Geophysical characterization of the shallow subsurface in sites P2 and P3 from high-resolution active-source seismic profiling and downhole data

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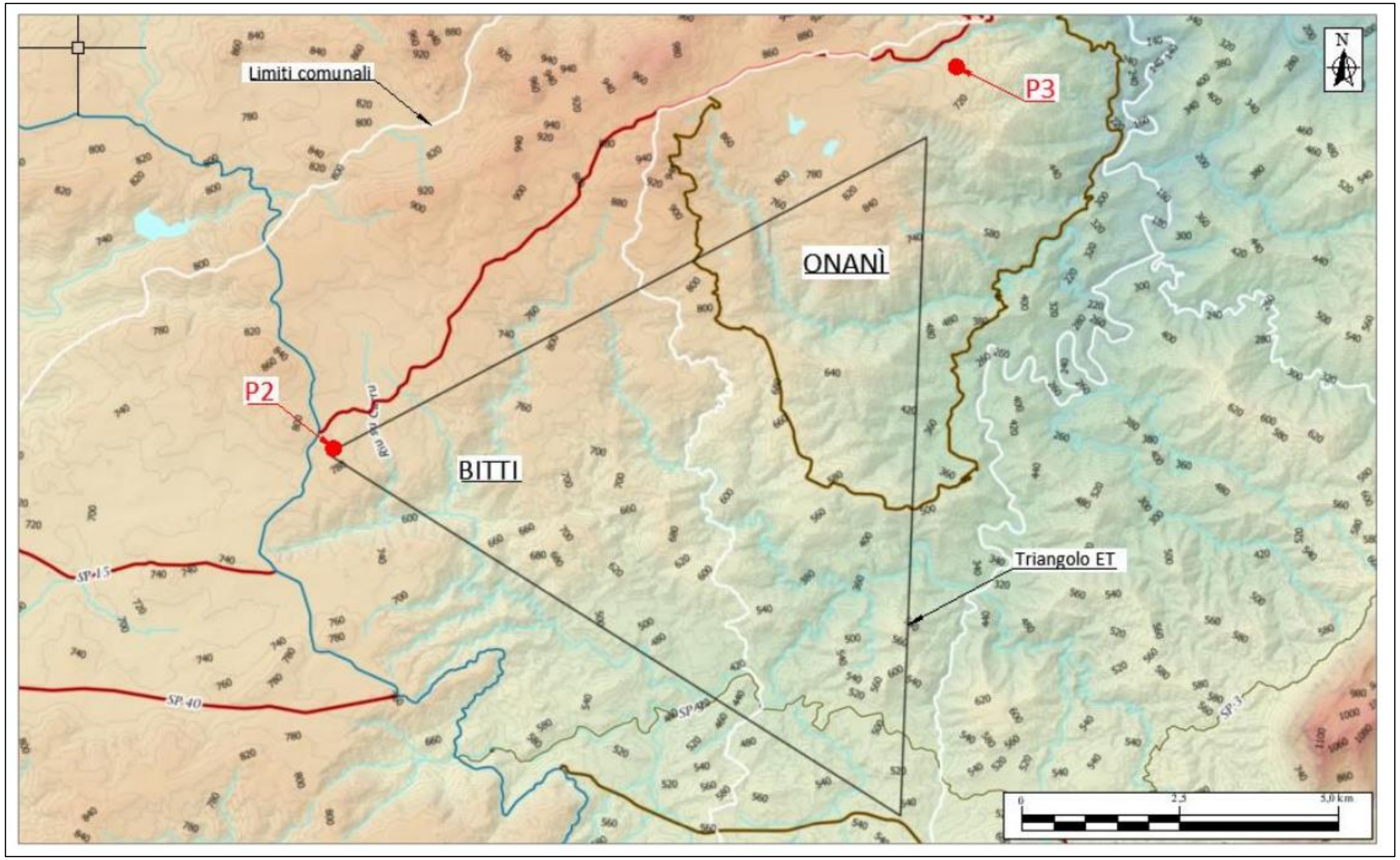
In the framework of the Project Einstein Telescope Sos Enattos, we report the results of the active-source seismic surveys performed by the INGV team in drilling sites **P2** and **P3** in July and September 2021.
The main goal of these surveys was the reconstruction of the shallow subsurface velocity structure surrounding the two drilling sites P2 and P3.

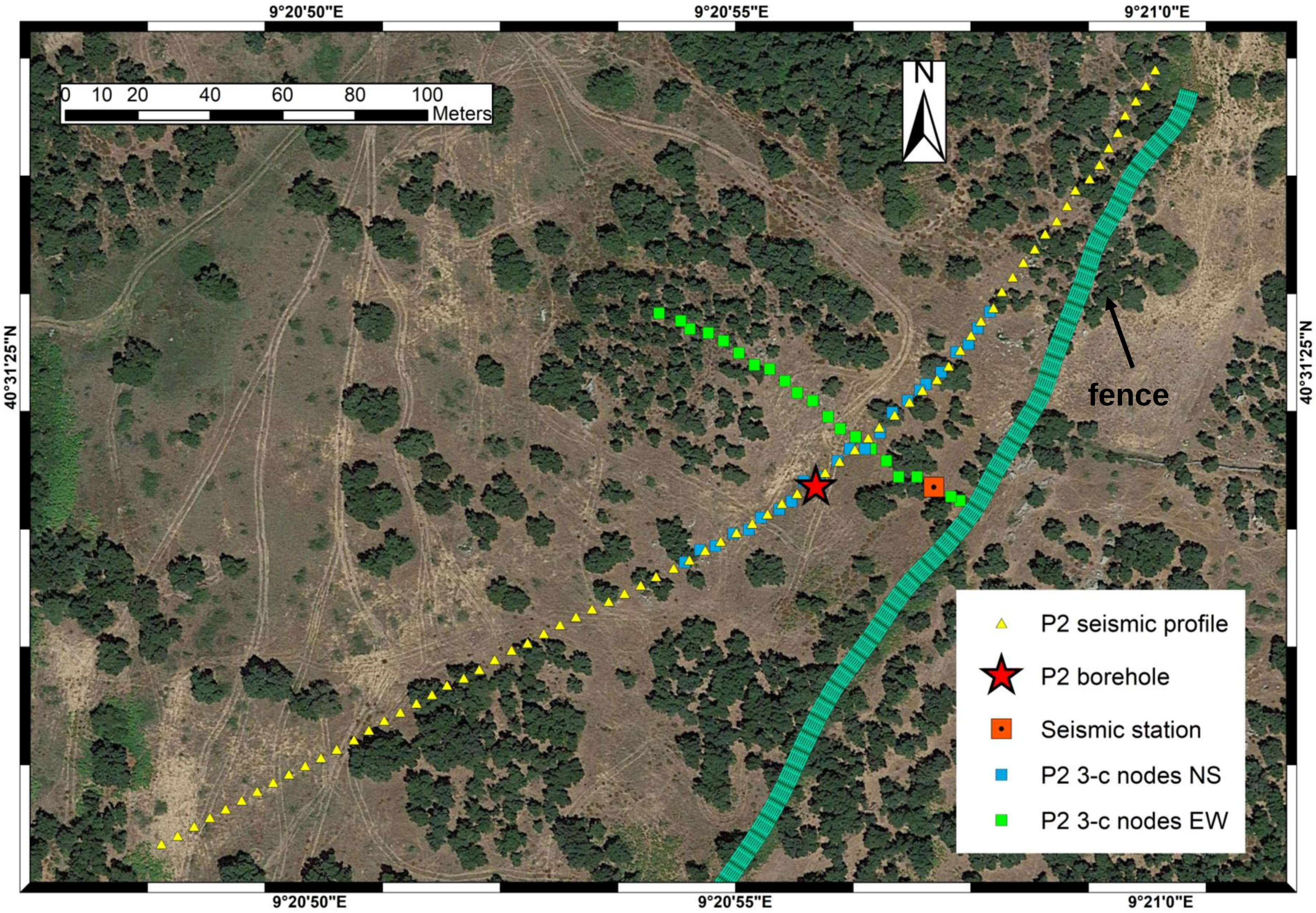
We combine **seismic refraction tomography** and **downhole** measurements. We also performed analysis of seismic reflection data.



INGV-INFN Agreement (Technical Annex, Activity n. 2)

The aim of the Agreement was the collection of active seismic data to estimate the elastic properties of the two drill sites P2 and P3 to support the design of the Einstein Telescope infrastructure.

1. Refraction/reflection seismic profiling
2. Borehole vertical seismic profiling
3. Combined interpretation of seismic images and vertical velocity profiles, and comparison with data collected by other teams (ERT surveys, field structural surveys)



Site P2
location map and seismic surveys

Unfavourable local logistical conditions hampered the acquisition of two long (> 350 m) and intersecting seismic profiles.

Thus, we have collected:

1 high-resolution seismic profile
1 vertical seismic profile (downhole)

Instruments deployed by other teams:
2 linear arrays of 3-c nodes (**K.I.T.**)
1 broadband station (**INGV-Pisa**)

Site P2:
active-source seismic data

All the available space in the site was used.
It was not possible to deploy profiles > 360 m long

Seismic Profile	
Source	**Minibang**
N° Sources	39
Sources spacing	10 m
N° Geophones	72
Geophones spacing	5 m
Profile lenght	360 m
Total traveltime readings	2,520

Vertical Seismic Profile	
Source	**Minibang**
N° Sources	100
Maximum depth	234 m
Acquisition interval	2-4 m

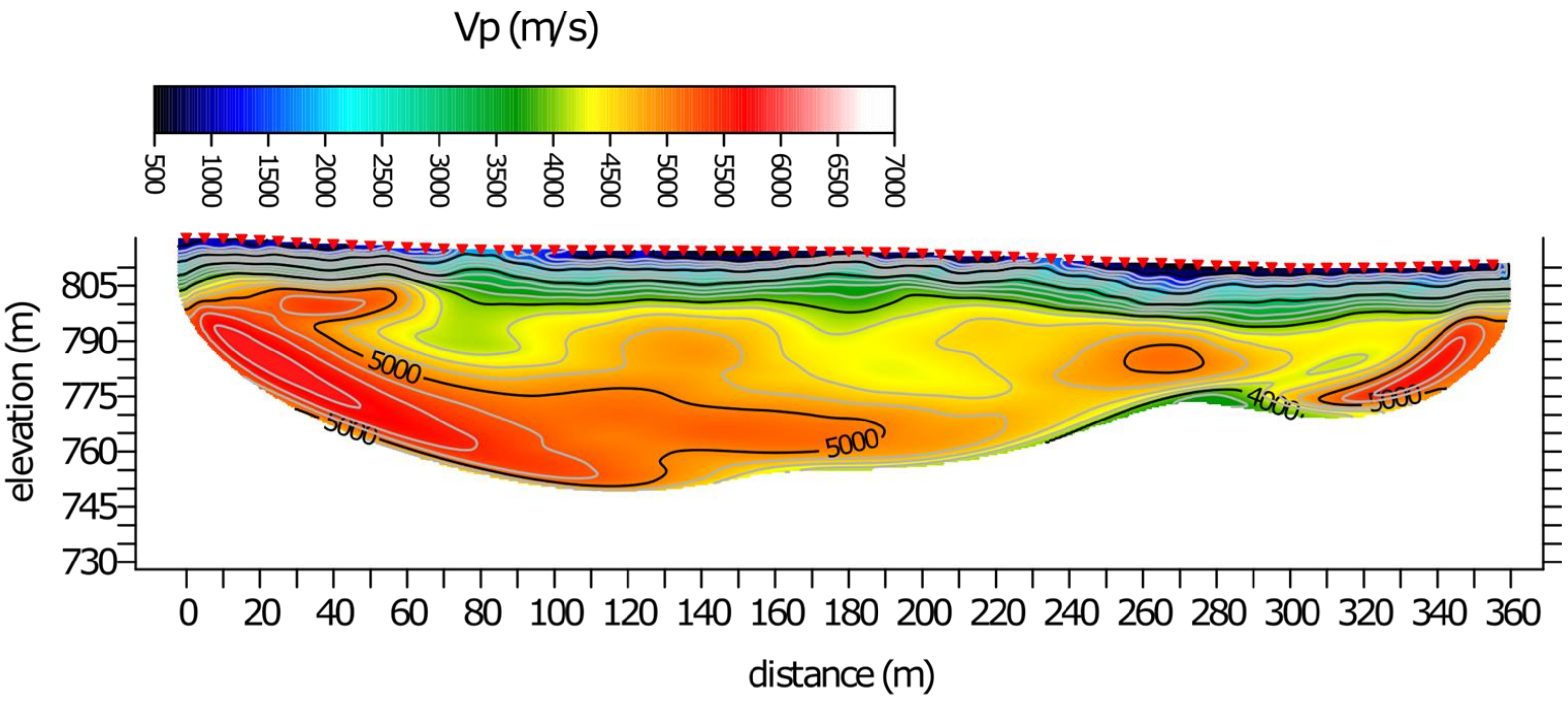
Seismic profile Site P2: active seismic survey

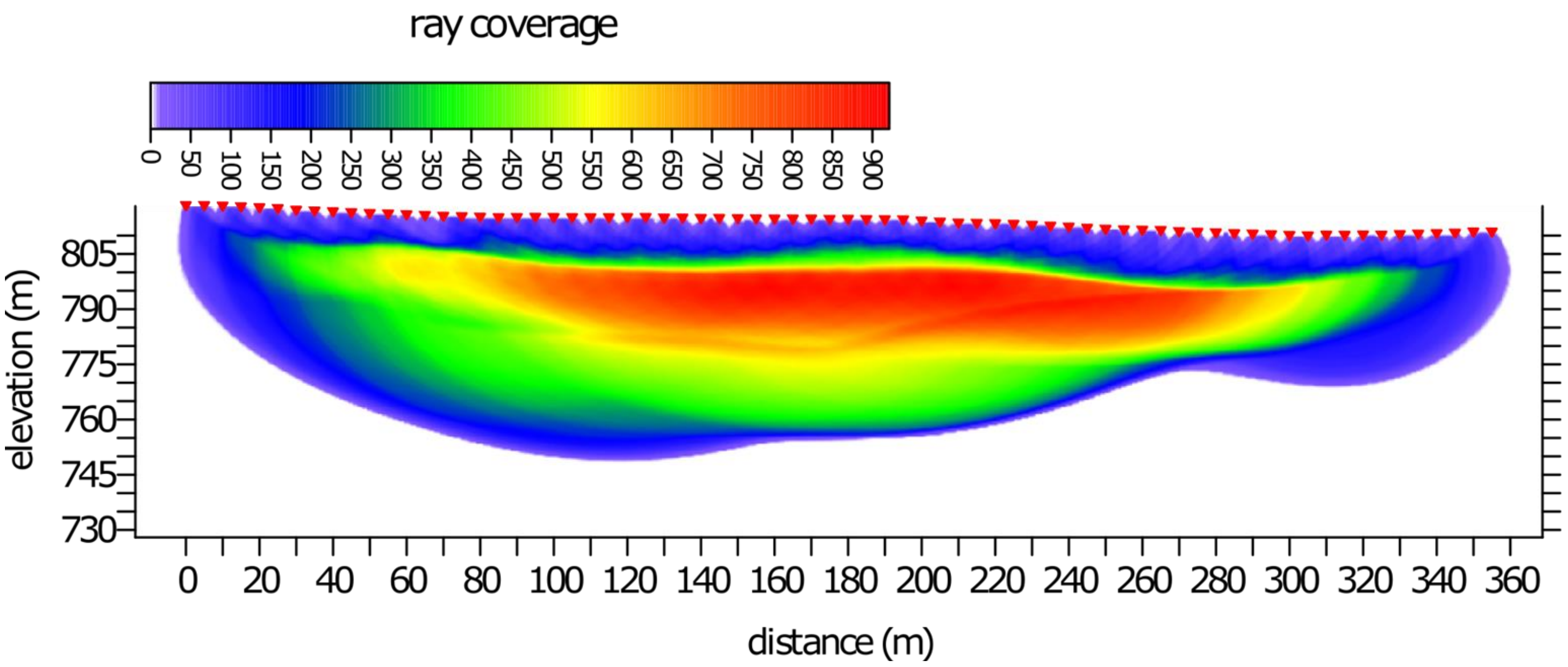
REFRACTION TOMOGRAPHY approach 1 (Rayfract© commercial code)

- Inverted dataset: 2,520 first arrival traveltimes (hand-picking; average uncertainty: 1.26 ms)
- smooth gradient starting model (from horizontally averaging 1-D profiles)
- model refinement through Wavepath Eikonal Tomography (WET[1])
- Advantage: fast determination of best-fit Vp model

