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Simposio de Evaluación de Formaciones: Maximizando la eficiencia a través de la innovación

ACOUSTIC PROPERTIES OF SHORT CORE SAMPLES FROM THE VACA MUERTA FORMATION, NEUQUÉN BASIN, ARGENTINA

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RESUMEN

Propiedades Acústicas de coronas de afloramiento de la Formación Vaca Muerta, cuenca Neuquina, Argentina.

Varios años de exploración y producción en curso en el Sistema Vaca Muerta-Quintuco de la cuenca Neuquina mejoraron enormemente el conocimiento sobre el tipo y la distribución de los sweet spots. La explotación exitosa de dichos reservorios está basada principalmente en sísmica 3D y una combinación de estratigrafía secuencial y modelos de física de rocas. Sin embargo, las propiedades físicas de las principales facies productoras aún no se entienden por completo. Los volúmenes de roca frágiles, porosos y ricos en kerógeno son difíciles de capturar con los modelos de física de rocas existentes. Por lo tanto, resulta primordial una documentación detallada de las propiedades y la calibración de los modelos físicos para la identificación sísmica de facies individuales y tipos de roca.

Para lograr este objetivo, más de 3000m de secciones de afloramiento se muestrearon cada metro para análisis químicos. También cada metro se midieron rayos gamma espectrales para correlacionar con el subsuelo. Se hicieron análisis de microfacies en más de 400 secciones delgadas, y se prepararon más de 200 muestras de 1” de diámetro para mediciones petrofísicas a partir de 98 coronas de 1m de longitud. La velocidad acústica se midió bajo una variedad de condiciones de presión y diferentes estados de saturación. Las propiedades acústicas medidas se analizaron en comparación con la mineralogía, el contenido orgánico total (COT) y la porosidad.

La porosidad varía entre 1 y 23%; las velocidades de compresión, entre 3 y 6.5 km/seg y la relación de Poisson, entre 0.19 y 0.33. Se determinó que el contenido de carbonato está entre 1% y 89%, mientras que el COT medido en un analizador elemental varía entre 1% y 6%. La comparación entre los datos acústicos obtenidos en este trabajo y muestras de referencia de diferentes edades y ubicaciones muestra que las fangolitas de la Formación Vaca Muerta poseen velocidades de corte y compresión sustancialmente más bajas. Las propiedades medidas relacionan todas las facies principales de la parte inferior de la Formación Vaca Muerta con sus propiedades petrofísicas y ayudan a calibrar la respuesta de impedancia de cada facies.

INTRODUCTION

The Neuquén Basin is one of the few marine basins with a complete record across the Jurassic-

Cretaceous boundary and had, thus, attracted the attention of bio- and chemo-stratigraphers (e.g. Howell *et al.*, 2005). With the discovery of the extensive organic-rich basinal strata in the Vaca Muerta Formation the focus shifted to research projects in various other disciplines (*e.g.* Massaferro *et al.*, 2014). In addition, with the transition from exploration to production a new level of detail is required to add value to these efforts. For example, a detailed knowledge of the sedimentologic and stratigraphic evolution of the basin is paramount to assess and understand the interaction between the facies, TOC content, and their seismic and log signature at any given position in the basin.

