Physical properties of seismogenic Triassic Evaporites in the northern Appennines (Central Italy)

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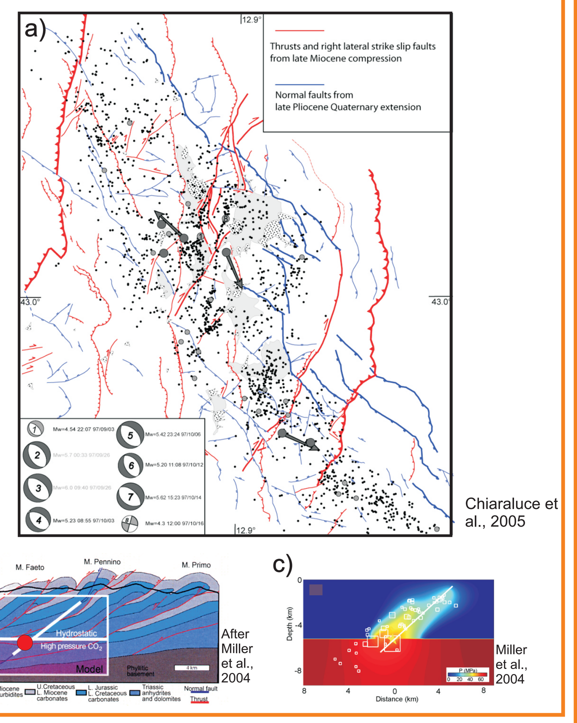
1. Aim

Two earthquakes of magnitudes Mw=5.7 and 6 marked the beginning of a sequence that lasted more than 30 days in the northern Apennines of Italy in September 1997, characterized by thousands of aftershocks and four additional events with magnitudes 5 <Mw< 6 (Fig 1a). Geologic cross-section integrating surface geology with seismic reflection profiles shows that the first two mainshocks and the largest aftershocks nucleated in the Triassic Evaporites (TE) at depth of about 4-6 km (Fig 1b). The TE formation is a sedimentary sequence up to1.5-2 km thick, at the base of the carbonatic multilayer of the northern Appennines. The time-space evolution of the seismic sequence seems to be driven by a fluid pressure pulse generated from the coseismic release of fluid overpressure trapped within TE (fig 1c). This interpretation is consistent with the CO_2 overpressure observed at two deep (~ 4 km) boreholes located close to the epicentral area within the TE at 85% of the lithostatic load.

The aim of this experimental work is to assess the evolutions of physical properties of TE at different crustal depth. In an area where P-wave measurements are available from different geophysical data (tomography, boreholes, seismic refraction) laboratory experiments are fundamental to provide a unique geological interpretation to the different sets of geophysical data.

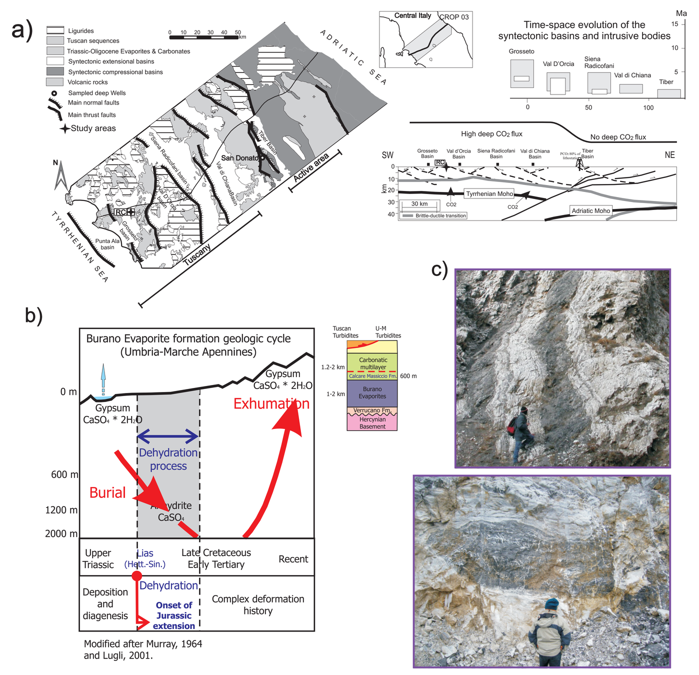


2. Study Area

Since extensional tectonic in the Northern Apennines migrated with time from west to east, as documented by the time-space evolution of the syntectonic basins (fig 2a), exhumed TE are exposed in the footwall of major normal faults in Tuscany (Fig.2a), whilst in the active area the major earthquakes nucleate at depth within TE (section 1).

