Jacopini:

Dear Editor,

I have been reading with extreme interest the paper submitted by Maurizio Ercoli et al. The paper transfers a long lived but also a now very sophisticated methodology of image processing/seismic attributes, developed within the O&G exploration domain, into the regional and fault interpretation using 2D seismic lines for seismic tectonic purposes. The aims of seismic attributes in this context is to unravel and enhance deep reflectors but also high angle features and then reframe those interpretative results to fine tune the discussion Norcia Mw earthquake. I am, in fact, rather surprised it took so long to use those techniques in this context, therefore I welcome this paper and I take the opportunity to make some constructive comments to the discussion triggered by this paper.

Authors:

We really thank David Jacopini for this positive note and for all the constructive and relevant comments. We are glad that he remarks the spirit of this work, highlighting the novelty of our study in suggesting the use of seismic attributes in seismotectonic research.

Jacopini:

I will be focusing more on the methodological aspect (given I have no experience on the Norcia seismotectonic area so I cannot make any comment on the tectonic implication of the results proposed).

a) Frequency content: the authors introduce the properties of seismic stating that “The average frequency spectra display bandwidths ranging from few Hz up to 60-70 Hz, whilst NOR02 extends up to 100 Hz”. Could they please clarify the significance of those numbers? usually a seismic line (especially onshore) barely reach those high frequency content below 1-2 second of depth.

Authors:

We meant to describe the whole frequency range of the seismic lines and in tab.1 we display the frequency contents using amplitude/frequency spectra computed on the entire time window of each processed line. In the case of NOR02 line the spectrum shows a slighter high frequency contents in the range 40-80 Hz, but basically the bandwidth is in the range 10-50 MHz, therefore we’ll modify the sentence, thank you for this note.

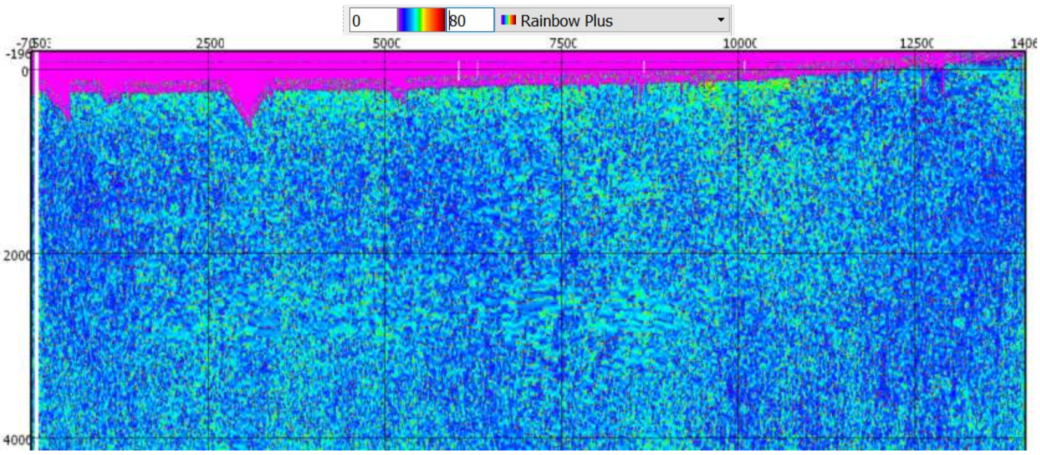
Jacopini:

Therefore, I am curious to see what the frequency decomposition and the distribution of those frequencies across the seismic line (through depth) look like. Source frequency in fact only partly relate with the frequency of the impulse signal coming from the source utilized..as the impulse will then convolve with an earth model losing by multi reflection and absorption the energy and therefore frequency content. Even a simple instantaneous frequency image would help.