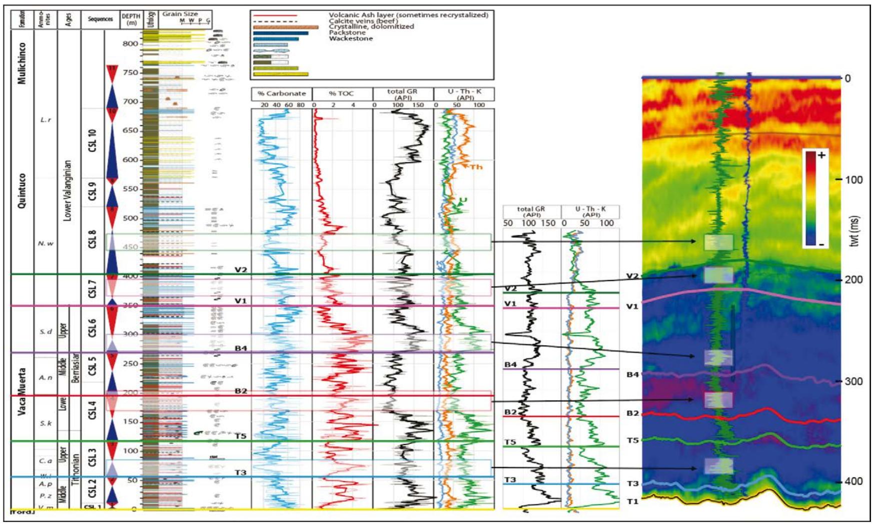

Figure 1. Left: Overview of the composite section at Puerta Curaco with carbonate content, TOC, and spectral gamma ray (modified from Rodriguez Blanco 2016 and Eberli *et al* 2017), Right: gamma ray, and acoustic impedance (Reijenstein *et al.*, 2017) from one of the subsurface wells from the Chevron El Trapial block. Outcrop-subsurface correlation follows nomenclature from Gonzalez *et al.* 2016.

Moreover, it is more important than ever to integrate and calibrate the TOC distribution and geochemical composition of individual facies to the seismic impedance in the Vaca Muerta Formation. To that end, several large operators adopted a philosophy of cooperation as a mechanism to enhance their understanding of both stratigraphic and facies distribution. (González Tomassini *et al.*, 2016) The result of this "Transecta project" was a giant seismic line poster composed of information from 15 hydrocarbon concessions, several wells, and three regional seismic lines within the Neuquén Basin (Sattler *et al.*, 2016). The same seismic transect was populated with acoustic impedance, and interpretations were presented of specific seismic facies and acoustic impedance ranges within the foresets and bottomsets of the clinoforms of the Vaca Muerta Formation (Reijenstein *et al.*, 2017).

In contrast to well/core information, outcrops display the facies away from the 1D section and as such are well-suited for a calibration of facies to seismic impedance cubes. The study presented here aims to provide a 2D outcrop overview of the acoustic impedance ranges used in the "Transecta Project". This outcrop to seismic correlation (Fig. 1) provides a unique opportunity to understand the seismic expression in terms of measured ultrasonic velocities and resulting elastic properties of Vaca Muerta Formation's mixed siliciclastic mud rocks.

The goal is to produce an accurate, high resolution outcrop – subsurface correlation to highlight how geologic sections collected in outcrop can enhance the understanding of seismic-derived acoustic impedance in the foresets and bottomsets of the subsurface clinofroms (Fig. 1). As numerous studied show, the clinoforms of the Vaca Muerta Formation consist of a mixture of clastic/carbonate mudstones with varying degrees of clay content, and total organic carbon In particular, we investigate which of the factors - porosity, TOC, and clay volume - most strongly influence the variability of acoustic properties on both log and seismic scale.

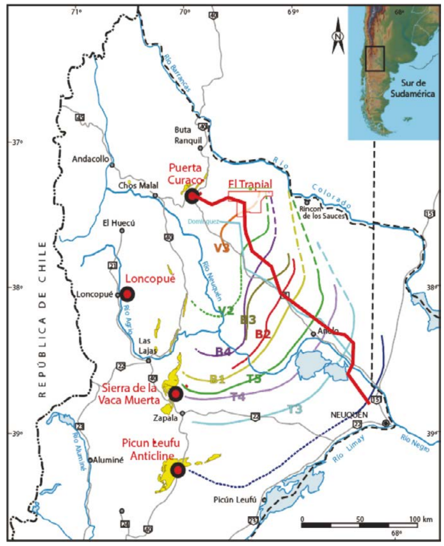

Figure 2. Location Map of outcrop and subsurface data. Clinoforms slope breaks after Dominguez *et al.*, 2017.

The composite section at Puerta Curaco (PC) provide a formidable framework for a comprehensive assessment of the distribution of the facies and total organic carbon (TOC), and its influence on the acoustic properties of the entire Vaca Muerta Formation (Rodríguez Blanco, 2016; Eberli *et al.*, 2017; Weger *et al.*, 2017). However, the fissile mudstones of the Vaca Muerta Formation and their associated lithofacies and sedimentary structures are prone to intense surficial weathering, which obliterates depositional structures and makes them inherently hard to sample in outcrop. To overcome this problem, we drilled over 100 one-meter-long short cores to retrieve unaltered samples suitable for petrophysical analysis and for observation of sedimentologic details at different stratigraphic intervals in both proximal and distal positions of the basin: Mallin de los Caballos (MdC) at Sierra de la Vaca Muerta (SdlVM), Loncopué (LP), and the Puerta Curaco (PC) (Fig. 2). The focus for this study was mostly on the basal portion of the Vaca Muerta Formation measured on samples from Puerta Curaco (Fig. 2).

