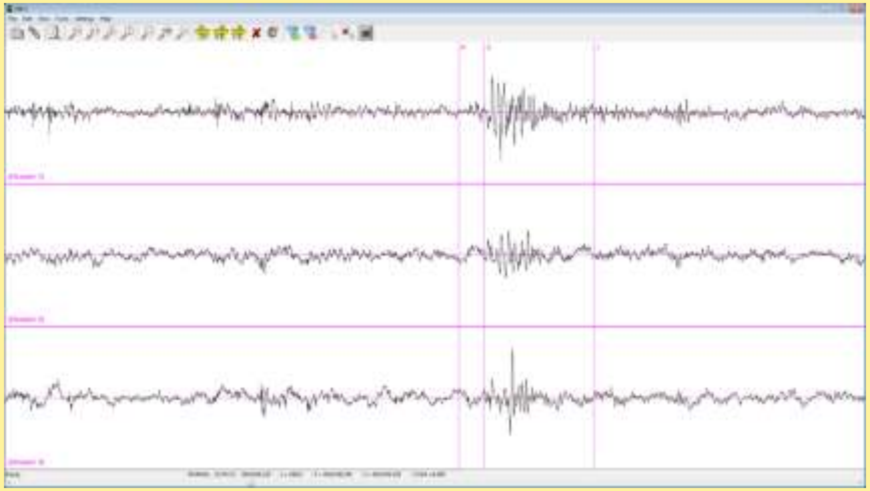
PST – Data Processing



Helicorder



Event Detection



SEISMPLUS

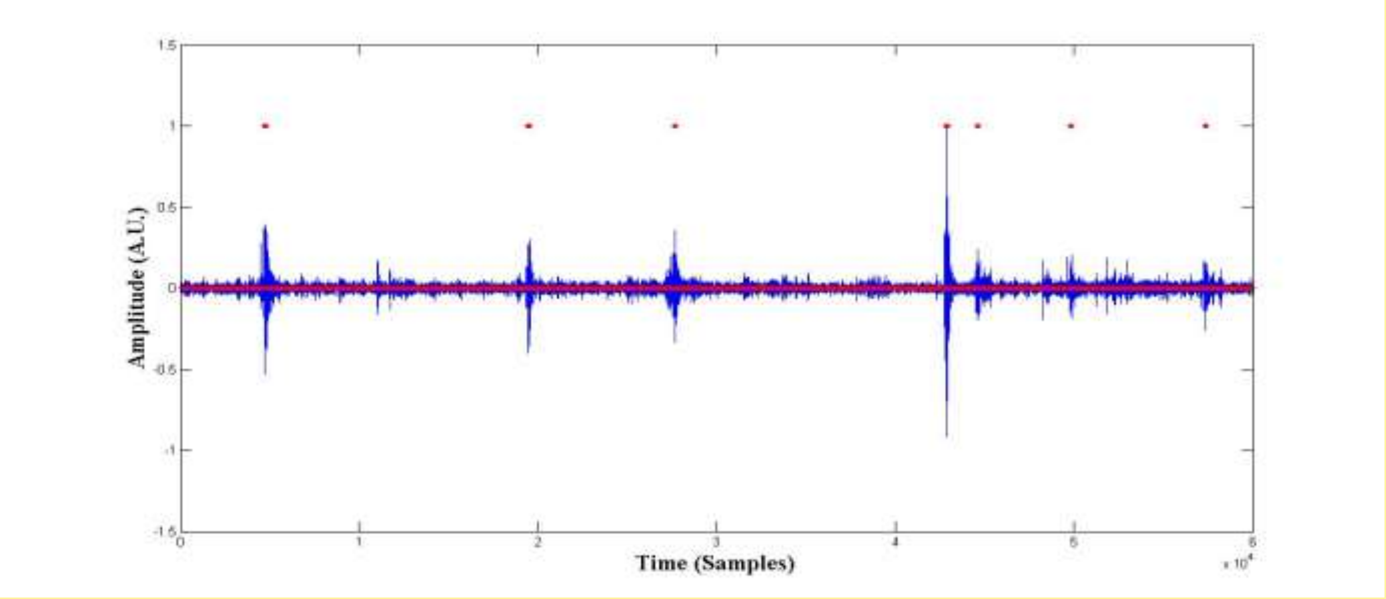
Phase Picking & Event Location

Data Processing- Latest Developments

Automatic Microseismic Event Detection

i. **Energy Based Algorithm (recommended for high seismicity records)**

- **Improved STA/LTA algorithm.**
- **Dynamic threshold based on the statistical properties of the STA/LTA “ratio”.**
- **Simple and fast, demands low computational resources.**



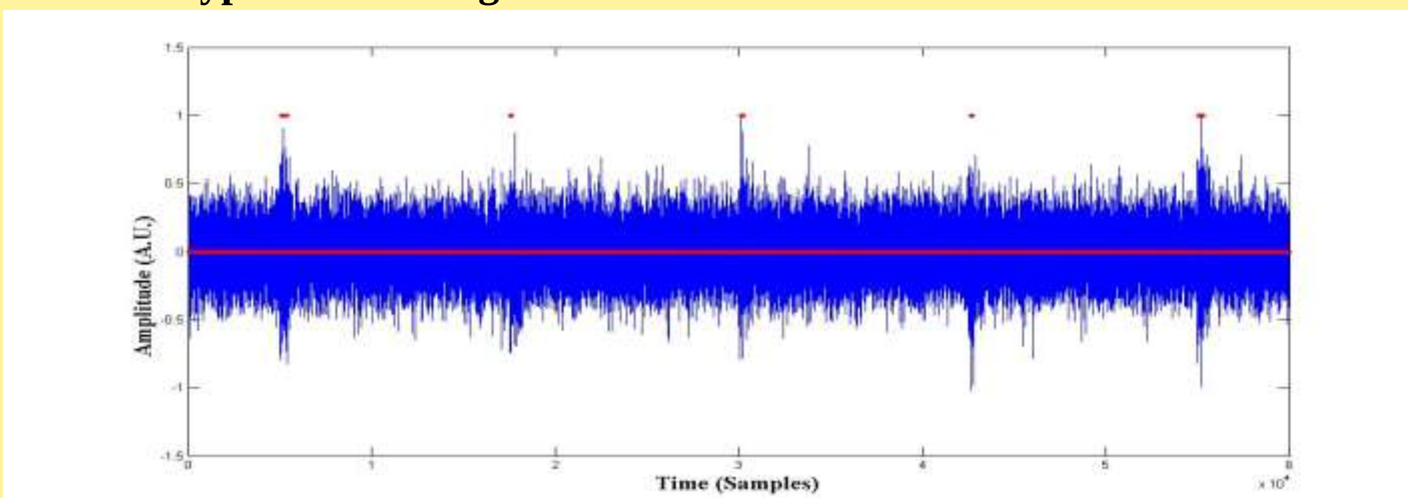
Data Processing- Latest Developments

Automatic Microseismic Event Detection

ii. Algorithm Based on Statistical Methods (recommended for noisy records)

Two – stage procedure, based on a non-strict hypothesis testing scenario:

- **First stage: Estimation of the empirical *pdf* of the seismic noise (using statistical methods such as sampling, modeling, clustering).**
- **Second stage: Use of a thresholding scheme in order to detect the microseismic events, in a non-strict hypothesis testing framework.**

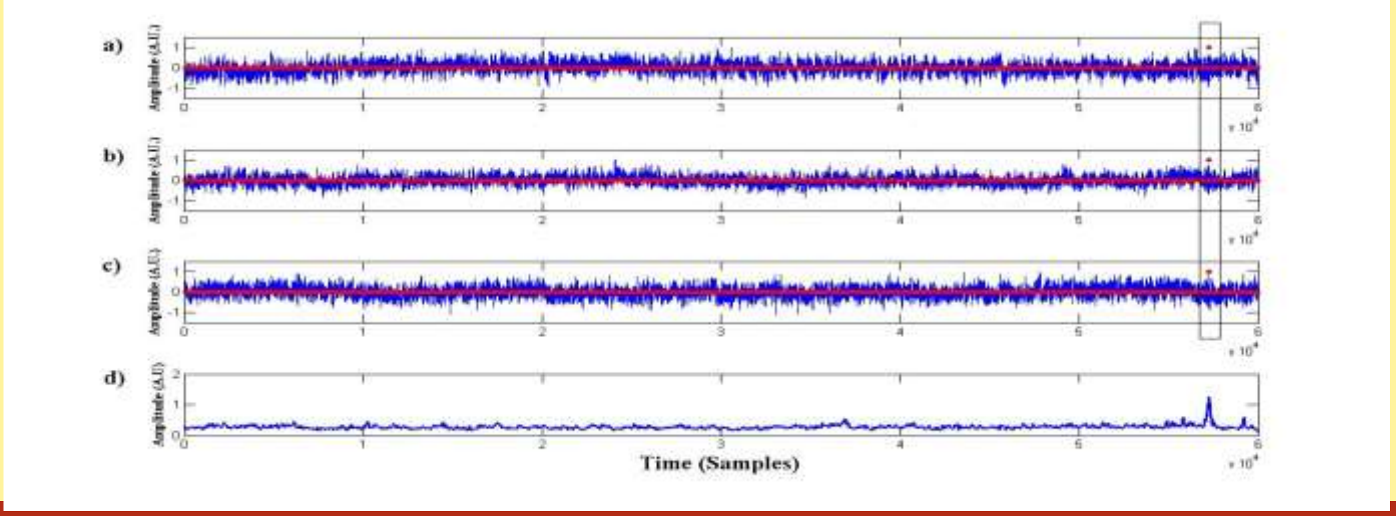


Data Processing- Latest Developments

Automatic Microseismic Event Detection

iii. **Algorithm Based on Signal's Polarization Attributes in Time-Frequency domain (recommended for extremely noisy records)**

- **Fourier analysis on different frequency sub-zones.**
- **Evaluation of the polarization differences among the three components.**
- **Regression analysis technique in order to correct errors due to sensor's interference.**
- **Development of a characteristic function based on the above differences, for the microseismic event detection.**



Data Processing- Latest Developments

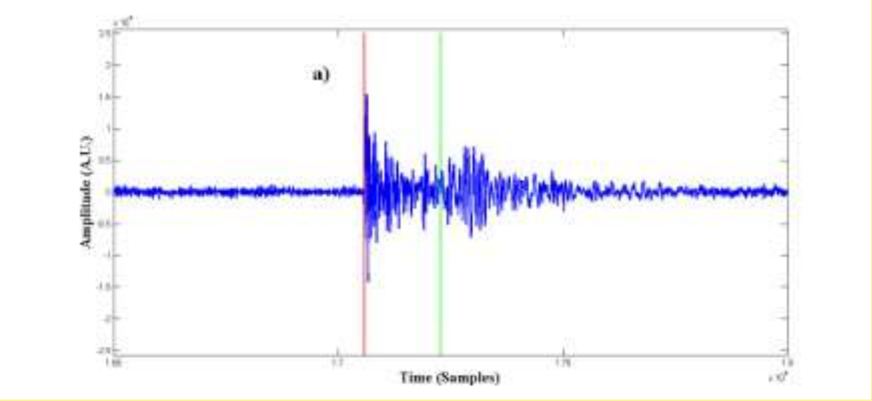
Automatic P&S Phase Picking

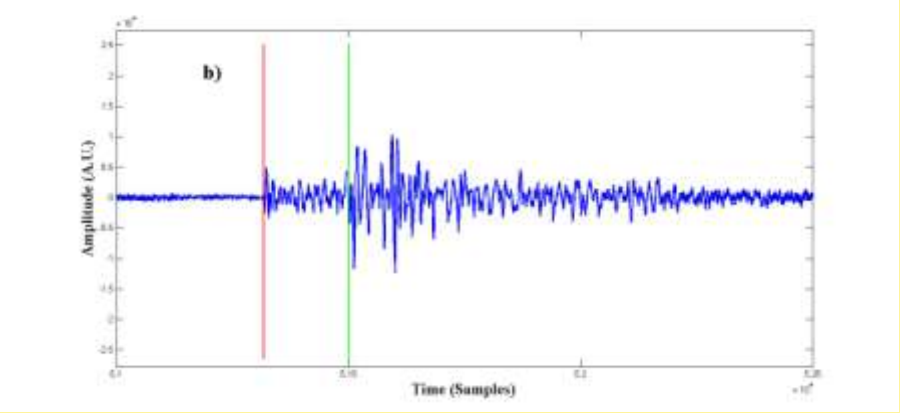
i. P-phase picking:

- **The kurtosis criterion is applied on the segment of the record that includes a seismic event.**
- **The maximum slope of the kurtosis curve is assigned to the P-onset time.**

ii. S-phase picking:

- **Eigenvalue analysis on 3C data.**
- **Development of a characteristic function, based on the maximum eigenvalues of the above analysis.**
- **Kurtosis criterion on the characteristic function.**



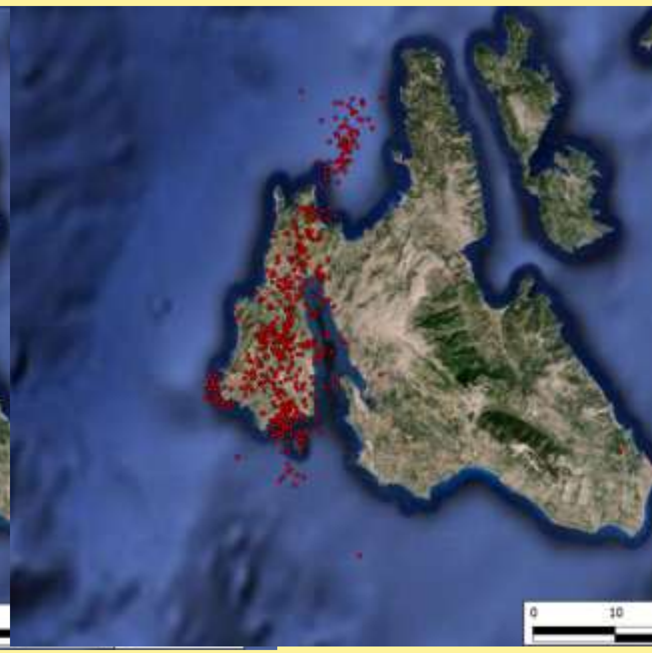


Data Processing- Latest Developments

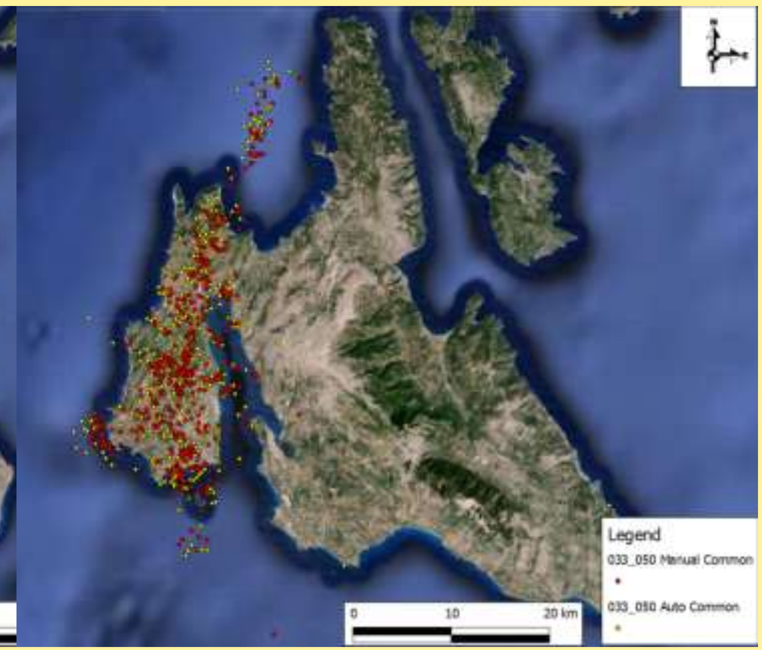
Case Study for Automatic Event Detection-P&S Phase Picking

