

Reassessing legacy seismic reflection data. Extracting new/more information through advanced seismic processing schemes

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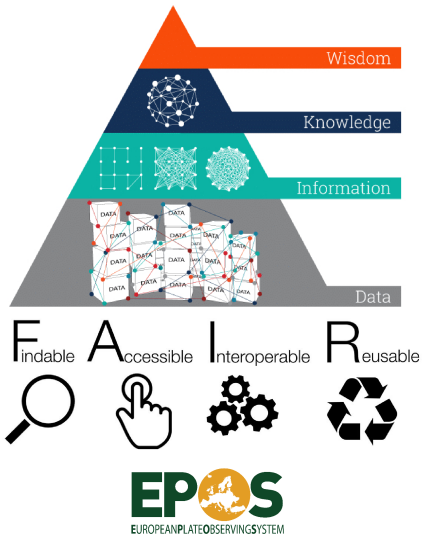
, Univ. Dipt. di Fisica e Geologia, Univ. degli Studi di Perugia, Italy



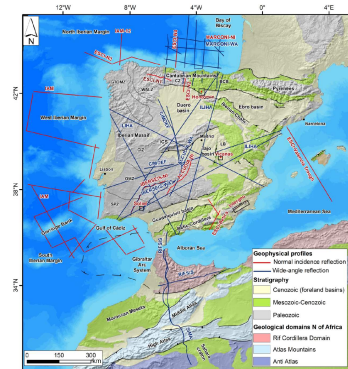
, Inst. of Computing, University of Campinas, Brazil



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- ▶ Seismic reflection data-sets are unique assets for solid Earth sciences, providing critical information on the physical properties and structure of the Earth's crust. They provide very unique high resolution images. Data-processing software and hardware are constantly evolving, thus new or additional information can be extracted from these data. Thus the outstanding value for open-access data repositories such as SEG.wiki, EPOS, IRIS-Data management center, SeisDare etc.
- ▶ Some Approches & Examples used to retrieve new valuable information from legacy data.
 1. **Seismic Attributes** Paleoseismic Study
 2. **Homogenized processing & Profile Integration** Composite Crustal transect Transect
 3. **New Hardware & optimization schemes** Comon Reflection Surface Stacking for better definition of the subsurface structure.
 4. **Machine Learning, Artificial Intelligence** Integration multidisciplinary data to constrain the nature of the subsurface.



Geological map of the Iberian Peninsula and north of Africa with the seismic profiles available through SeisDARE.

[DeFelipe, et al., 2021, ESSD]

SeisDARE is public access repository to ensure the legacy of 40 years of control source seismic data

Dataset title and objectives

IBERSEIS wide-angle reflection experiment

A wide-angle reflection experiment to constrain the physical properties for the lithosphere across the SW Iberian Massif.

General information:

- Two NE-SW wide-angle seismic reflection profiles.
- Acquired in 2003.
- Total length of 300 and 330 km.
- File format: SEG-Y

Technical specifications:

- Receiver type: single component, 10 Hz
- Receiver interval: 150 and 400 m
- Source: 9 shots
- 500-1000kg of chemical explosive each



Dataset characteristics

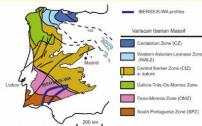
Content of the dataset, acquisition information, data format

Dataset location

Geographical location, tectonic setting, geological map

Settings:

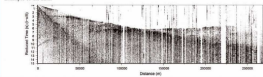
- South of Spain
- Southern Iberian Massif:
- South Portuguese Zone,
- Ossa-Morena Zone and southern Central Iberian Zone.



Record example

Example image of the data (shot-gathers or stacks)

Example of the data:



Main references

References to published peer-reviewed articles featuring the data

Main references:

- Aguirre et al. (2010), doi:10.1016/j.petro.2010.05.004
- Flecha et al. (2009), doi:10.1016/j.tecto.2008.05.013
- Palomares et al. (2003), <http://dx.doi.org/10.20380/digitalCSIC/9018>
- Palomares et al. (2009), doi:10.1029/2007JB005650
- Palomares et al. (2011), doi:10.1029/2011JG001577

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- Spanish Ministry of Science and Innovation: CGL2004-04623, CSD2006-00041.
- Generalitat de Catalunya: 2005SGR000374, Servei de Anàlisi.

Funding information

Funding agencies and grant codes

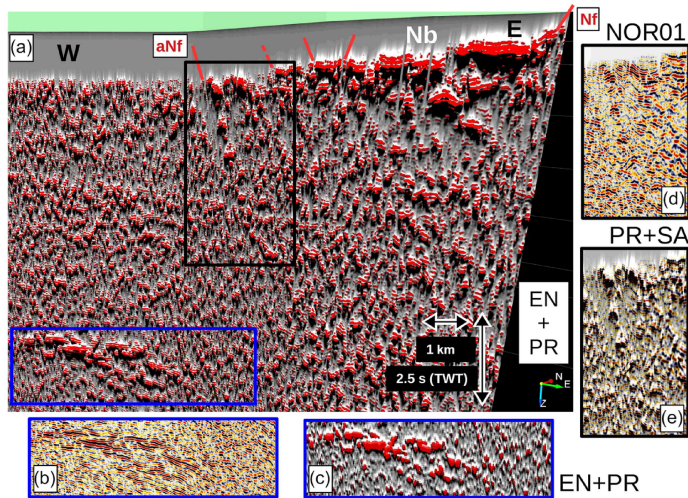
Example of the index card containing the IBERSEIS-WA project information.