Authors:

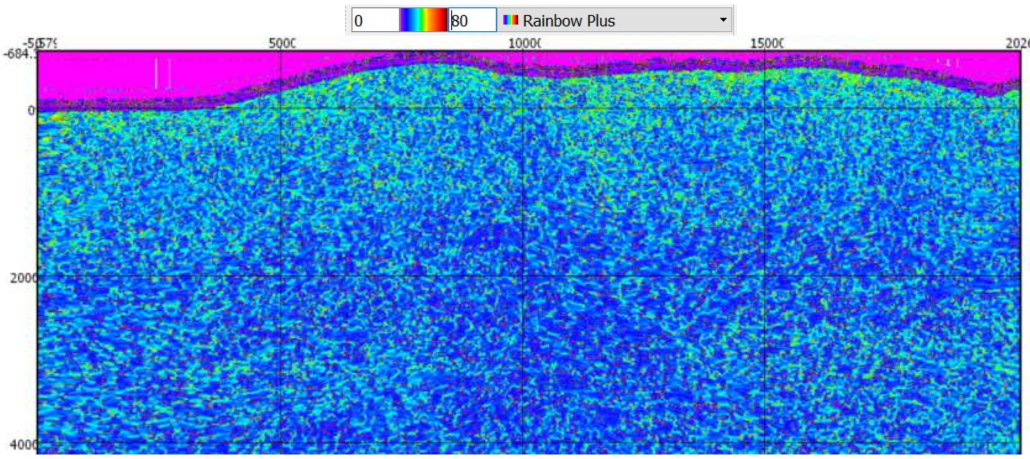
Two images of the instantaneous frequency are provided as requested. The sections are clearly contaminated by high frequency noise, however also higher frequency components of the signal are visible in the shallow portion (0-2 seconds), whilst progressively lower frequencies are visible more in depth.

In addition to your comment, we can state that other more sophisticated and quantitative techniques, like spectral decomposition, are not useful on the data here analysed due to the overall low signal-to-noise ratio and high phase variability.



NOR01

Distance [m] vs TWT [ms]



NOR02

Distance [m] vs TWT [ms]

Jacopini:

A frequency decomposition may help (if an interval velocity model can be assumed) to further constrain and understand the resolution, therefore estimate the thickness and therefore discuss the significance of some of the main reflectors. Given that there are no well core and well log to tie the seismic any sort of information to constrain the scale of those reflector need to be attempted.

Authors:

We already reported in this work an estimation of the average resolution in the caption of table 1. We had computed for these lines a value ranging between 70-80 m assuming an average velocity of 6000 m/s and the worse scenario considering a frequency of 20 Hz. This value is sufficient to resolve the main regional reflectors belonging to the multilayer formations of the Umbria-Marche succession. Unfortunately, in addition to the low S/N, also the phase continuity is in general quite poor thus preventing a detailed analysis on, for instance, the occurrence of interference phenomena investigated through sophisticated spectral decomposition techniques based on STFT or wavelet analysis.

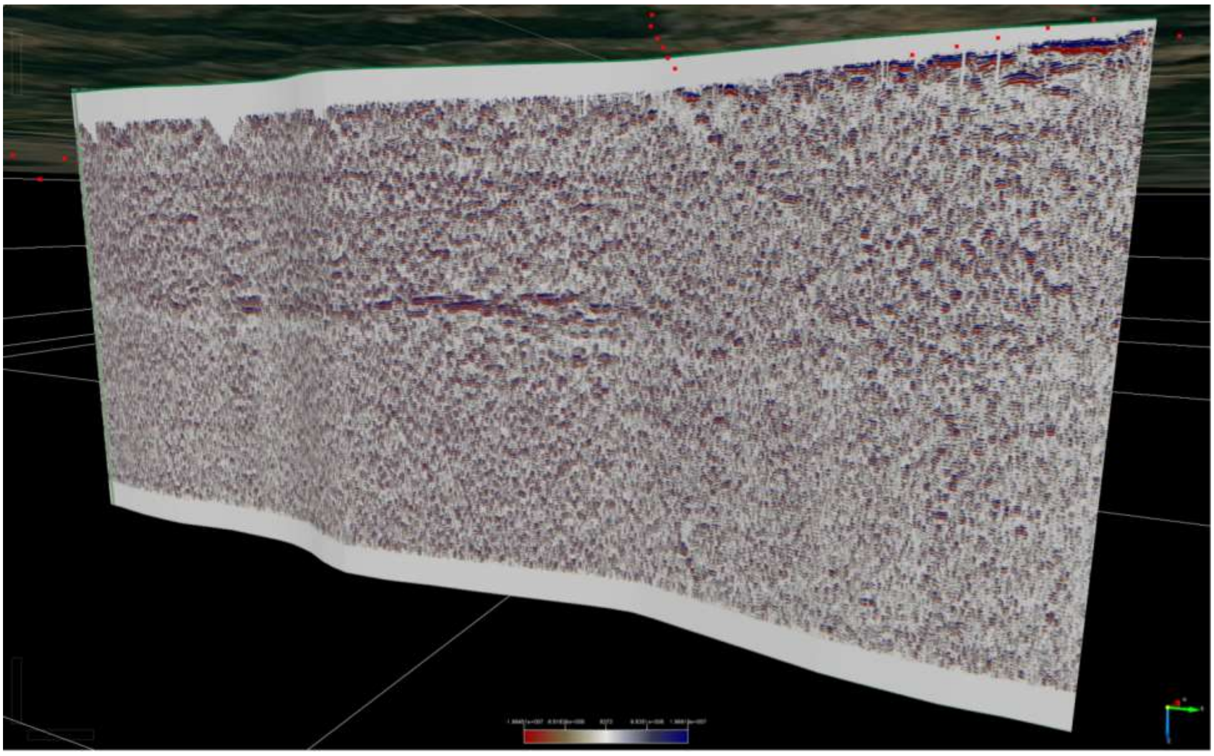
Jacopini:

b) Noise analysis. What is missing in the methodology and results description of this paper is a proper discussion of the noise content into the seismic and work done to isolate m understand and extract it before interpreting the seismic response using attributes. This is what in seismic interpretation we call conditioning process of the data. Every seismic lines or volume data include acquisition footprint, backscattered ground-roll, migration operator aliasing, aliased shallow diffractions, multiples, and low reflectivity that falls below the ambient noise level. The expression of these noise features has negative value in mapping geology; such noise is also exacerbated by seismic attributes. So, the author should discuss in depth the issues related to the seismic which imply, getting back to the pre stack data and processing aspect or re run an image processing conditioning. There has been a lot of literature and there are software's or algorithms producing filters called edge preservation or structural oriented edge preservation which help the interpreter to smooth low and high frequency oriented and random noise around the structure of interest (once recognized.); If they have not been tempted (comparing the image with attributes before and after the conditioning) that should be done to understand the seismic noise affecting the stacked image.

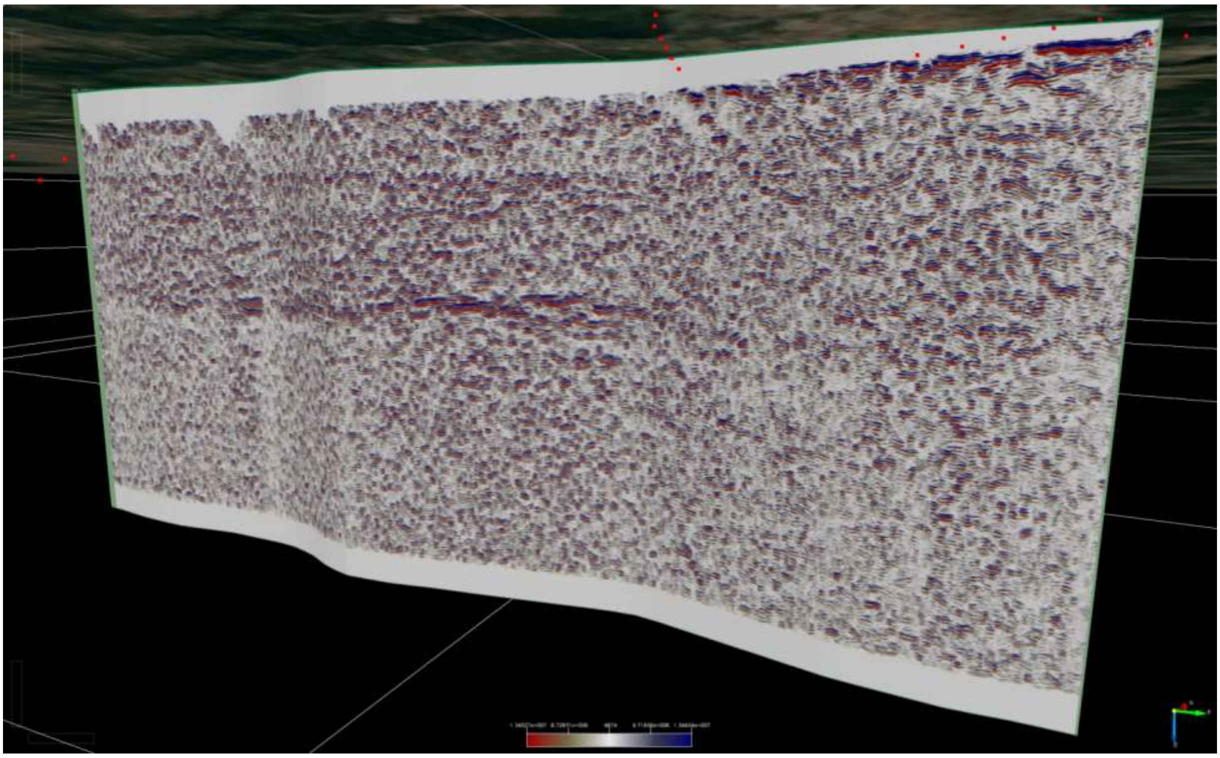
Authors:

The question is relevant and we agree about the importance of a detailed noise analysis and data conditioning. These seismic lines are mainly characterized by random high-frequency noise. We have made an extensive analysis and filtering tests to attenuate such components, using the steering algorithms implemented in OpendTect (e.g. 1 - Phase Gradient, FFT and PCA, also specifying 70° as maximum dip angle of the events to exclude possible (sub) vertical artefacts/noise components, and using a median filter tested using different n° traces/samples). Here below two images (Energy Gradient attribute NOR01) for comparison: without and with data conditioning with a dip-steering filter. Slight benefits can be appreciated on the continuity of reflectors as well as, for example, on continuity of the high deep antithetic fault of Norcia (the small red dots suggest its approximate surface location). However, after the data conditioning we did not observe dramatic improvements in our 2D lines, probably because the data conditioning performs more efficiently of 3D seismic volumes. For this reason, we have decided to summarized very shortly this procedure in the text, avoiding a too detailed and technical treatment to weight down the methodological section. However, we can surely introduce the problem briefly describing the data pre-conditioning, if necessary. Thank you for the suggestion and in particular for the useful references provided.

No data conditioning



Data conditioning



Jacopini:

Again, the following paper should be taken into account in order to avoid to reinvent the wheel with differently energy named attributes (I know those are the commercial name given into open source software): - Gersztenkorn, G., Marfurt, K.J., 1999. Eigenstructure-based coherence computations as an aid to 3-D structural and stratigraphic mapping. Geophysics 64, 1468e1479. I also suggest to read on that line also the paper Pitfalls and limitations in seismic attribute interpretation of tectonic features Kurt J. Marfurt1 and Tiago M. Alves published into the seg AAPG interpretation: - Marfurt, K.J., Alves, T.M., 2015. Pitfalls and limitations in seismic attribute interpretation of tectonic features. Interpretation 3, 5e15. http://dx.doi.org/10.1190/INT-2014-0122.1.

Authors:

We agree with this comment, currently there are many papers reporting the name "Energy" for this attribute, but we surely improve the attribute description in the methodological part adding these references. Regarding the papers related to the Pitfalls, we have shorty reported some references about pitfalls in the introduction (line 79), when describing the pros and cons of the seismic attribute use in two 2D seismic data. However, we'll improve the text following your suggestion.

