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**Upscaling of elastic properties in carbonates:
a modeling approach based on a multi-scale geophysical dataset**

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Key Points:

- Acquisition of multi-scale P-wave velocities at seismic, sonic and ultrasonic frequencies from the field to the lab at a single study site
- P-wave velocity decrease from ultrasonic to seismic frequencies with an increasing representative elementary volume
- Crack/fracture porosity control on the P-wave velocity at sonic and seismic scales leads to loss of matrix porosity control

Abstract

Linking ultrasonic measurements made in the laboratory on samples, with sonic logs and seismic subsurface data is a key challenge for the understanding of carbonate reservoirs. To deal with this problem, we investigate the elastic properties of dry lacustrine carbonates. At one study site, we perform a seismic refraction survey (100 Hz), as well as “sonic” (54 kHz) and ultrasonic (250 kHz) measurements directly on outcrop and ultrasonic measurements on samples in the laboratory (500 kHz). By comparing the median of each dataset, we show that the P-wave velocity decreases from laboratory to seismic scale. Nevertheless, the median of the sonic measurements acquired on outcrop surfaces seem to fit with the seismic data, meaning that sonic acquisition may be representative of seismic scale. To explain the variations with upscaling, we relate the concept of Representative Elementary Volume (REV) with the wavelength of each scale of study. Indeed, the wavelength varies from millimetric at ultrasonic scale to pluri-metric at seismic scale. This change of scale allows us to conclude that the behavior of P-wave velocity is due to different geological features (matrix porosity, cracks, fractures) related to the different wavelengths used. Based on effective medium theories, we quantify the pore aspect ratio at sample scale and the crack/fracture density at outcrop and seismic scales using a multi-scale REV concept. Results show that the matrix porosity that controls the ultrasonic P-wave velocities is progressively lost with upscaling, implying that crack and fracture porosity impacts sonic and seismic P-wave velocities, a result of paramount importance for seismic interpretation based on deterministic approaches.

1. Introduction

For isotropic rocks in dry conditions, upscaling of elastic properties can be done on the assumption that the velocity acquired at ultrasonic (MHz), sonic (kHz) and seismic (Hz) frequencies are the same. Indeed, if the investigated porous medium is homogeneous and dry, it is theoretically not dispersive, *i.e.* the velocity does not depend on the frequency (Bourbié et al., 1987). This assumption is widely used in the literature (*e.g.* Wang et al., 1991; Marion and Jizba, 1997; Baechle et al., 2005; Adam et al., 2006; Verwer et al., 2008; Adelinet et al., 2011; Regnet et al., 2015 Borgomano et al., 2017) for inferring frequency dispersion of elastic wave velocity in homogeneous porous and fluid saturated rocks.

This equality of dry elastic moduli at all frequencies is only valid if the Representative Elementary Volume is uniform at each investigated scale (REV: volume of rock for which a physical property is constant, *e.g.* Bear, 1972), in other words if a rock is homogeneous at all scales. As outlined by Corbett (2009), this statement is far from true in geological medium which present “multiple length scales and multiple scales of homogenization”. Indeed, following the conceptual geological scales of Haldorsen and Lake (1984), several scales of geological heterogeneities exist (Figure 1a), including : i) the microscopic scale (*i.e.* pore scale, μm to mm); ii) the macroscopic scale (*i.e.* the plug scale, cm); iii) the megascopic scale (*i.e.* outcrop scale, m to dm) until iv) the gigascopic scale (*i.e.* regional scale, km).

These different geological scales imply different heterogeneities that may impact the upscaling of the elastic properties of rocks. This point is of importance for the characterization of reservoirs based on a deterministic approach, *i.e.* the use of velocity-porosity relationships based on laboratory and/or well data (*e.g.* Wyllie et al., 1956; Raymer et al., 1980; Anselmetti and Eberli, 1993) for inferring petrophysical properties (like porosity) from seismic data through impedance inversion (*e.g.* Marion and Jizba, 1997; Cichostępski et al., 2019). Indeed, as outlined by Wollner and Dvorkin (2018), a rock-physics model built from a given scale (*i.e.* centimetric in the laboratory) may not be applicable to another scale (*i.e.* pluri-metric at seismic). According to Matonti et al. (2015), the direct comparison of P-wave velocities acquired on carbonates at two different scales (plug *versus* outcrop) highlights a decrease of the P-wave velocity with

scale. These authors pointed out here a “scale effect” that they partly attribute to the presence of structural features (fractures). This finding joins the conclusions of previous authors, who suggest that the presence of cracks/fractures in crystalline rocks, due to upscaling, decrease of P-wave velocity (Stierman and Kovach, 1979; Moos and Zobach, 1983).

Figure 1. Comparison between upscaling in geology and geophysics. (a) Conceptual geological scales (from Haldorsen and Lake, 1984), highlighting the different scales of heterogeneities, including microscopic scale (pore size), macroscopic scale (plug size), megascopic (outcrop size) toward gigascopic scale (*i.e.* regional scale). (b) Frequencies and wavelengths for an elastic wave propagating at ultrasonic, sonic and seismic scales at a velocity of 1000 m.s⁻¹. The four different scales investigated in the present study are highlighted in different colored stars. They are associated with their frequencies and wavelengths for a P-wave velocity ranging between 2000 and 6000 m.s⁻¹. (c) Wavelength sketches of the four different scales studied on this work.