Attribute Analysis: A tool for earthquake hazard assesment

Use seismic attributes of conventional exploration seismic reflection data, combined with seismological information (i.e., focal mechanisms, earthquake locations), contribute to the identification and, characterization of possible seismogenic structures, aiding earthquake hazard assessment. Seismic attributes were used in seismotectonic research focused on the Norcia Mw = 6.5 earthquake (30 October 2016) in central Italy Profile NOR01: (a) Composite multi-attribute display main outcropping structures are marked. Seismic facies in the blue (b, c) & black (d, e) boxes comparison the original amplitude image and the combinations of the atributes.

Attributes

- ▶ EN Energy
- ▶ PR Pseudo-relief
- ▶ SA Standard-amplitude



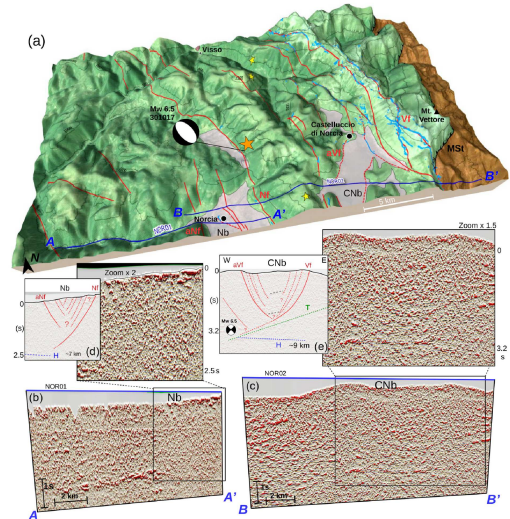
[Ercoli et al., 2020, Solid Earth]

The Norcia Mw = 6.5 EQ, (Central Italy) Seismogenic Structure

Integration of the surface topography and the composite multi-attribute displays of the seismic images: Black boxes focus on Nb and CNb.

- ▶ (a) Top 3D view DEM section, across the Norcia and Castelluccio di Norcia basins (Nb and CNb). Location & source mechanism of the main-shock are indicated. **Outcropping fracture network & surface ruptures**; **Legacy Seismic reflection exploration transects**
- ▶ (b) NOR01 Composite multi-attribute display
- ▶ (c) NOR02 Composite multi-attribute display
- ▶ (d) & (e) sketches proposed interpretation. Two conjugate basins, master faults along their borders with minor synthetic & antithetic splays.

Attribute images provide additional details on the geometry of structures of the seismogenic fault zones.



Crustal X-section across the Variscan Crust of Iberia

Building a complete crustal transect of the Iberian Massif by Integrating highly heterogeneous control source seismic reflection datasets, acquired within 30 years time span.

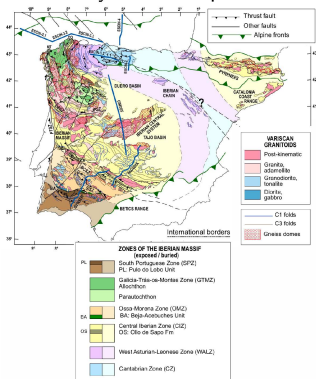


TABLE 1: IBERSEIS

Acquisition Parameters	
Recording instrument	SERCEL 388
Number of active	240 minimum (400 total)
Station spacing	35 m
Station configuration	12 Geophones/string in line
Receiver type	10 Hz natural frequency
Filters	Out
Source type	4, 22 TM Vibrators
Source spacing	70 m
Sweep frequencies	8 – 80 Hz
Sweep type	Nonlinear
Sweeps per VP	6
Sweep length	20 s
Recording length	40 s listening time
Record length after correl	2 m
Sample rate	20 s
Sweep type	asymmetric split spread
Nominal fold	60 (minimum)
Noise suppression	Diversity stacking
Field processing	sweep corr

TABLE 2: ALCUDIA

Acquisition Parameters	
Recording instrument	SERCEL 388
Number of channels	240 minimum
Station spacing	35 m
Station configuration	12 Geophones/string in line
Receiver type	10 Hz natural frequency
Filters	cut
Source type	4 (±1 spare) 22 TM Vibrators
Source spacing	70 m
Sweep frequencies	8–80 Hz
Sweep type	Nonlinear
Sweeps per VP	60 (minimum)
Sweep length	20 s
Recording length	20 s
Correlation length	20 s
Sample rate	4 ms
Spread type	Asymmetric (120 active)
Nominal fold	60
Notes	Diversity stacked
	7500

TABLE 3: ESCIN-1

Acquisition Parameters	
Source Charge	Dynamite—single-hole
Trace interval	20 Kg at 24 m depth
AP of traces	60 m
Spread configuration	240 m
Coverage	Symmetrical split-spread
Geophones per group	3000/00%
Total spread length	18 m
	14.5 Km
Processing	
Record length: 25 s	
Sampling	
Surve datum plane	
Demultiplexing	
Amplitude recovery	
Dynamic trace	
	prediction lag: 0-25 s
Slalom line CMP	
CMP interval	25 s
Resampling	30 m nominal
Anti-alias filtering	8 ms
Elevation replacement	
Spatially variant mute	
NMO correction	datum +1000 asl
Surface consistent residual statics	
Stack	3000% coverage nominal