Automatic | **Manual** | **Auto vs Manual**

8400 Events



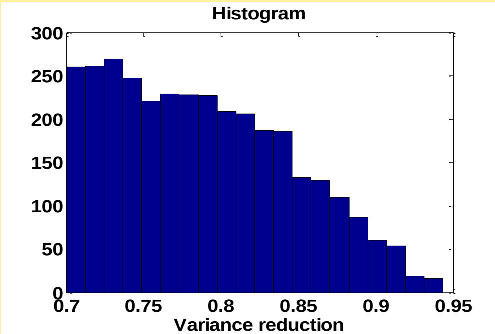
600 Events

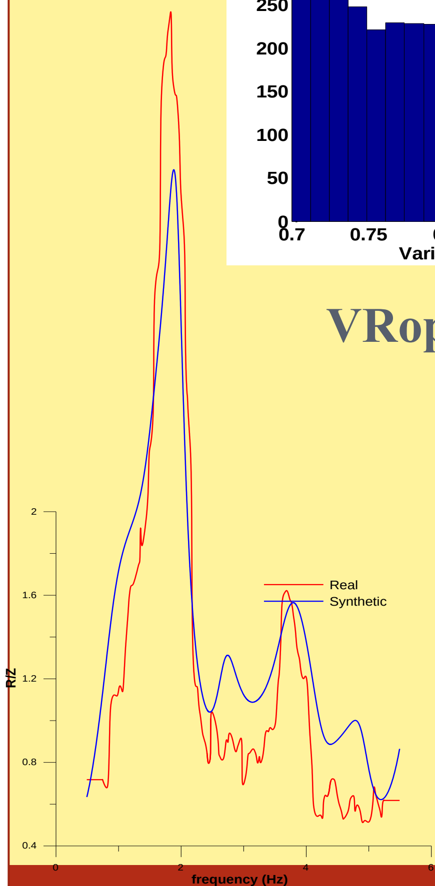


500 Common Events

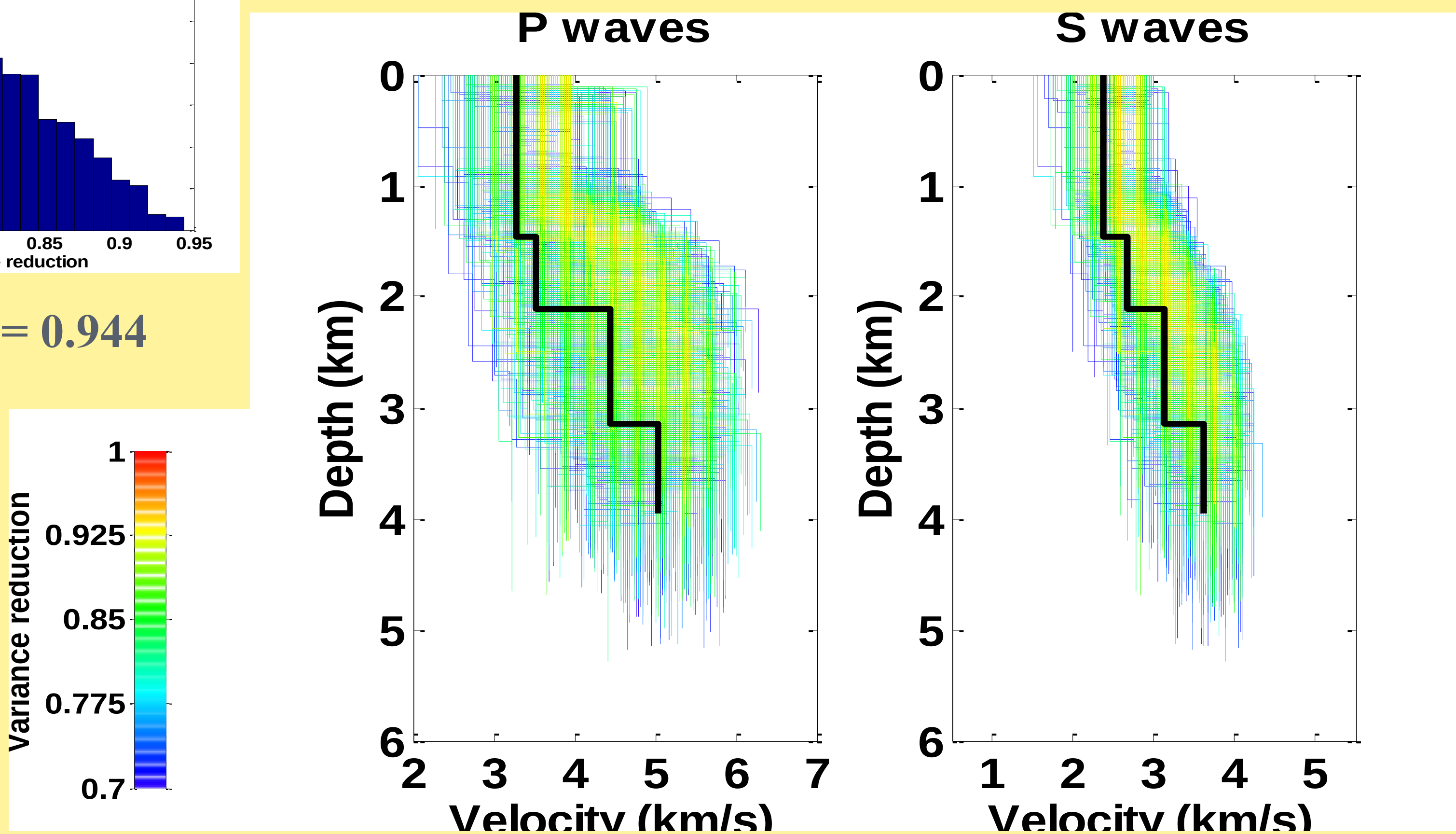
Data Processing- Latest Developments

1D Vp &Vs model estimations using Teleseismic Data-Receiver Functions

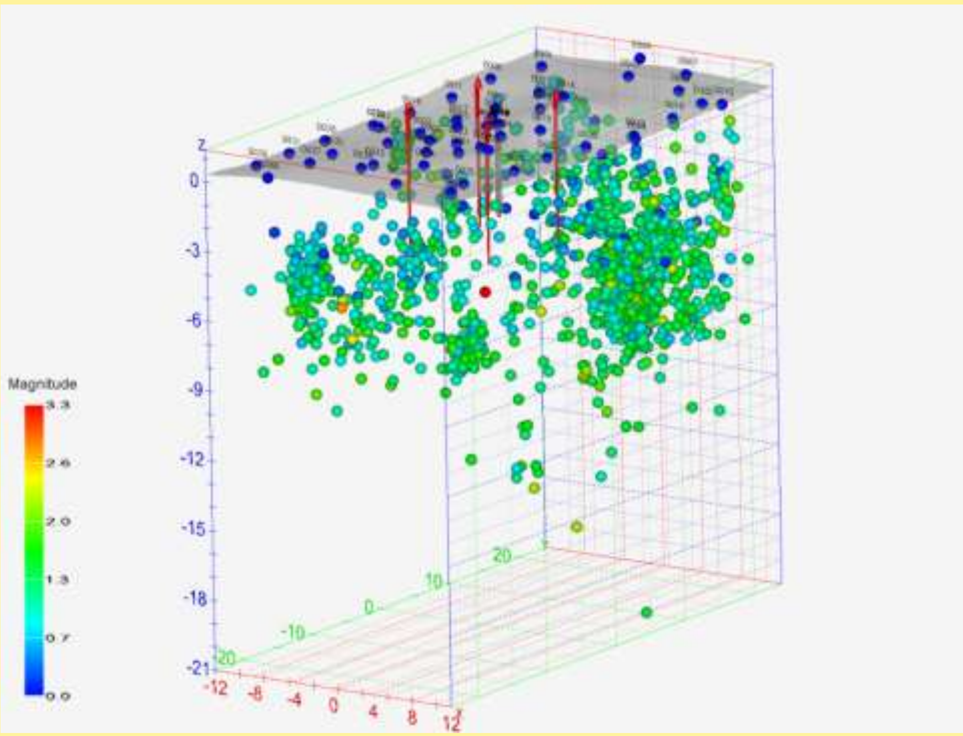


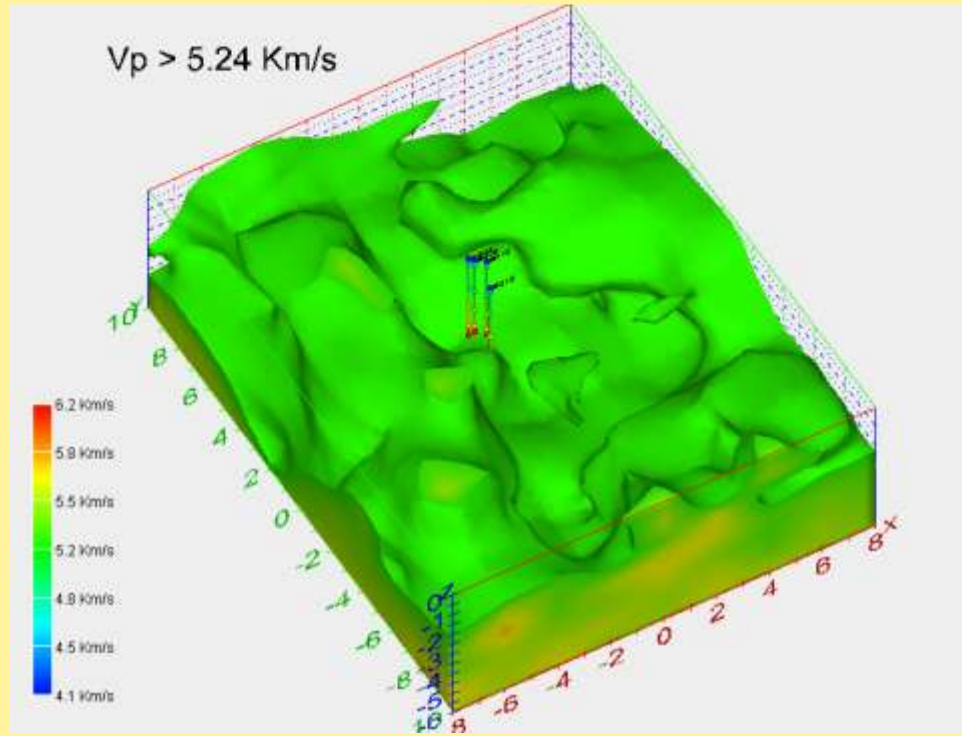


VRopt = 0.944

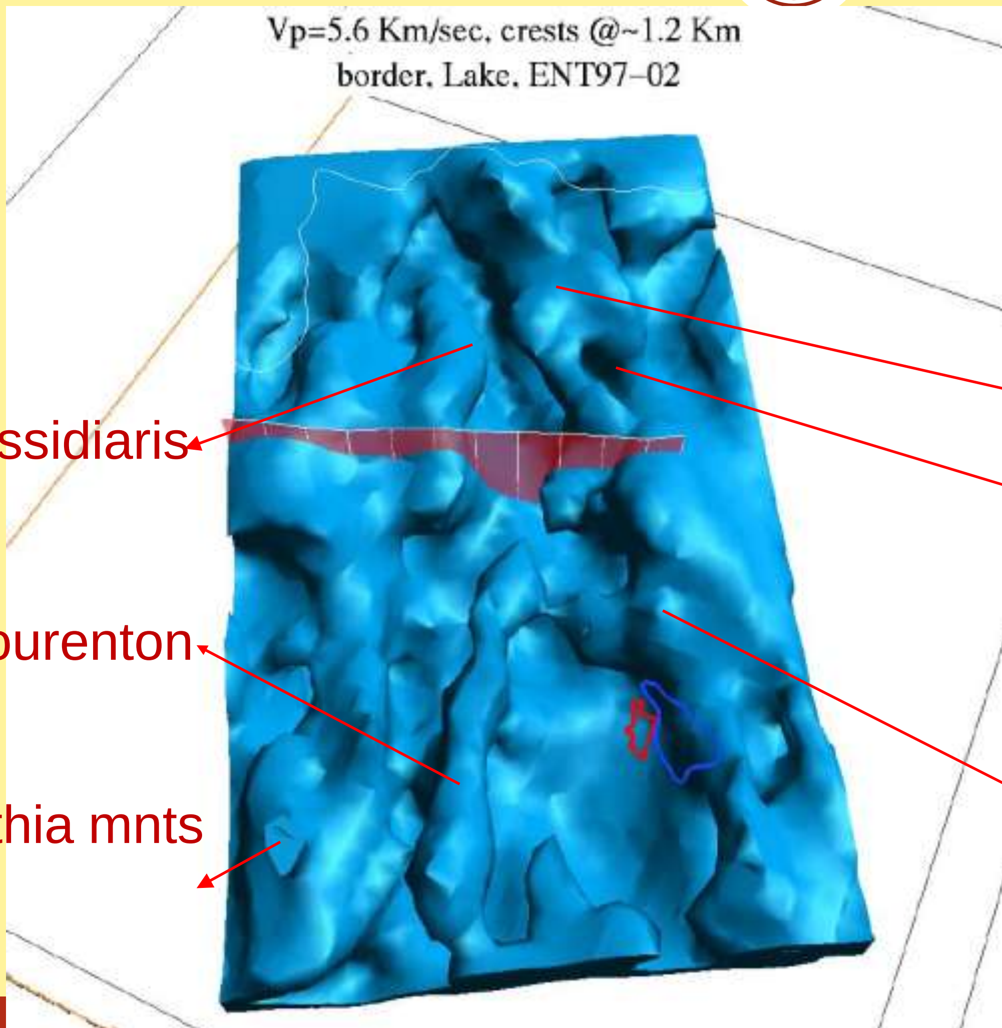


Passive Seismic Tomography Results





3D Vp Structural Information - Carbonates

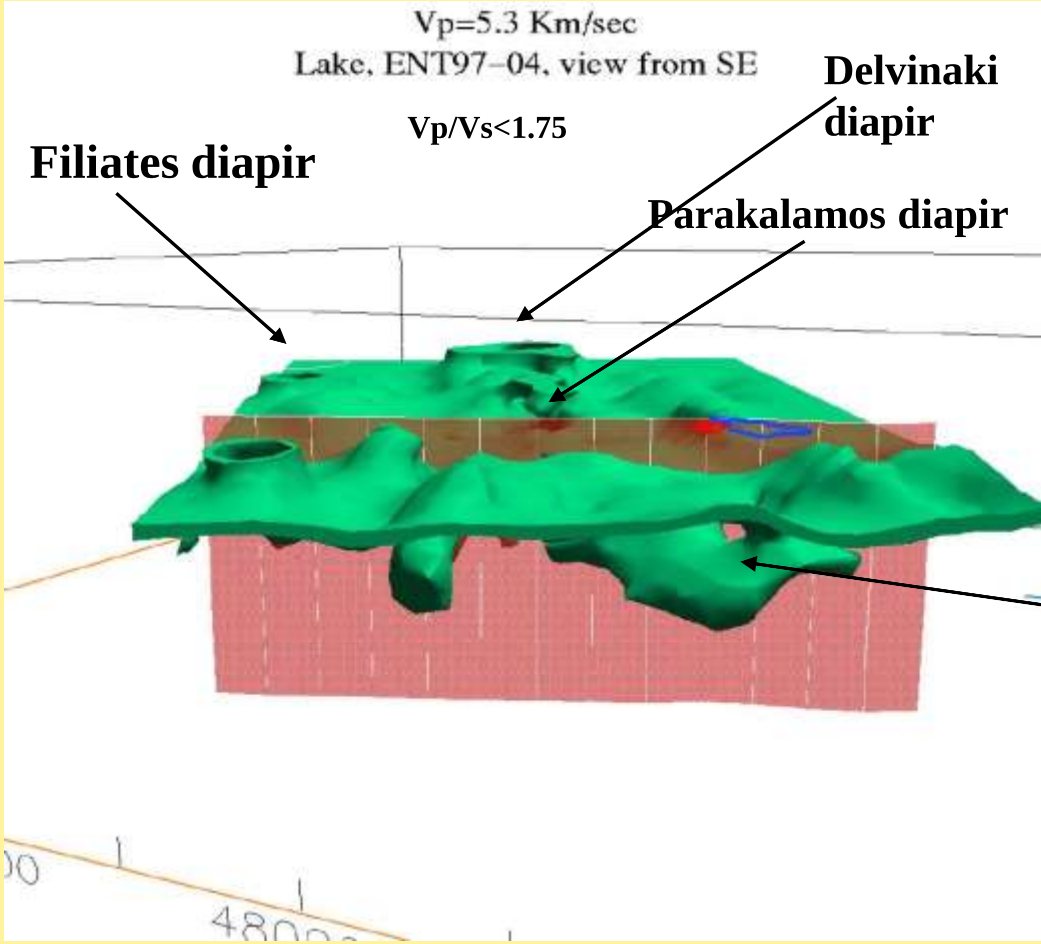


3D Velocity Structure