Indeed, a P or S wave velocity measurement is representative of the elastic properties at a scale close to the wavelength. On one hand, seismic measurements (low frequency, f , and thus large wavelength - $\lambda=c/f$, where c is the velocity of the wave - in the order of several meters) will tend to erase small scale heterogeneities (Sheriff, 2002) (Figure 1b,c). On the other hand, ultrasonic measurements (high frequency, small wavelength) on samples are representative of the elastic properties at a scale of the order of the

millimeter (Figure 1b,c). Using a multi-scale geophysical dataset, it is thus possible to relate the elastic properties acquired at different frequencies, and so defining effective elastic properties at different scales of investigation. This purpose follows the previous works of Nordahl & Ringrose (2008) and Ringrose et al. (2008) who argued that a multiscale geological medium has to be related to multiscale REV's. A fundamental challenge here is to measure elastic properties of the same geological object across all scales (Corbett, 2009). To do so, we study Miocene lacustrine carbonates from Samos Island (Greece).

We measure their dynamic elastic properties using several geophysical tools at different scales, from field to laboratory (Figure 1): seismic refraction method (~ 100 Hz), sonic/ultrasonic measurements directly on outcrop (54 kHz and 250 kHz), and ultrasonic measurements on plugs (500 kHz). These measurements enable us to link and discuss the impact of different geological features (such as pores, cracks and fractures) on the measured P-wave velocities from millimetric scale to decametric scales. Finally, based on asymptotic approximations of Differential Elementary Medium scheme (DEM, David and Zimmerman, 2011a,b), we compare the multi-scale elastic properties of the studied carbonates using a concept of multi-scale REV's that take into account different scales of heterogeneities. In the following manuscript, the terms “cracks” and “fractures” will refer to the occurrence and modeling of very low aspect ratio inclusions isotropically distributed.. The cracks correspond to small-scale inclusions (mm to cm scale) while the fractures are attributed to large-scale inclusions (dm to m scale).

2. Study framework

Our study is focused on lacustrine carbonates of Samos, a Greek island located on the eastern part of the Aegean Sea, near Turkey (Figure 2a). This island presents two sedimentary basins in which lacustrine sedimentation occurred during the Upper Miocene (Weidman et al., 1984). Figure 2b points out the study site on which we perform a seismic survey together with an outcrop description (Figure 2c). This study site is localized on the Mytilini Basin, infilled with a huge diversity of rocks (such as volcanoclastic, siliciclastic and carbonate rocks, Figure 2d). Our study focuses on the topmost part of the Hora Formation composed

of lacustrine and palustrine carbonates (Figure 2d). These carbonates are deposited right before a major exposure, expressed as an erosional surface (Hora-Mytilini transition) according to Weidman et al. (1984) and Stamatakis et al. (1989). This emergence may result from a tectonic uplift (compressive phase of Ring et al., (1999)) and/or an increase in aridity causing a global drying of the lake (Owen et al., 2011).

Figure 2. General framework: (a) Location of Samos Island in the Aegean Sea. (b) Sedimentary basins of Samos Island and location of the study area (N37°44'21"; E26°53'45"). (c) GoogleEarth© view of the study area showing the studied outcrop and the location of the seismic line. (d) Stratigraphic column modified after Weidmann et al. (1984) showing the sedimentary infill of Mytilini Basin divided into four lithostratigraphic formations. The stratigraphic location of our studied section is highlighted in red.

SEISMIC SCALE

OUTCROP SCALE

LABORATORY SCALE

Figure 3. Applied methodology for this work and corresponding relative evolution of the Representative Elementary Volume (REV): (a) Seismic measurements. On the left, sketches of the refracted wave propagation (SR) produced by a sledgehammer source. The acquisition system (DAQLINK IV and geophones) and a field view of the seismic line are indicated on the right. (b) Outcrop measurements. On the left, sketch of the wave propagation in outcrop (with L corresponding to the covered distance). On the middle, outcrop view in reality with examples of the transducer positions during measurements. On the right, 250 kHz and 54 kHz transducers used for P-wave acquisitions. (c) Plug measurements. On the left, sketch of the wave propagation in plug (average length of 5 cm). On the right, acquisition device used for P-wave and S-wave measurements.

3. Multi-scale methodology

The study site enabled us to acquire acoustic measurements at different scales while keeping a geological control thanks to the outcrop. The frequencies of the different tools used in this work are summarized in Figure 1 and are paired with their wavelengths. A thorough description of this multi-scale geophysical methodology is highlighted in Figure 3. All the acoustic measurements presented in this work were acquired **under dry conditions**. The field campaign was carried out during the end of June 2018, with an average temperature of 25°C and an average humidity of 70 %. Last rainfall occurred 2 days before the measurements, with an amount of water lower than 0.3 mm.

3.1. Outcrop characterization & sampling

A sedimentary description of a 40 m thick sedimentary succession was undertaken ('Studied outcrop', Figure 2c) alongside a high-resolution sampling in order to acquire physical properties (one sample every 20 cm along a vertical section). Depending on the sample size, plugs were cored with a diameter of 23 mm for 81 samples and 40 mm for 20 samples. Furthermore, panorama pictures aim to highlight outcropping structural features (*e.g.* bedding planes, fractures and faults), showing the structural heterogeneity at outcrop scale (Figure 4).