TABLE 4: ESCIN-2

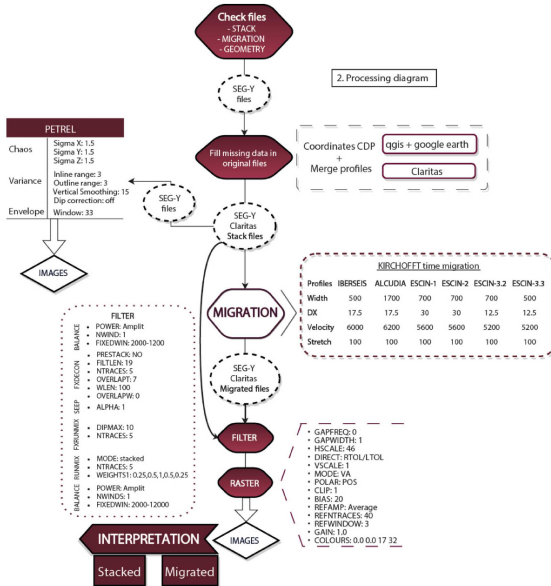
Acquisition Parameters	
Source	Dynamite (GSC 20D)
Charge	20 kg at 24 m depth
Trace interval	60 ms
Number of traces	240
Spread configuration	Symmetrical split-spread
Coverage	3000, 00%
No. geophones	16
Geophone	linear
	3.33 m
	60 ms
	SERCEL SN 34
	Low cut off
ape format/density	SEG-B/6250 BP

TABLE 6: ESCIN-3.3

Acquisition Parameters	
Air guns volume	5490 cu in (90 cu m)
Pressure	2000 p.s.i.(13.8 MPa)
Shot spacing	75 m
Receiver interval	380 ms spaced 12 m
Nominal fold	30 (4450/75)/2
Offset	240 m
Processing	
Record length: 20 s	
Sampling: 4 ms	8 ms
Corrections	-127 ms
Direction	
Bandpass filtering	5, 24, 48 Hz
Dip filtering	15, 25, 48 ms
Prestack Deconvolution	Prediction lag: 0.00 m
	Operator length: 500 ms (40-500 m)
	Prediction lag: 80 m
	Operator length: 500 ms (5000-20000 m)
Frontal mute	
FK filtering	
Adaptive trace summation	12 ms/trace
CMP sorting	1, 2, 4, 2, 1
Velocity analysis	Every 3 km
NMO correction	
Stack	

[Ayarza et al., 2021, Solid Earth]

Homogenized Processing Flow & Integrating Profiles

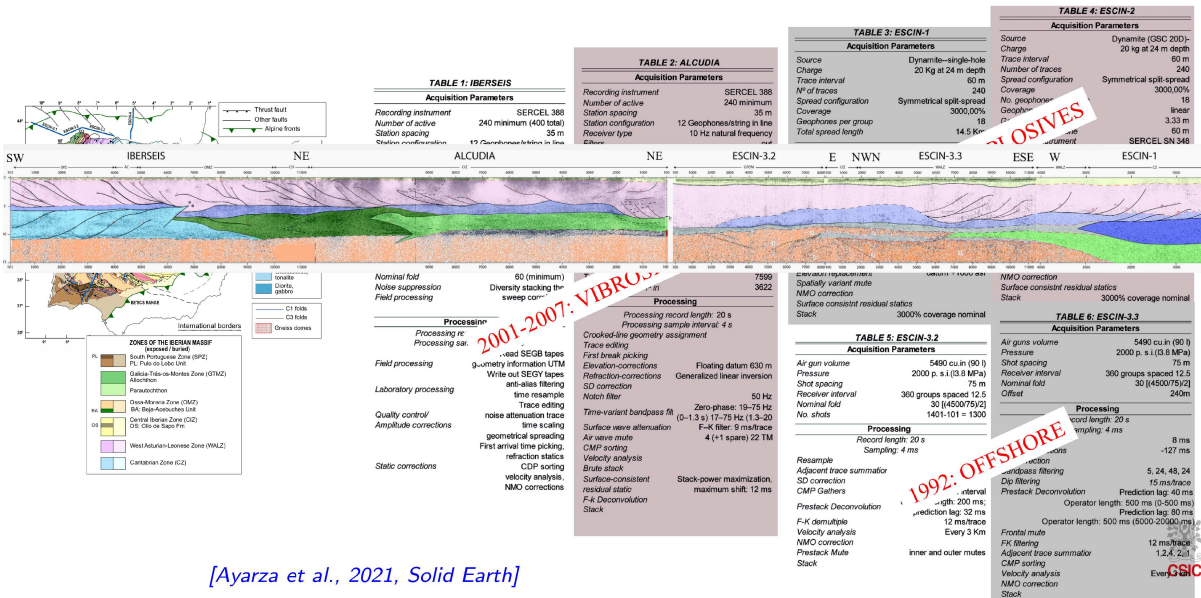


Processing flow carried over the SEG-Y original stack sections. This task was geared to improve and homogenize the resolution of the seismic images while creating new migrated sections.