METHODS

To analyze the acoustic properties of the different facies in the Vaca Muerta Formation we extracted over 250 plug samples from ~100 m of short cores that were drilled in the above described outcrop locations. All plugs where cut in pairs or triplet of plugs containing both vertical and horizontal bedding (and additionally approximately 28 diagonal plugs) at almost identical depth.

Porosity and Grain Density

Porosity and Grain Density was determined by calculating the difference between the outside volume of the core plug (*e.g.*, 1-in. [2.54-cm] diameter plug length) and grain volume measured using a Micromeritics AccuPyc 1330 helium pycnometer. Grain density was calculated from the measured mass of the sample and the measured grain volume. To assess the errors associated with this measurement the ends of the samples were polished parallel within 0.01 mm. Repeated length/diameter measurements showed the variability in length and diameter to be less than 0.01 mm. Error in porosity can originate from accuracy of the balance (within ~0.001 g), accuracy of the length (within ~0.01 mm), and grain density measurement (average ~0.05 g/cm^3). Combined, the resulting sum error in porosity is estimated to be approximately 1%.

Carbonate content and Total Organic Carbon content

To determine carbonate content and TOC samples were homogenized and dissolved using 10% hydrochloric acid to determine their carbonate content by weight difference. Subsequently, weight percent carbon of the insoluble residue was obtained on a Costech Elemental Analyzer and cross-checked with a mass spectrometer to determine % (by weight) TOC. As a side product, the $\delta^{13}C$ of the organic material ($\delta^{13}C_{org}$) was obtained.

Mineral composition

X-Ray Diffraction (XRD) analysis of bulk sample powder was used to establish qualitatively the main mineral constituents of the samples. In addition, for some samples broad-ion-beam milled Scanning Electron Microscope (SEM) images were generated for further qualitative determination of some of the clay components. Gamma ray from outcrop measurement was combined with chemically derived carbonate and TOC content to derive an estimate of clay volume (Vclay) to obtain rough estimates of fractional mineral composition.

Acoustic velocity

Plug samples were cut from 96 short cores that we drilled in outcrop. Ninety pairs of plugs were extracted at almost identical depth at both vertical and horizontal orientation. Twenty-seven of these groups where cut in triplet including one diagonal plug at 90-degree angle to bedding.

All samples are measured under both dry and water-saturated conditions in order to analyze the variability of Vaca Muerta mudrock acoustic properties under different saturation states. Measuring the velocity of fissile mixed carbonate-siliciclastic mudrocks under dry and water-saturated conditions with variable confining pressure is challenging because the sample might be altered during pressurization. To overcome this experimental dilemma, we adopted the following procedure.

We first saturated all samples with 35 ppt brine (NaCl) and placed them into a vacuum chamber for 48 hr. Next, all samples were inserted into rubber sleeve and mounted onto the acoustic core holder transducer set. Subsequently, acoustic velocity of all plug samples was measured under saturated conditions, using variable hydrostatic confining pressures. During measurement, the pore-fluid pressure was kept constant at 2 MPa to create a series of small steps of effective pressure from 5 to a maximum of 40 MPa and back down to 5 MPa. The data is plotted at 20 MPa effective pressure in most figures.

After the measurements under saturated condition, a sample was considered "unaltered" if, upon completion of the pressure cycle, no hysteresis effect was detected and no decrease in the velocity during the increasing pressure cycle was observed. Subsequently, all plug samples were first placed into fresh water for ~48 hrs to dilute all NaCl, and then dried in an oven at 50°C for three days. After drying, all plugs were placed in a drying chamber containing moisture-absorbing crystals to protect them from humidity. The samples were then considered room dry with insignificant moisture content. Under dry conditions, velocities were measured under the same effective pressure steps as in the saturated sequence.

All ultrasonic velocities were measured at a center frequency of 1 MHz using a pulse-transmission technique (Birch, 1960). A single compressional wave and two independently orthogonally polarized shear waves were simultaneously measured using the Autolab 1000 transducer arrangements. The precision of our experimental velocity measurement is within 3%. This precision is represented in the size of the data dots ($\sim^{+}/_{-}70$ m/s) in the figures that show velocity versus porosity relationships.