The diagenetic history of the Triassic Evaporites is strictly related to the tectonic evolution of the area and it began since the early Jurassic/late Cretaceous, after about 1km of burial, when gypsum, originally deposited within shallow water environments, became unstable and was replaced by anhydrites (Fig. 1b) (Murray, 1964; Ciarapica and Passeri, 1976; Lugli, 2001). After deposition and burial the TE have been affected by a complex deformation history that have driven mainly flow on anhydrites rock and boudinage of dolostones.

The result of this intense tectonic activity is an highly deformed protolith (Fig 1c).



3. Micro-structural characterization

The TE formation is composed of alternating gypsum-anhydrites and dolostones. Samples of different lithologies have been collected:

Anhydrites

Anhydrites samples are characterized by:
Foliation,
Presence of dolostones clasts.
Gypsum rim that border all crystals
FESEM analyses show damaged dolostone clasts, fractures and porosity.

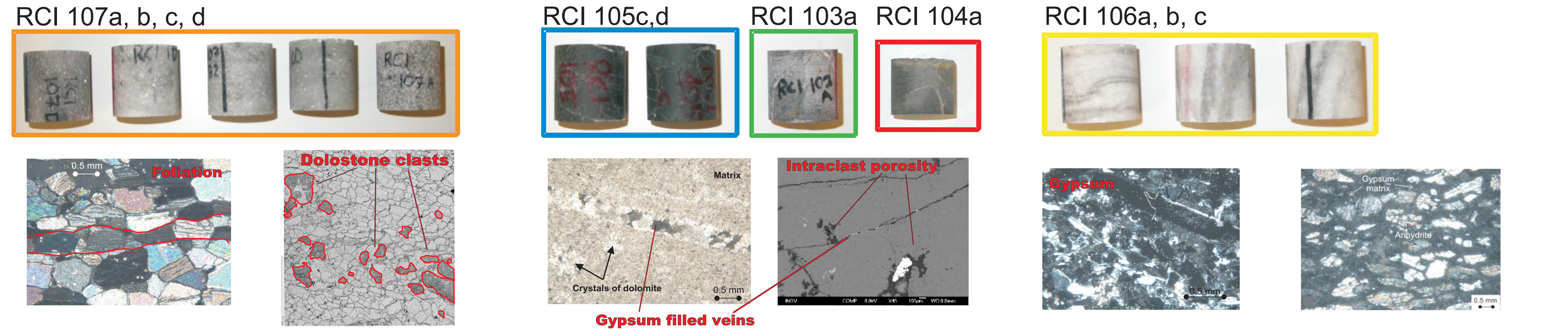
Dolostones

Dolostones are characterized by:
Centimetric micritic clasts cut by millimetric gypsum and calcite filled veins.
Optical microscope and FESEM analyses show intraclast porosity.

Gypsum/Dolostones

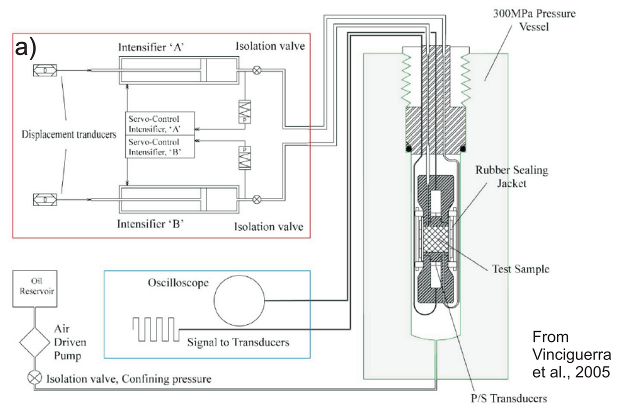
Secondary gypsum (due to re-hydration of anhydrites) alternated with dolostones layers is abundantly present in outcrop. These samples are composed by crystalline gypsum interbedded with thin dolostones layers. The secondary gypsum clasts are smaller than the anhydrites ones and do not follow the foliation planes.