3.2. Seismic refraction acquisition

We carried out a seismic survey that encompasses an 80 m long line ('seismic line', Figure 2c). The sound source is a 4 kg sledge-hammer striking a Teflon plate (central frequency of 100 Hz, Figure 1). Forty-eight geophones with a natural frequency of 10 Hz were regularly spread along a line with a 1 m-spacing and recorded the wave acceleration (Figure 3a). They were covered with sandbags to ensure a good coupling with the ground and limit the ambient noise. Seven shots were done along the seismic line. In order to

increase the signal/noise ratio of the recorded waveforms we stacked three times each shot (21 hammer strikes). Refraction processing was then done using Pickwin and Plotrefra software packages from SeisImager, following the processing used by Adelinet et al. (2018). The seismic refraction processing only allowed us to characterize an increase in P-wave velocity with depth. This method provides a wavelength in the range of 20-60 m (decametric wavelength of Figure 1) that offer the opportunity to characterize a large REV (REV 4 of Figure 3).

3.3. Outcrop acoustic measurements

While the seismic refraction survey was carried out at the top of the outcrop (Figure 2c), P- wave velocities were directly measured on the outcrop surface using a Pundit PL-200 (Jeanne et al., 2012; Matonti et al., 2015) and two types of transducers (Figure 3c). To probe alteration of the outcrop, freshening of the rock surface was done with a hammer. The travel-time (first break) was directly pointed out on the oscillograph and the P-wave velocity is obtained by using the total distance travelled (L of Figure 3). The measurements were obtained with a high vertical sampling (one measurement every 20 cm) and two different spacings between the receiver and transmitters. The 54 kHz transducer were used for measuring P-wave velocity with a spacing of 40 cm between the transducers and two kinds of measurements: i) a vertical transect (orange points of Figure 3b) and ii) a horizontal transect (yellow points of Figure 3b). In parallel, the 250 kHz transducers allowed the measurements of P-wave velocity with a spacing of 20 cm along a horizontal transect (green points of Figure 3b). The peak shape of the 54 kHz transducers made it possible to perform measurements without a coupling gel. However, coupling gel was used for the 250 kHz transducers (Sonctec 54-T04). For the spacing between the transducers, we assume an error of 1 cm. The travel-time error is lower than 5 %. The resulting mean errors are equal to 10 % for the 54 kHz and 250 kHz. These sonic (54 kHz) and ultrasonic (250 kHz) outcrop measurements give us centimetric and millimetric wavelengths (Figure 1) that offer the opportunity to characterize the intermediate length scale (REVs 3 and 2 of Figure 3).

3.4. Laboratory measurements

Measurements were done in the laboratory on samples cored blocks coming from the outcrop. Porosity and density of 101 were measured with the Archimedes' method (plug mass obtained under three conditions: dry, fluid-saturated and suspended in the saturating-fluid). P- and S- ultrasonic wave velocities were obtained on oven-dry samples (60°C during 48 hours) using 500 kHz transducers connected to an oscilloscope (Figure 3c). The arrival times of P-waves (first break) were directly measured on the oscillograph and divided by the length of samples to calculate P-wave velocities. As indicated by Bailly et al. (2019), the error of this dataset is mainly related to the first break picking (lower than 5 %). Ultrasonic measurements provide millimetric wavelengths that are used to characterize the smaller scale (REV 1 of Figure 3).

3.5. Kernel smoothing

We applied non-parametric Kernel regressions to smooth the vertical trends of the P-wave velocities acquired at plug and outcrop scales. Then, based on the standard error measured on the smoothed curves, a calculation of the 95 % confidence interval was done using R software.

4. Results : Multi-scale dataset, from megascopic scale to microscopic scale

4.1. Structural features at outcrop

Figure 4 highlights the studied section and a thorough description of the observed structural features. The mapping of bedding planes (horizontal black lines) outlines a highly stratified pattern that is laterally and vertically persistent (around 3 bedding planes per meter). Furthermore, stratabound and non-stratabound fractures (vertical red lines, around 8 per meter) affect beds, overprinting the horizontal

structural features. Finally, a few normal faults are observed (dipping red lines) and crosscut the bedding planes.

Figure 4. Outcrop view highlighting the presence of bedding planes (in dark), fractures and faults (in red).

4.2. Seismic refraction dataset, a 2D characterization of elastic properties

Figure 5 presents the P-wave velocity profile obtained after inversion (seismic line of Figure 2a). The topography is nearly flat. The first meter of depth correspond to a P-wave velocity equal or lower than

1200 m.s⁻¹. Then, the P-wave velocity quickly increases up to 2000 m.s⁻¹ between 2 to 5 meters of depth, depending on the horizontal location. Finally, P-wave velocity increases more slowly, up to 2400 m.s⁻¹ between 5 to 10 meters depth depending also on the horizontal localization.

Figure 5. Seismic section obtained after inversion. P-wave velocities are indicated in colors.

4.3. Log dataset, a 1D vertical evolution of P-wave velocities

Figure 6a introduces the sedimentary log described on the field and the associated physical measurements acquired at multi-scale. The 40 meters thick sedimentary column exhibits mainly carbonate rocks. The lower part of the sedimentary column shows muddy and grainy carbonates with episodic exposure surfaces associated with pedogenesis (between 0 and 14 meters). Because of the vegetation cover, a part of the sedimentary succession has not been studied between 23 and 29 meters; we recognize some metric beds of grainy carbonates. Then, the top of the sedimentary section highlights again grainy and muddy carbonates alternating with beds of marls (between 32 and 40 meters). Note that Bailly et al. (2019) give a more detailed description of the studied outcrop.