As context for the newly measured acoustic data from mudstone samples of the basinal portion in the Vaca Muerta Formation, the samples are compared (Fig. 3) to mixed siliciclastic samples collected and measured by Zeller (2015) in the more proximal parts of the Neuquén Basin, the shaley Fontainebleau Sandstone samples from Han (1986), and clean carbonates from different ages and locations measured by Weger *et al*. (2009).

RESULTS AND IMPLICATIONS

Individual seismic facies characterized by Reijenstein *et al*., (2017) show outcrop expressions that can easily be subdivided into two mayor endmember rock types. The first rock type is composed of mainly, dark, fissile, organic rich, mixed carbonate-siliciclastic mudstone containing substantial input of several different clay minerals. This rock type (hereafter called "background mudrock") is the dominating facies within the lower part of the Vaca Muerta Formation. The second rocktype is a more carbonate-rich (50-90%), mostly massive but sometimes laminated, light to dark gray mudstone, wackestone, and even some packstone, with varying degrees of skeletal content (hereafter called "Carbonate-rich beds").

An example of these two endmembers in outcrop is displayed in Fig. 4. For example, at Puerta Curaco, the most striking difference in outcrop expression between the lower portions (Tithonian-Early Berriasian) and younger upper section (Late Berriasian-Early Valanginian) of the Vaca Muerta Formation is the increasing amount of both massive and laminated carbonate beds. In the lower portion the basinal organic-rich mudstone (background mudstone) is only sporadically intercalated with thin carbonate beds (Fig. 4A), whereas in the upper portion of the Vaca Muerta Formation in Puerta Curaco area these mudrocks are often only thin packages in a facies dominated by the second endmember of carbonate-rich beds (Fig. 4B).

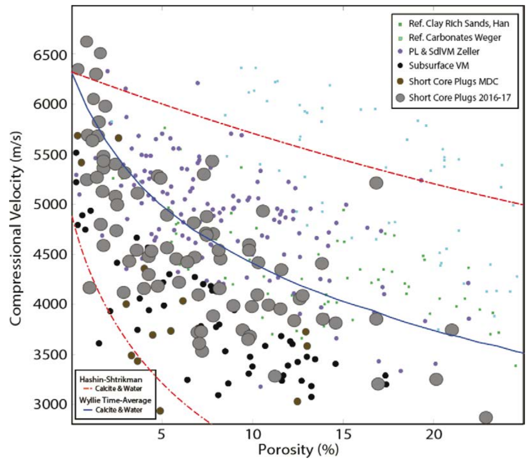

Figure 3. Compressional velocity measurements at 20 MPa of vertical plug samples versus porosity. Large circles are newly measured plug samples form outcrop short cores compared to both reference data and subsurface data from El Trapial Block.

While in the lower, older and more basinal portion of the Vaca Muerta Formation (0 – 250 m) the first endmember rock type is dominant and carbonate-rich intercalations are rare, in the second endmember rock type (carbonate-rich beds), the amount of fissile background mudstone becomes less and less prevalent and in several places gives way to entire sections of massive or laminated carbonate beds only intercalated with very thin packages of background material.

A histogram of the porosity of all plug samples illustrates the porosity distribution in the two endmembers. In the carbonate-rich beds, porosity ranges from 0 - ~10% with a sharp peak at approximately 2-2.5% regardless of rock texture (Fig. 5). The plugs composed of background mudrock, which are more fissile, clay and organic rich, mixed carbonate siliciclastic mudstones (CO3% <60%), show a porosity distribution that ranges from ~5 to over 15% with no dominant

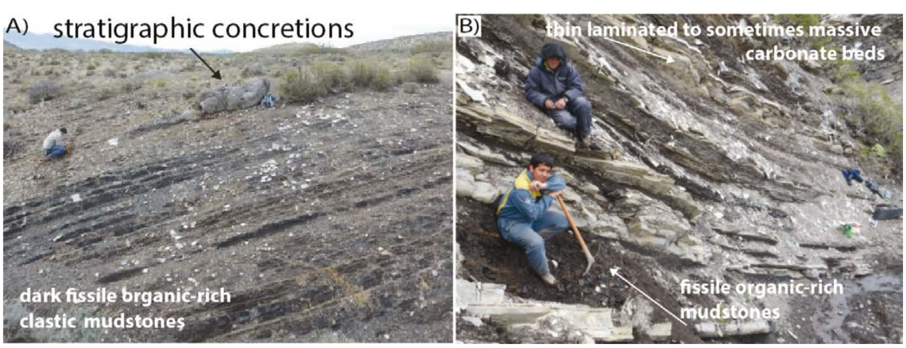

Figure 4. Comparison of two outcrop sections at Puerta Curaco: (A) Middle Tithonian and (B) Lower Valanginian. The older section is dominated by the background mudstone within a few carbonate beds, while the younger section is rich in carbonate-rich beds.