Final model + ray coverage (100 iterations)
RMS of traveltimes residual: 1.89 ms

maximum investigation depth: about 50-60 m



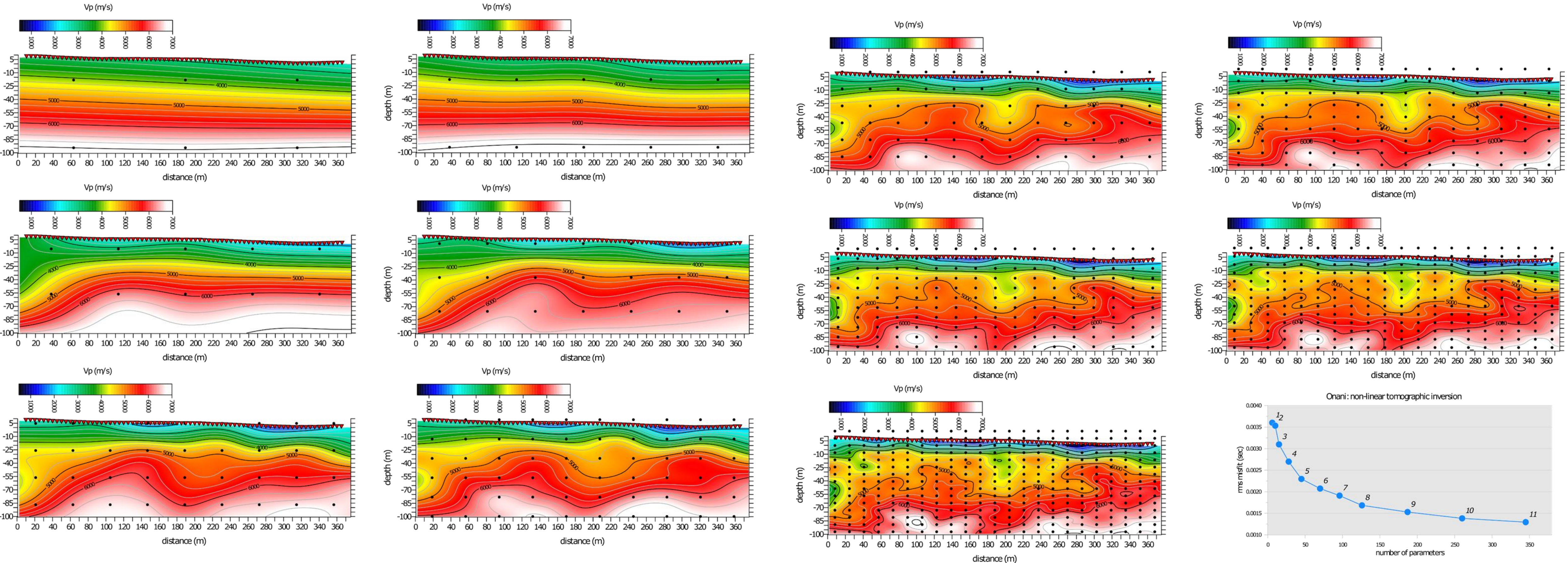


1 Lecomte, I. et al., (2000). Geophysical Prospecting, 48(3), https://doi.org/10.1046/j.1365-2478.2000.00201.x
Schuster G.T, and Quintus-Bosz, A. (1993). Geophysics, 58(9) https://doi.org/10.1190/1.1443514

Seismic profile Site P2: active seismic survey
REFRACTION TOMOGRAPHY approach 2 (Invdfe code: developed by University of Naples/INGV)

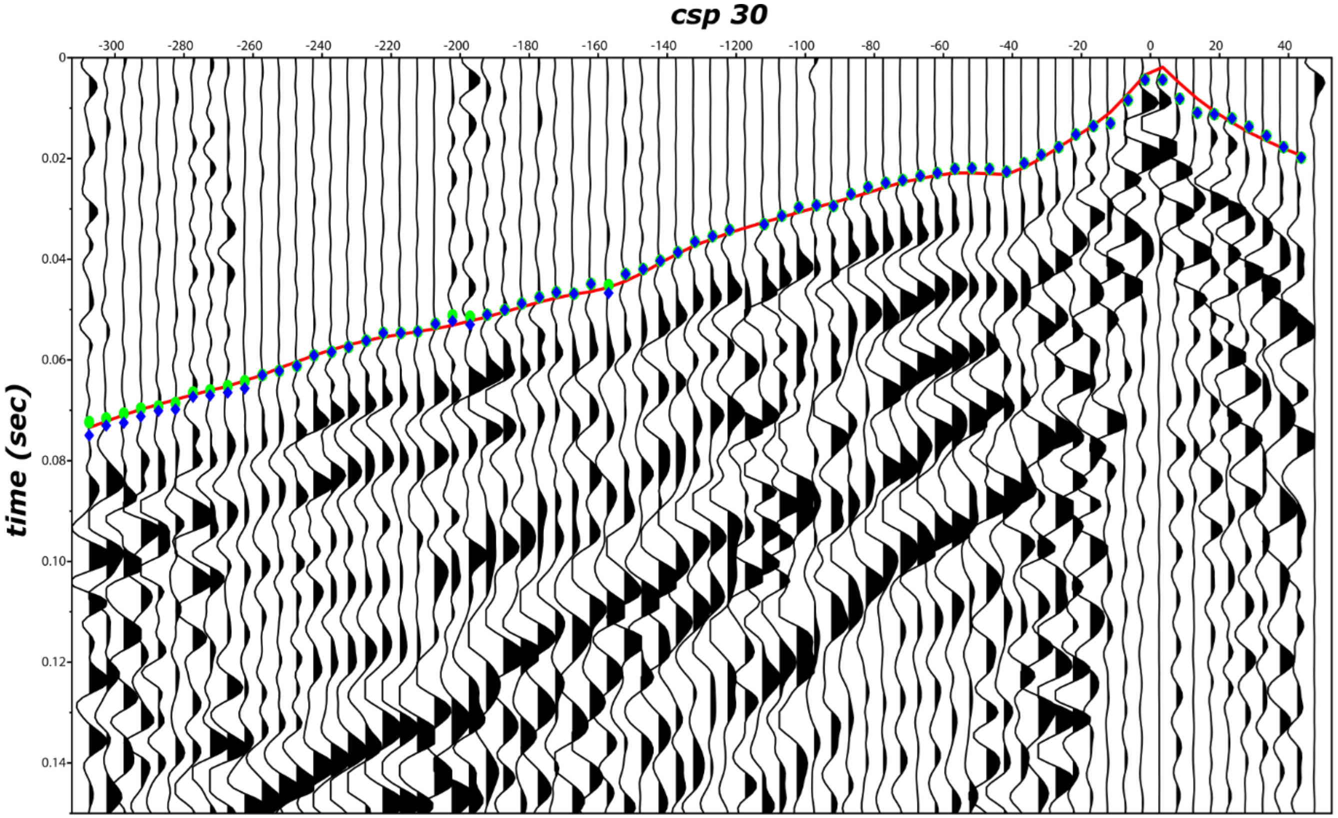
- Inverted dataset: 2,351 first arrival traveltimes (hand-picking; rms uncertainty: 1.26 ms)
- non-linear inversion of first arrival traveltimes (no reference starting model)
- non-linear optimization scheme: global-random search + local search
- multi-scale inversion strategy
- forward problem: high-precision finite-difference Eikonal solver (no raytracing) with modelling of direct, refracted and diffracted phases
- model appraisal: ray-density plots + checkerboard resolution tests

Effective for crustal-scale and near-surface imaging of strongly heterogeneous or contrasted structures (i.e., fault-zones, weathered layers)

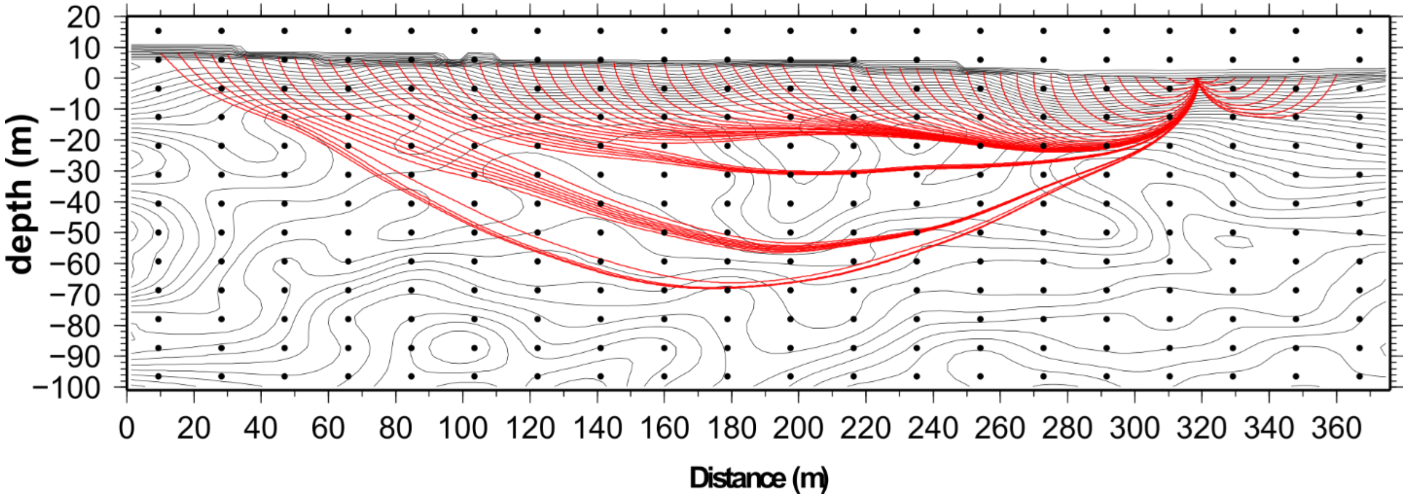


Seismic profile Site P2 : active seismic survey

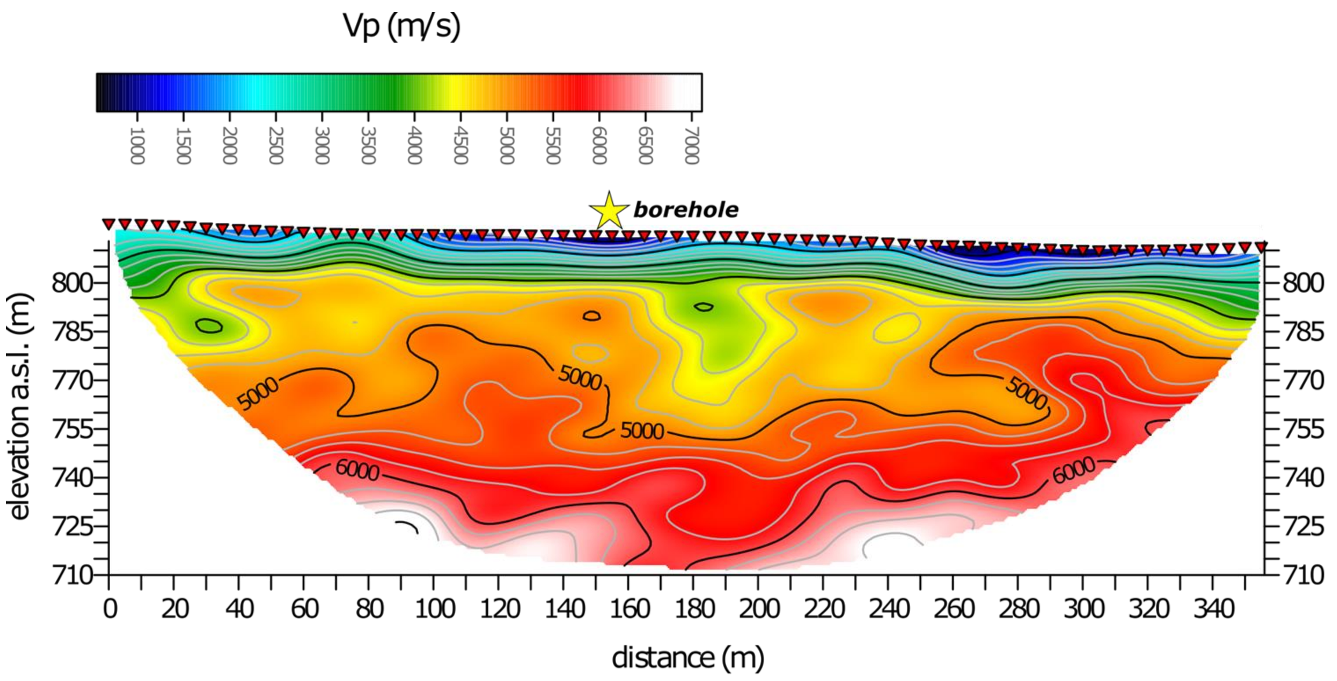
Non-linear refraction tomography: seismic data and synthetic traveltimes



Example of Common Shot Gather (CSG #30, low-pass filter 150-200 Hz) with manual picking and computed traveltimes