CARBONATES

- Vp highs ⌫ topographic highs

3D Vp/Vs Lithological Information - Evaporites



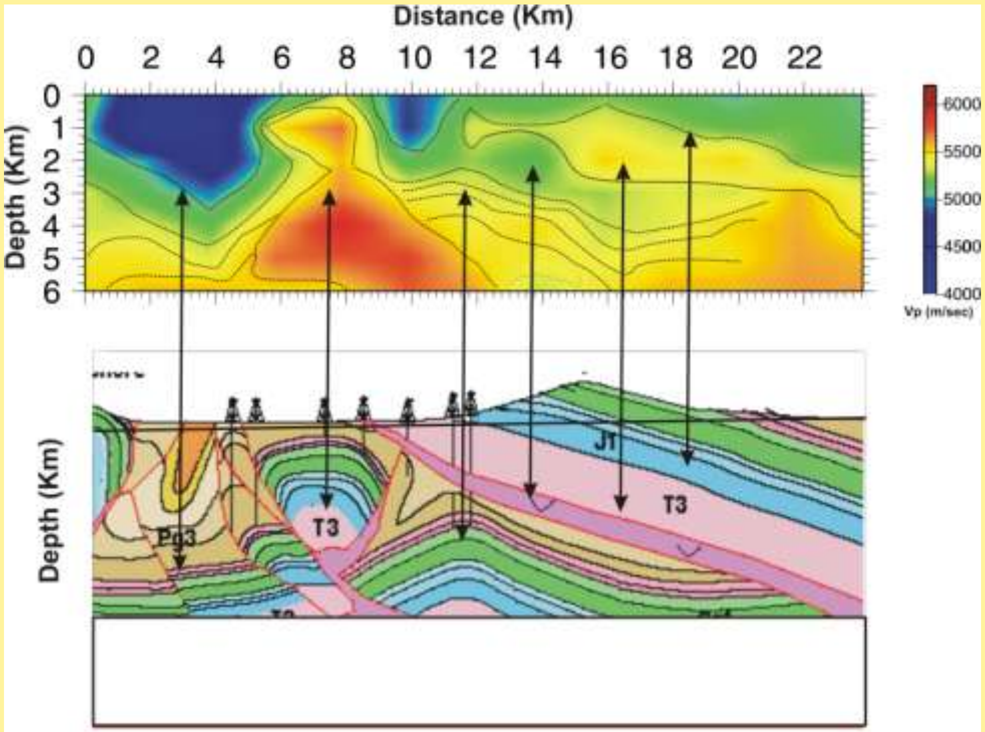
EVAPORITES

Ioannina Plateau <u>thick evaporites</u>

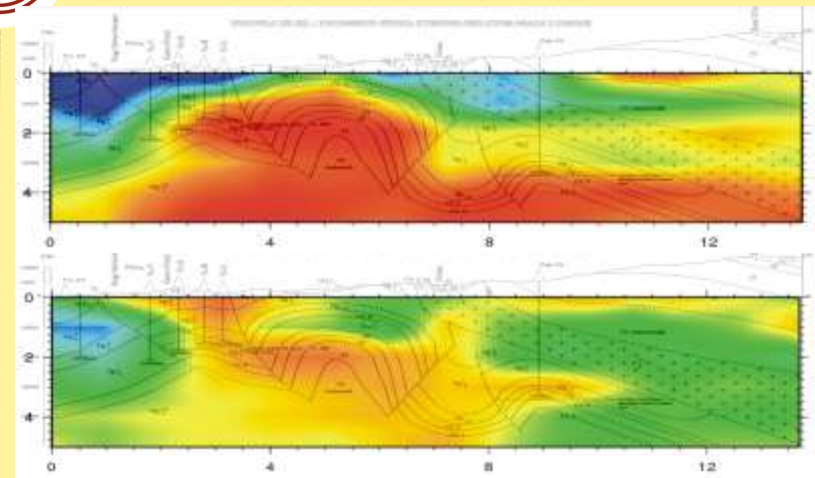
(“low” gravity/ “high”resistivity)

Passive Seismic Tomography Results: Areas with Difficult Geotectonic Conditions/Poor Quality Seismic Data/Difficult Topography

Vp Cross-Section (PST)



Geological Cross-Section based on Well Info &Surface Observations

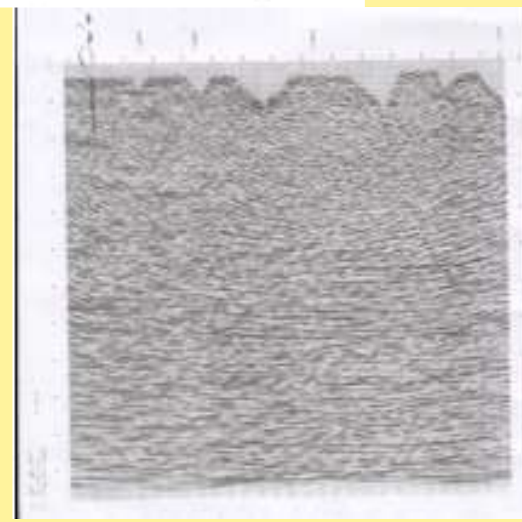


Vp

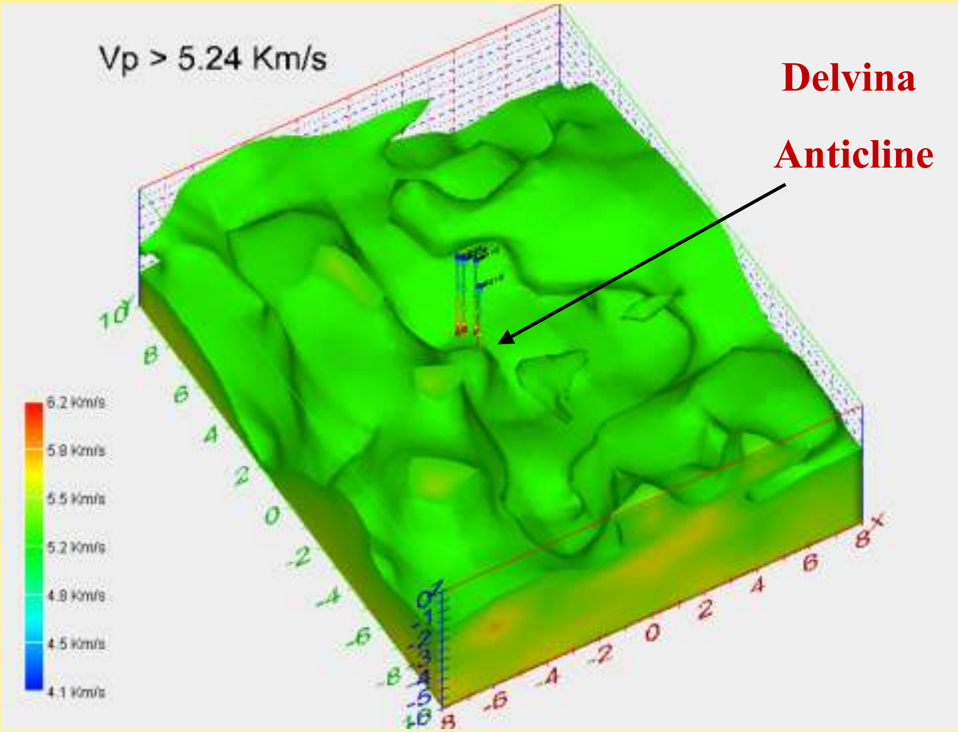
Vp/Vs

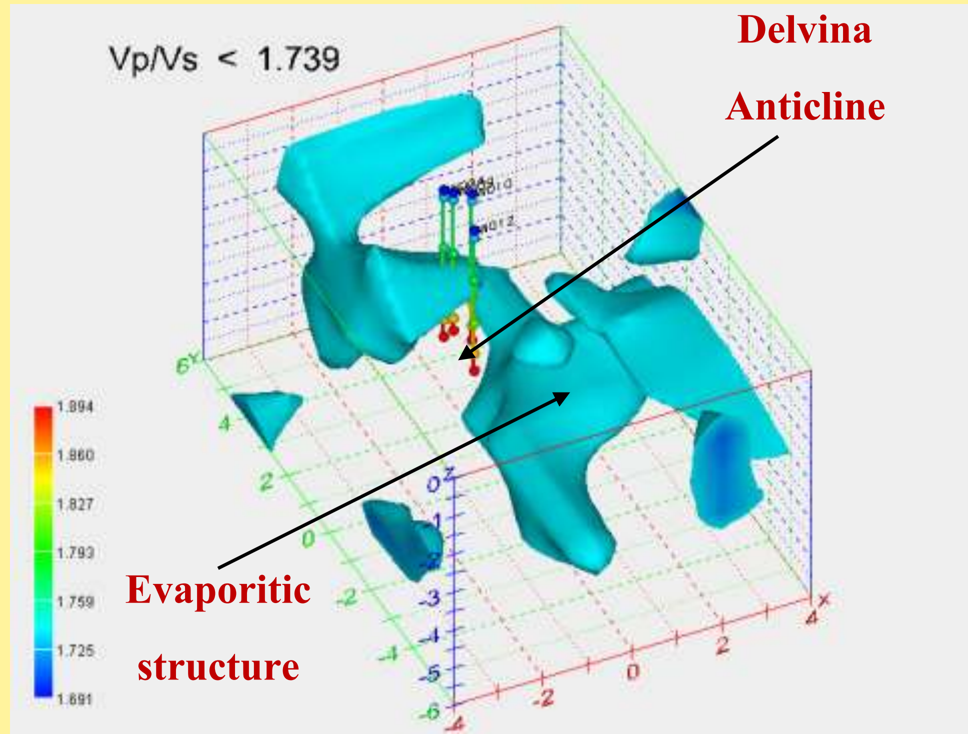
(PST)