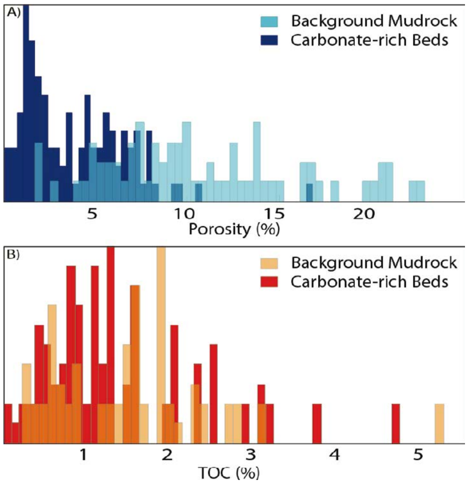

Figure 5. Histogram of (A) porosity and (B) Total Organic Carbon distribution.

peak (Fig. 5A). Total organic carbon (TOC) is distributed evenly throughout all samples ranging from 0-5.3% and no separation between different rock types can be observed (Fig. 5B).

The compressional velocities of the measured samples range from ~3000 m/s to over 6500 m/s with considerable variation at any given porosity (Fig. 3). The average spread of the data at any given porosity is approximately 1500 m/s. Considering the fact that almost all samples are of uniform composition, dominated by microporosity, this variability cannot be caused by variations in pore geometry as is common in pure carbonate rocks (Weger *et al.*, 2009). In the mixed carbonate-siliciclastic setting of the Vaca Muerta Formation, these variations are more likely to be caused by variations in mineralogic composition and total organic content. Compressional velocities for almost all of the saturated measurements fall below the Wyllie Time-Average equation for calcite and water. Almost all samples fall well within the region delineated by the Hashin-Shtrikman lower bound and Wyllie Time-Average equation as upper bound (Fig. 3).

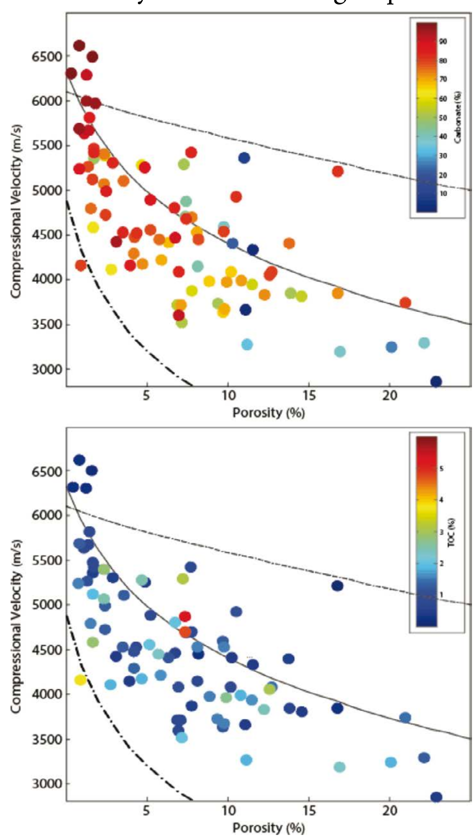

Figure 6. Compressional velocity (at 20 MPa) versus porosity. Color coding for each samples is carbonate content (Top) and total organic carbon content (Bottom).

Although some, low porosity, high carbonate content samples show very high compressional velocities, well above the Wyllie time average equation, the vast majority of samples falls well below it despite their often rather high carbonate content. Samples with almost identical carbonate content and very similar porosity sometimes vary in compressional velocity by more than 1000 m/s.

Generally, TOC has a very strong influence on acoustic velocity, but no clear trend can be observed (Fig. 6b). Usually, samples with high organic carbon content have lower velocities but in our data set several of the samples with relatively high total organic carbon content (up to 6%) show very high compressional velocities for their porosity.