Vertical evolution of porosity acquired in the laboratory are displayed (Figure 6b). From the base of the outcrop up to 5 m, porosities between 10 % and 25 % are observed and the associated smooth curves don't show an obvious vertical evolution. Then, between 5 and 14 m, the porosity presents higher values (up to 35 %) and lower values (down to 5 %) as well as some noticeable vertical fluctuations (metric

decrease and increase of porosity). Then, between 24 and 30 m, the smooth curve does not show a significant vertical evolution of porosity (average value of 10-15 %). Between 32 and 36 m, porosity decreases from 25 % down to 5 %. Finally, the last part of the sedimentary column exhibits higher values of porosity centered around 20-25 %.

Beside the porosity curve, the P-wave velocity acquired on plug, outcrop and seismic scales are displayed. V_{p500} (plug measurements) exhibits ultrasonic P-wave values between 2900 and 5600 m.s^{-1} (Figure 6c). Its metric vertical evolution is related to the porosity changes described above: when porosity increases, P-wave velocity decreases and *vice versa* (see also Figure 7b).

V_{p250} (*in-situ* horizontal outcrop measurements) shows P-wave values between 1000 and 5000 m.s^{-1} (Figure 6d), its fluctuations are higher than V_{p500} . From the base of the outcrop up to 14 m, the smoothed curve associated with V_{p250} presents metric fluctuations of P-wave velocity with values centered around 2000 and 4000 m.s^{-1} with values up to 4500 m.s^{-1} between 10 and 12 meters. Later, between 24 and 30 meters, V_{p250} presents obvious vertical fluctuations that were not recorded with V_{p500} . Between 32 and 40 meters, V_{p250} highlights meter-scale fluctuations with values up to 5000 m.s^{-1} and down to 1000 m.s^{-1} .

V_{p54H} (horizontal *in-situ* outcrop measurements) presents P-wave values between 500 and 4500 m.s^{-1} (Figure 6e). For the first part of the sedimentary column (0 to 14 meters), most of the vertical fluctuations of V_{p54H} are similar to V_{p250} , showing P-wave velocity values centered around 2000 and 3000 m.s^{-1} . Then, between 24 and 30 meters, the fluctuations of V_{p54H} mimic V_{p250} with lower P-wave velocity values (500 to 4000 m.s^{-1}). Between 32 and 35 meters, V_{p54H} presents a more chaotic vertical fluctuation not similar to V_{p250} , with P-wave velocity values comprised between 500 and 3500 m.s^{-1} .

V_{p54V} (vertical *in-situ* outcrop measurements) presents P-wave values between 1000 and 3500 m.s^{-1} (Figure 6f). Its vertical fluctuations are partly similar to V_{p54H} (e.g. between 3 and 6 meters,

around 25 and 28 meters, between 32 and 34 meters) but present a more chaotic fluctuation in the remaining part of the sedimentary column.

Finally, V_{p100} (seismic data) is also presented for comparison of the overall P-wave velocity dataset on a vertical way (Figure 6g). Because of the vertical resolution, the lower part of the sedimentary column is not imaged (*non-visible zone* in Figure 6g). As previously showed in Figure 5, the highest P-wave velocity value of V_{p100} is about 2400 m.s^{-1} , reached between 25 and 28 meters. Then, between 28 and 37 meters, V_{p100} decreases linearly down to 2000 m.s^{-1} . At the top of the sedimentary column (37 to 40 meters), V_{p100} decreases drastically down to 800 m.s^{-1} .

4.4. Porosity-ultrasonic velocity relationship at plug scale

Figure 7a shows the P- and S-wave velocities acquired on plugs. V_{p500} values range between 2800 and 5600 m.s^{-1} , while V_{s500} values range between 1600 and 3100 m.s^{-1} . The V_{p500} *versus* V_{s500} plot exhibits a good linear trend ($R^2=0.89$) that indicates a V_p/V_s ratio equal to 1.84, consistent for carbonate rocks (assuming a Poisson ratio equal to the one of pure calcite, a ratio of $V_p/V_s=1.91$ is expected, Mavko et al., 2009).

Figure 7b exhibits V_{p500} *versus* porosity. It shows a clear decrease of velocities with an increase of porosity. For explaining the scattering of velocities for a given porosity, we use the analytical expressions of David and Zimmerman (2011b) that aims to compute the effective elastic properties of an isotropic solid containing randomly oriented spheroidal pores. Thanks to this DEM model, we compute the aspect ratio ($0.01 < \alpha < 0.3$, ratio between the longer and the shorter length of an ellipse) embedded in a pure calcite medium ($V_{p\text{Calcite}} = 6400 \text{ m.s}^{-1}$). The resulting mean pore aspect ratio is about $\alpha = 0.16$ ($\sigma = 0.04$), shows a minimum of 0.04 and a maximum of 0.25. These results about the aspect ratio in carbonate rocks are consistent with previous studies (*e.g.* Fournier et al. (2018); Regnet et al. (2019a)).

Figure 7. Plug data: (a) V_{p500} versus V_{s500} and associated trend (red line). (b) V_{p500} versus porosity. Curves of constant aspect ratio of pores are indicated for a pure calcite matrix.

4.5. Statistical distribution of the multi-scale P-wave velocity

The boxplots, of each P-wave velocity dataset acquired in this work, are shown in Figure 8a. For V_{p500} , half of the dataset is comprised between 3800 and 4700 m.s⁻¹, with a median of about 4300 m.s⁻¹. Then, V_{p250} displays lower values of velocity, with half of this dataset comprised between 2500 and 3800 m.s⁻¹, and a median of 3200 m.s⁻¹. The interquartile of V_{p54H} is comprised between values of 1500 and 2900 m.s⁻¹, and partly overlaps V_{p250} with a median equal to 2300 m.s⁻¹. V_{p54V} completely overlaps V_{p54H} , with half of its values comprised between 1500 and 2600 m.s⁻¹, and a median equal to 2000 m.s⁻¹. Finally, half of the values of V_{p100} are comprised between 1700 and 2300 m.s⁻¹, with a median of 2200 m.s⁻¹.