Poor Quality Conventional 2D Seismic



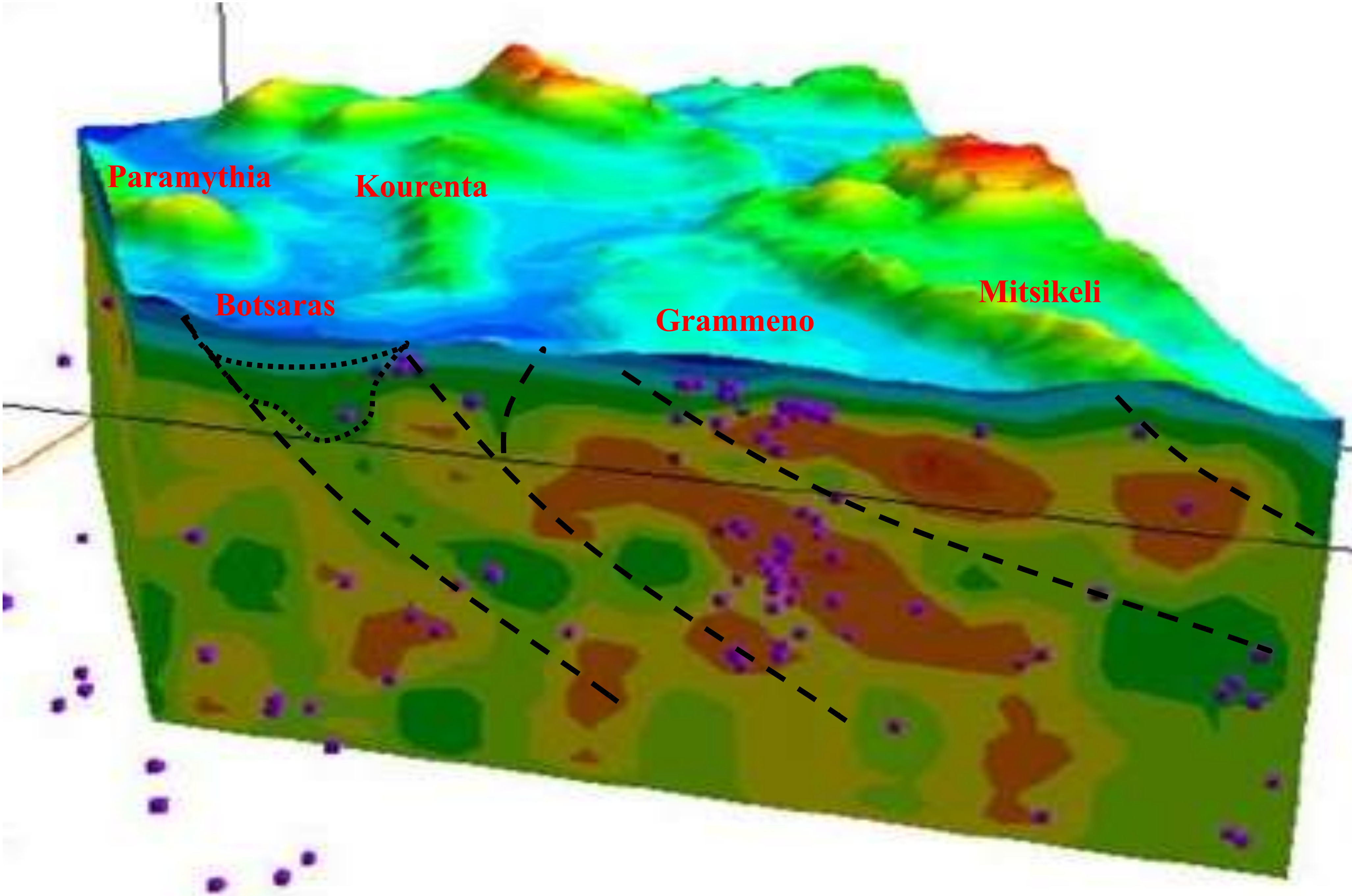
PST-Delvina Results (3D View Vp & Vp/Vs)



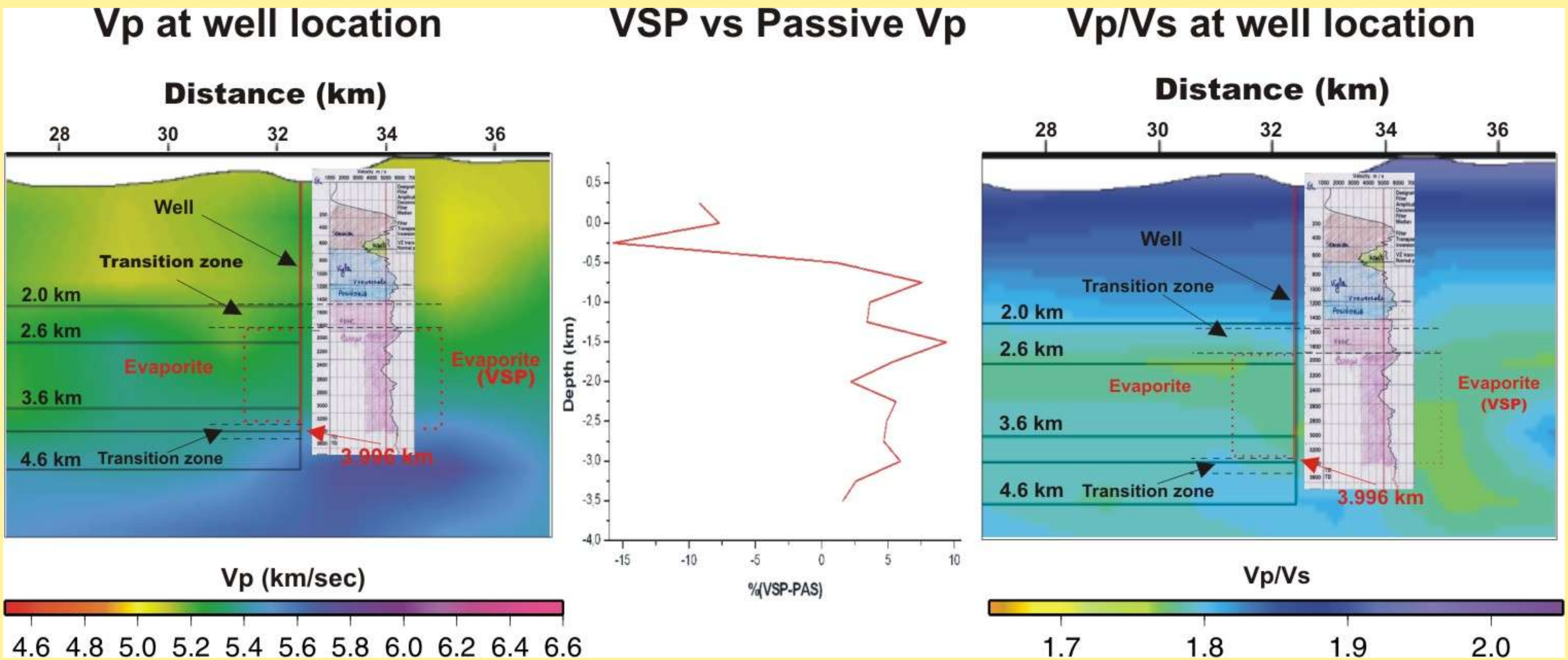


Passive Seismic Tomography – QC

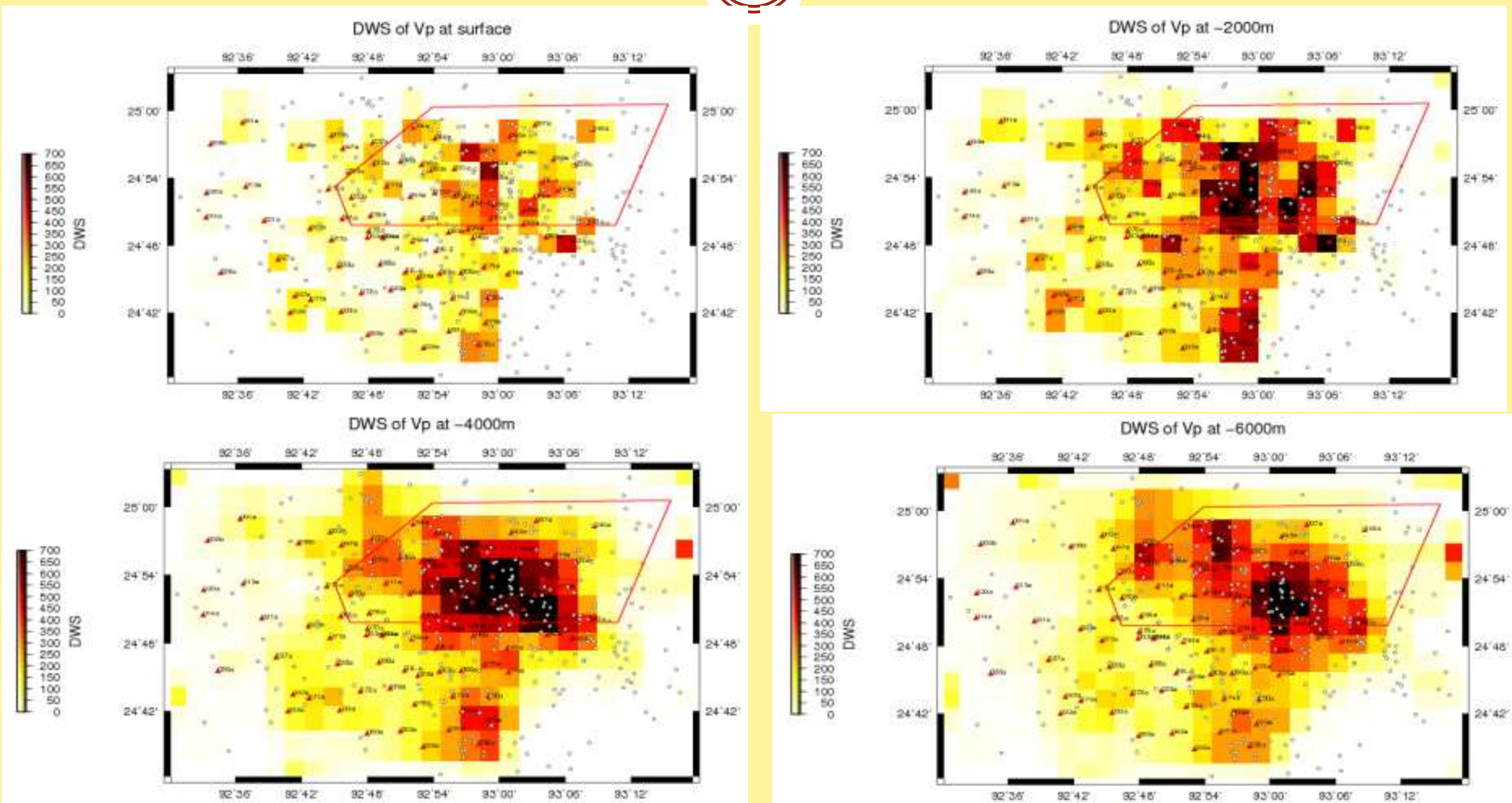
- Minimization of model and travel-time RMS residuals
- Comparison to local geology or well data if available
- Internal QC tests like ray density (DWS) or resolution matrix diagonal elements (RDE)
- Synthetic tests (i.e Checkerboard Test)


Paramythia
Kourenta
Botsaras
Grammeno
Mitsikeli

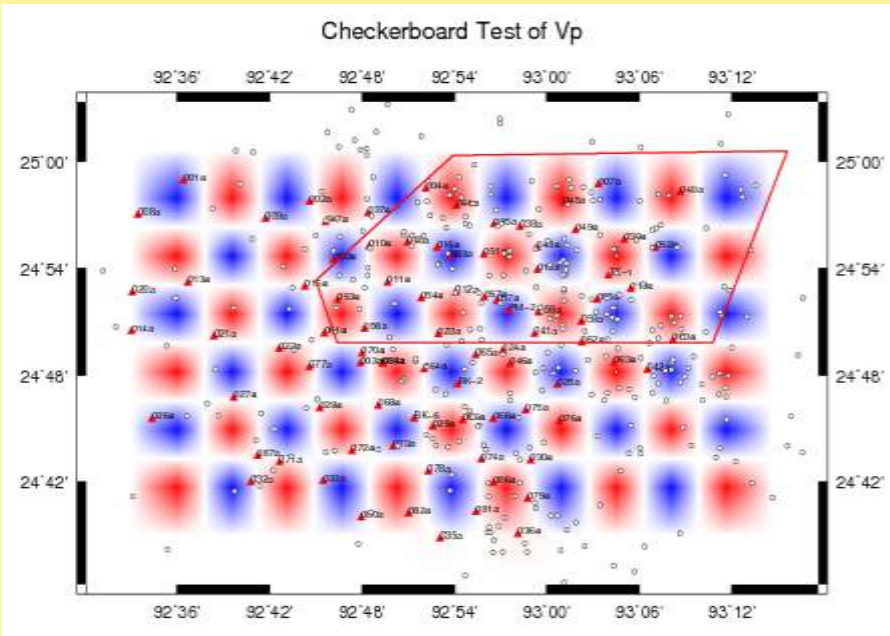
PST results QC - Comparison to Well Information

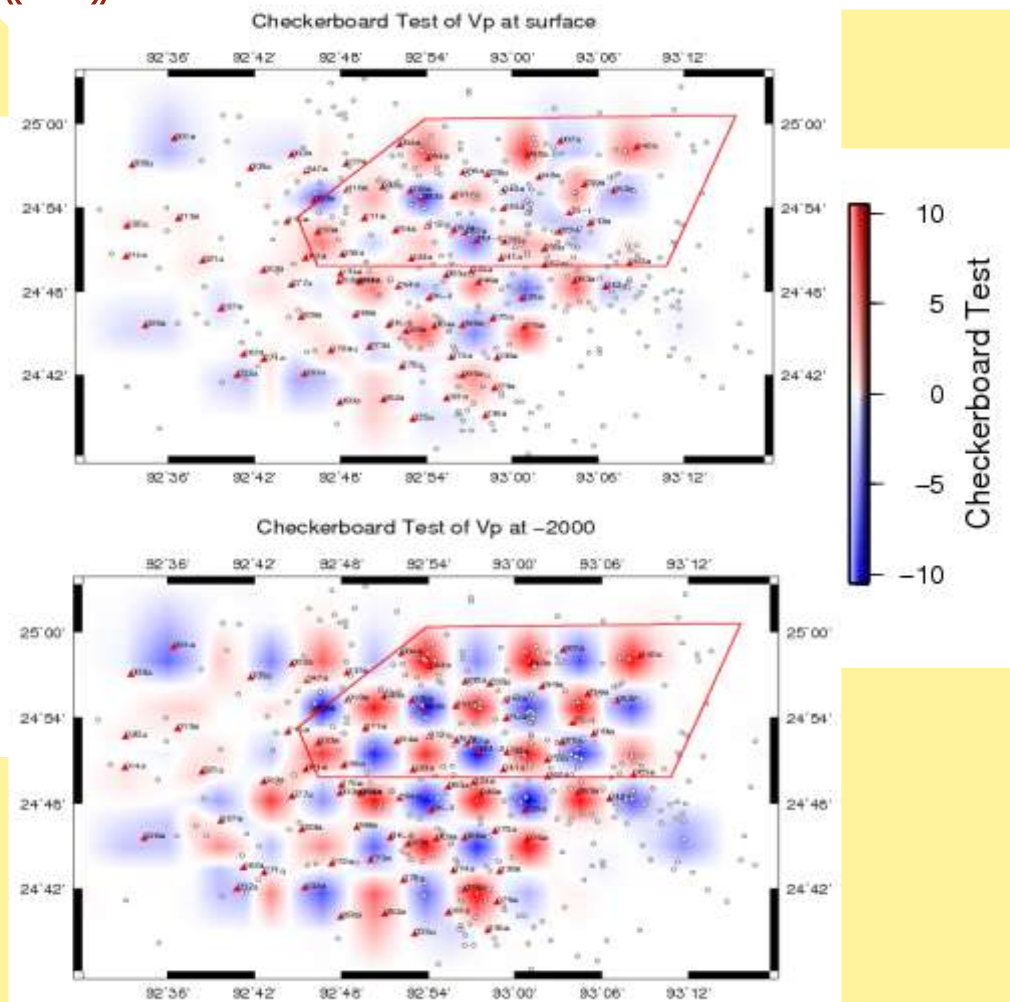


PST Results Quality Control: DWS of Vp (Ray Density)