Example of back-raytracing for CSG #30

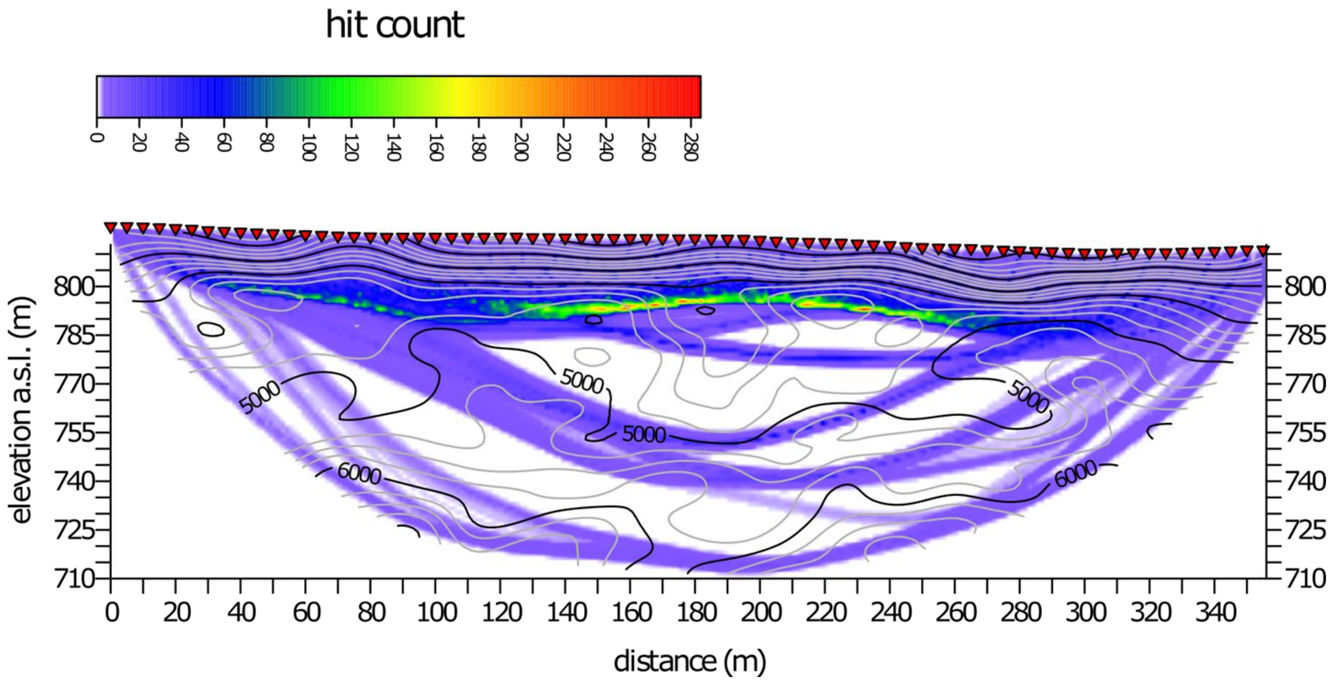


Seismic profile Site P2: active seismic survey

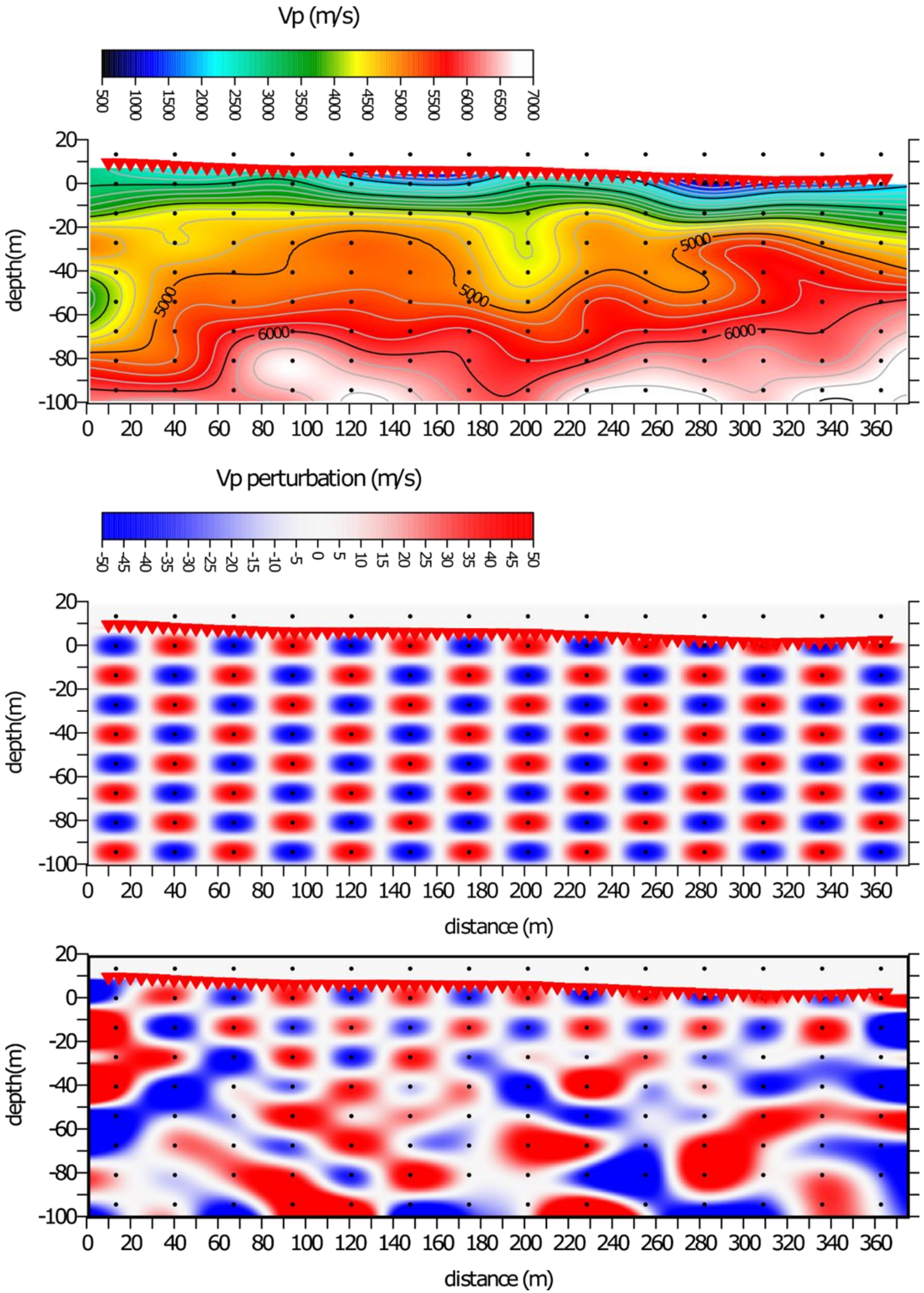
Non-linear refraction tomography

Final best-fit model

- 11 inversion steps
- RMS of traveltimes residual: 1.29 ms
- 345 inverted parameters
- maximum investigation depth: about 90 m



Final model: ray coverage



Seismic profile Site P2 : active seismic survey

Non-linear refraction tomography

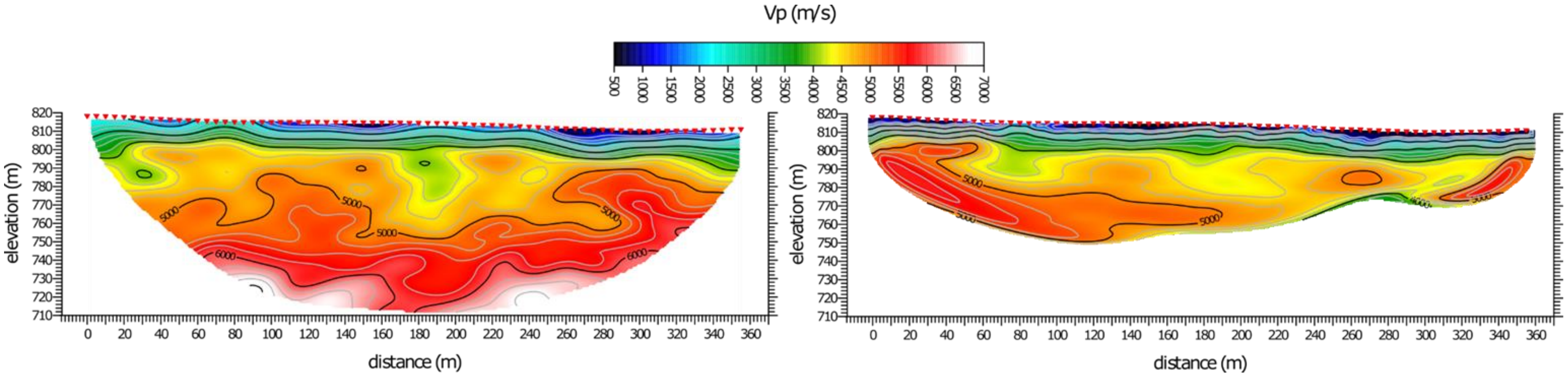
Model appraisal through checkerboard resolution test:

Central-eastern part: model resolved down to -70/80 m depth
Western part: model resolved down to -50/60 m depth

Model resolution is very high in the uppermost 50 m

Seismic profile Site P2:
active seismic survey

comparison of results from the two tomographic approaches

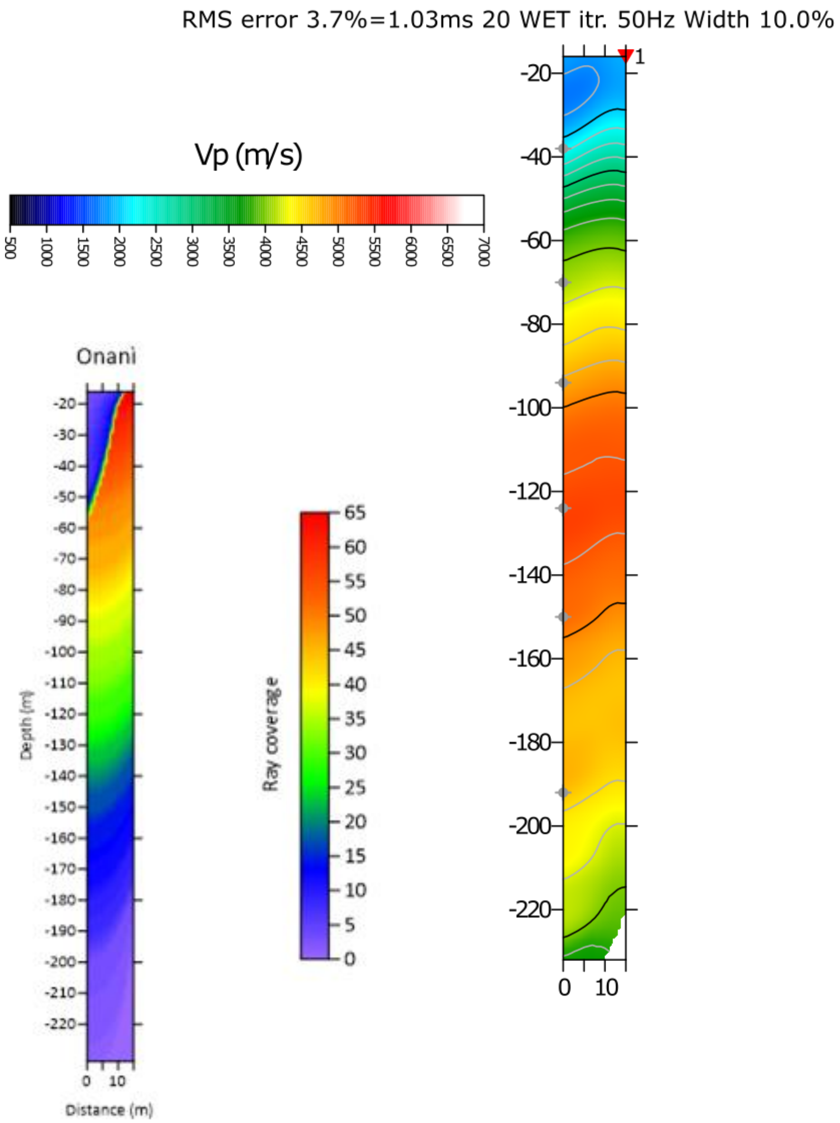


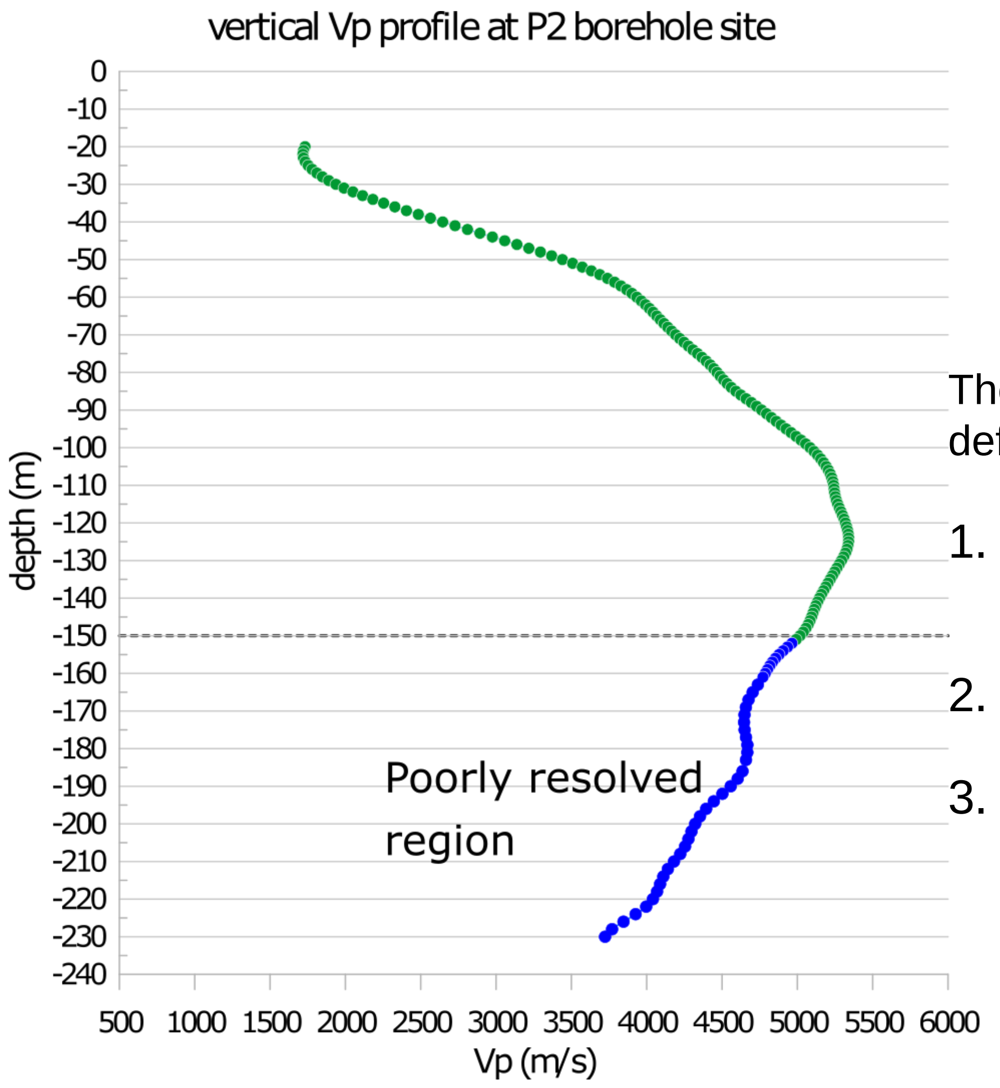
Invdfe code (final rms = 1.29 ms)

Rayfract© (final rms = 1.89 ms)

The models obtained with the two techniques show similar Vp range.
The multi-scale approach of the Invdfe code enables a deeper investigation depth.

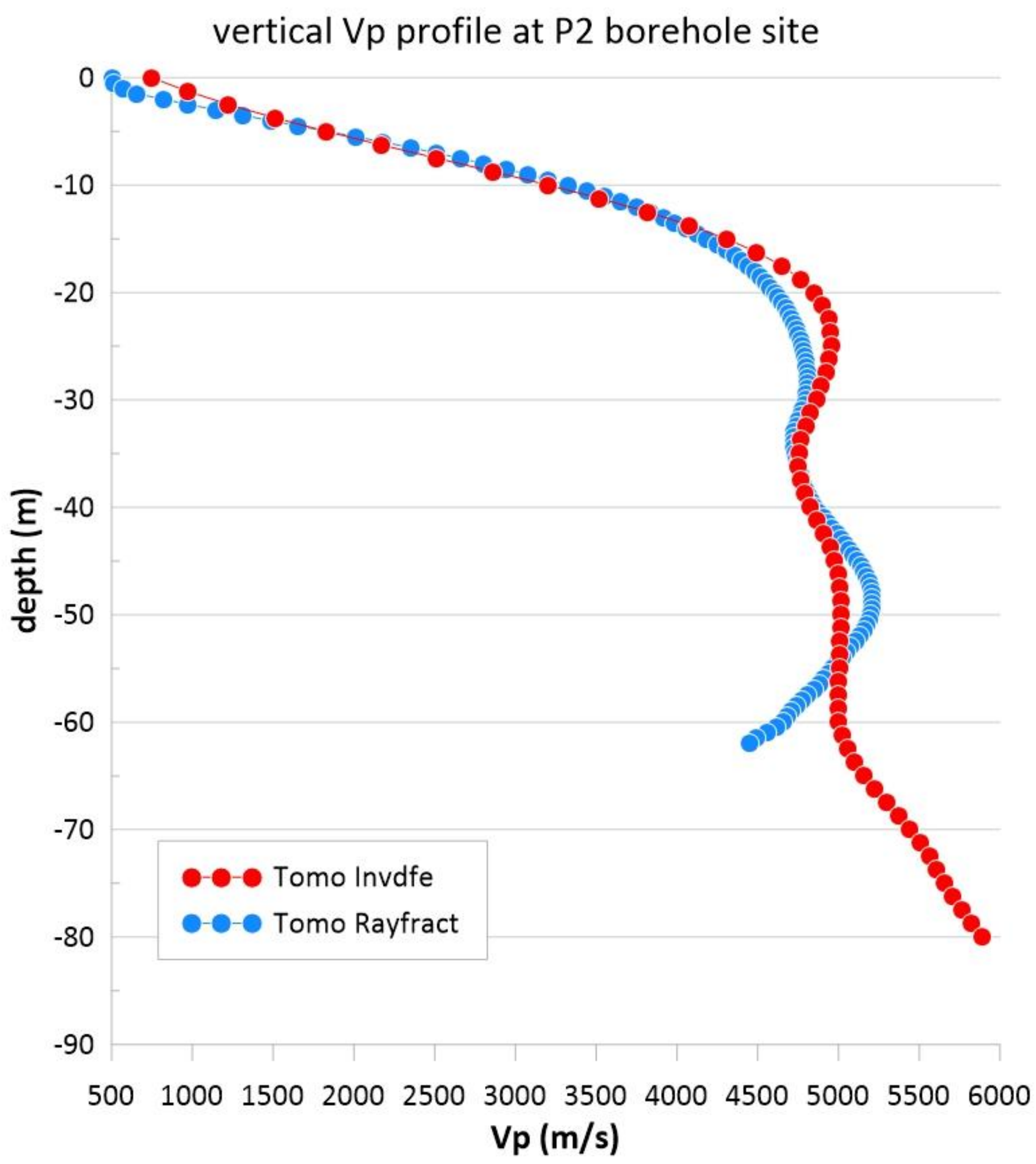
Site P2: Vertical Seismic Survey





The vertical seismic profile defines three zones:

1. Very strong vertical velocity gradient in the first 50 m (2000 =>4000 m/s)
2. Weaker increase up to 120 m depth (5000 m/s)
3. From 100 to 150 m depth Vp in the 5000-5500 m/s range