The normal laws of each dataset are shown in Figure 8b. Data acquired in the laboratory and outcrop exhibit a nearly symmetrical distribution (median $\approx$ mean). Contrarily, V_{p100} shows an asymmetric distribution, (median < mean). It has to be noted that V_{p500} , V_{p54V} and V_{p100} show less scattering than V_{p250} and V_{p54H} (flattening of the curves).

Figure 8. Statistical distribution of P-wave velocities at all scales. (a) Boxplots of each dataset with mean indicated. (b) Normal laws of each data set, showing the difference of mean and standard deviation.

Figure 9 summarizes the descriptive statistics of P-wave velocity of each dataset (Figure 8a) versus their corresponding wavelength. In addition, the four curves of constant frequency induced by the different geophysical tools are plotted. An overall decrease of P-wave velocity is observed, from ultrasonic to seismic frequency (Figure 9). This shift of P-wave velocity is particularly well-defined by the interquartile domain and the median of each dataset. The main decline of the P-wave velocity is observed between V_{p500} and V_{p54H} , with a decrease of about $2000 m.s^{-1}$, associated with an increase of the wavelength size, from 6-10 mm for λ_{500} to 2-6 cm for λ_{54} . Then, between V_{p54} and V_{p100} , the P-wave velocity decreases to a lesser extent (decrease of $200 m.s^{-1}$) despite that, the associated wavelength increases from 2-6 cm for λ_{54} to ~ 20 m for λ_{100} . This last result (comparison between V_{p54} and V_{p100}) suggests that the elastic properties characterized at a sonic frequency are representative of elastic properties acquired at seismic frequency, at least for the study site that we investigate.

Figure 9. P-wave velocities of four datasets versus wavelength size (REV). Only the descriptive statistics of P-wave velocity and wavelength are displayed. The grey area corresponds to the interquartile range and the red curve shows the median. Curves of constant frequency are also indicated. Boxplots showing the evolution of the wavelength with scale are displayed on the top.

The descriptive statistics of P-wave velocity of each dataset can be also investigated through probability density maps (PDM, Figure 10). In Figure 10a, most of the dataset exhibits V_{p500} higher than V_{p250} even if a few data points are located close to the line of equality. The highest values of PDM indicate V_{p500} between 4000 and 5000 m.s^{-1} while V_{p250} scatters between 2000 and 4500 m.s^{-1} . This observation is further reinforced by Figure 10b, showing V_{p500} always higher than V_{p54H} . Again the highest values of PDM suggests V_{p500} between 4000 and 5000 m.s^{-1} while V_{p54} scatters between 1000 and 3500 m.s^{-1} . Figure 10a,b clearly shows that there is no direct relationship between plug and outcrop measurements, an observation that points to a scale effect. Indeed, outcrop measurements take into account greater scales of heterogeneities than plug measurements, including the impact of interfaces at the outcrop scale (e.g. cracks, fractures, Figure 4).

Figure 10. Comparison of P-wave data acquired at the outcrop and laboratory with probability density maps (PDM). Line of equality between datasets are also indicated. (a) V_{p500} versus V_{p250} . (b) V_{p500} versus V_{p54H} . (c) V_{p250} versus V_{p54H} . (d) V_{p54H} versus V_{p54V} .

Further findings at the outcrop scale are highlighted with the Figure 10c which compare V_{p250} with V_{p54} . In this plot, the major part of the dataset exhibits V_{p250} higher than V_{p54H} with a few data points located close to the line of equality. Moreover, despite the scattering of the dataset, the PDM shows a linear trend that mimics the line of equality, suggesting that V_{p250} and V_{p54H} are sensitive to the same features. This result goes hand in hand with the previous observations made in Figure 10a, b, cracks and fractures affect mainly the elastic properties of outcrop measurements. Finally, the Figure 10d compares V_{p54H} with V_{p54V} acquired at outcrop on the same locality. Despite the scattering of the dataset, the highest values of PDM are around the line of equality, indicating an almost elastic isotropy. This finding denotes that the defects affecting the elastic properties of outcrop scale are almost randomly distributed.

5. Discussion: Upscaling of physical properties in carbonates

5.1. Insight through the pore compressibility evolution from plug scale to outcrop scale

We use a simple effective medium model to determine the evolution of the pore compressibility with scale: from plug to outcrop, assuming a homogeneous, isotropic and dry medium. According to the Mori-Tanaka scheme, Benveniste (1987) shows that the effective bulk modulus, K_{eff} , is related to the porosity, Φ , the bulk modulus of the pore-free matrix, *i.e.* the bulk modulus of the calcite ($K_0 = 71$ GPa) and the pore compressibility (P) is normalized to the compliance of a spherical pore (David and Zimmerman, 2011a):

$$\frac{K_0}{K_{\text{eff}}} = 1 + \frac{\Phi}{(1 - \Phi)} P(v_0). \quad (1)$$

Figure 11. Pore compressibility control on P-wave velocity. (a) P-wave velocity versus pore compressibility for three datasets calculated for a Poisson ratio of 0.29. (b) Real versus modelled pore compressibility for ultrasonic laboratory data. (c) Relationship between aspect ratio and pore compressibility for a calcite medium (red line calculated for an equivalent ellipsoidal pore). The blue dots represent the aspect ratio determined for spheroidal pores at the plug scale (Figure 7b).