PST Results Quality Control: Vp Checkerboard Test

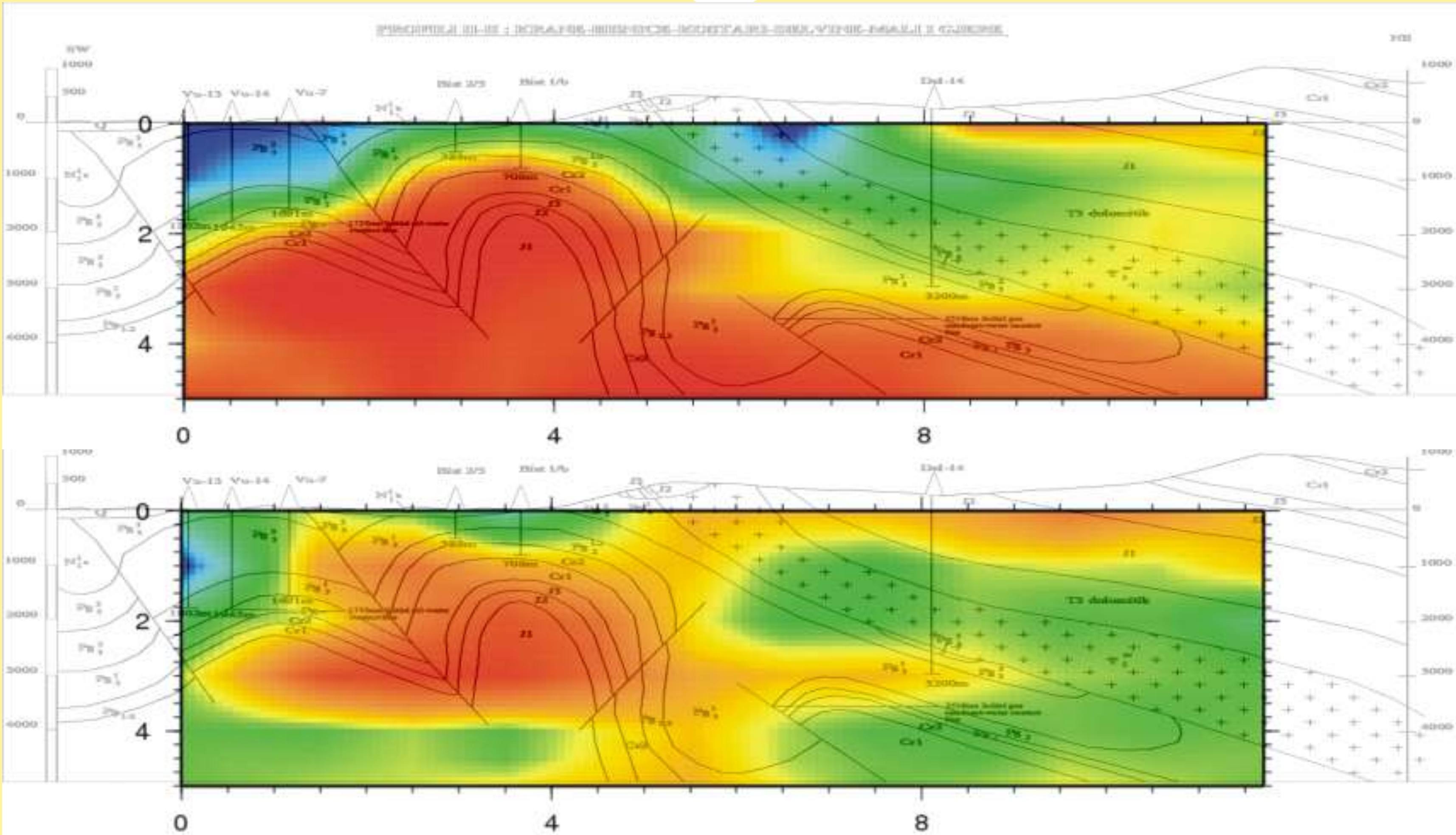




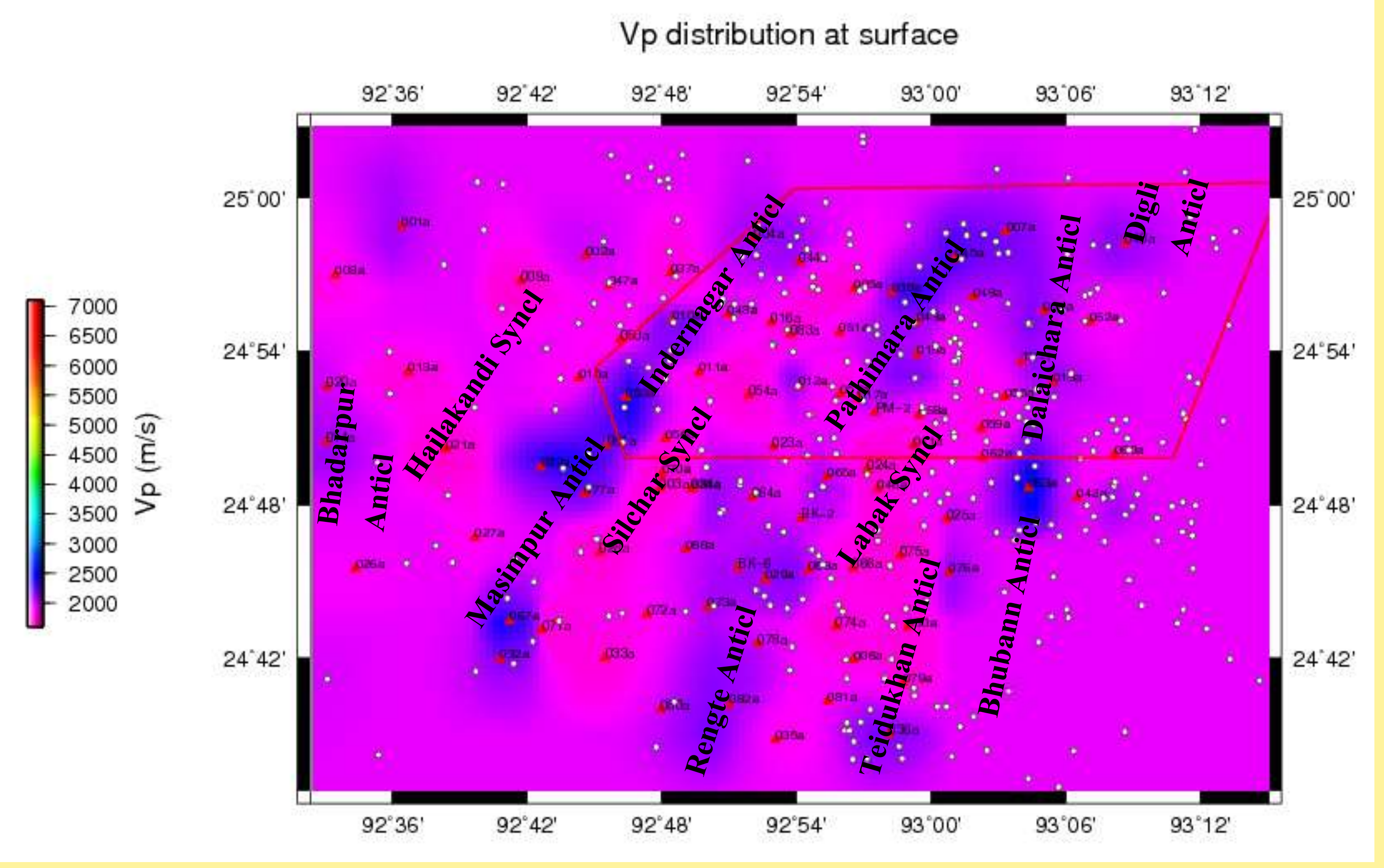
PST Interpretation/Integration

- Comparison/Calibration to local geology or well data if available
- Fault Characterization according to recorded Seismicity and PST 3D Models
- Structure identification and characterization according to Vp and Vp/Vs values
- Integrated processing and interpretation with existing Geophysical /Geological Data
- Reprocessing Low Quality Conventional Seismic based on PST Models

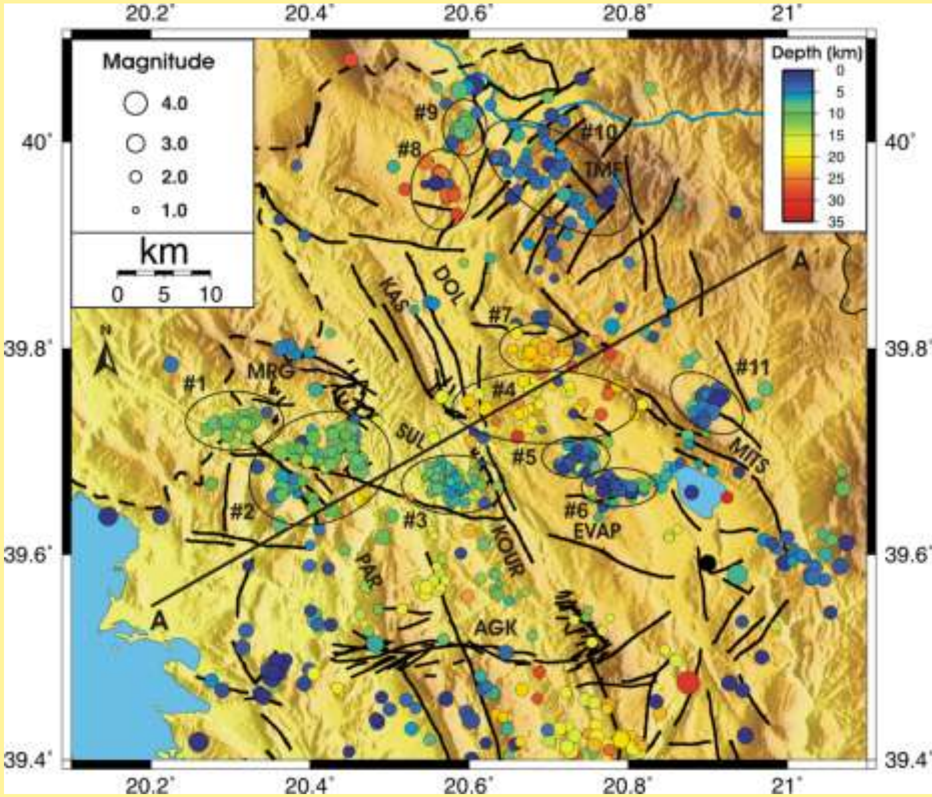
Geology & Well Info vs. PST results | Profile II (Delvina)



Local Geology vs. PST results | Assam (India)