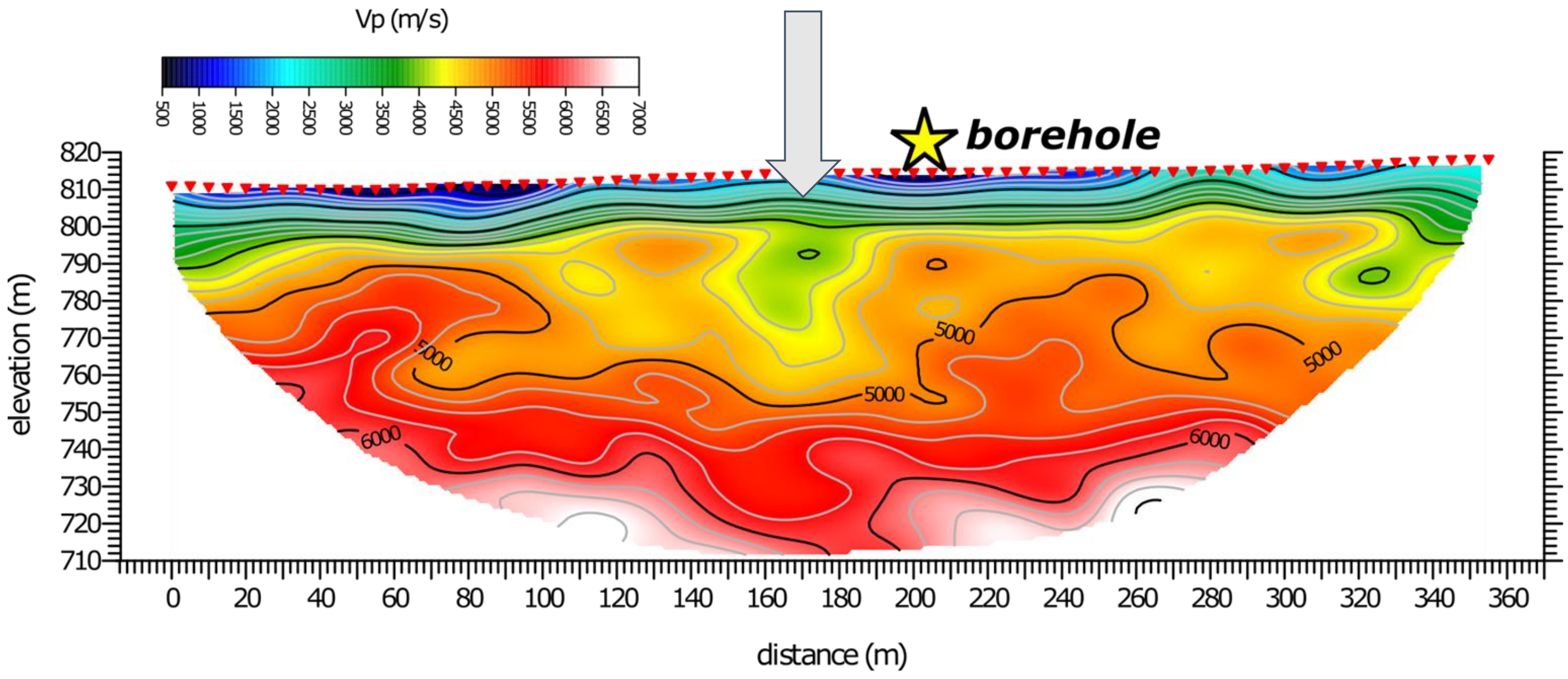
Site P2 - Main results of 2-D tomography beneath the drilling site:

1) The Invdfe and Rayfract inversions provide very similar results.
2) Vp rapidly increases in the uppermost 20 m (up to 4500 m/s)
3) Low Vp gradients in the depth range -20m/-60 m (around 5000 m/s).
4) The Invdfe model suggests Vp as large as 5500 m/s below 70 m depth.

Comparison with Vertical Seismic Profile data:

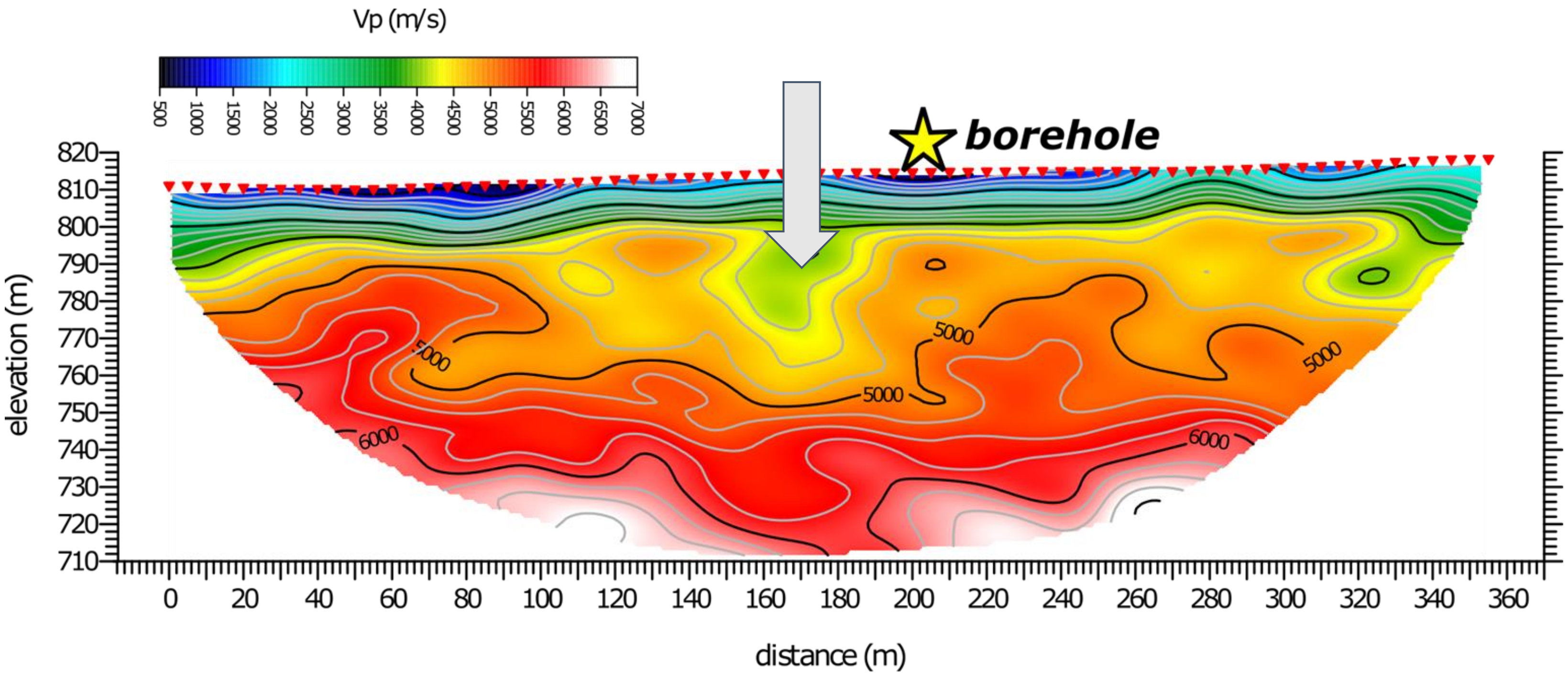
1) Both 1-D and 2-D inversions show a very rapid Vp increase in the shallowest layer.
2) All models unravel very high Vp beneath the shallow weathered layer (about 5000-5500 m/s)
3) The tomographic inversion doesn’t resolve evident low velocity zones under the drilling site

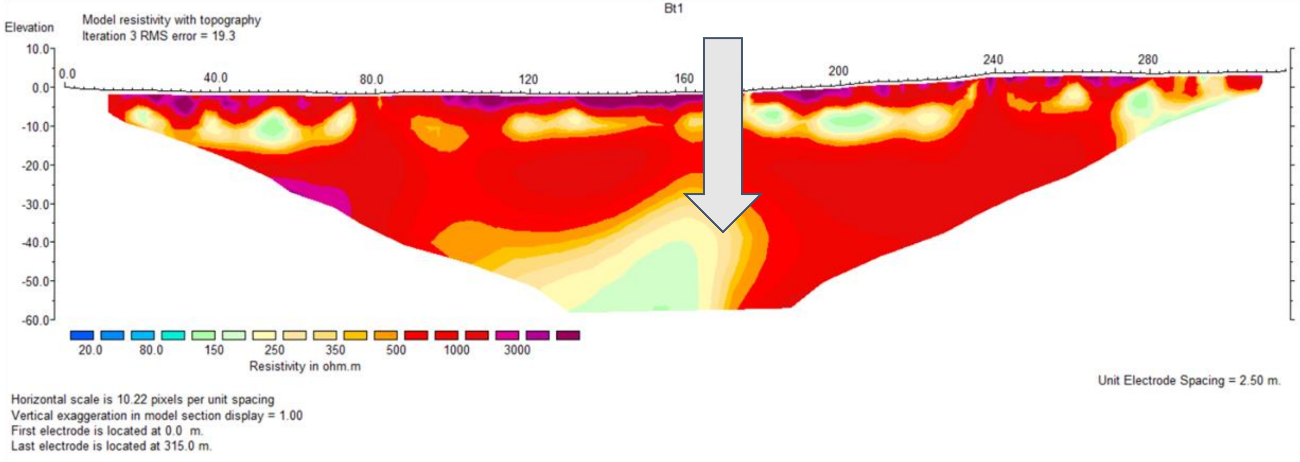
Seismic profile Site P2: interpretation of the Vp model



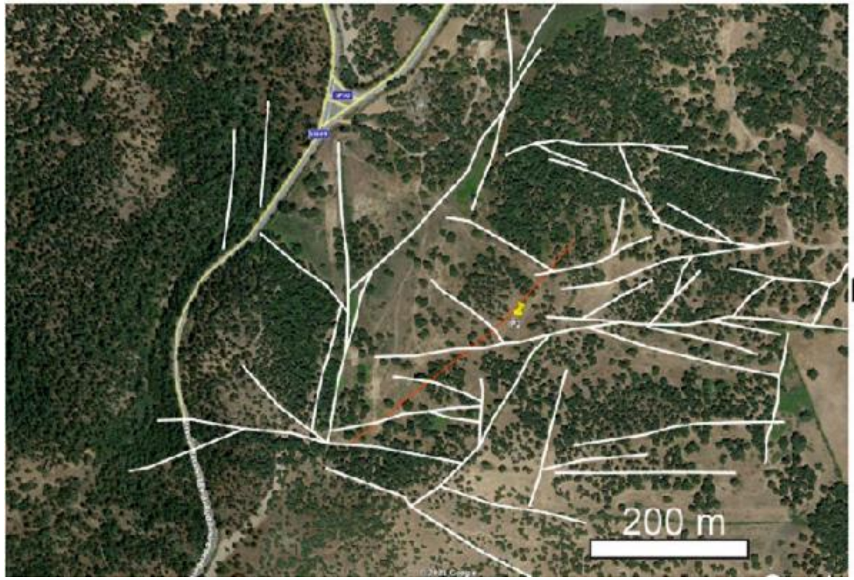
1) Near-surface high-Vp (about 3000m/s) agrees with exposed granites
2) The relatively thin shallow layer with very high vertical gradient defines the granite weathered zone
3) Vp values around 5000 m/s indicate a low degree of fracturing of the granitoids
4) Higher Vp on the southern side suggest poorly fractured or stiffer granitoids
5) A narrow vertical anomaly with relatively low Vp (4000-4500 m/s) indicates a fractured zone to the south of the borehole
6) We estimate a thickness of the presumed fractured zone < 10 m (resolution test)

Seismic profile Site P2: comparison of 2-D Vp with ERT model





1) Seismic tomography and ERT agree in the thickness of the near-surface low-Vp/conductive layer (weathered granitoides)
2) Very high Vp and resistivity point to a weakly fractured bedrock
3) The vertical low-Vp zone agrees with a low resistivity region, confirming the presence of a steeply dipping fractured zone to the south of the borehole



ERT model and fracture map courtesy of:
V. Longo, G. Cardello, G. Oggiano, D. D'Urso (University of Sassari)

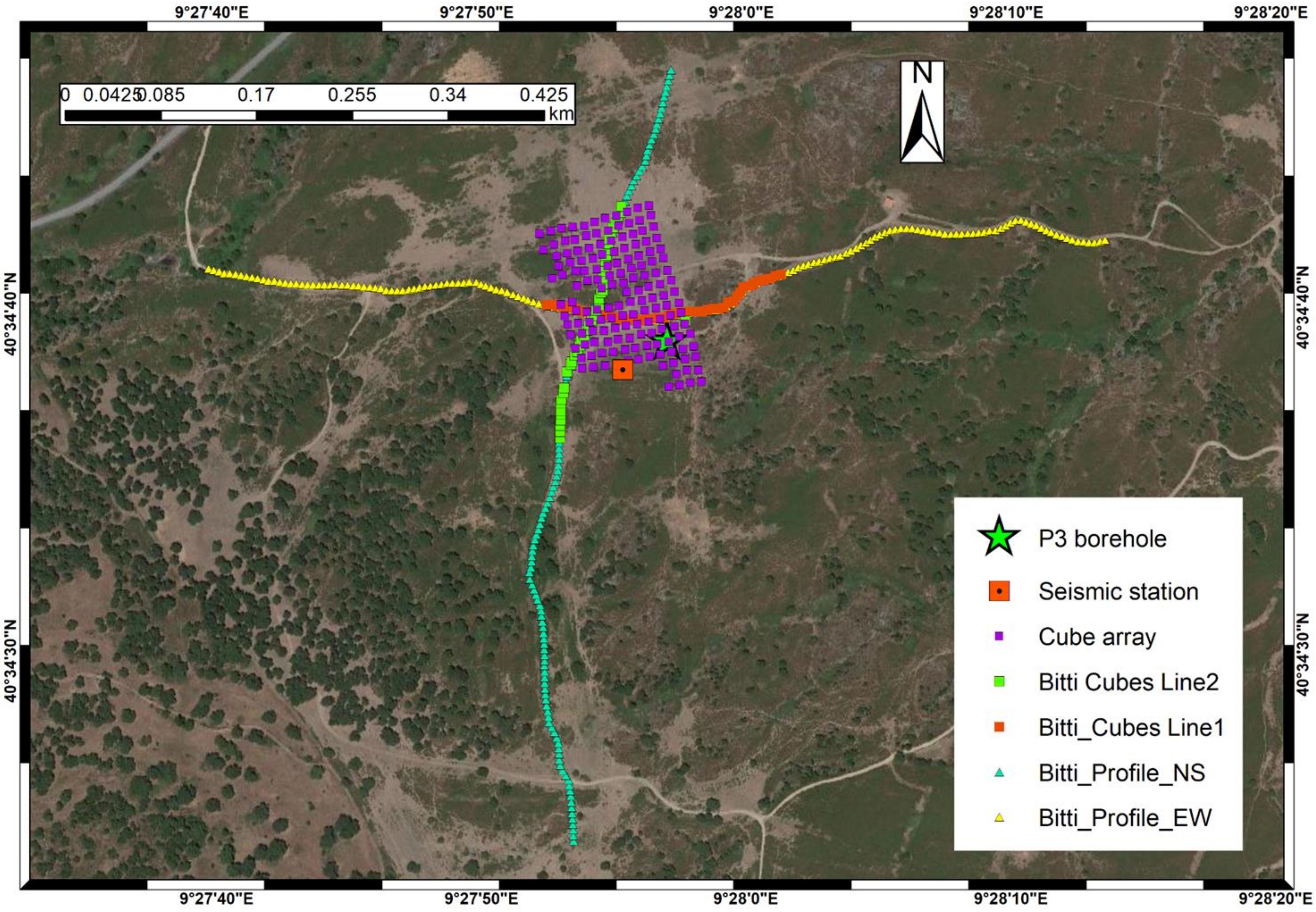
Site P3: surveys

1 vertical seismic profile

2 high-resolution seismic profiles with multi-fold wide-aperture geometry

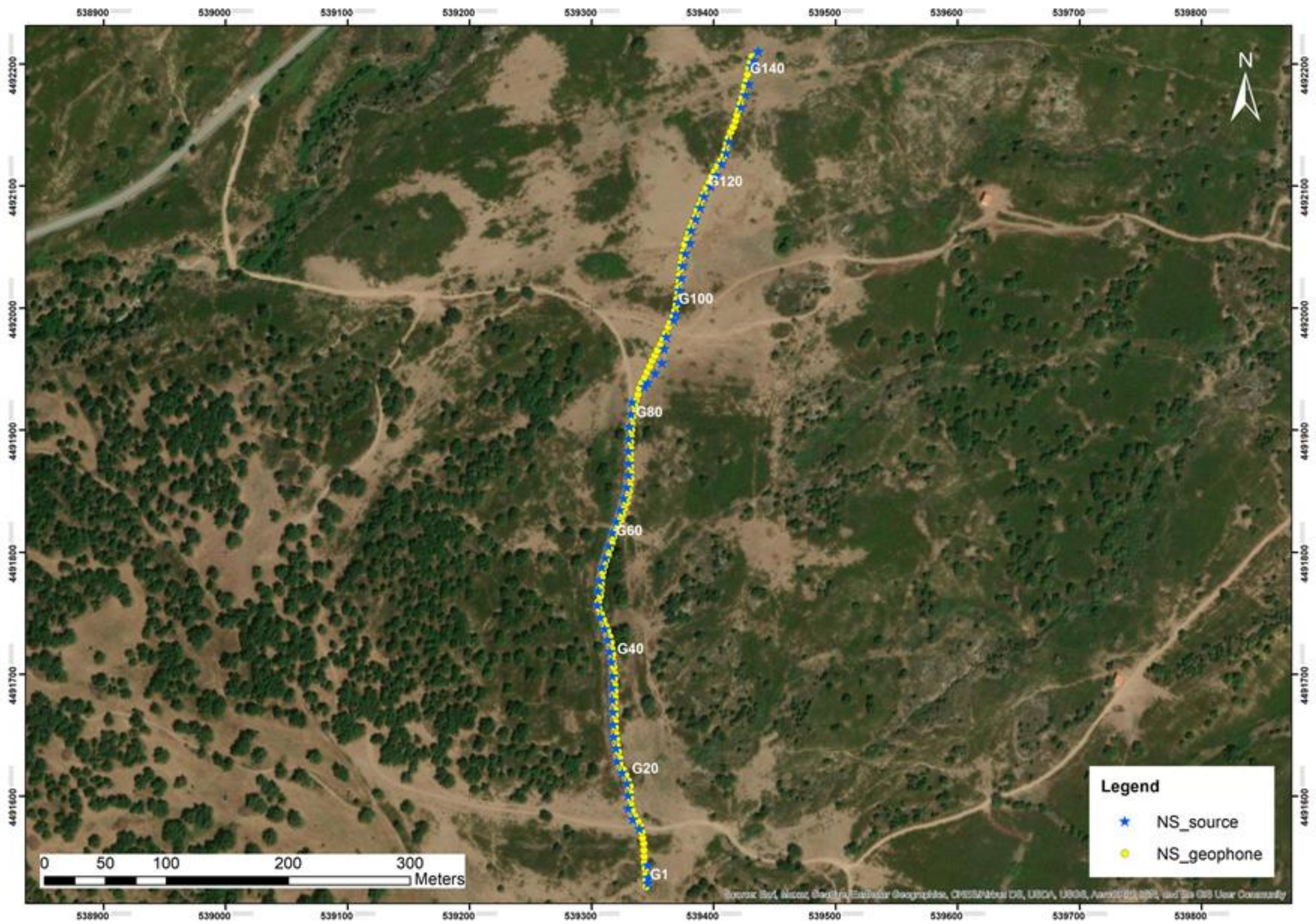
Deployment by other teams:

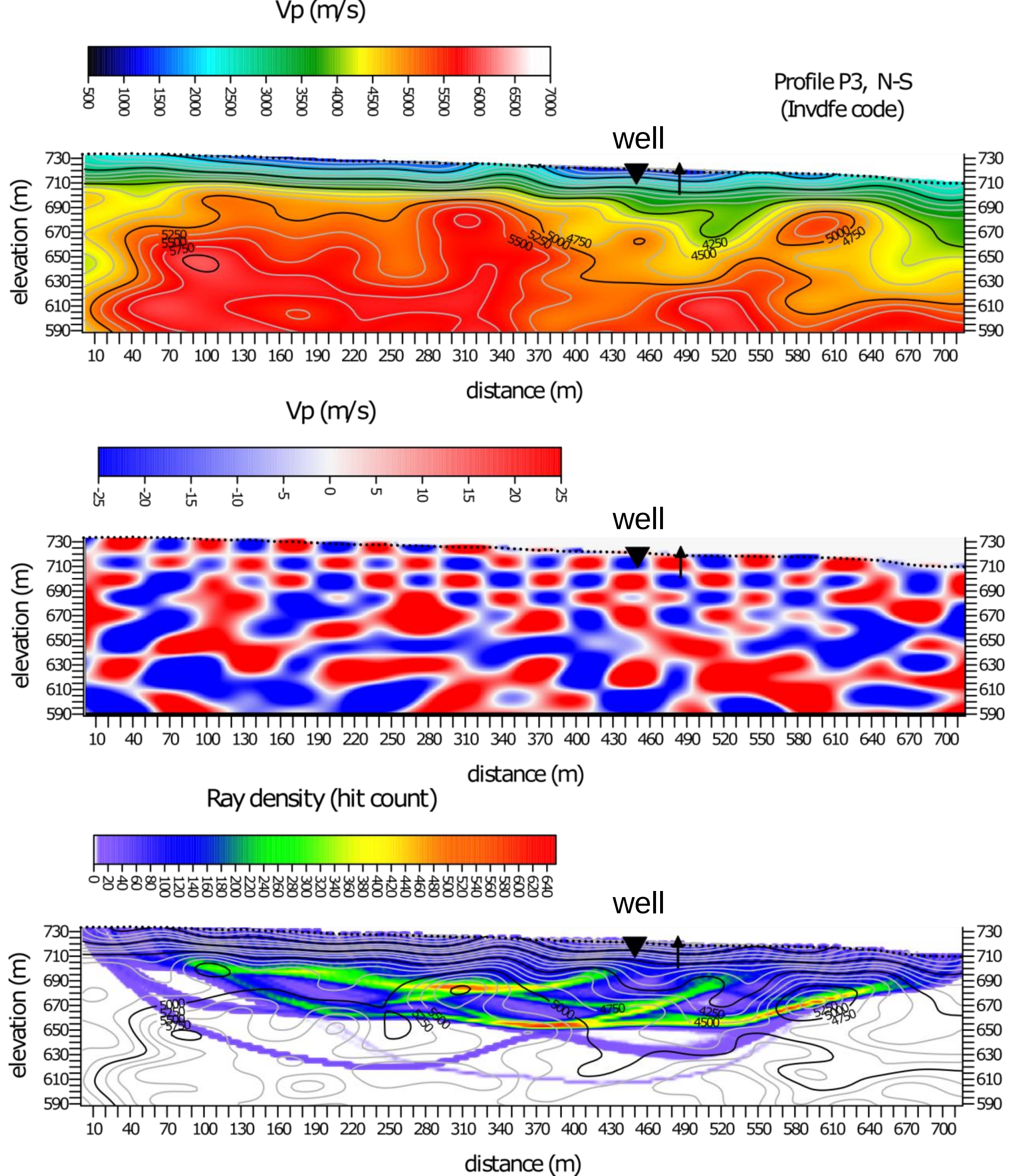
nodal array of 153 3-D component cubes (K.I.T.)
2 linear arrays of 3-D component cubes (K.I.T.)
DAS vertical array (K.I.T.)
1 broadband seismic station (INGV-Pisa)



Site P3: seismic profile N-S

N-S HR seismic profile	
Source	**IVI-Minivib**
N° Sources	69
Sources spacing	10 m
N° Geophones	144
Geophones spacing	5 m
Profile lenght	720 m





Seismic profile Site P3, N-S:

Non-linear refraction tomography (Invdfe code)

Inverted dataset: 7,994 first arrival traveltimes
(hand-picking; rms uncertainty: 2.23 ms
maximum offset of first arrival reading: **715 m**)

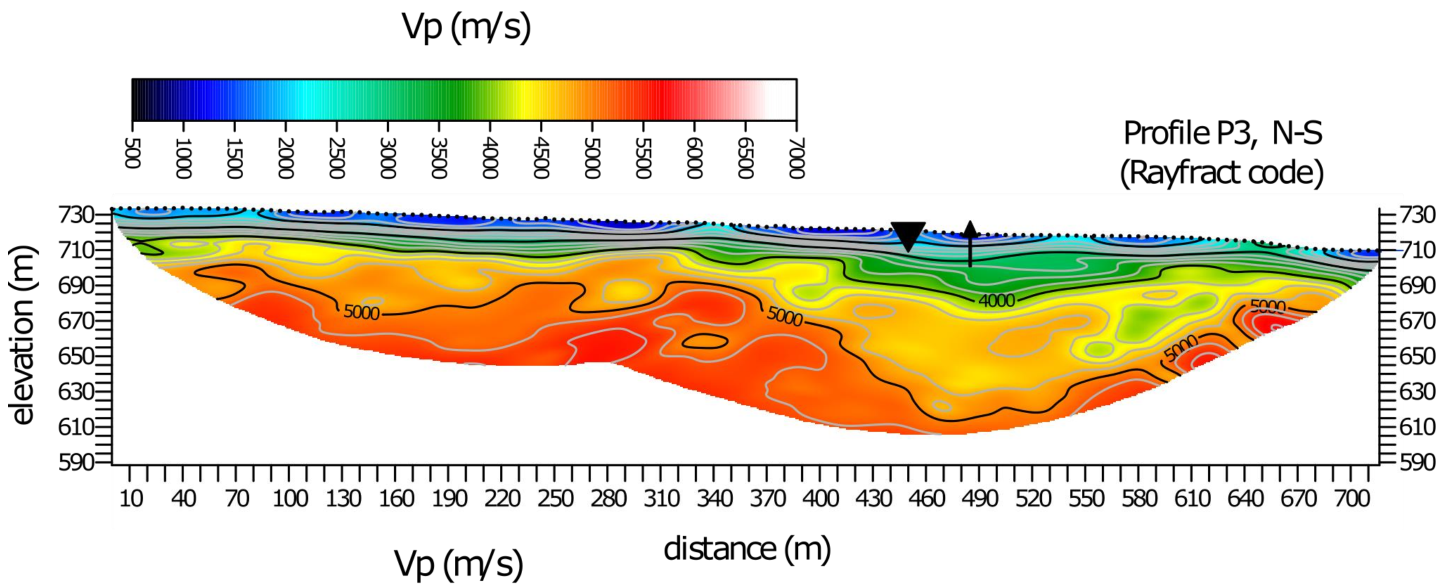
Final best-fit model

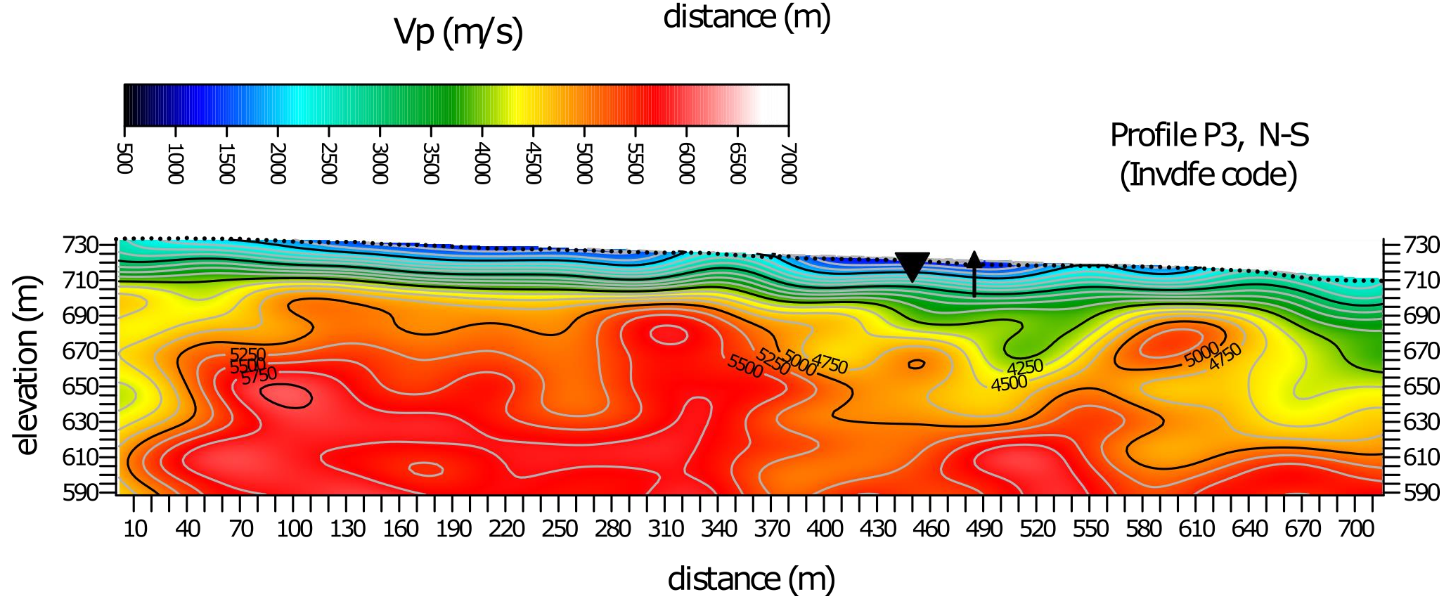
- 11 inversion steps
- RMS of traveltimes residual: 2.3 ms
- 360 inverted parameters
- maximum investigation depth: about 70-80 m

Model appraisal through checkerboard resolution test:

Northern part: model resolved down to -40 m depth
Central-southern part: model resolved down to -70/80 m depth

Model resolution is very high in the uppermost 60/70 m



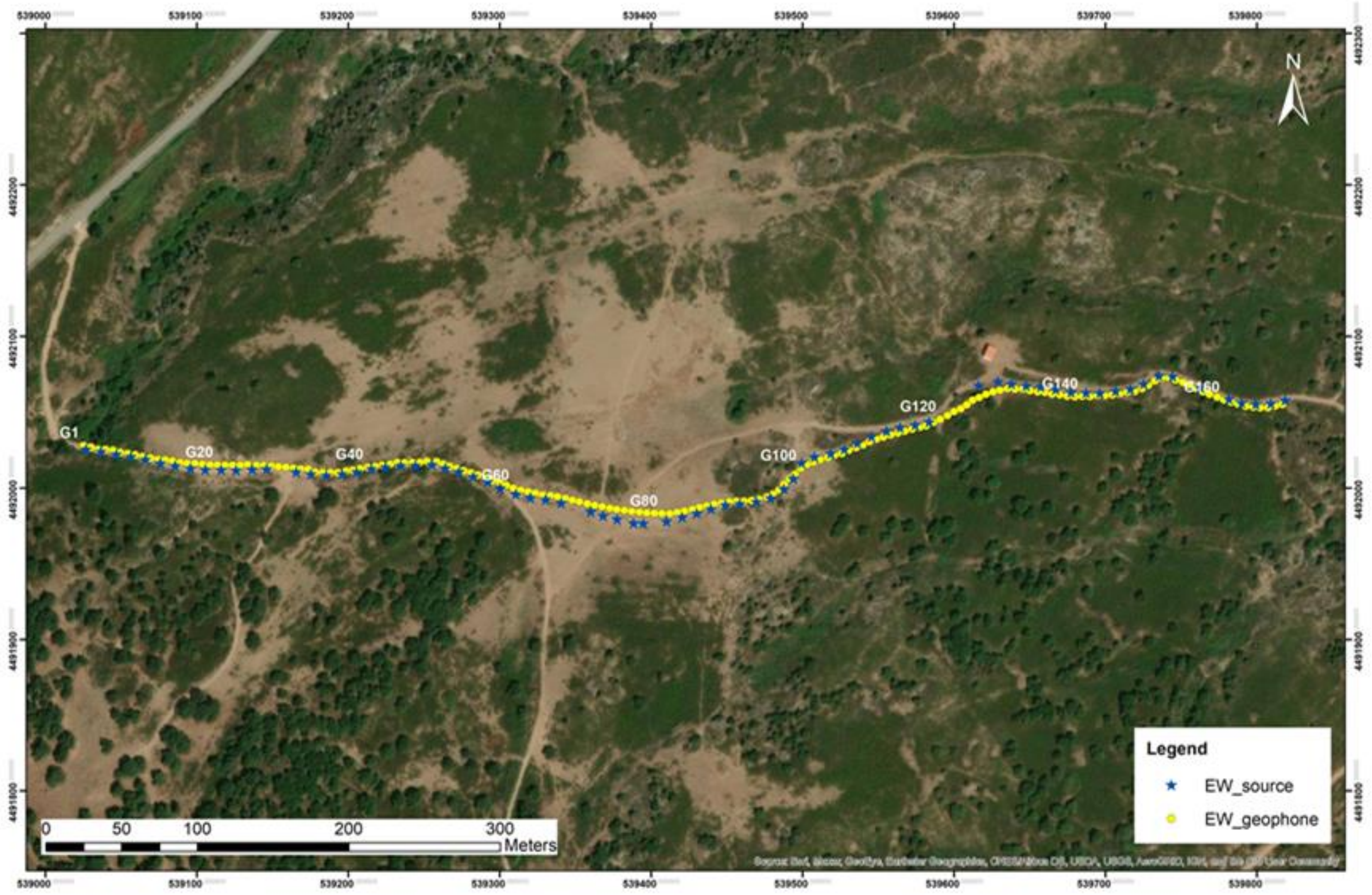


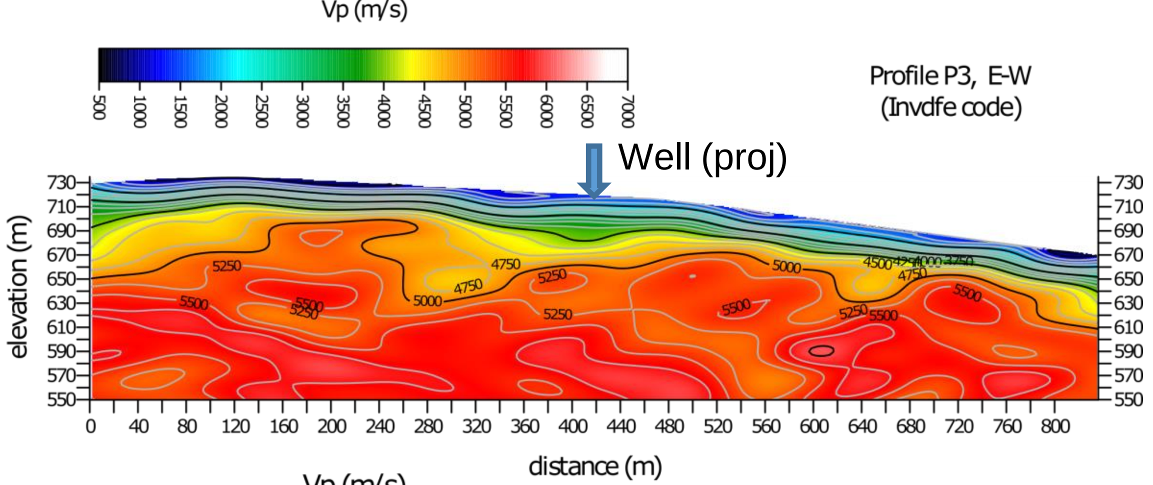
Seismic profile Site P3, N-S:

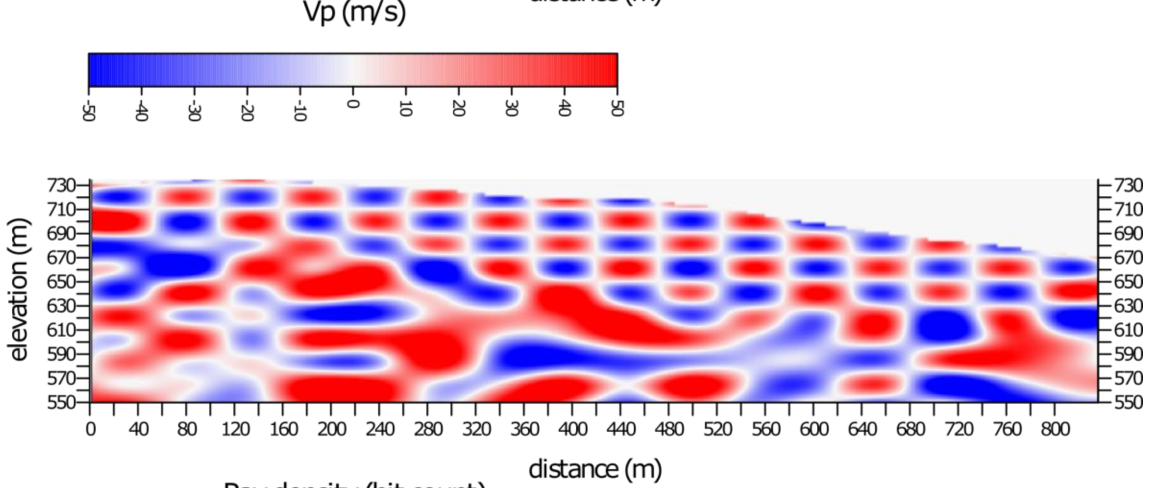
Comparison of results obtained with Invdfe and Rayfract codes

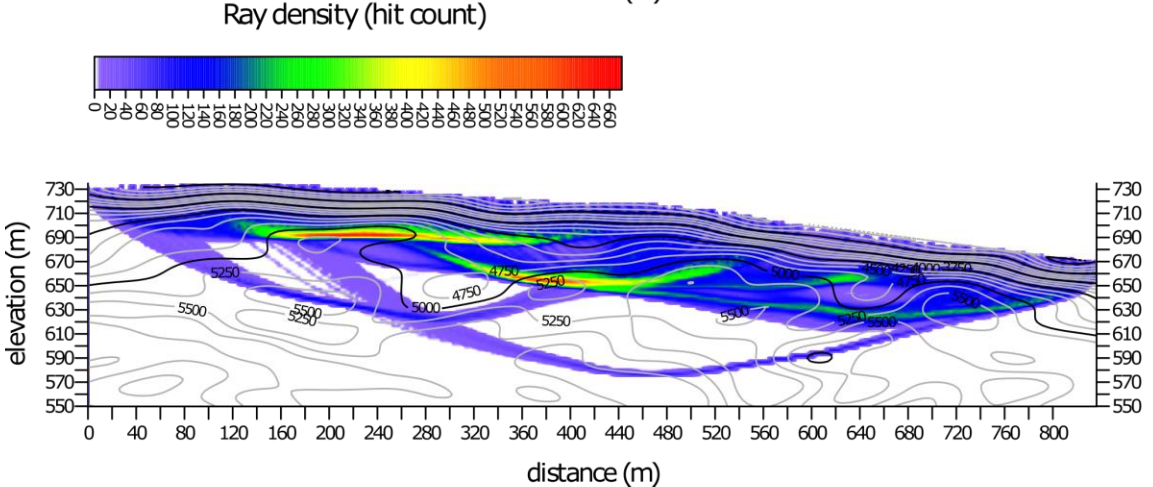
Site P3: seismic profile E-W

E-W HR seismic profile	
Source	**IVI-Minivib**
N° Sources	79
Sources spacing	10 m
N° Geophones	168
Geophones spacing	5 m
Profile lenght	840 m









Seismic profile Site P3, E-W:

Non-linear refraction tomography (Invdfe code)

Inverted dataset: 9,539 first arrival traveltimes
(hand-picking; rms uncertainty: 2.34 ms;
maximum offset of first arrival reading: **725 m**)

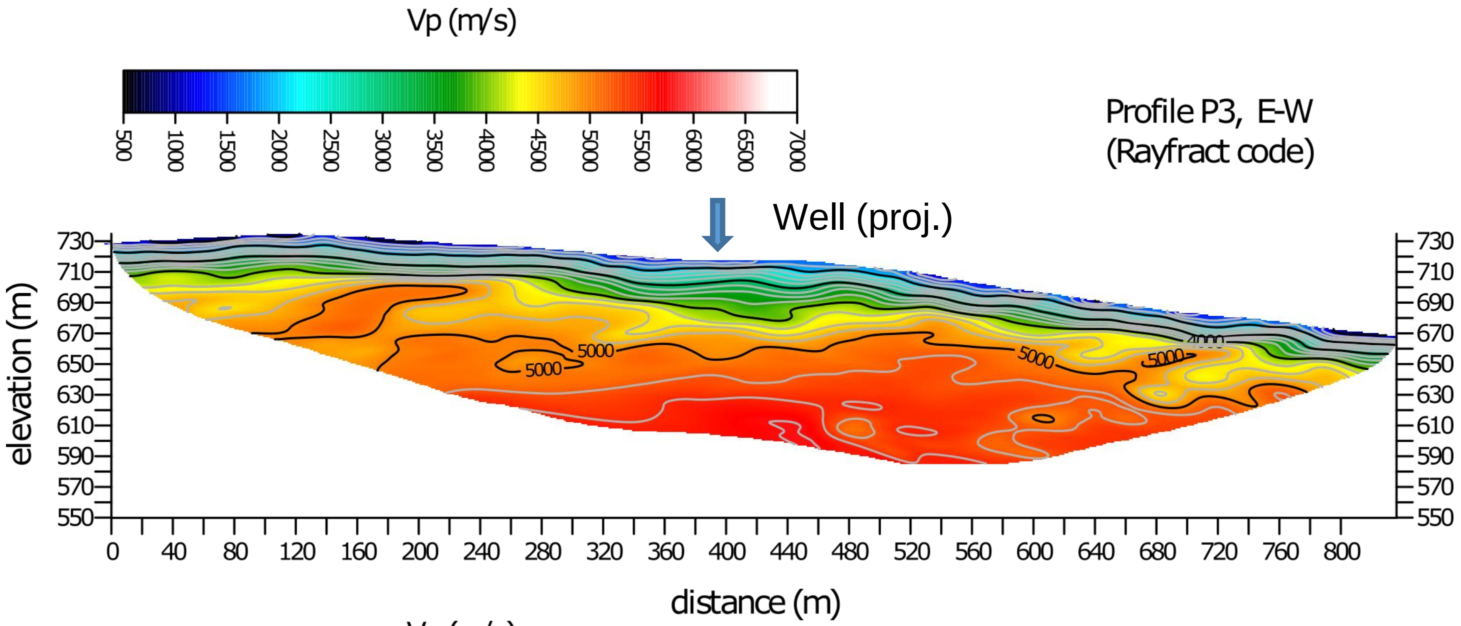
Final best-fit model

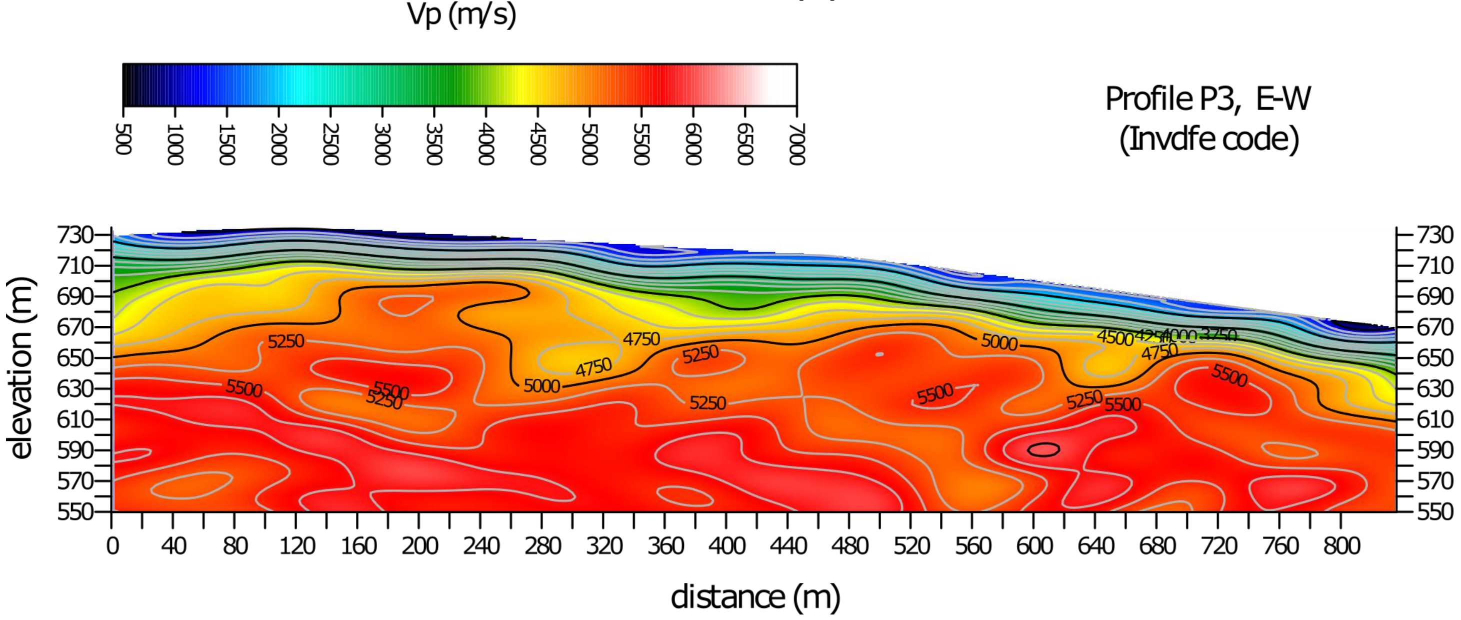
- 8 inversion steps
- RMS of traveltimes residual: 2.3 ms
- 336 inverted parameters
- maximum investigation depth: about 90 m

Model appraisal through checkerboard resolution test:

Western part: model resolved down to -50 m depth
Central-eastern part: model resolved down to -80/90 m depth

Model resolution is very high in the uppermost 60/70 m





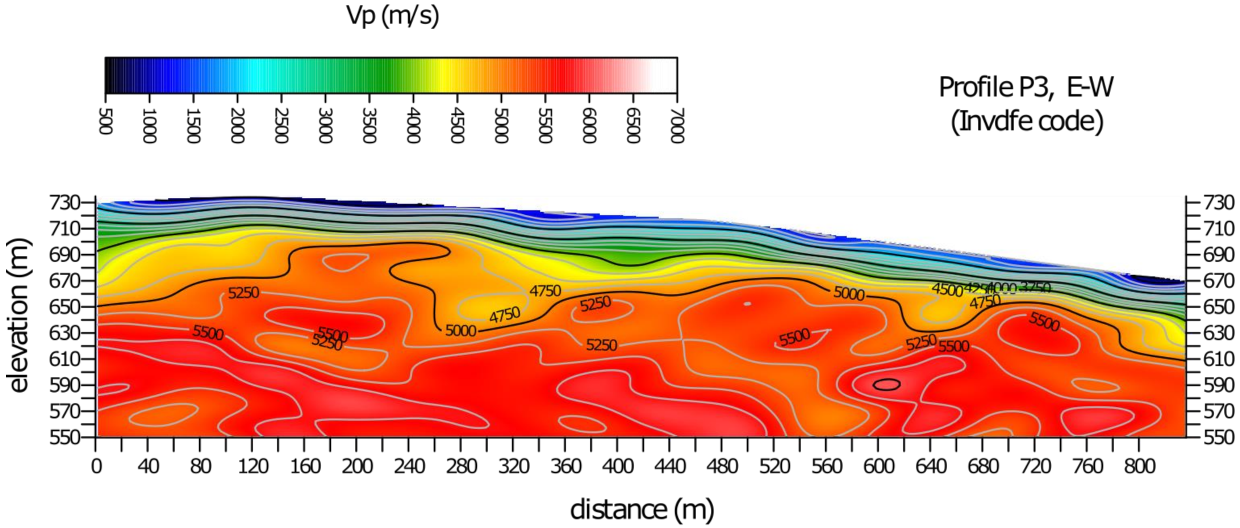
Seismic profile Site P3, E-W:

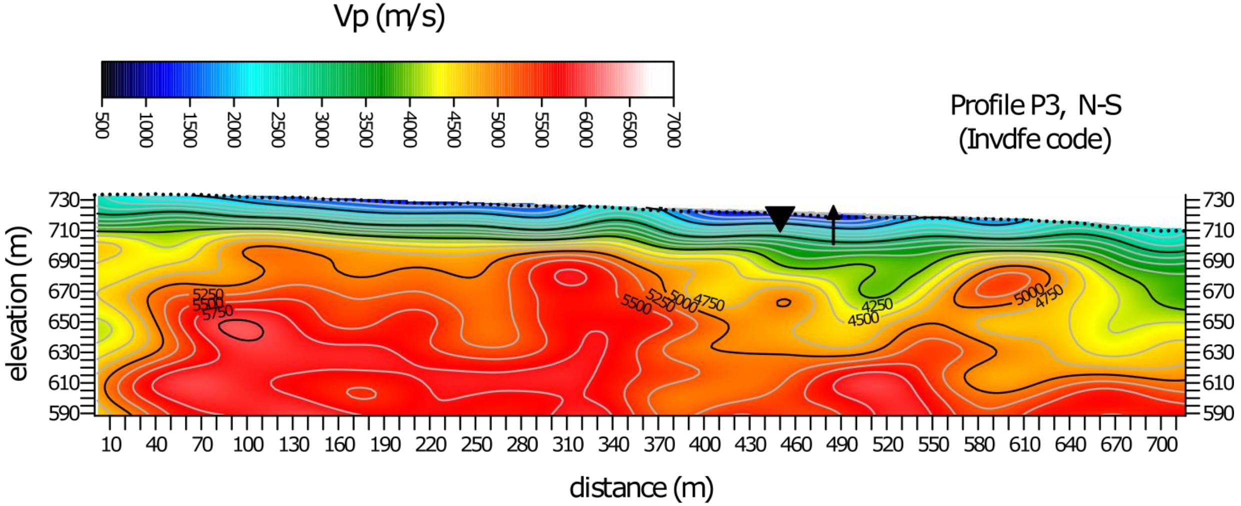
Comparison of results obtained with Invdfe and Rayfract codes

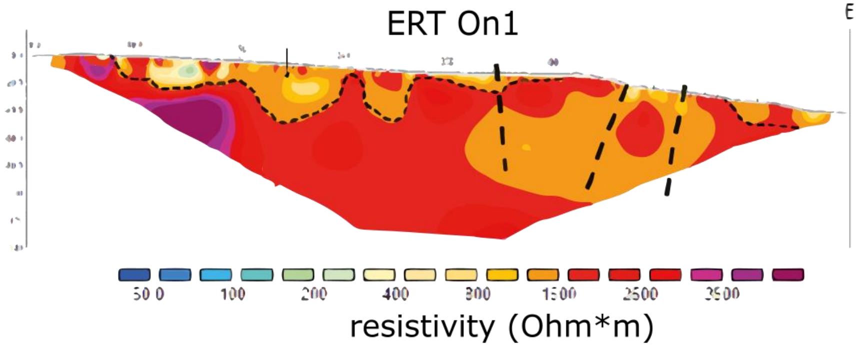
The velocity structure obtained with the two inversion codes is very similar but the multi-scale inversion strategy of **Invdfe** code allows to retrieve a slightly deeper model