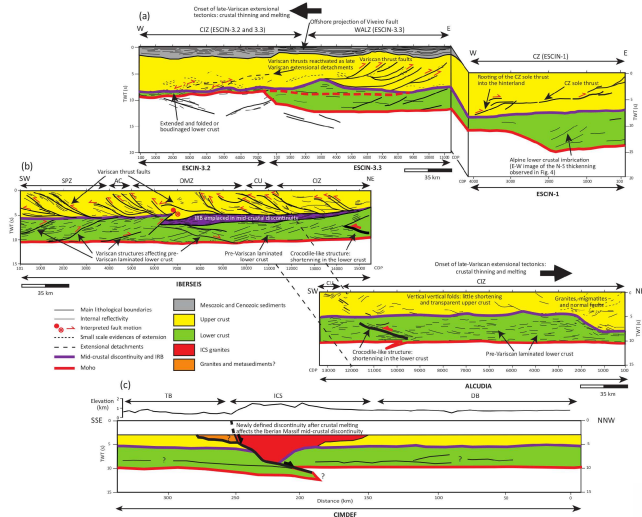
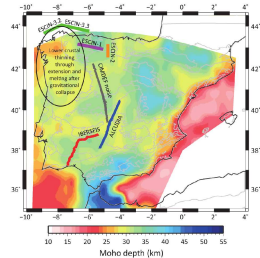
The integrated x-section resulting from the reassessment of the different profiles contribute to define the internal architecture of the westernmost exposure of the European Variscides.

[Ayarza et al., 2021, Solid Earth]

Crustal X-section across the Variscan Crust of Iberia



X-section across the Iberian Massif



Integrated geological interpretation of the composite seismic X-section Integrated deep seismic reflection transects include (a): ESCIN-1, ESCIN3-3 and ESCIN-3.2. (b): ALCUDIA and IBERSEIS. (c): CIMDEF. Special relevant is the lateral geometrical consistency of the Moho and mid-crustal discontinuities.

[Ayarza et al., 2021, Solid Earth]

Common Reflection Surface Stacking Operator & Optimization

$$t^2(\Delta x, h) = \left(t_0 + \frac{2 \sin \alpha \Delta x}{v_0} \right)^2 + \frac{2 t_0 \cos^2 \alpha}{v_0} \left(\frac{\Delta x^2}{R_N} + \frac{h^2}{R_{NIP}} \right)$$

h : half offset between shot and receiver

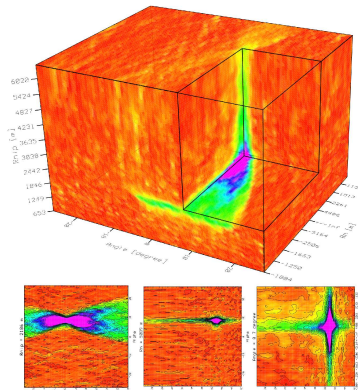
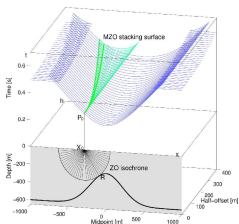
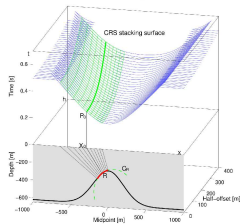
Δx : midpoint distance

α : emergence angle of the normal ray

R_{NIP} : radius of curvature of the NIP wave

R_N : radius of curvature of the normal wave

Mathematical operator for stacking processes. Stacking is carried out by going through all the values for R_N, R_{NIP}, α .

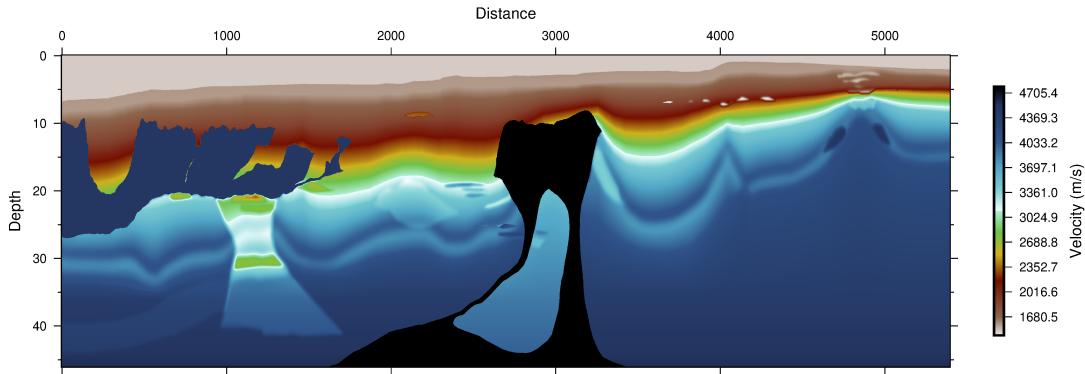


Graphical sketch of the CMP-NMO (Left) vs the CRS (right) operators

Thus an optimization algorithm based on coherence is required in order to search for the values for R_N, R_{NIP}, α that result in the stack with maximum coherence.

[Mann, et al., 1999, J. App. Geoph.]