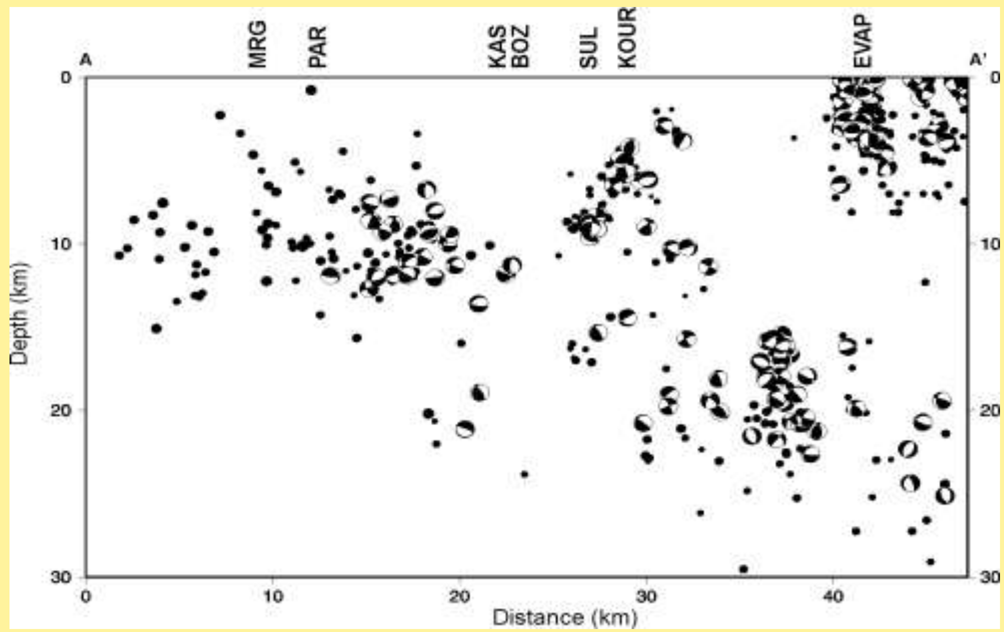


Event Distribution – Fault Identification/Characterization

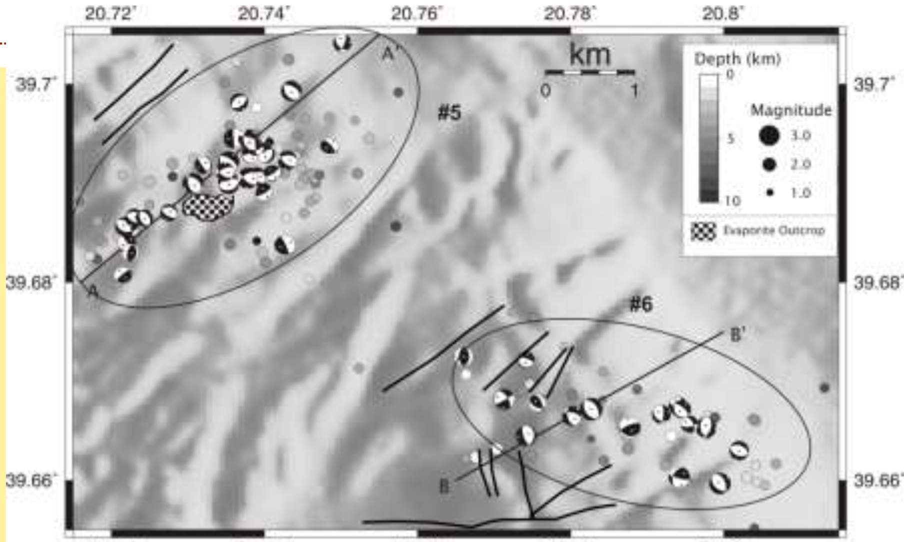


Global view of event distribution

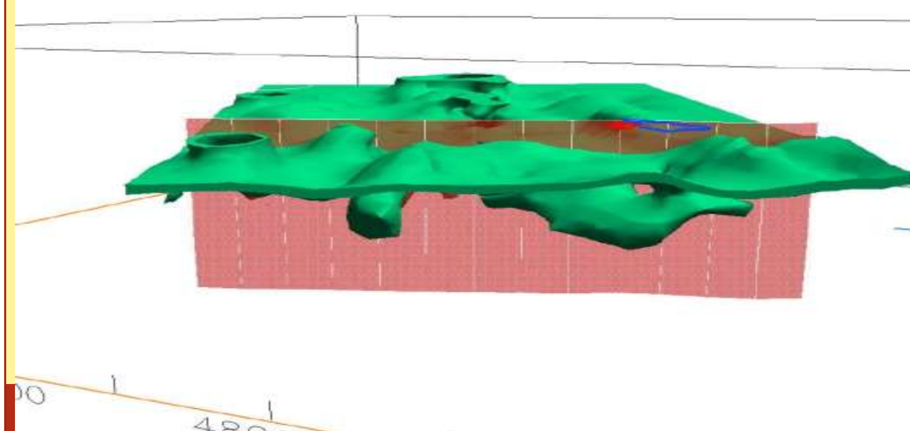
Depth distribution



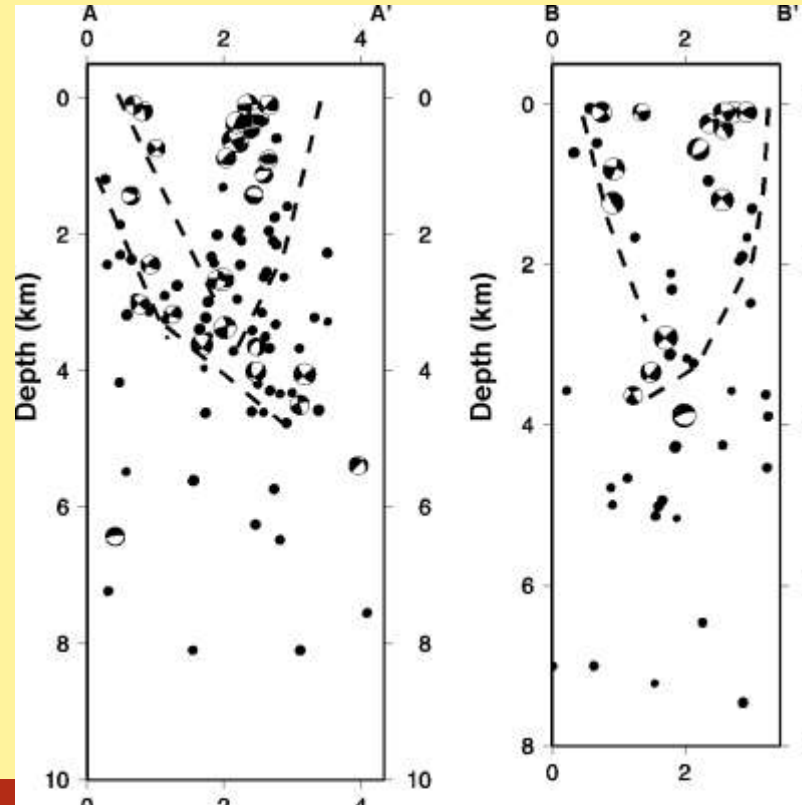
Focus on events around the evaporitic uplift



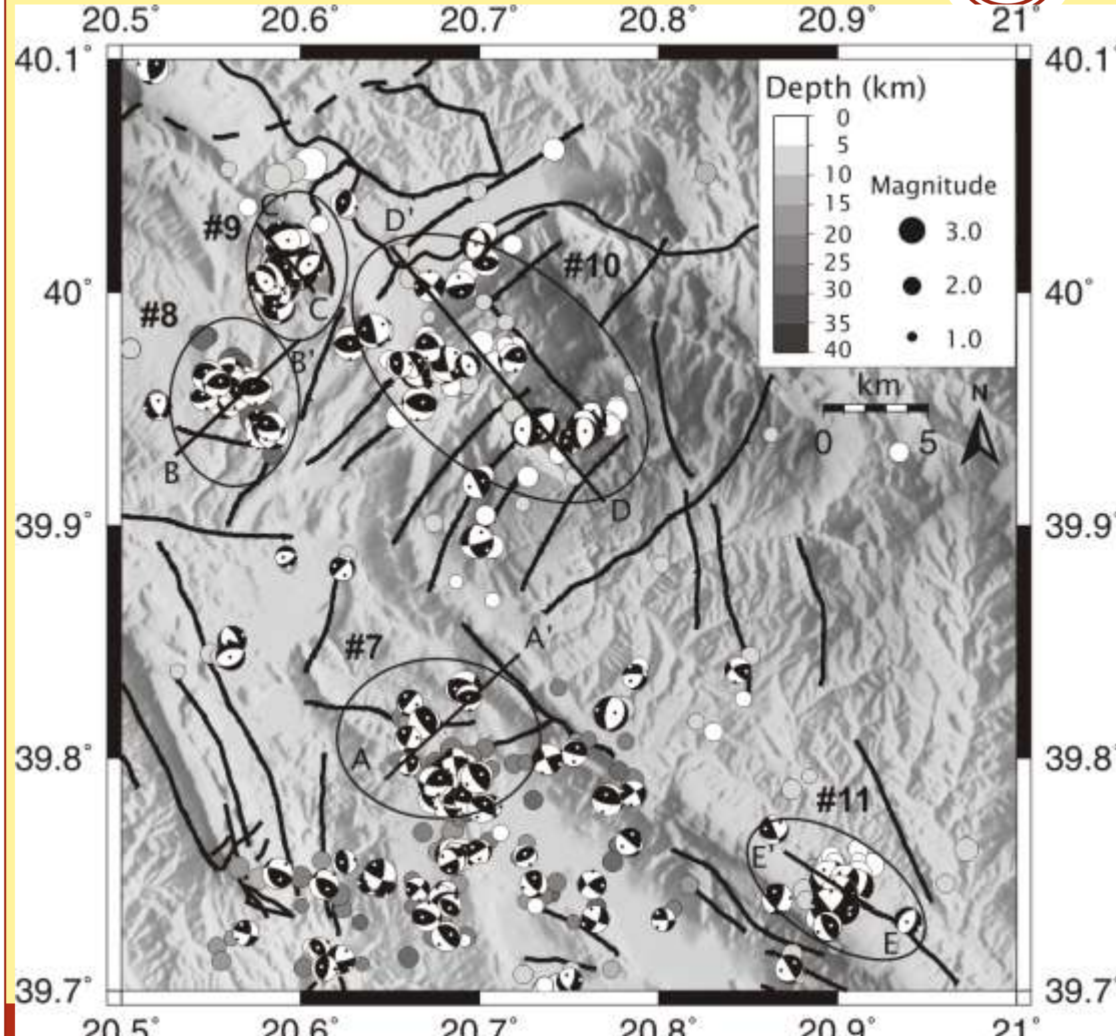
Vp=5.3 Km/sec
Lake, ENT97-04, view from SE



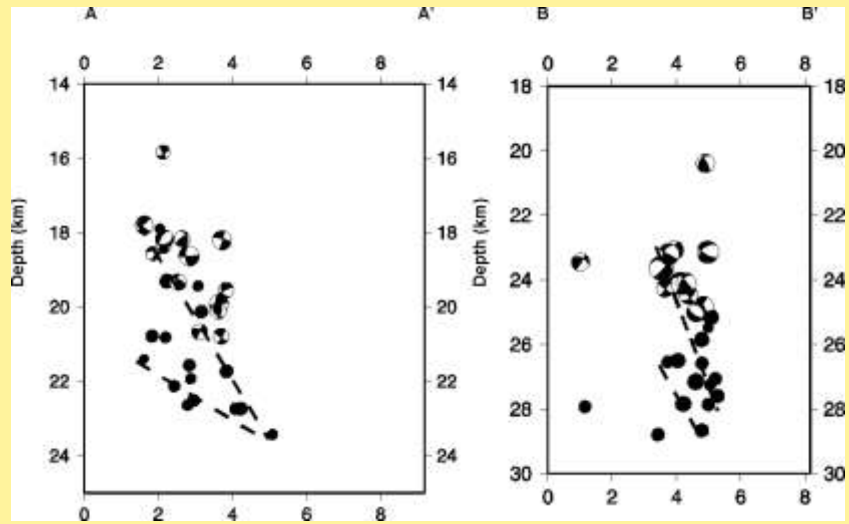
Normal Faulting



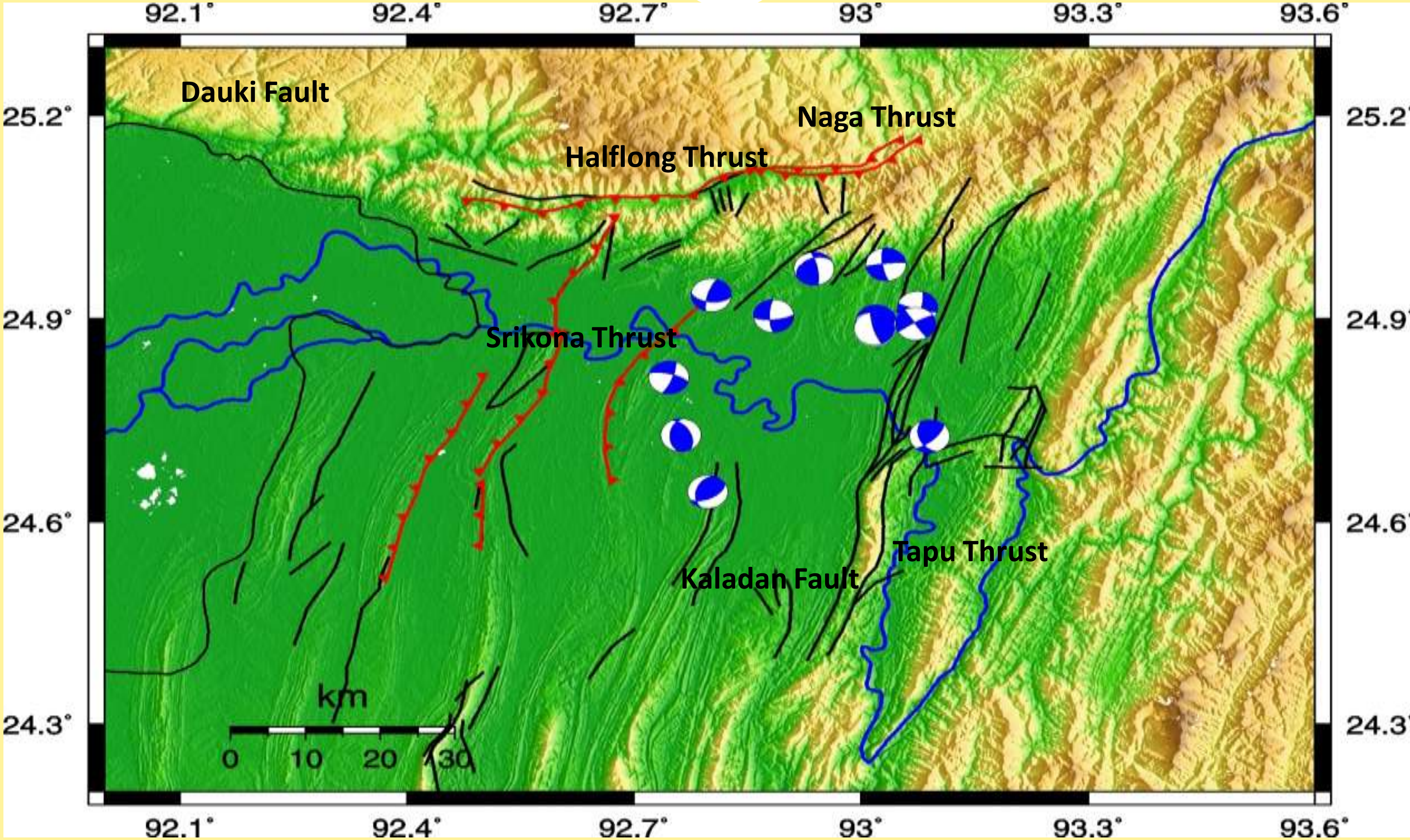
Deeper events associated with the thrust