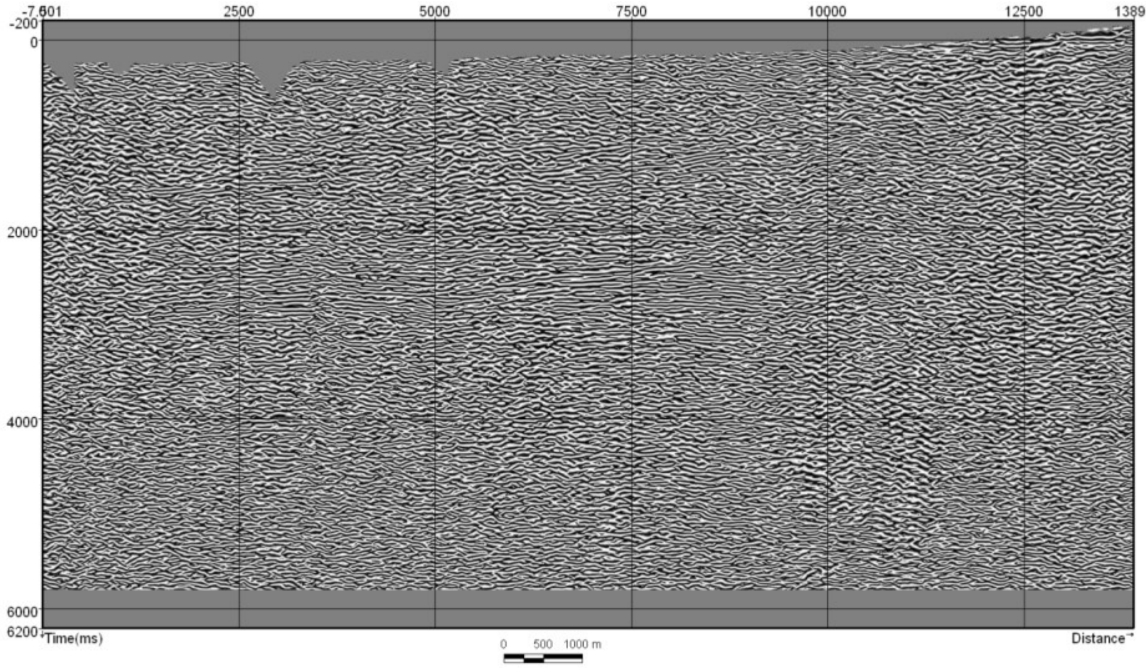
Jacopini:

c) I notice that the authors have avoided to use coherency and dip related attributes. In some case they may help to unravel subtle details and more importantly to distinguish noise surrounding certain dipping structure. In some other they may be totally useless (if too much noise distributed is affecting the seismic). Again, a mention should be given by the authors if those attributes have been attempted. The papers that tempted this approach in 3D volume (which imply using modified algorithms) should be take into account when discussing the results. Those methodologies are in fact now moving beyond into detailing damage structures surrounding large scale faults, exploring strain/fault facies using various statistical and soon machine learning approach. Here some of the pioneering examples: … (Literature list) Another attribute who may certainly help to visualize any sort of oriented structure without adding smoothing is the instantaneous phase and/or the cosine of it (called cosine of the phase).

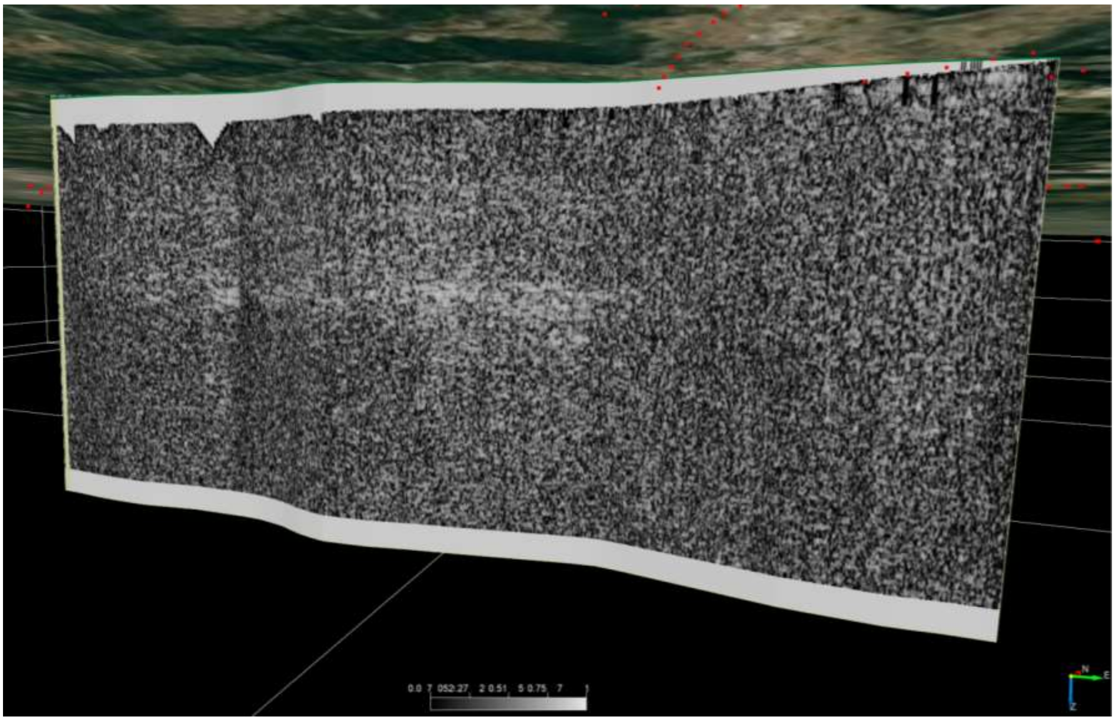
Authors:

Thank you for the request. Among the tested seismic attributes we have also calculated coherency-based ones, also considering the effects of the dip on them. However, we have decided to discard them in this work, because in our opinion they are not performing particularly well on our data. As suggested, probably the noise limits their efficiency (also in the conditioned lines) and, again we speculate that they may perform better on 3D seismic volume instead of this type of 2D vintage lines. We report an example of a similarity attribute, as an example of the test performed. We'll add some references as you suggested to make the discussion more exhaustive, also suggesting possible further innovative approaches like machine learning applications on this topic. Regarding the phase attributes, we have also used these during our tests, obtaining quite helpful results. We provide an image of the cos-phase here below that highlights the lateral continuity of some interesting reflectors, representing quaternary deposits infilling the Norcia Basin (about 12.5 km along the line). In any case in the paper we have preferred the Pseudo-Relief attribute that efficiently shows the continuity/discontinuity of the reflectors linked with reflection amplitude information.

COS-PHASE applied on the conditioned seismic line NOR01:



Similarity attribute computer on line NOR01:



Jacopini:

A different approach, that is now very important to guide the interpretation of certain seismic signal, come from the series of paper of the Bergen-Stavanger school running forward seismic modelling test. I suggest to read those papers and use them in the discussion when interpreting seismic, as they may be inspiring in discussing what the interpretation and acquisition pitfall who may biases the fault interpretation but also to compare what the results obtained in a more wide and up to date scientific framework.

- C. Botter, N. Cardozo, S. Hardy, I. Lecomte, A. Escalona. From mechanical modelling to seismic imaging of faults: a synthetic workflow to study the impact of faults on seismic. Mar. Petrol. Geol., 57 (2014), pp. 187-207
- C. Botter, N. Cardozo, I. Lecomte, A. Rotevatn, G. Paton. The impact of faults and fluid flow on seismic images of a relay ramp over production time. Petrol. Geosci., 23 (2017), pp. 17-28.

Authors:

Thank you, we'll surely look at such papers and possibly improve the discussion inserting this relevant topic, which is ancillary to the main focus of our paper.

Jacopini:

e) processing strategy: another approach has been taking by the Bruno&Improta work on the processing procedure to better image shallow structure using exploration data. Those need to be included in the discussion of the results obtained as well… (Bruno et al., 2010 and Improta et al., 2010).

Authors:

Thank you again for this advice. As we have reported in the introduction, two main strategies can be attempted in this type of studies. The first is the use of an attribute analysis as we propose here; a second possibility is the reprocessing of the original shot gathers, using modern processing tools and an improved computational power. However, we had only stack and migrated seismic lines available for this specific work (as is quite common when dealing with vintage data). Only recently we have received some original pre-stack raw data and we are currently working on a dedicated reprocessing workflow, particularly focused on the refinement of the static corrections, improved velocity analysis and interpretive processing. However, this second approach and workflow will be presented in another dedicated paper.

Jacopini:

I hope those comments may help to fine tune the paper and the discussion of the interpreted data proposed.

Best wishes David Iacopini

Authors:

We have really appreciated all your relevant comments and we are sure that they contribute to considerably improve our work.