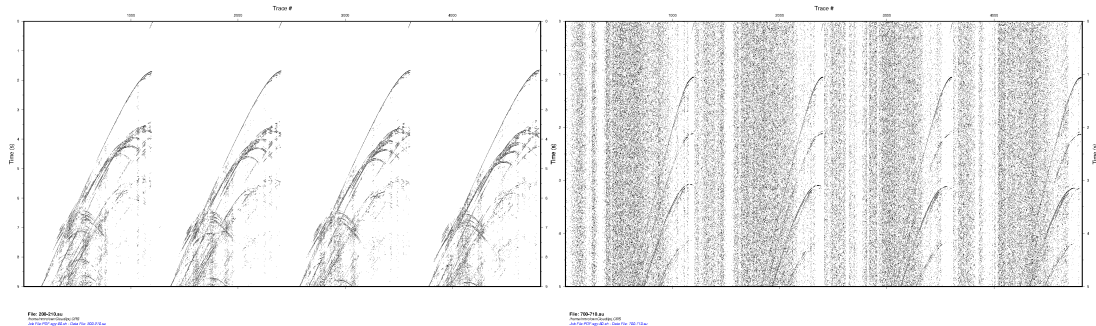
BP Bench Mark Model & Synthetic Seismic Data



Data fl: BPB-Vp.su Plot fl: aa

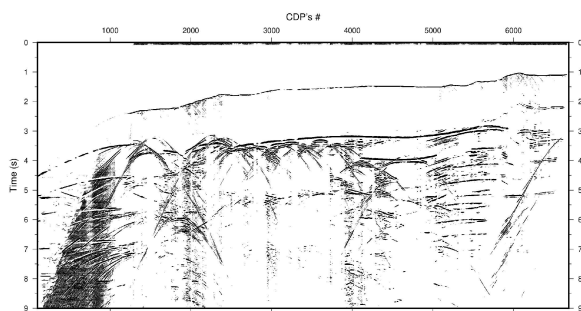
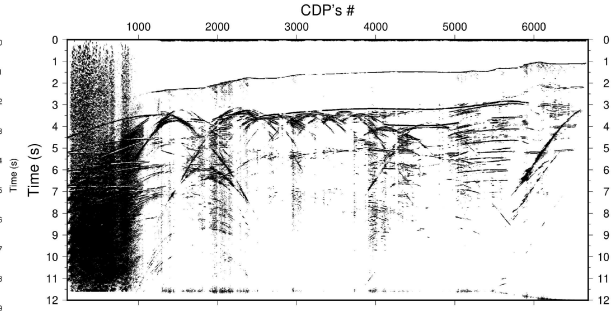
This model was created by F. Billette and S. Brandsberg-Dahl as a blind test for the Velocity workshop at the 66th EAGE international meeting in Paris, France, in June 2004. The model is a simplified representation of geologic features that pose imaging difficulties. A composite of structures from: the Eastern/Central Gulf of Mexico, off-shore Angola, Caspian Sea, North Sea and Trinidad. The model is used for benchmarking advanced processing approaches, prestack depth migration, reverse time migration. Here it is used to challenge CRS. [Billette & Brandsberg-Dahl, 2005, EAGE]

Synthetics clean & noise, shot records



Example of synthetic shot gathers. The original dataset was calculated using a mixed-domain 2D finite-difference acoustic wave propagation solver. (Left) clean synthetic shot gathers; (right) noise has been added to the shot gathers. Amplitude of the noise is of 20% of the amplitude of the signal. The velocity model is 67km long and 12km deep, and was built on a 6.25m x 6.25m grid, in total the size of the model grid is 1911x5395 points. The data were generated simulating a 15 km streamer (offset range from 0 to 15 km) with 12.5m group spacing and a 50m shot interval. Shot records go down to 14 s of data with at 0.006s sample rate. The dominant frequency is 27Hz (reaching up to 54Hz). The low-cut frequency is 0.5Hz. A total of 1340 shots were generated each with 1201 receivers.