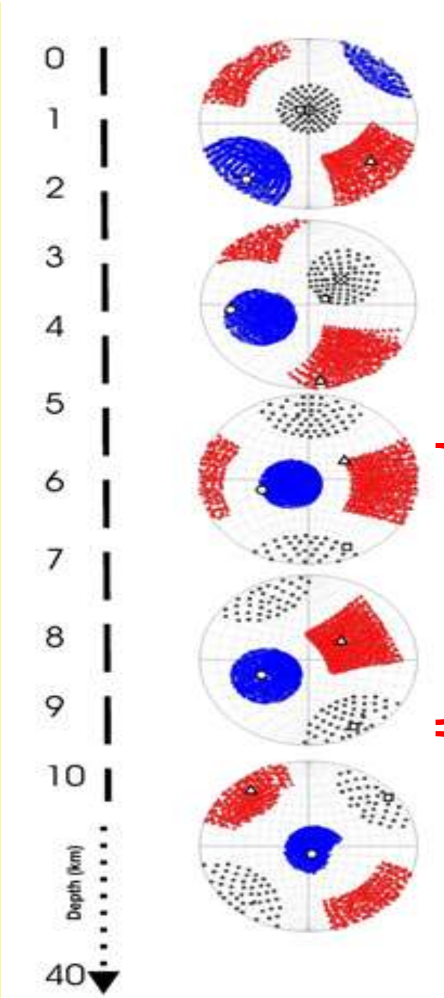
Reverse faults



Moment Tensors



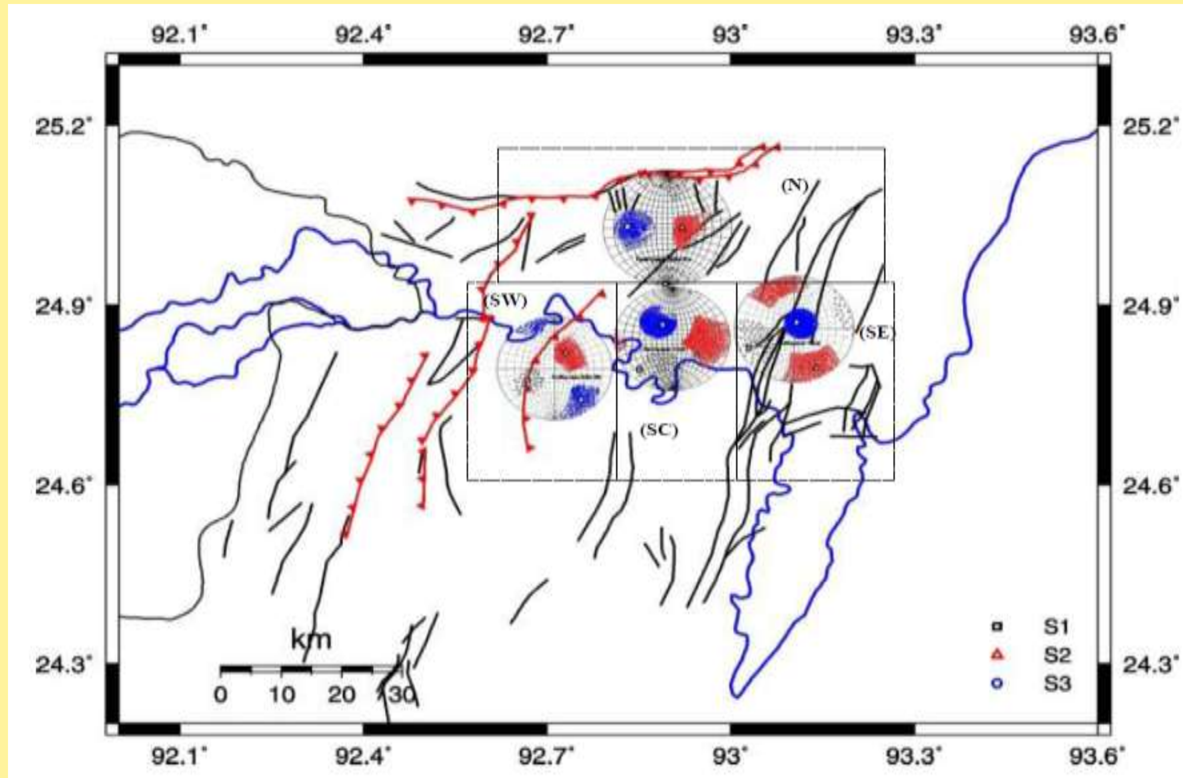
Stress Tensors - Depth & Spatial Distribution



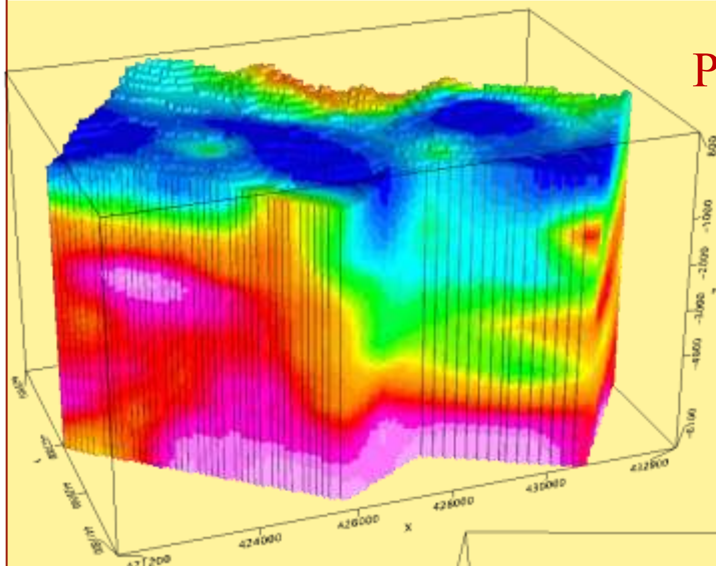
Normal

Complex setting of several fault types

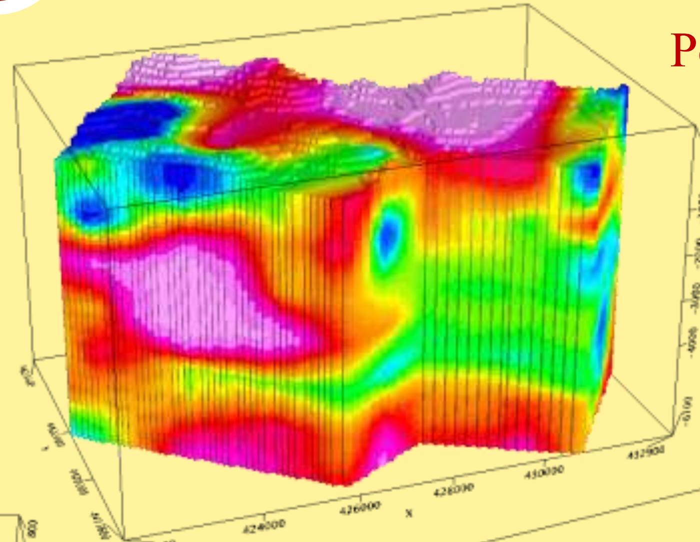
Thrust



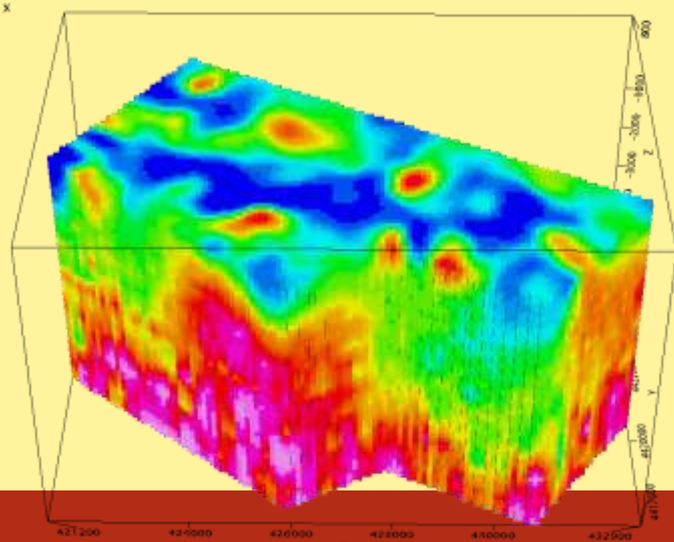
Latest Developments - PST– Gravity – MT Data Integration | Delvina Gas Field



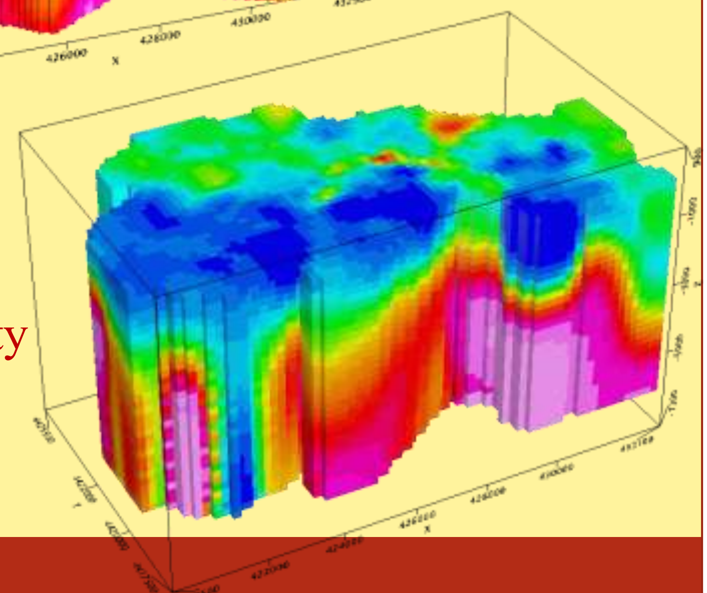
P-wave velocity



Poisson's ratio

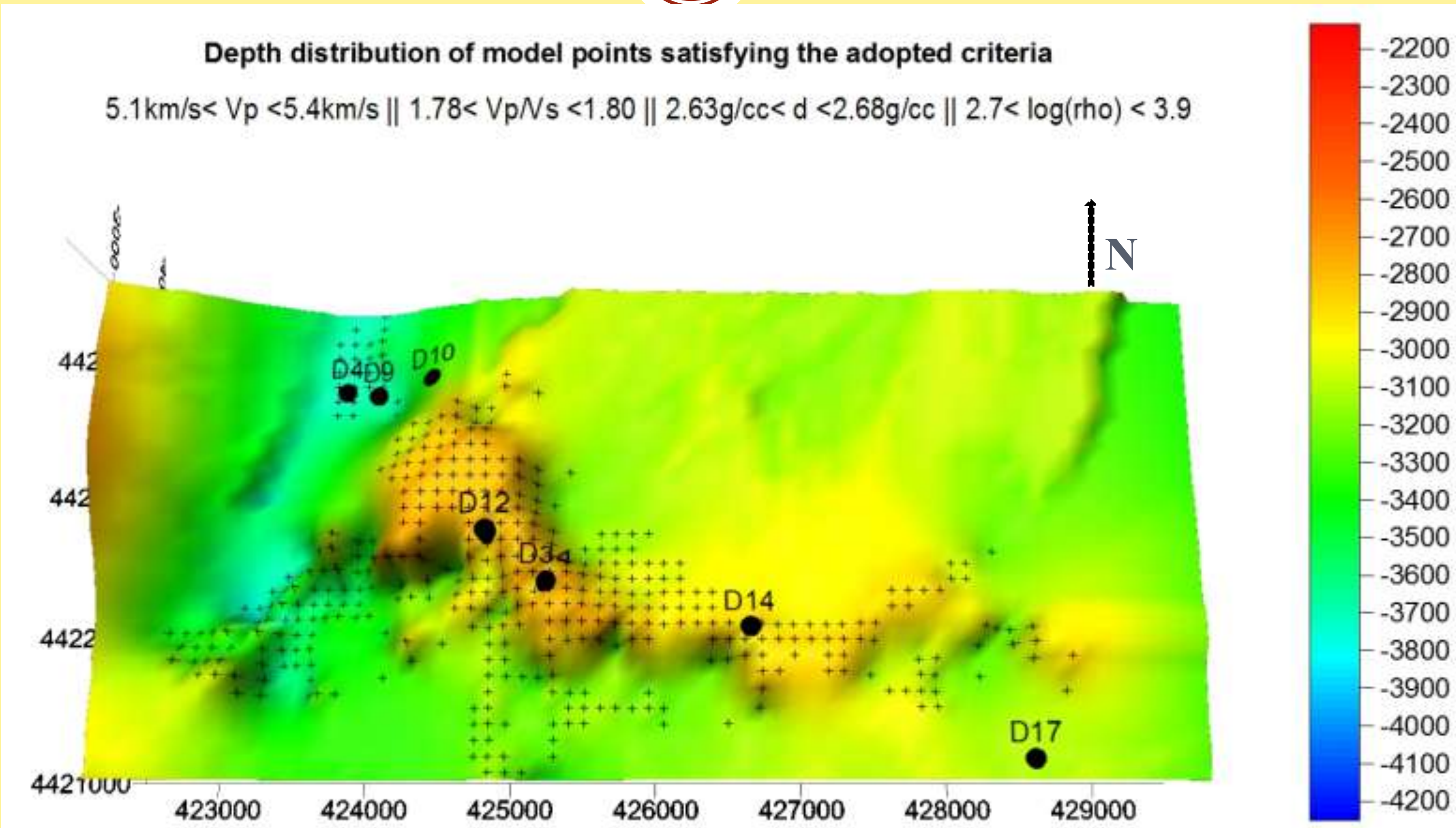


Density



Resistivity

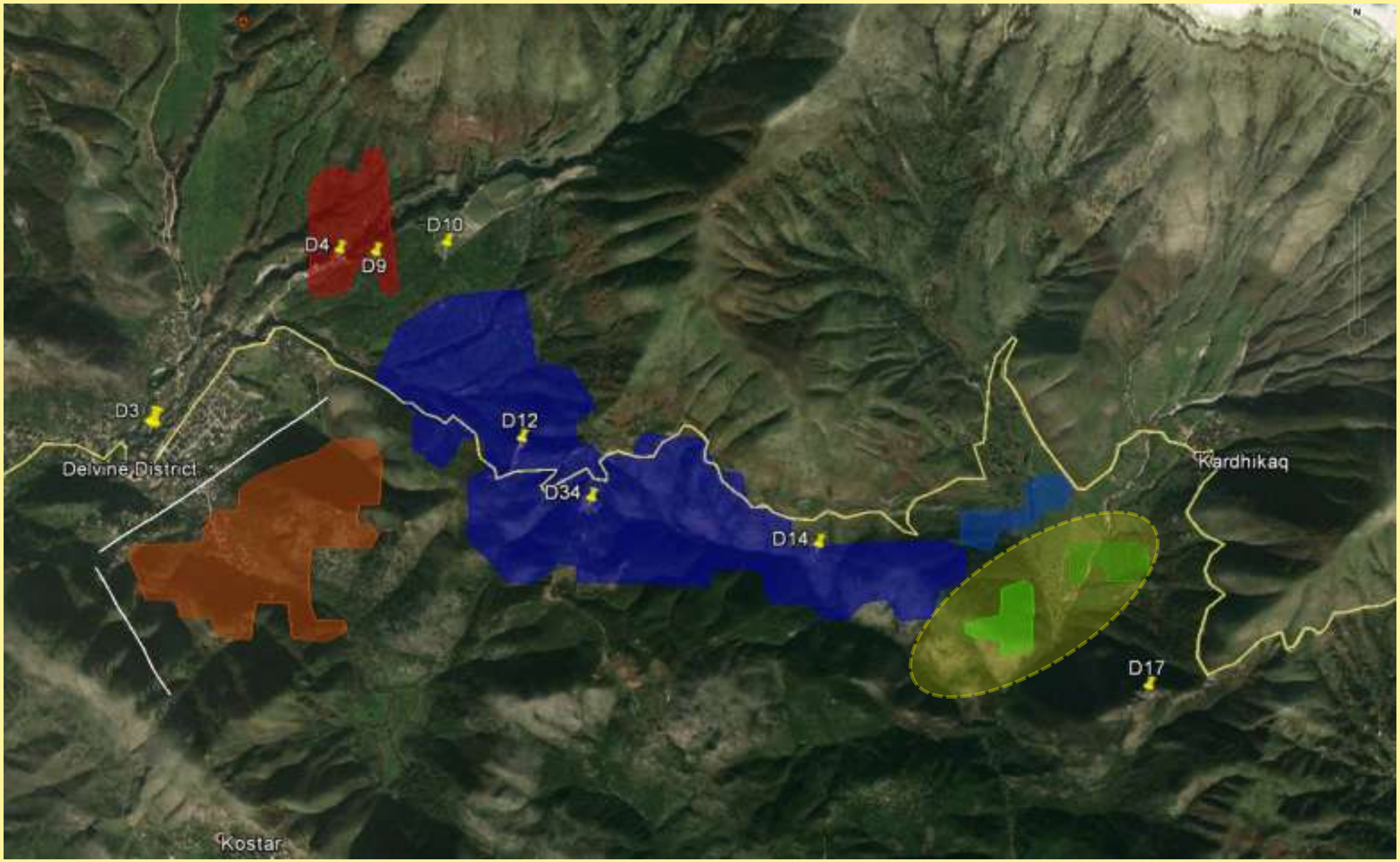
Passive Seismic Tomography – Gravity – MT Data Integration | Delvina Gas Field