The effective bulk (K_{eff}) and shear (G_{eff}) moduli are related given by the following set of equations

(2) and (3):

$$V_p^2 = \frac{K_{\text{eff}} + \frac{4}{3}G_{\text{eff}}}{\rho_b}, \quad (2)$$

$$V_s^2 = \frac{G_{\text{eff}}}{\rho_b}, \quad (3)$$

where ρ_b is the density of the studied medium. At the plug scale, V_p , V_s and Φ are measured. Using equations (2) and (3) one can compute the effective bulk modulus, and then compute the pore compressibility at plug scale (P_{500}), using equation (1). Results are plotted in Figure 11a (dots in blue) and show values for P_{500} between 12 and 17.

Then, for computing P at outcrop scale without knowing V_s , we make the approximation that the Poisson ratio (ν) obtained at plug scale is constant whatever the scale. At the plug scale, $V_p/V_s = 1.84$, leading to ν_{eff} equal to 0.29, a value close to the one of a pure calcite mineral ($\nu_{\text{Calcite}} = 0.31$). Equations (2) and (3) can be combined to get :

$$K_{\text{eff}} = \frac{V_p^2 \rho_b}{1 + 4 \left(\frac{1 - 2\nu_{\text{eff}}}{2 + 2\nu_{\text{eff}}} \right)} \quad (4)$$

At the plug scale, the comparison of the “real” pore compressibility P (*i.e.* the one calculated by using V_p and V_s data) and the one calculated under the assumption that ν_{eff} is constant and equal to 0.29 (“Modelled pore compressibility” in Figure 11b) aims to show that the “modelled” P is slightly underestimated, *i.e.* under the assumption that ν_{eff} is constant, pores appear slightly stiffer than they are in reality (Figure 11b). We also assume that there is no significant porosity change between the plug and the outcrop scale, which is a valid approximation, as the porosity of the plugs are in the range 10-30 % and at larger scale the additional porosity due to the cracks and fractures is expected to be ≤ 3 %. Thus, we can use the set of equations (1) and (4) to compute the pore compressibility at an outcrop.

The P-wave velocity acquired at plug and outcrop are plotted *versus* their associated pore compressibility (Figure 11a). Results show that there is an increase of the pore compressibility with upscaling, implying a softening of the porous network from laboratory scale to outcrop scale (porous medium containing more and more compressible/soft pores, *e.g.* cracks). Indeed, from V_{p500} to V_{p54} , P increases and can reach values up to 600. The Figure 11a shows that for P-wave values range between 1000 and 2000 m.s^{-1} , the associated P values tend to be higher than 50-100 (threshold value). According to David and Zimmerman (2011a), we can relate P with the aspect ratio (α) of an equivalent ellipsoidal pore. We use their asymptotic approximations to compute an “effective” aspect ratio for a given P (red curve of Figure 11c). For plug data, the equivalent aspect ratios calculated using the model of David and Zimmerman (2011a) are slightly lower than the effective aspect ratios previously obtained with DEM modeling (David and Zimmerman, 2011b). Comparing the threshold value observed on Figure 11A (P around 50-100) with the Figure 11C allows us to conclude that upscaling from the plug to outcrop scale is characterized by an addition of very soft pores ($\alpha < 0.01$, cracks). These very soft pores may be linked with the structural features observed on the outcrop (Figure 4).

5.2. Upscaling modeling of elastic properties, from ultrasonic to seismic frequencies

As stated before, the upscaling of elastic properties in carbonates need to take into account different geological scales (Figure 1). Using an effective medium model, it is possible to model the evolution of P-wave velocity with scale, as described by the Figure 12.

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427 **Figure 12.** Modeling of the elastic properties at different scales by adding pores ($0.01 < \alpha < 0.3$) and
 428 cracks/fractures ($\alpha < 0.01$) of different sizes relating to the REV.

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At the matrix scale, the elastic properties of the medium are equal to the one of a pure calcite mineral ($K_0 = K_{\text{calcite}} = 71$ GPa, $G_0 = G_{\text{calcite}} = 30$ GPa; Mavko et al., 2009). Then, at plug scale, the elastic properties K_1 , G_1 are assumed to be the one of a calcite matrix containing spheroidal pores of a given equivalent aspect ratio. These elastic properties are computed employing the asymptotic expressions given by David and Zimmerman (2011b). In Figure 7b, the obtained results show that most of the plug-scale data corresponds to an aspect ratio between 0.1 and 0.2, a range close to the reference of carbonates ($\alpha_{\text{ref}} \sim 0.15$) given by Xu and Payne (2009) and Fournier et al. (2018) who also used DEM modeling. This first step of inverting P-wave velocity and porosity data in terms of equivalent pore aspect ratio is now widely used in the literature (e.g. Baechle et al., 2008; Fournier et al., 2011, 2014, 2018; Regnet et al., 2019a; Xu and Payne, 2009). It aims to explain the scattering of P-wave velocity for a given porosity and is of crucial importance for reducing the uncertainties in inverting and interpreting seismic data (Eberli et al., 2003). Nevertheless, the aspect ratio obtained, at plug scale, are representative of a small REV containing millimetric pores, and are not necessarily equal to the one of a larger volume (Figures 8, 9, 10 and 11).