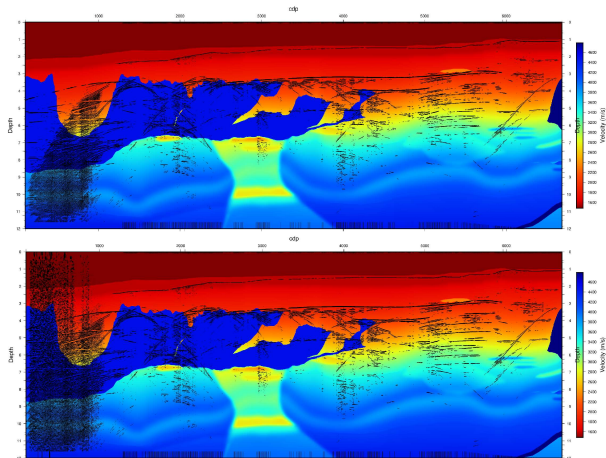
CRS Stacks BP-Bench Mark



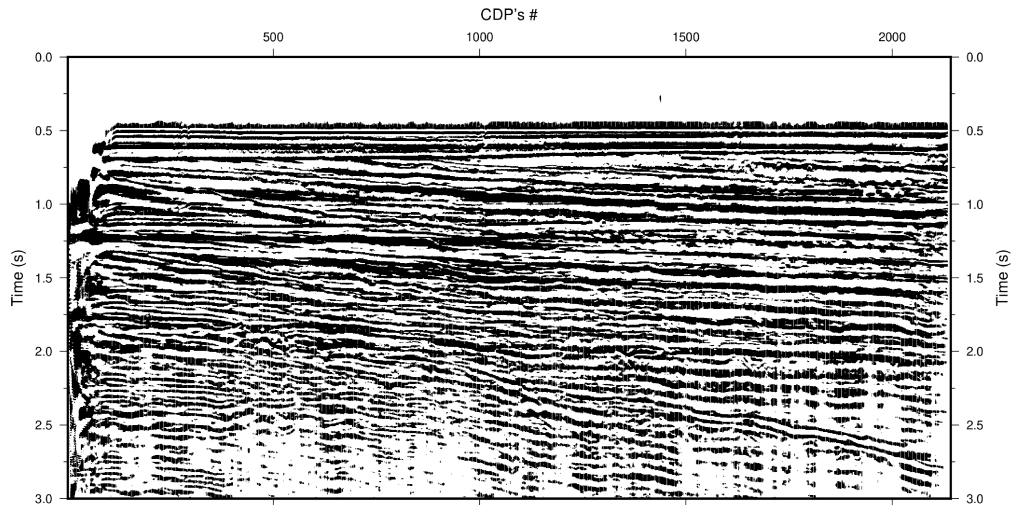
Stacks obtained by the CRS scheme, of the central part of the velocity model. (left) CRS stack obtained by using the clean synthetic data; (right) CRS stack obtained by using the shot gathers with added noise.

CRS Staks & velocity model

Stacks obtained by the CRS scheme, the staks are overlayed on the corresponding part of the of the velocity model. The images correspond to the central part of the velocity model. (top) CRS stack obtained by using the clean synthetic data. (bottom) CRS stack obtained by using the shot gathers with added nosie.

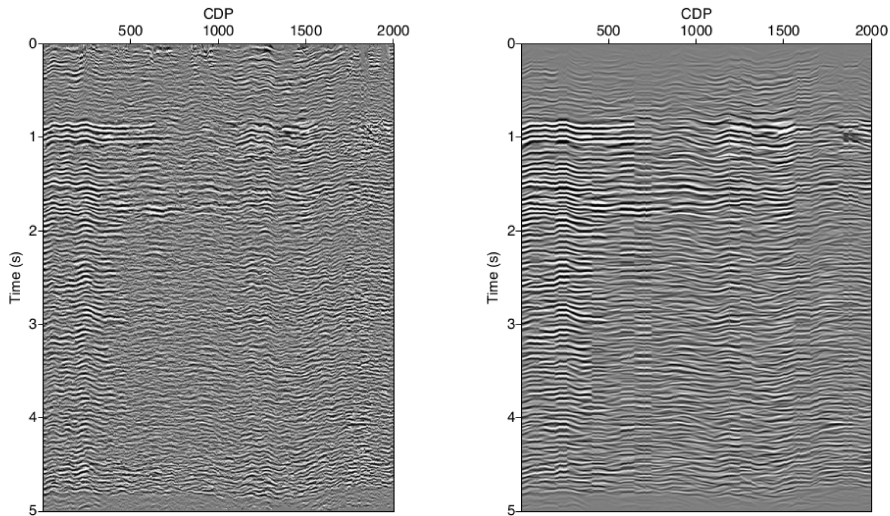


CRS Stack MOBIL Viking Graben L 12



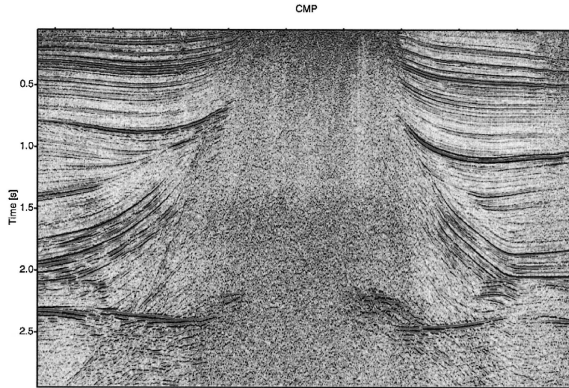
Exploration 2D marine normal incidence seismic reflection profile MOBIL Viking Graben L 12. It was released for the 1994 SEG workshop. The data set is in the public domain and accessible through SEG Wiki (<https://wiki.seg.org/>) [Keys, Forster, 1988, SEG]

Comparison of NMO vs CRS real data example



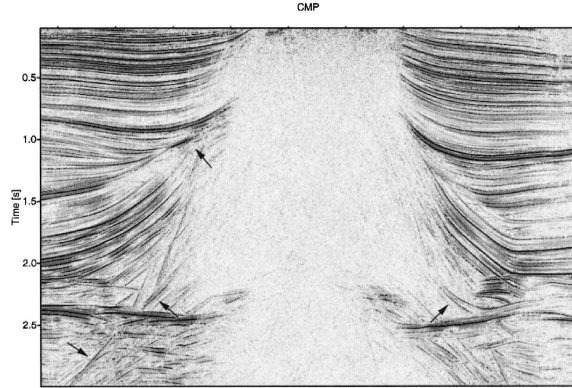
Exploration normal incidence seismic reflection dataset acquired in the Parana Basins. Left conventional zero offset CMP stack CMP and Right Common reflection surface stack. [Okita, et al., 2019, SEG]

CMP vs CRS real exploration case



Unconstrained automatic CMP stacked section. An automatic gain control was applied to reveal weak events

Stack
[Mann, et al., 1999, J. App. Geoph.]