RCI 107a, b, c, d — RCI 105c,d — RCI 103a — RCI 104a — RCI 106a, b, c



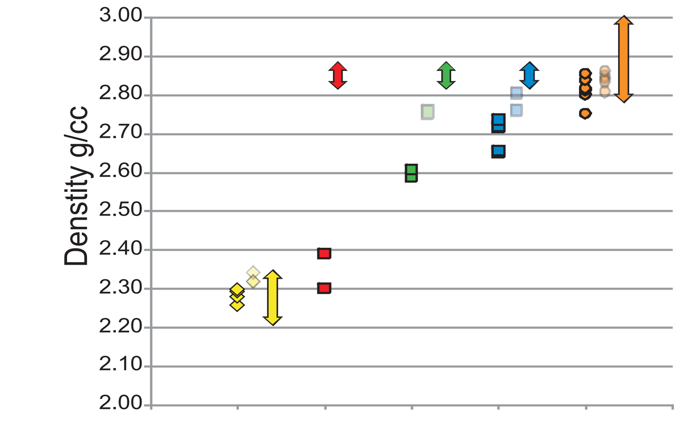
4. Laboratory Experiments

Velocities measurements at Rock Physics Laboratory (University College of London) were carried out after a preliminary measurement of bulk density (a) and porosity (b) by saturating the samples in a vacuum pump . A 900V pulser was used to excite a 1MHz resonant frequency piezo-electric transmitting transducer. Waveforms captured from an identical receiver were first pre-amplified and then recorded and displayed on a digital storage oscilloscope.
Radial measurements were made in 10° increments around the circumference of each sample at ambient pressure to infer anisotropy (c).
P wave velocity measurements (d) were also performed inside an hydrostatic pressure vessel, using silicone oil, equipped for measuring P velocity with 1MHz piezo-electric resonance frequency transducer crystals. Servo-controlled fluid pressure intensifiers (volumometers) were used to provide pore pressure (fig 4a).



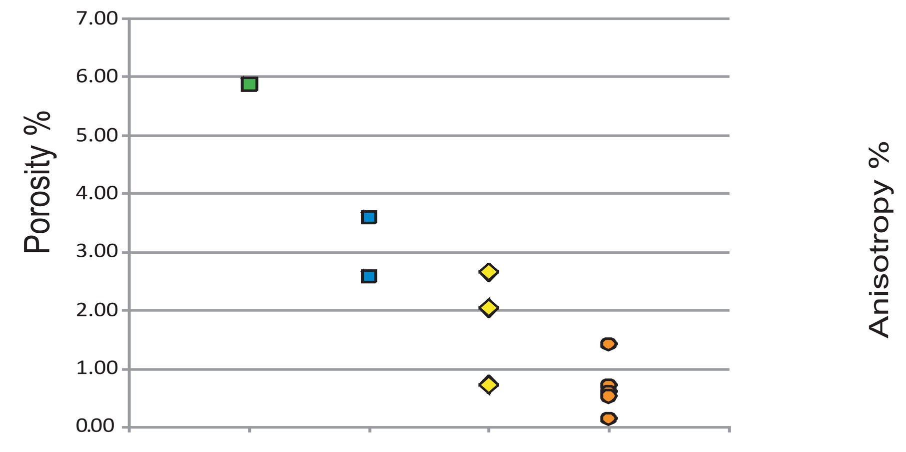
Bulk Density

Bulk densities of the investigated material (rhombus, squares and circles in the graph) are generally lower than correspondent single phases (arrows) (Schön 1998, Carmichael 1982, Ahrens,1995).
This is due to the fractured and altered nature of the field samples. In fact real densities (bulk density - open porosity) are closer to the reference values (shaded dots).



Open Porosity

The porosity is, in general, quite high (from 0.4 to 5.88) since the original lithology is considered "pore free"(e.g. Schön, 1998). We can infer that most of the porosity is due to exhumation-related processes.