At the outcrop scale, one should take into account a second family of inclusions, characterized by a low aspect ratio ($\alpha < 0.01$, Figure 11) related to the cracks/fractures observed in the field (Figure 4). We can use the crack density (ρ_c) defined by Walsh (1965) for quantifying the amount of circular cracks at different scales (Figure 12, equation 5):

$$\rho_c = \frac{1}{V} \sum_{i=1}^n c_i^3, \quad (5)$$

ρ_c is the crack density for n cracks of radius c in a volume V . Following David and Zimmerman (2011b), asymptotic solutions for the DEM in the case of crack-like pores ($\alpha < 0.01$) give us expressions of the effective moduli K and G as explicit functions of ρ_c :

$$\frac{K_{i+1}}{K_i} = \frac{(1 - 2\nu_i) e^{-\frac{16}{9}\rho_c}}{1 - 2\nu_i e^{-\frac{8}{5}\rho_c}}, \quad (6)$$

$$\frac{G_{i+1}}{G_i} = \frac{(1 + \nu_i) e^{-\frac{16}{9}\rho_c}}{1 + \nu_i e^{-\frac{8}{5}\rho_c}}, \quad (7)$$

where K_i , G_i and ν_i are the effective elastic moduli of the lower scale ($i=1, 2, 3$). Note that in the set of equations 6 and 7, we remove the previous assumption of constant Poisson ratio that was only used to compute pore compressibilities. In the following, the plug scale (Vp_{500}) corresponds to the scale 1 (REV 1 of Figure 12), the first outcrop scale (Vp_{250}) corresponds to the scale 2 (REV 2 of Figure 12), the second outcrop scale (Vp_{54}) corresponds to the scale 3 (REV 3 of Figure 12) and the seismic scale (Vp_{100}) corresponds to the scale 4. As an exemple, for the upscaling from scale 1 to scale 2: K_1 and G_1 are taken as the median value deduced from the data obtained on plugs (Vp_{500}); K_2 is taken as the median value deduced from the data obtained on outcrop (Vp_{250}); then, using equation 6 and 7, one can compute the crack density ρ_{c2} (Figure 13).

Figure 13 shows the calculated ρ_{ci} between scales based on the median values of P-wave velocities obtained for each dataset. First, the decrease of P-wave velocity with upscaling from scale 1 to scale 2, is

associated with a ρ_{c2} value of 0.27 related to the presence of cracks with a size ≤ 2 cm (λ_{250} , Figure 9). The resulting medium, REV2 of Figure 12, thus presents cracks ≤ 2 cm embedded within a porous carbonate with spheroidal pores ≤ 1 cm characterized by an aspect ratio around 0.15 (α_{ref}).

Then, the P-wave velocity decreases again with upscaling between V_{p250} and V_{p54} . The transition from scale 2 to scale 3 is linked with an addition of another crack density $\rho_{c3} = 0.3$ related to the presence of cracks with size ≤ 6 cm (λ_{54} , Figure 9). The resulting medium, REV 3 of Figure 12, thus contains two different scales of crack density, ρ_{c2} and ρ_{c3} , embedded in a porous medium. Finally, passing from scale 3 to scale 4 implies again an addition of another crack density ($\rho_{c4} = 0.07$) related to cracks/fractures of a size ≤ 20 m (λ_{100} , Figure 9). The resulting REV 4 includes three different scales of cracks, ρ_{c2} , ρ_{c3} and ρ_{c4} , embedded within a matrix porosity characterized by pores with an equivalent pore aspect ratio equal to 0.15. This multi-scale concept aims to explain the overall decrease of P-wave velocity from plug to seismic scale by taking into account different scales of heterogeneities, corresponding to different REV's, that have geological and physical significances (*i.e.* pores, cracks and fractures). It is therefore of importance for understanding of the physical properties of subsurface reservoirs (*i.e.* fractured carbonate reservoirs).

Figure 13. P-wave velocity versus computed crack densities for the median of each acoustic dataset.

5.3. From elasticity to reservoir properties of carbonates, implications of the crack porosity

As shown by several authors, reservoir properties (like porosity and permeability) are controlled by different factors (*e.g.* pore types and sizes) regarding the scale of investigation (Corbett, 2009; Haldorsen and Lake, 1984; Nordahl, 2004; Ringrose et al., 2008; Ringrose and Bentley, 2015). The multi-scale elastic properties obtained in this work are similar to what is found in the literature. At the lower scales of investigation (microscopic and macroscopic scales of Figure 1), the microstructure controls the physical properties of carbonates (Anselmetti and Eberli, 1993; Regnet et al., 2019b). Indeed, the microstructures present a huge diversity of sedimentary textures that may be modified by diagenetic processes, implying an important heterogeneity of their physical properties. DEM modeling shows that most of the dataset indicates an equivalent pore aspect ratio range equal to the reference value of carbonates ($\alpha_{ref} = 0.15$), despite samples present a high variability of microstructures. Then, for higher scales of investigation, the presence of large scale structural features impact the elastic properties (Figure 4). Again, using DEM modeling, we invert the

P-wave velocity evolution with scale in terms of crack density, highlighting that the different scales are impacted by structural features (Figures 12 & 13). Furthermore, based on the assumption that the cracks and fractures have an aspect ratio equal to 10^{-3} (Figure 11) we can compute the crack porosity thanks to the following equation (David and Zimmerman, 2011b):

$$\Phi_{crack} = \frac{4}{3} \pi \rho_c \alpha_{crack}, \quad (8)$$

where Φ_{crack} is the computed crack porosity, ρ_c is the crack density and α_{crack} is the crack aspect ratio (here assumed to be equal to 10^{-3}). Using equation (8), with the values of crack density previously obtained, (Figure 13) give us a total amount of megascopic crack/fracture porosity equal to 0,27 % ($\Phi_{crack2} + \Phi_{crack3} + \Phi_{crack4}$). This value is close to the one recently obtained by Panza et al. (2019), who used a stochastic approach (Discrete Fracture Network modeling based on field structural analysis) to compute the fracture porosity of a 1 m³ block of tight carbonate (mean $\Phi_{crack} = 0.3$ %).