Final result of the optimized CRS stack. The major differences to the conventional stack indicated by arrows for comparison.

Machine learning: a group of algorithms that can make predictions and/or classifications on data sets without the prior need to specify what to predict or classify.

Learning Algorithms:

- ▶ Supervised algorithms: learn from a labeled external dataset (training set). This brings expert knowledge of the physical reality to the analysis. Classification: label each element within a population according to external rules (supervised learning).
- ▶ Unsupervised algorithms: learn from the internal structure of the datasets themselves without any reference model (avoiding inputs from physical reality). Clustering groups elements within a population according to their similarity (unsupervised learning).

Simple clustering and classification algorithms are commonly used in genetics, image processing, market research.

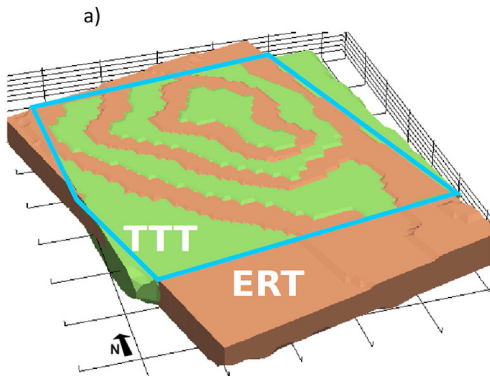
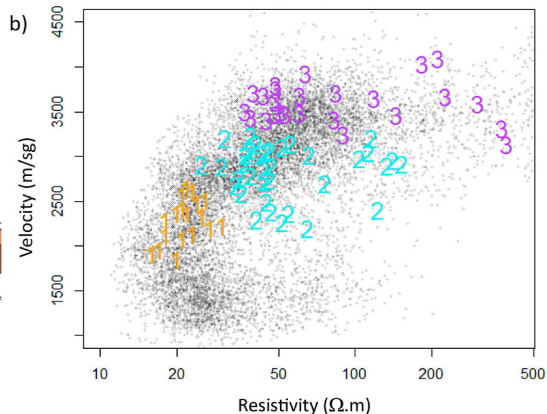


Joint interpretation scheme use machine learning techniques to derive 3D lithological model from different and independent datasets.

1. the pseudo-3D resistivity model,
2. the 3D seismic velocity model,
3. the well-logs information

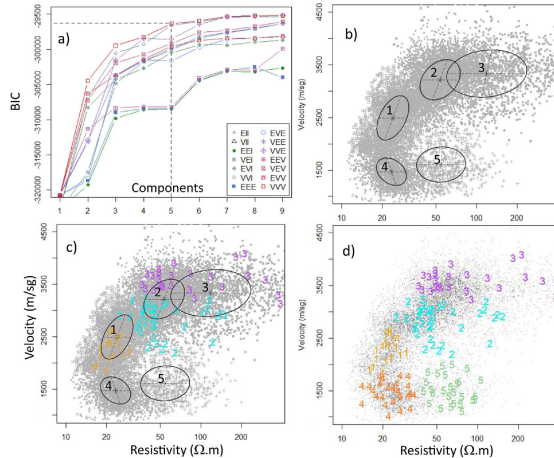
The joint interpretation scheme consists in:

1. integration of the datasets,
2. training set preparation,
3. classification,
4. validation of the final model.



Data integration. a) Intersection of the 3D velocity model (TTT) and the pseudo-3D resistivity model (ERT) in blue. b) R-Vp cross-plot of the bi-parametric model made from the intersection of TTT-ERT. The colored numbers represent the classifiers obtained from the **well-logs** gathered in the training set (orange 1 is LT, blue 2 is Ytr, and purple 3 is Ym). Low velocities nodes lack classifiers. [\[Marzan, et al., 2021, J. Engin. Geol.\]](#)