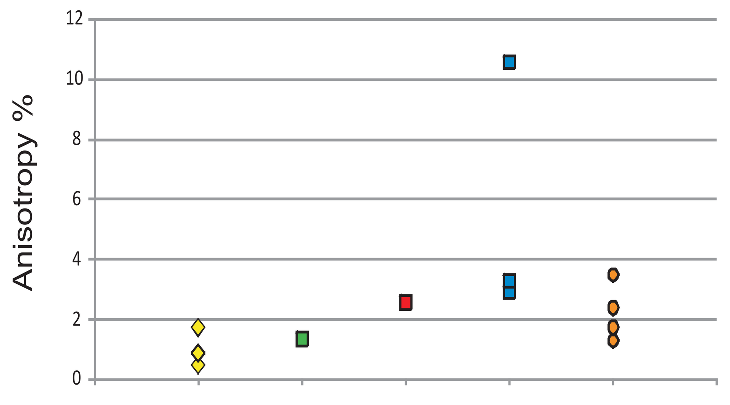


Anisotropy

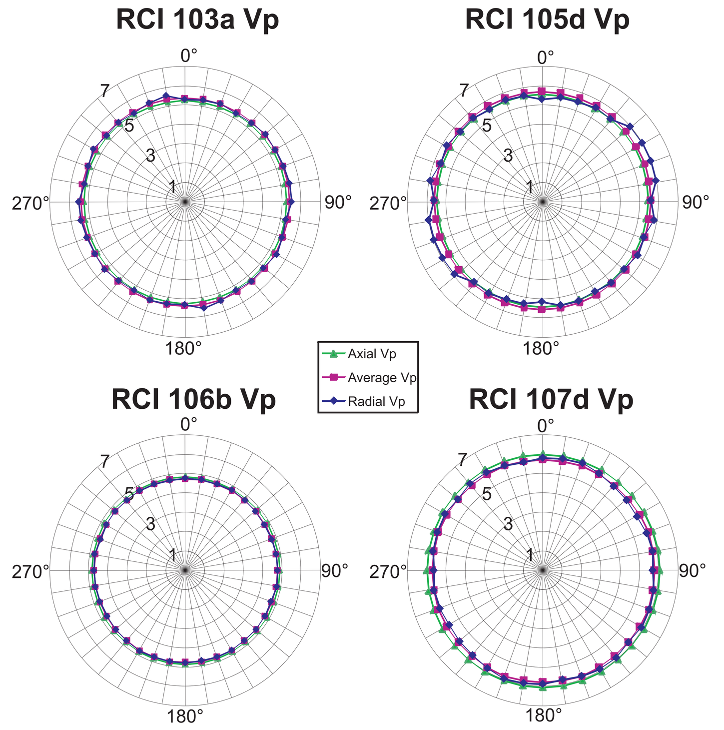
Evaluation of anisotropy (A) were inferred from radial Vp measurements by defining:

$$A = \frac{Vr(i) - Vr(average)}{Vr(average)}$$

Anisotropy is extremely low



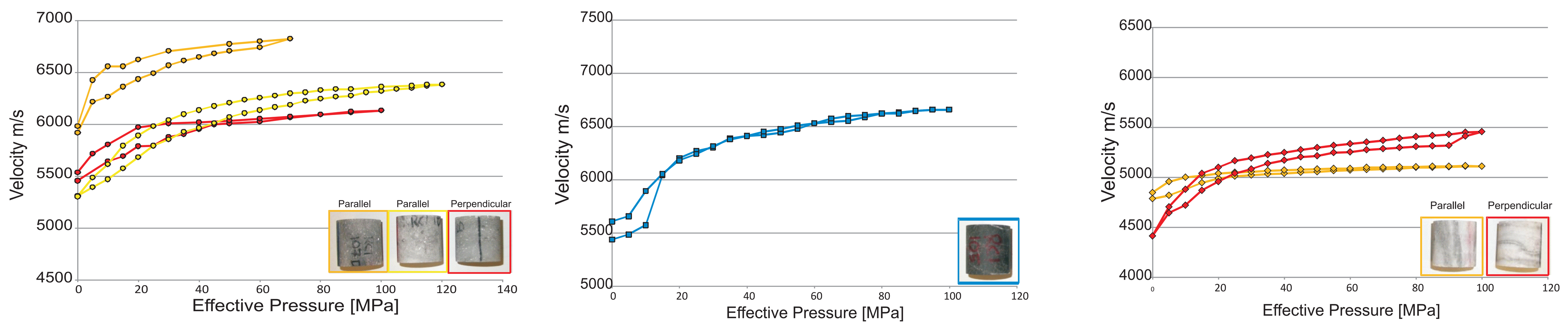
Anhydrites — Black Dolostones — Dolostones (fracture mesh) — Grey Dolostones — Gypsum/Dolostones