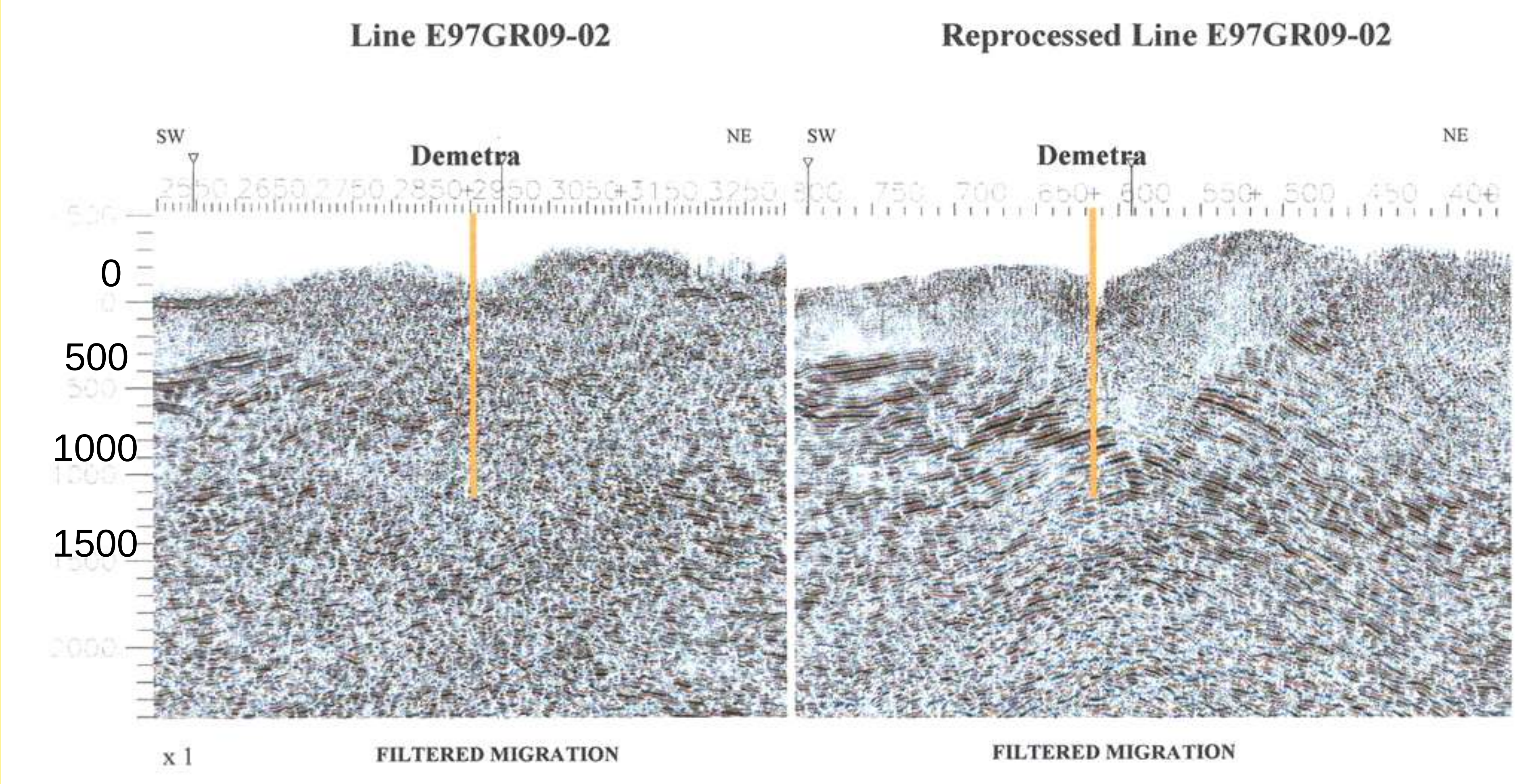
Selection Criteria: value ranges observed around a known productive horizon

Vp : 5.1 to 5.4km/s || Vp/Vs : 1.78 to 1.80 || Density : 2.63 to 2.68g/cm^3 || Log(rho) : 2.7 to 3.9-Depths below 2km

Passive Seismic Tomography – Interpretation Results (Delvina Gas Field-ALBANIA)

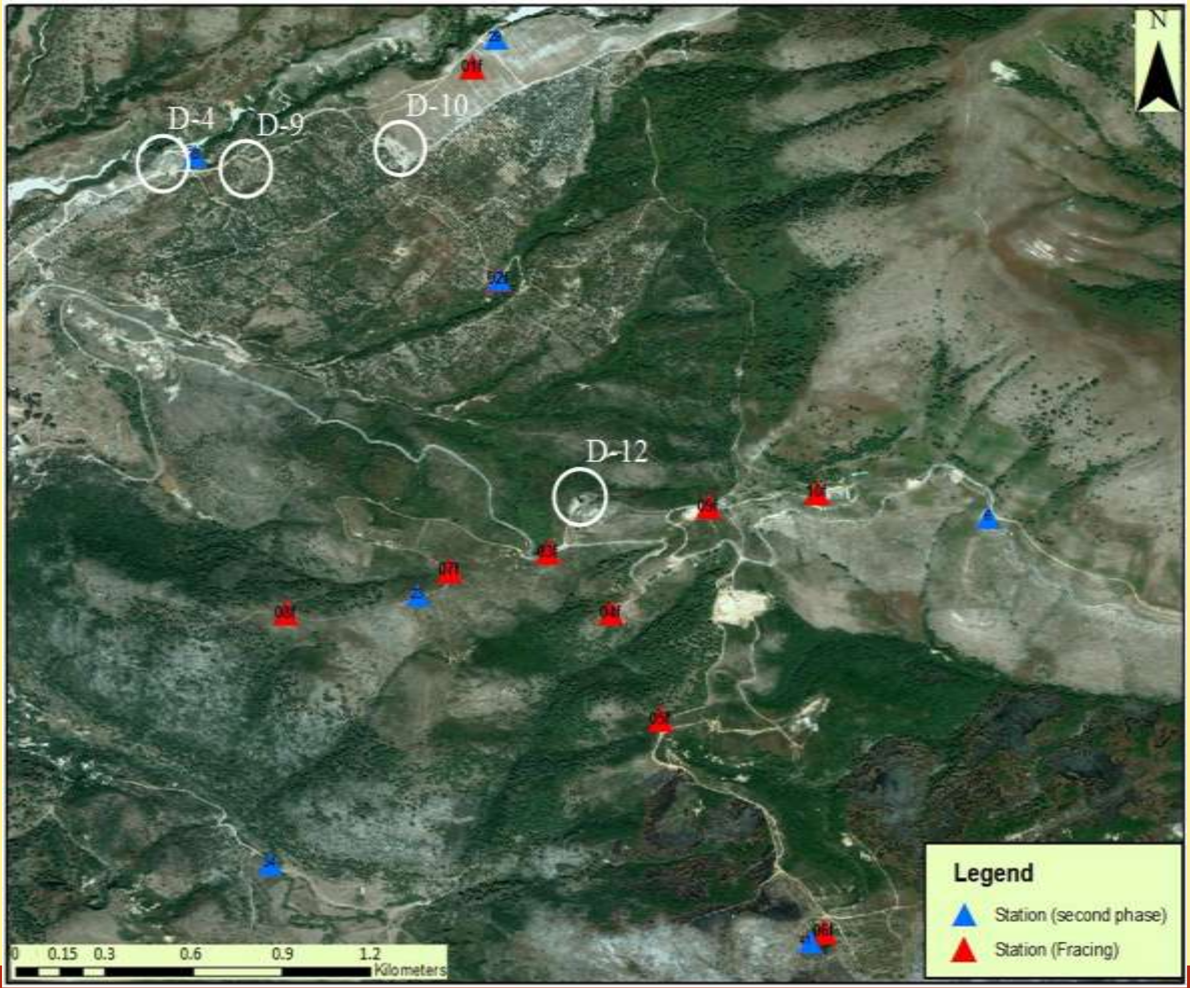


2D Seismic Data Re-processing



Reprocessing was based on the velocity model derived by PST

Fault Characterization – Reservoir scale / Delvina



Hydraulic Acid Fracing Monitoring

(using shallow borehole seismic sensors)

Injection performed in the well D-12

Injection depth:

2800-3100m (MSL)

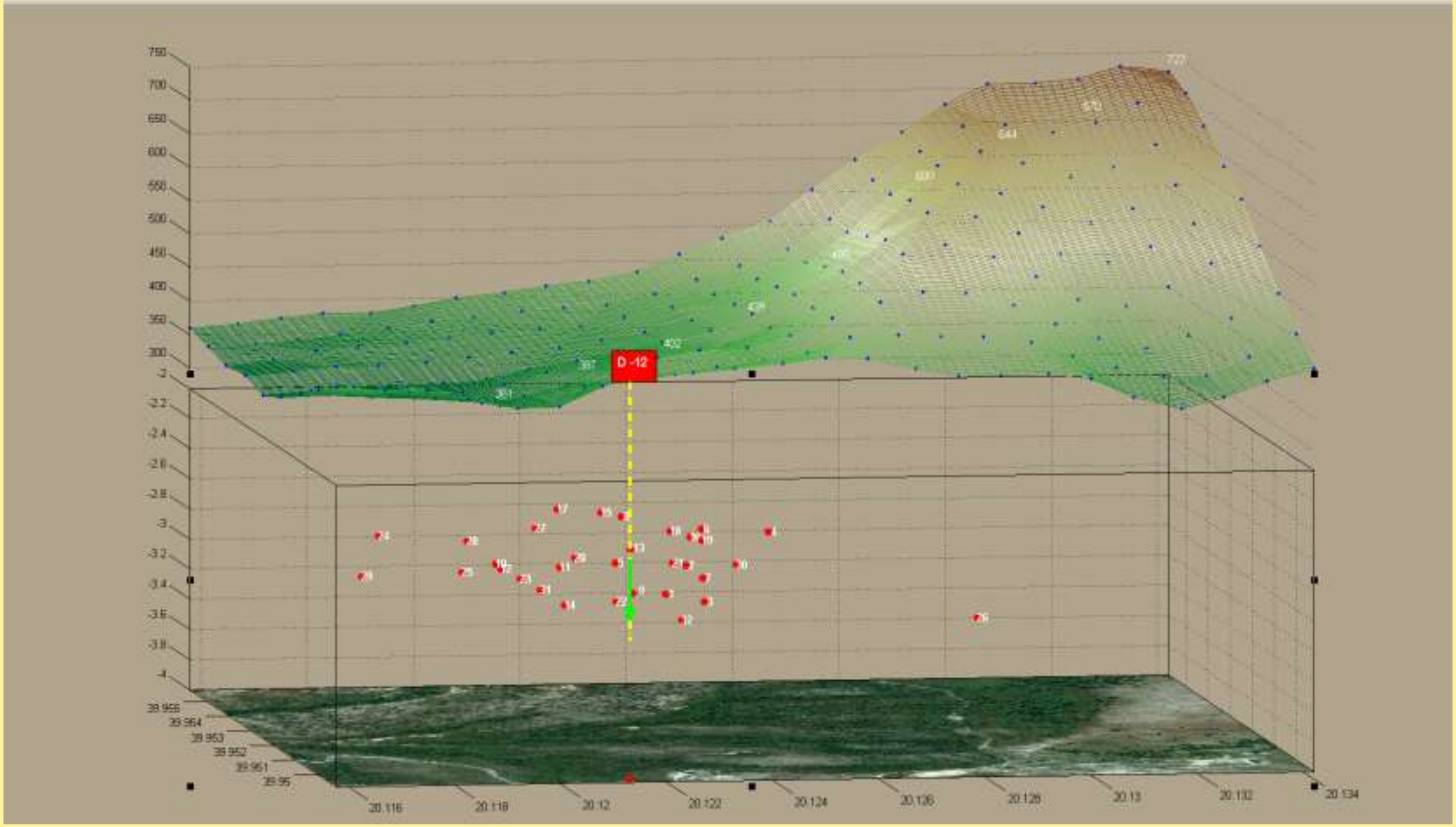
32 events recorded at the surface

Event Magnitudes: -0.25 to 2.3R

Event Depths: 2.5 – 3.1km below MSL

Events located using 3D Vp and Vp/Vs models deriving from PST

3D Event Distribution



Contents

Passive Seismic-Projects

Summary

...Going back to 2001 in Amsterdam EAGE Annual Meeting.....

.....People were wondering when they looked at our moto:

" USE EARTHQUAKES to FIND OIL"

Now after 13 years... PASSIVE SEISMIC is a very useful and common tool for E&P.....

SEIMOTECH/LANDTECH have done significant progress....

- **EQUIPMENT**
- **SOFTWARE**
- **DESIGNING/ACQUISITION/PROCESSING/INTERPRETATION**

....and with the experience from our projects.....we are ready for any new challenge!!!!!!!!!!

SeismoTech
Geophysical Solutions

Thank you !!!!!