The above described endmember classification is able to separate our samples in two populations clearly distinguishable in ultrasonic velocity-porosity space (Fig. 7). The background mudstone facies occupy almost exclusively the higher porosities (~5% - >20%) and range in velocity from as low as 3000 m/s rarely exceeding 4500 m/s. In contrast, the carbonate-rich beds consisting of massive or laminated carbonate facies exhibit overall lower porosities, ranging from less than 1% to under 10% with velocities being, with one exception, over 4000 m/s and sometimes as high as 5900 m/s (Fig. 7).

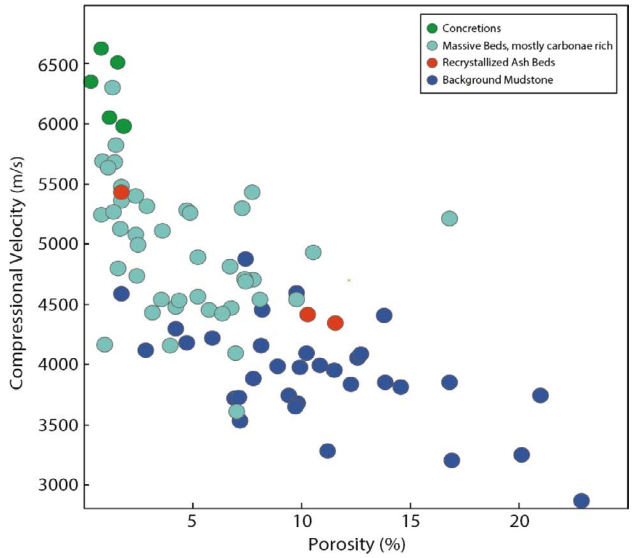

Figure 7. Compressional velocity at 20 MPa vs. porosity cross plot color-coded by different types of rocks. Dark blue circles are samples collected in background mudstone while lighter blue samples are those from more carbonate-rich wackestone to packstone beds. Green circles are concretions, and orange samples are recrystallized volcanic deposits.

Within the lower part of the Vaca Muerta Formation the acoustic impedance values of the seismic section varies little when correlated to our outcrops. The entire interval from the initial flooding of the basin during the Middle Tithonian until the Upper Berriasian/Lower Valanginian is dominated by overall low acoustic impedances. Only small variations can be observed, and outcrop data measurements at 20 MPa suggests that these small changes are mostly caused by increasing amounts of carbonate-rich beds. The acoustic impedance values of the two different endmember rock types defined above show clear separation between the values of the samples from background mudrock and those from carbonate-rich massive or laminated beds (Fig. 8).

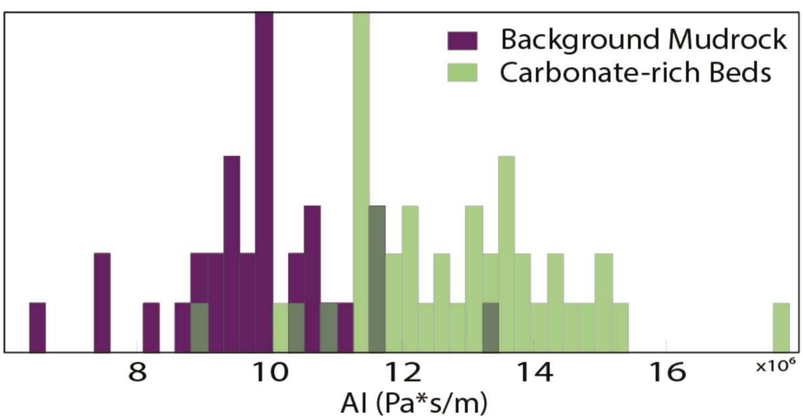

Figure 8. Acoustic Impedance values (at 20 MPa) of background mudstone (purple) and carbonate rich wackestone to packstone beds (green).

CONCLUSION

Unfortunately, neither Carbonate content nor percent TOC alone or combined provide much insight into the acoustic strength of the Vaca Muerta Formation. However, in outcrop, most of the basinal and slope deposit can be distinguished by estimating the degree of carbonate intercalations present within the more clastic fissile background mudstone. Acoustic velocities measured on plug scale in the Vaca Muerta Formation provide insight into the acoustic properties of basic endmember rock types that compose most of the facies in the Vaca Muerta Formation. Large scale acoustic impedance values can then be used to approximate the different degrees of carbonate intercalations present in a given subsection of the Formation.

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