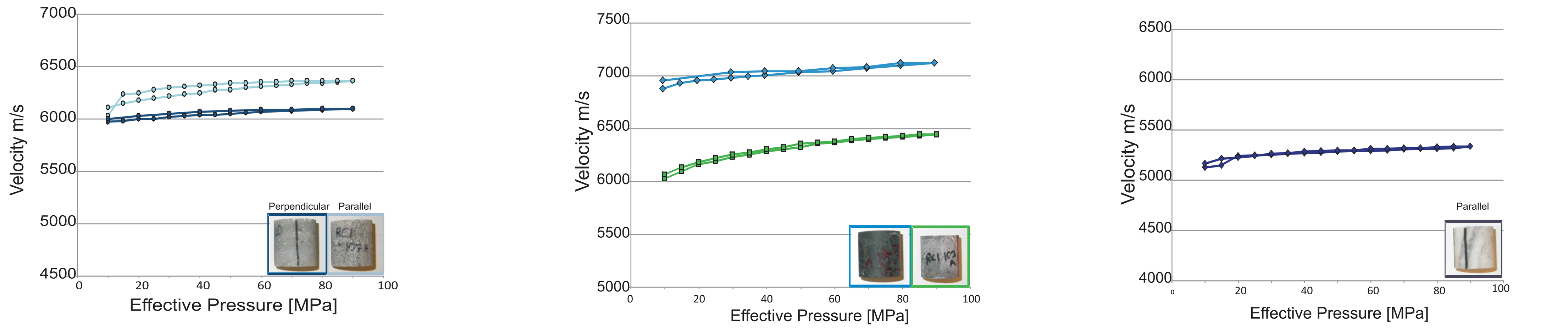
Velocity vs Pressures

Velocity vs Pressure experiment have been carried out for both dry (after 24h in a 40°C oven) and wet samples statured at ambient pressure in a vacuum pump with distilled water.

P wave velocities in DRY samples



P wave velocities in WET samples



Radial Velocity measurements:
From radial velocity measurements we infer a low anisotropy that can be interpreted in two ways:
1. The gypsum-anhydrites samples are strongly etherogeneus where dolostone clasts are present and locally foliated. The dolostone clasts are highly fractured and altered. The presence of dolostone within anhydrites crystals overprints the original fabric and controls the propagation of Vp more than the original foliation resulting in a very low average anisotropy;
2. The dolostones samples are highly fractured and the fractures are filled by gypsum and calcite so the samples are physically strongly heterogeneous, but the quasi-constant radial velocities implies that those fractures are homogeneously distributed in the space.

Velocity vs Pressure measurements:
Dry samples: Around the 80% of the increase in velocity is achieved before 50% of maximum confining pressure and absolute velocity increase is about 20%. Above a value of confining pressure of about 40 MPa velocity increases slightly with pressure. These results are independents from the orientation of the samples i.e. the foliations seem to have a minor effect on velocities.
Bulk of compaction is maybe due to cracks closure and pores collapse. Low velocities hystereses observed after the pressurization-depressurization cycle, suggest that the bulk compaction in hydrostatic stress conditions is elastic and the small hysteresis founded can be related to anelastic effects such are pore collapse.
Wet samples: The variation of absolute velocity increasing pressure is about 5% and shows a linear trend. Lack or very small hysteresis was found suggesting an elastic behavior.
The limited hysteresis found indicates the competing role of pore pressure. Velocities are found to be higher due to the increased transmissivity of samples.

5. Discussion

Physical characterization of TE shows that the collected field sample have different characteristic respect to pure and single phase samples (Schön 1998, Carmichael 1982, Ahrens,1995); however these differences have a minor effects in Vp especially for high value of confining pressure. Therefore it is possible to compare our samples with TE located at seismogenic depth. The next step will be compare our dataset with independent Vp measurements for TE (boreholes, tomography, seismic refraction). As a first approximation we can observe that: at the surface our Vp measurements are lower than pure samples (dolostones and anhydrites in particular) (see table below) and this is likely to be due on the presence of secondary gypsum. At depth (i.e. 100 MPa of confining pressure) our dataset seems to be consistent with down hole logs measurements whilst lower values are obtained for both seismic refraction and tomography.

Velocities Km/s	This work 0 MPa	Handbooks [1,4,13]	This work 100 MPa	Down hole logs [2,3]	Refraction [11,12]	Tomography [5]
Anhydrites	5.3-6	6.1	6.1-6.8	6.0-6.7	6.0	6.1- 6.4
Dolostones	5.4-6.4	5.7	6.6-7.1	6.0-6.7	6.0	6.1- 6.4
Gypsum	4.4-4.8	4.88-5.80	5.1-5.4			

This confirms that laboratory elastic velocity measurements are critical for interpretation of geophysical data.

6. Future work

Laboratory derived Vp measurements seem in good agreement but necessitate upscaling to infer realistic velocities at depth.
Future work will aim to upscaling laboratory measurements to down hole seismic velocities taking in to account the dependence on frequencies.

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