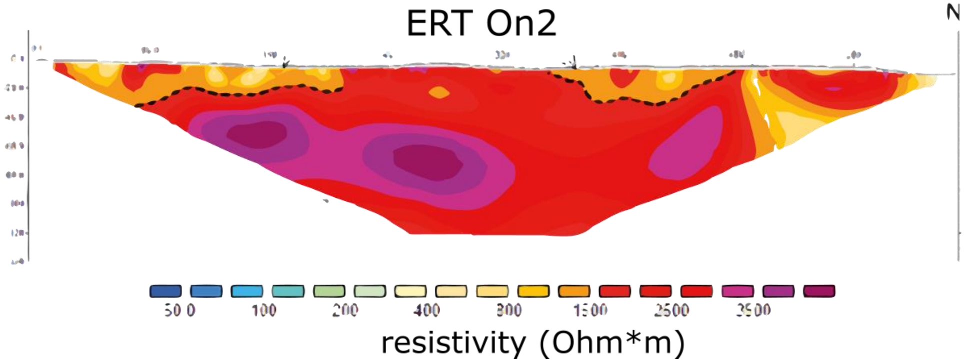
Comparison between Vp refraction tomography and ERT models in site P3

ERT model courtesy of: V. Longo, G. Cardello, G. Oggiano, D. D'Urso (University of Sassari)





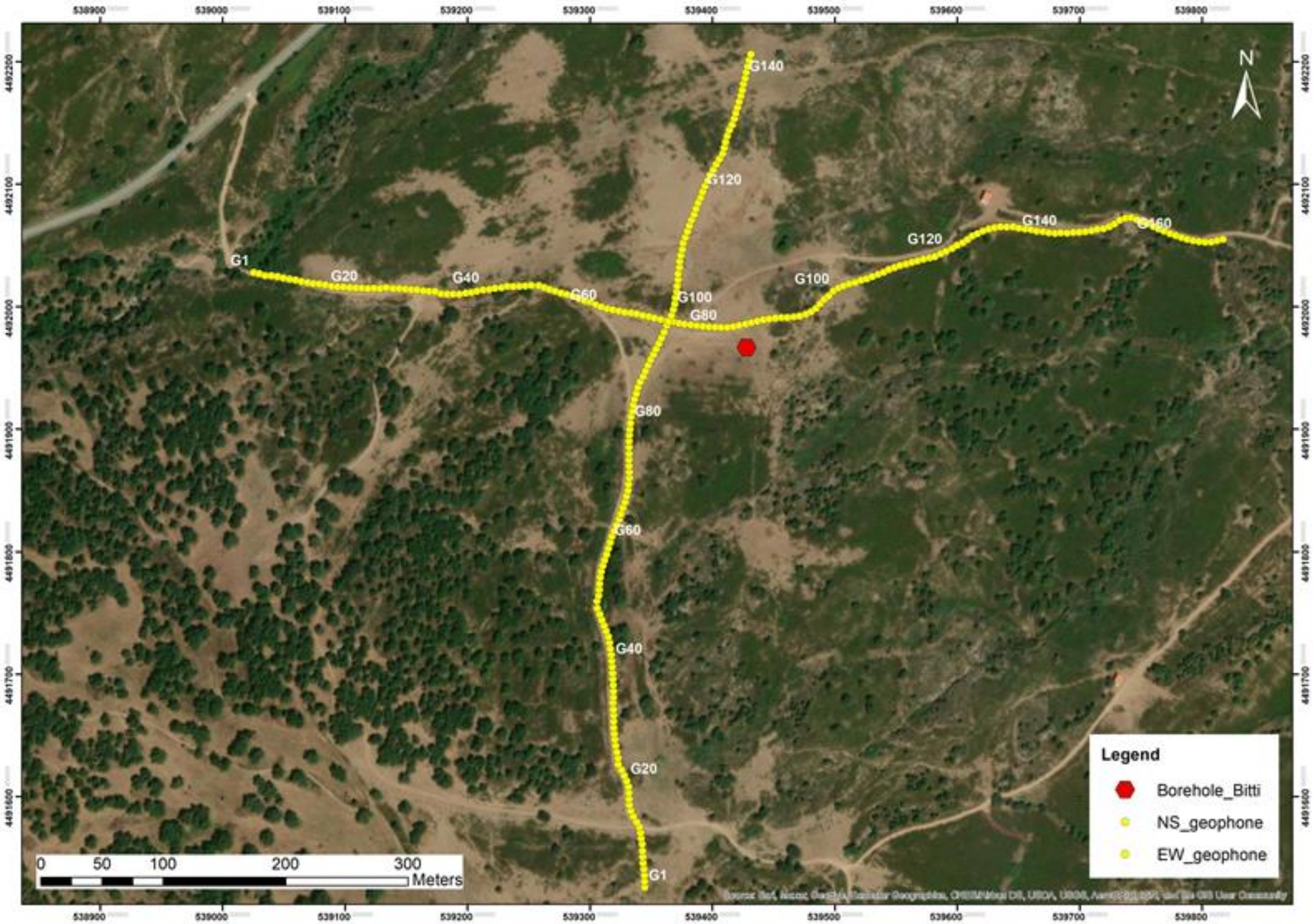




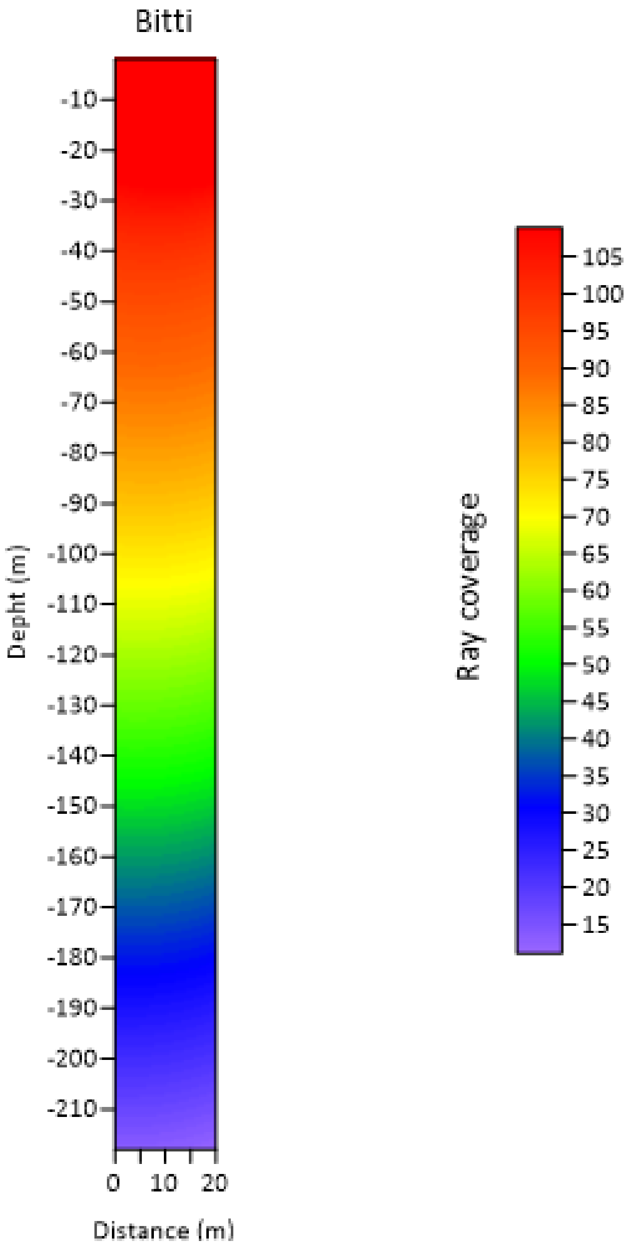
- In the E-W profile, to the west the high-Vp and high resistivity bodies are very shallow. The region at x 480-540 m with weak resistivity does not correspond to an evident decrease in velocity. The near surface weathered zone is very thin in the western slope.
- In the N-S profile, there is a good match between the high-Vp body (5500 m/s) and the high resisitivy region (3000 Ohm*m) The thinning of the very low-Vp near surface layer matches the region with low resistivity in the near surface.
- The lateral variation of resistivity at 500 m may be related to the region of low-Vp (4000-5000 m) to the north of the well: change in the physical properties of the bedrock?

Site P3:
Vertical Seismic Profile

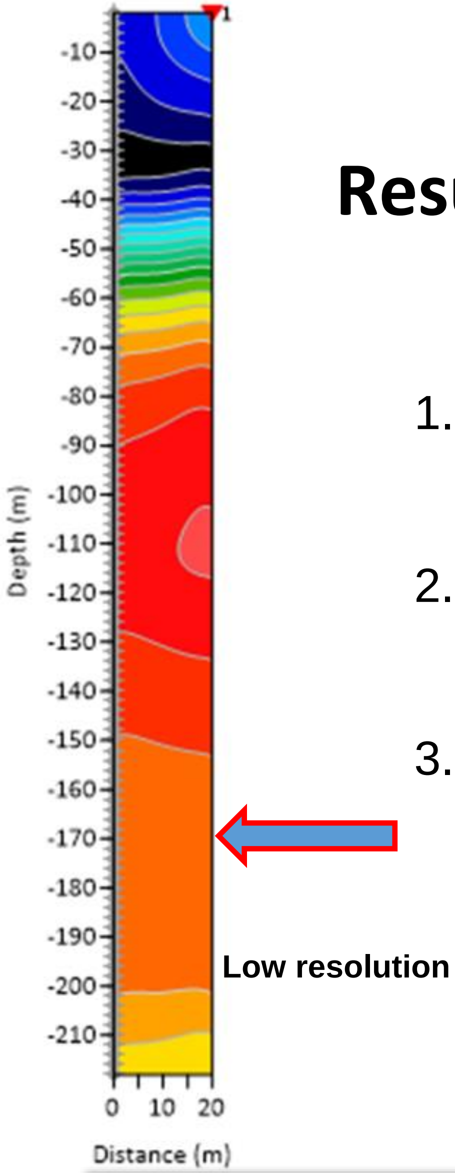
Vertical Seismic Profile	
Source	IVI-Minivib
N° Sources	112
Maximum depth	240 m
Acquisition interval	2 m

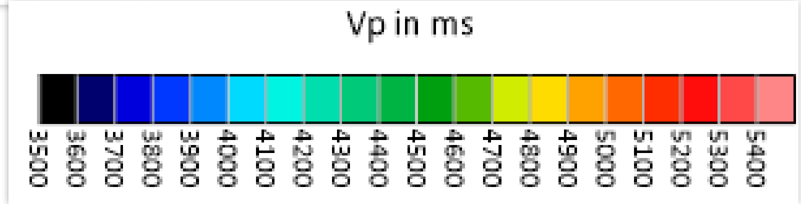


Site P3:
Results of the Vertical Seismic Survey

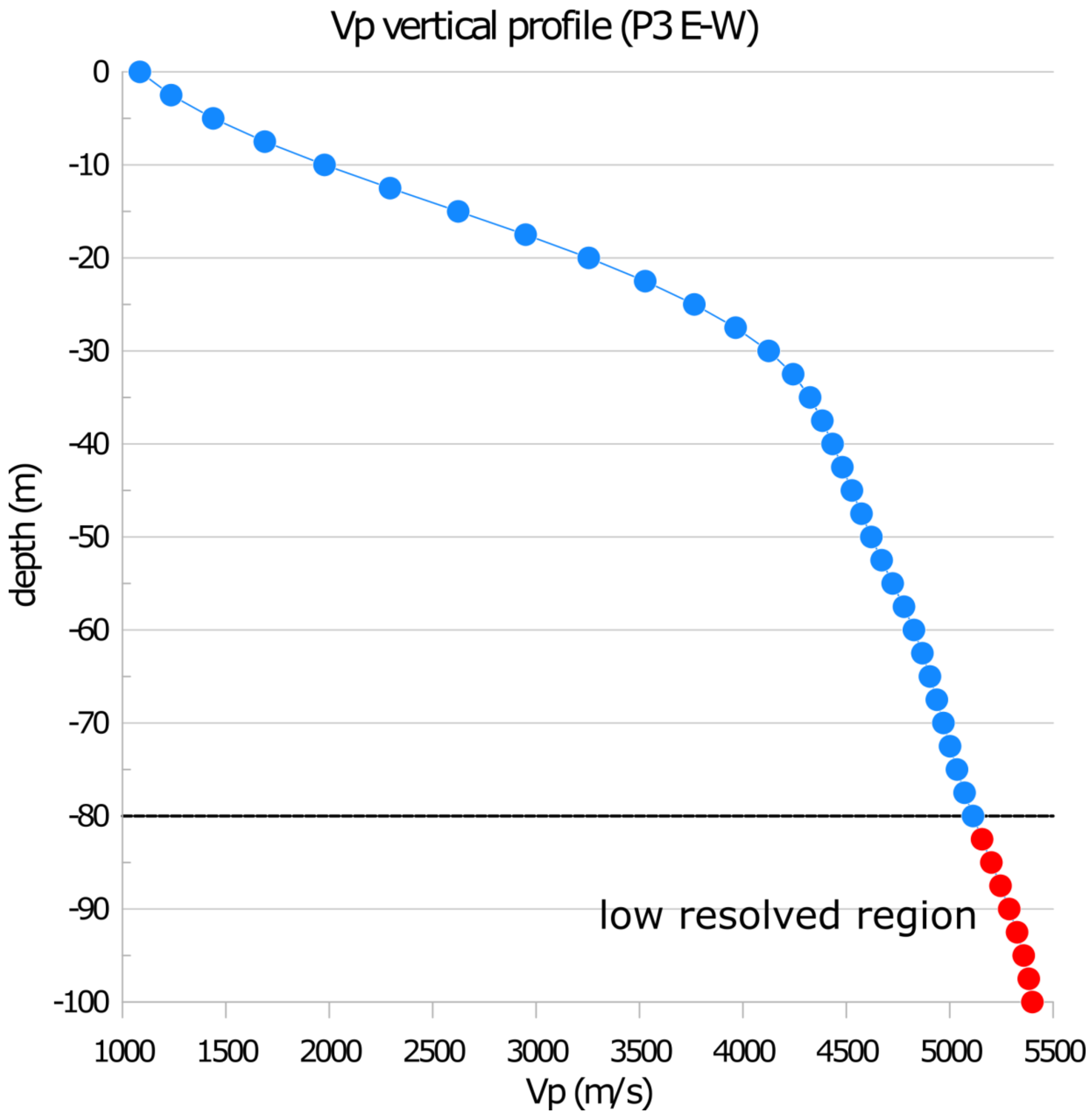


Ray coverage.