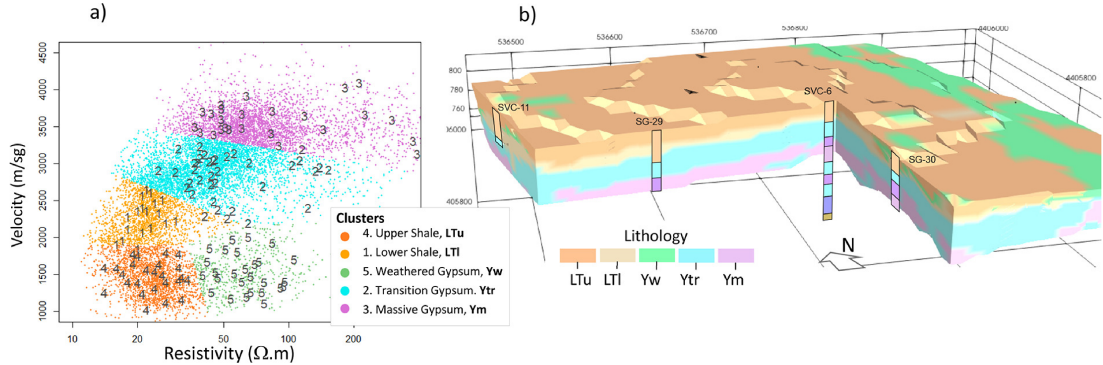
Clustering Approach



Clustering result. a) Score of the 14 models explored by the unsupervised clustering algorithm. According to the BIC value and applying the elbow method, the most reliable model is the VVV with 5 components. b) The Res-Vp cross-plot overlapped by the Gaussian ellipsoids of the VVV-5 model. c) Same as in the previous plot plus the classifiers deduced from the well-logs (colored numbers). Components 4 and 5 fill the gap in classifiers for low-velocity nodes. d) The Res-Vp cross-plot covered by the final training set is composed of the classifiers from boreholes (1, 2, and 3) and the classifiers 4 and 5 from the clustering analysis.

[Marzan, et al., 2021, J. Engin. Geol.]

Machine Learning: Classification result



Classification result. a) The Res-Vp cross-plot classified by the supervised algorithm (LDA), overlapped by the training set classes. The two new classes obtained for the shallowest nodes are labeled as LTu (Upper Shale) and Yw (Weathered Gypsum). The introduction of class 4 forced us to divide the layer called LT in two: LTu and LTI. b) The final lithology model showing clipped sections and correlations with the boreholes' geophysical lithologies

[Marzan, et al., 2021, *J. Engin. Geol.*]

Summary & Conclusions

- ▶ Seismic reflection data-sets provide high resolution, critical information on the physical properties and structure of the Earth. (unique assets for solid Earth sciences) The data-processing software and hardware developments enable new ways to retrieve valuable information from these data.
- ▶ Seismic attributes provide new details on the geometry of structures of the seismogenic fault zones.
- ▶ The homogenized reassessments of multiple transects enables integrated views of crustal/lithospheric X-sections.
- ▶ Detailed high resolution automatic imaging, through computer expensive algorithms such as CRS, now available to laptops through NVIDIA, CUDA, and other distributed seismic processing programs on the cloud.
- ▶ Artificial Intelligence, Machine Learning, Deep Learning model building through integration of multidisciplinary data.

References

- ▶ Ayarza, P., Martz Catal J. R., Martz Garc A., Alcalde, J., Andr J., Simancas, J. F., Palomeras, I., Mart., DeFelipe, I., Juhlin, C., and Carbonell, R.: (2020) Evolution of the Iberian Massif as deduced from its crustal thickness and geometry of a mid-crustal (Conrad) discontinuity, Solid Earth doi: 10.5194/se-2020-158
- ▶ Billette, F., and S. Brandsberg-Dahl (2005) The 2004 BP velocity benchmark. 67th Annual Internat. Mtg., EAGE, Expanded Abstracts EAGE-2005-B035,
- ▶ DeFelipe, I., Alcalde, J., Ivandic, M., Mart., Ruiz, M., Marz I., Diaz, J., Ayarza, P., Palomeras, I., Fernandez-Turiel, J.-L., Molina, C., Bernal, I., Brown, L., Roberts, R., and Carbonell, R.: Reassessing the lithosphere: SeisDARE, an open-access seismic data repository, Earth Syst. Sci. Data, 13, 10531071, doi:10.5194/essd-13-1053-2021, 2021.
- ▶ Ercoli, M., Forte, E., Porreca, M., Carbonell, R., Pauselli, C., Minelli, G., and Barchi, M. R. (2020) Using seismic attributes in seismotectonic research: an application to the Norcia Mw=6.5 earthquake (30 October 2016) in central Italy, Solid Earth, 11, 329348, doi: 10.5194/se-11-329-2020, 2020
- ▶ Keys, R.G. and Foster, D.J., 1998. A data set for evaluating and comparing seismic inversion methods. Comparison of seismic inversion methods on a single real data set, pp.1-12.
- ▶ Lobato-Gimenes, T., Pisani, F., and Borin, E., (2018) Evaluating the Performance and Cost of Accelerating Seismic Processing with CUDA, OpenCL, OpenACC, and OpenMP, 2018 IEEE International Parallel and Distributed Processing Symposium (IPDPS), Vancouver, BC, Canada, May 2018, pp. 399-408.
- ▶ Mann, J., R. Jager, Th. Muller, G. Hocht, P. Hubral Common-reflection-surface stack, a real data example J. App. Geoph. 42, 1999. 301-318
- ▶ Marzan, I., D. Mart. Lobo, J. Alcalde, M. Ruiz, J. Alvarez-Marron, R. Carbonell, (2021) Joint interpretation of geophysical data: Applying machine learning to the modeling of an evaporitic sequence in Villar de CaSpain), Engineering Geology, 2021, doi: 10.1016/j.enggeo.2021.106126.
- ▶ Okita, N.T., T.A. Coimbra, M. Tygel, and E. Borin, (2019), A heuristic to optimize the execution cost of distributed seismic processing programs on the cloud, SEG Technical Program Expanded Abstracts 4004-4008. doi: 10.1190/segam2019-3216462.1