1. Strong vertical Vp gradient down to 50-60 m depth (from 3500 to 4500 m/s)
2. Weak velocity varations from 70 to 170 m depth with Vp around 5000-5400 m/s.
3. Model well resolved down to 150-170 m



Site P3 - Main results of 2-D tomography beneath the drilling site:

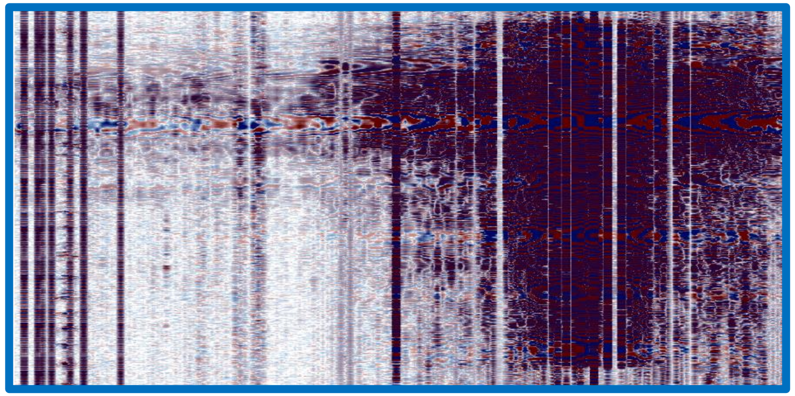
1) Vp rapidly increases in the uppermost 30 m (from 1000 to to 4200 m/s)
2) Regular and weak Vp increase from 30m to 80/90 m depth m (from 4200 to 5200 m/s).
3) The very high Vp (> 5000 m/s) resolved beneath the shallow layer with strong vertical gradient agree with results from the Vertical Seismic Survey

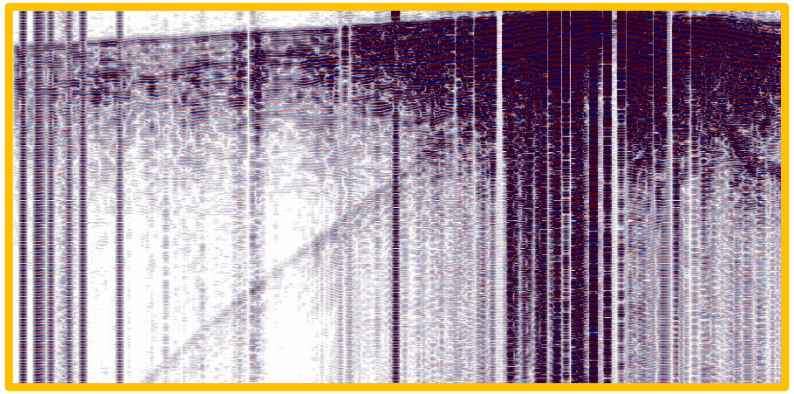
Seismic reflection data

(main processing steps)

Raw data ->

Vibroseis-correlation ->



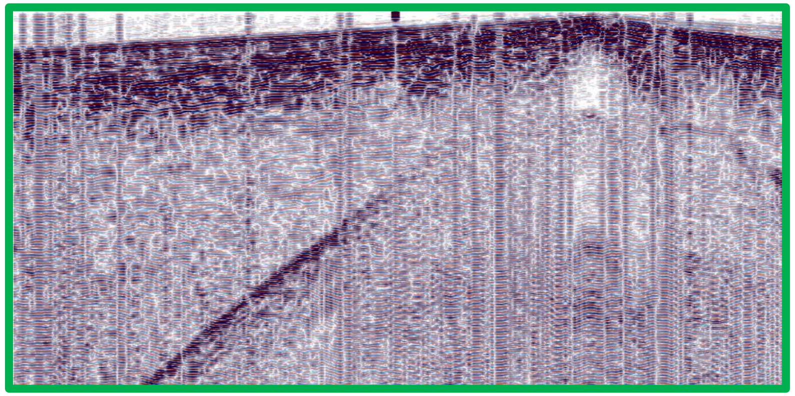


Geometry

Minimum-phase

Band-pass filter and gain functions

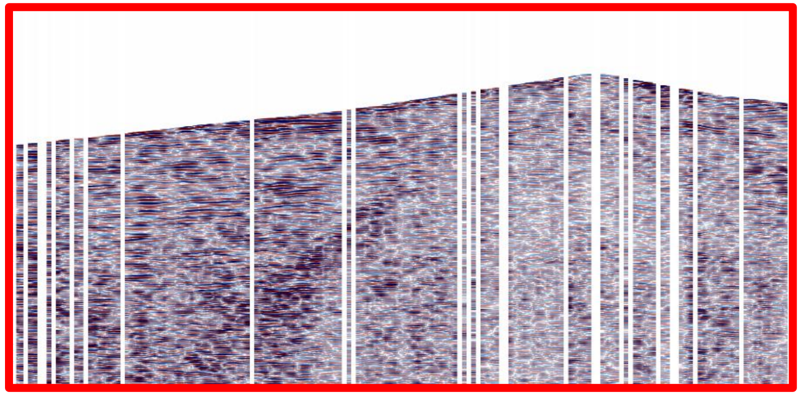
Statics corrections ->



Linear noise attenuation and top-mute

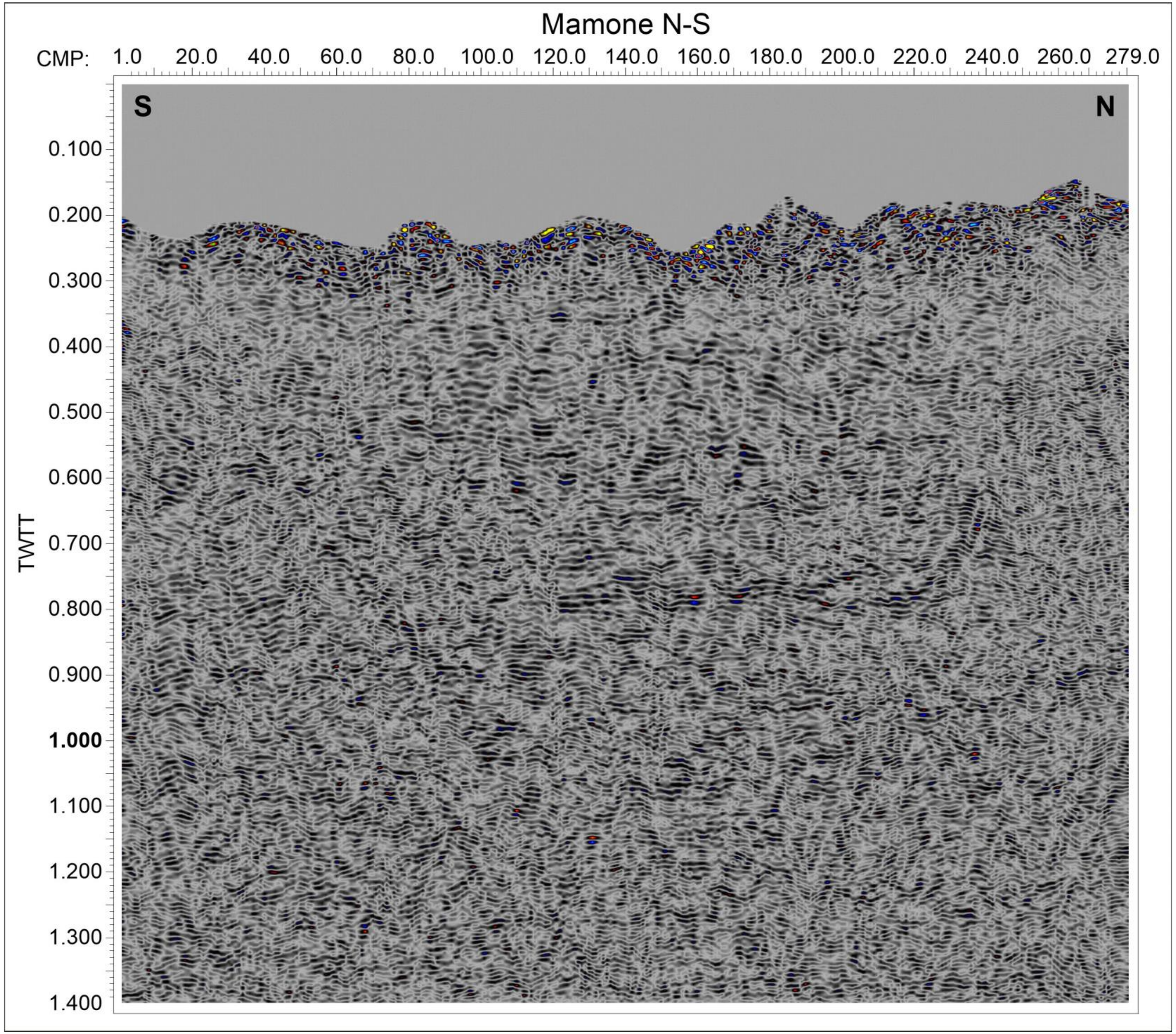
FK-filtering and trace-kill

Predictive deconvolution ->



Velocity analysis, stacking, gain functions, FX deconvolution and trace mixing

-> (see next slides…)

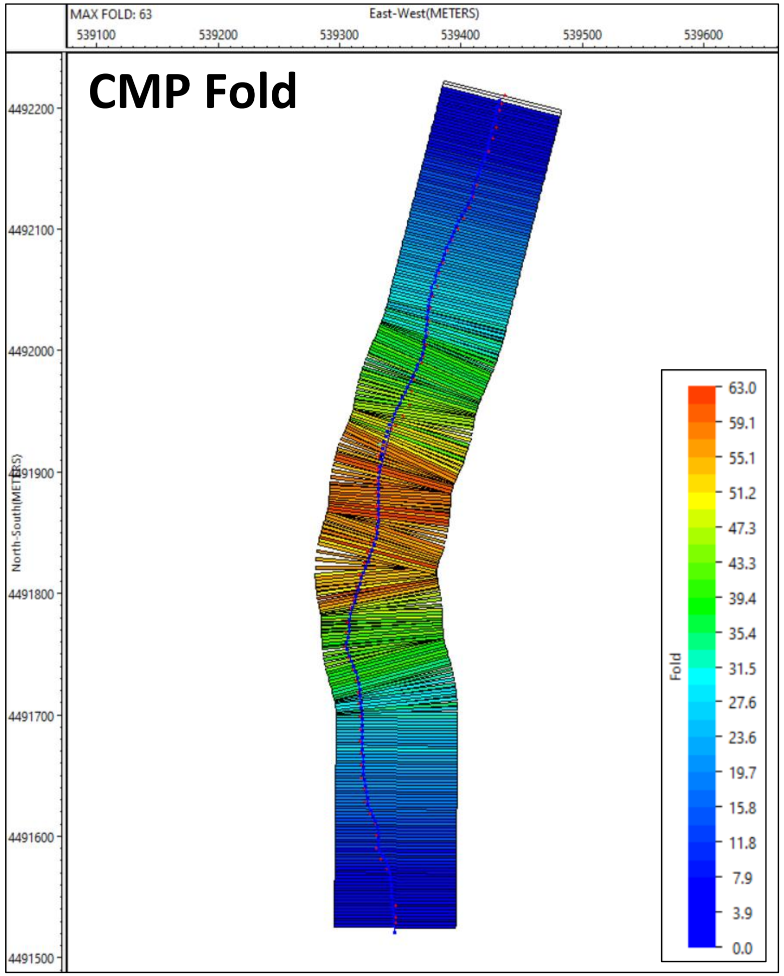


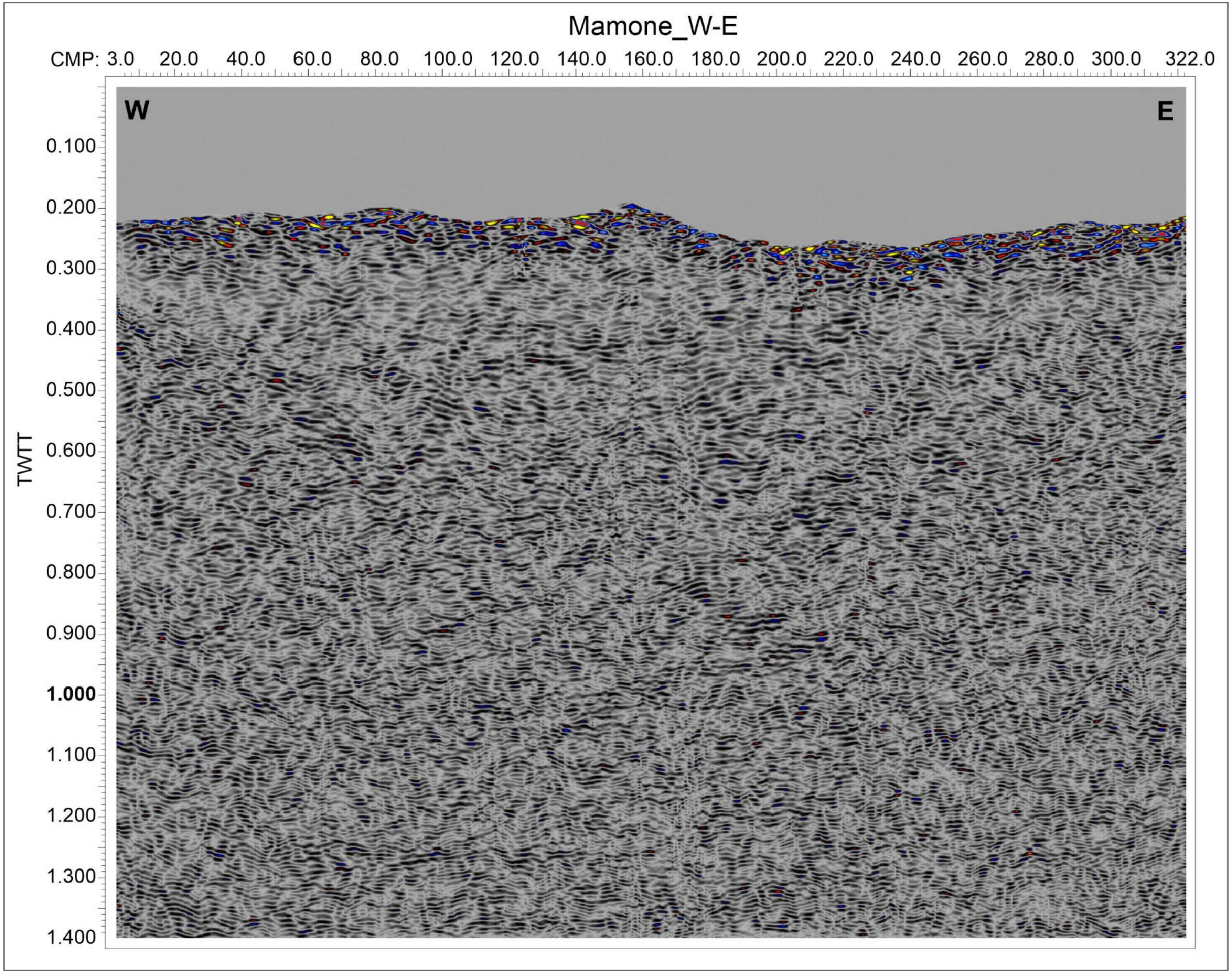
Seismic reflection profile
Site P3, N-S

CMP spacing: 2.5 m

Profile lenght: 700 m

Some possible reflections at 0.7-0.8 sec

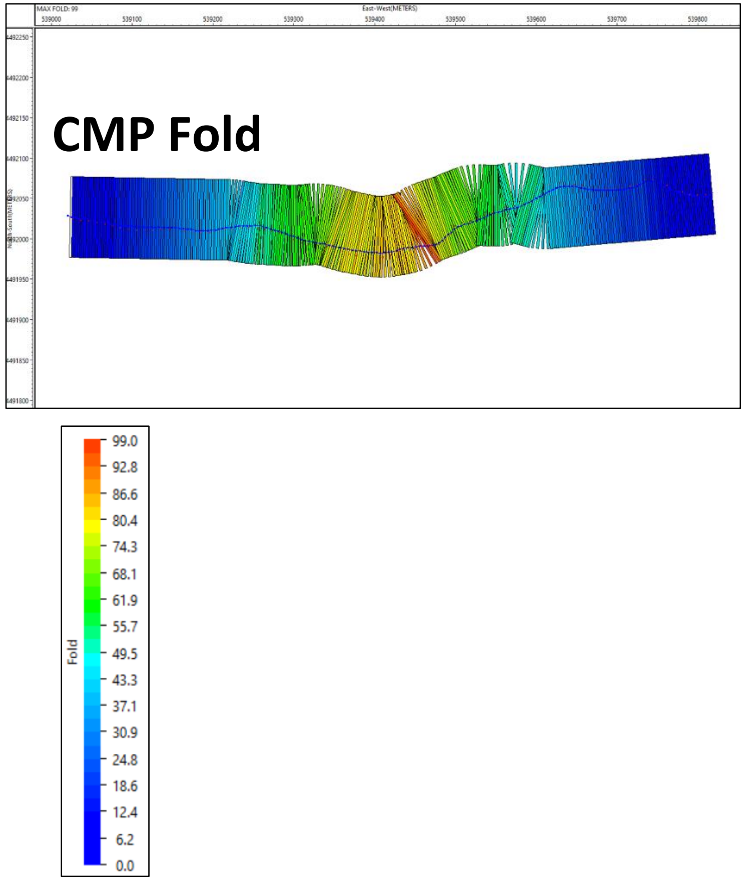




Seismic reflection profile Site P3, W-E:

CMP spacing: 2.5 m

Profile lenght: 800 m



Seismic Reflection Data: main results

- The geological environment in the survey sites is not suitable for seismic reflection techniques.
- The adopted processing flow does not evidence coherent reflectors in the topmost 0.2 sec TWT, which based on tomographic velocities correspond to an investigation depth of about 500 m.
- This suggests the absence of important seismic impedance contrasts (e.g. varations in the elastic properties of the rockmass) in agreement with results of seismic refraction tomography.

General conclusions

- 2-D tomographic models indicate the presence of very stiff crystalline bedrock (Vp 5000-5500 m/s), in agreement with a shallow propagation of seismic waves (50-90 m), despite the use of 720 and 835 m long arrays (with maximum offset of first arrival traveltimes readings of 715-725 m).
- The results of seismic surveys point out the absence of deep important fault zones with significant changes in the elastic properties in site P3.
- In site P2, there is hint for a fractured zone close to the drill site, in agreement with ERT models.