The estimation of the crack-fracture porosity done above is computed using the median Vp value for each dataset. We can also compute “local” crack porosity for scales 2 and 3. For example for scale 2, (i=1, in equation 6 and 7) we can use the plug values for K₁, and K₂ from local log measurement (instead of using the median value of the dataset), then we can compute local crack/fracture porosity. Figure 14 shows the dataset for scales 1, 2 and 3 in a velocity-porosity plot. As expected before with the Figure 10a, b, the primary control of matrix porosity on the P-wave velocity tends to be lost with upscaling (Figure 14). Indeed, for the scale 2, almost all Vp₂₅₀ values are lower than the $\alpha_{ref=0.15}$ curve (Figure 14b). In the upper part of the PDM, most of the dataset presents Φ_{crack} values lower than 0,1 % and tends to mimic the matrix trend. In the lower part of the PDM, the scattering increases and is associated with an increasing Φ_{crack} (up to 0,6 %). For the scale 3, all Vp₅₄ values are lower than the $\alpha_{ref=0.15}$ curve (Figure 14c). The highest velocity values shown in the PDM do not highlight any links between P-wave velocity and porosity. Furthermore, for medium porosity (between 10 and 20 %), the Figure 14c shows a huge fluctuation of P-wave velocity (between 3500 and 1000 m.s⁻¹) associated with an increase in Φ_{crack} (from 0,1 to 0,6 %). The progressive

scattering of the velocity-porosity data, in Figure 14b, c, shows that the “matrix-porosity” control does not affect the elastic properties anymore with upscaling from laboratory scale to outcrop scale.

Figure 14. Impact of the crack density/porosity on the elastic properties. (a) P-wave velocity (500 kHz) versus matrix porosity (i.e. plug porosity). The grey dots indicate the data obtained at plug scale that follow the curve of equivalent $\alpha = 0.15$ without crack porosity. (b) P-wave velocity (250 kHz) versus matrix porosity with curves of constant crack porosity. The colored dots indicates the inverted crack porosity value for all the data (Φ_{crack2}). (c) P-wave velocity (54 kHz) versus matrix porosity with curves of constant crack porosity. The colored dots indicates the inverted crack porosity value for all the data ($\Phi_{crack2} + \Phi_{crack3}$). (Grey dots = no crack porosity; red = crack porosity of 1 %).

5.4. How to define the elastic properties of carbonates at different scales?

Figure 15 summarizes the upscaling of the wavelength size, P-wave velocity and porosity and their associated major controlling factors (porosity of the matrix, cracks and fractures). In order to be representative of a medium, the geological interpretation of an elastic measurement needs to be within the constraints of the REV size (λ , Figure 15a) which depends on i) the tool frequency (f) and ii) the P-wave velocity (v) using the well-known relationship : $\lambda = v/f$. Following the theory of homogenization, the upper limit size of an elastic REV has to be lower than the wavelength size induced by the used geophysical tool. Conversely, by analogy with seismic investigation, the lower limit of an elastic REV has to be higher than the quarter wavelength size (Sheriff and Geldart, 1995). Indeed, this resolution corresponds to the minimum

interval between two interfaces to be seen as two separate objects and not a single one, it therefore can be used as the minimum size of an elastic REV (Al-Chalabi, 2014). Furthermore, as defined by Sheriff (2002), the detectable limit in seismic is “the minimum thickness for a bed to give a reflection that stands out above the background”. It has a size equal to a thirtieth of the wavelength size (Sheriff and Geldart, 1995).

Between ultrasonic ($\sim$ MHz) and seismic ($\sim$ Hz) measurements, the change of frequency implies a variation of wavelength size, from millimetric to metric (Figure 15a). This upscaling implies a change of the characterized geological object. At plug scale ($\sim$ 5 cm of investigation, blue zone of Figure 15), the P-wave velocity is lower than the velocity of calcite and fluctuates because of the intrinsic variability of matrix porosity composed of micro/millimetric pores (Figure 15b). It has to be noted that the fluctuations observed in this dataset are related to the variation of the total porosity and the pore shapes, as already suggested by several authors (Anselmetti and Eberli, 1993; Eberli et al., 2003; Fortin et al., 2007; Soete et al., 2015; Fournier et al., 2018; Regnet et al., 2019a, b). Then, the upscaling to the outcrop scale 2 ($\sim$ 20 cm of investigation for the green zone of Figure 15) is again associated with a decrease of the P-wave velocity. Indeed, for that scale, the fluctuations of the P-wave velocity (Figure 15b) are controlled by both the crack and matrix porosity (Figures 14b and 15c, d). Going a step further with measurements at the outcrop scale 3 ($\sim$ 40 cm of investigation for the yellow zone of Figure 15) aims to highlight this conclusion. The P-wave velocity decreases because of an increasing crack-related porosity. These “scale effects” were already pointed out by Matonti et al. (2015) who also attribute the upscaled P-wave velocity decrease to the occurrence of outcropping structural features. Finally, at the seismic scale 4, the pluri-metric REV 4 highlights P-wave velocities is slightly lower than outcrop scale 3, implying that another scale of crack porosity materialized by metric fractures and bedding planes. Despite this slight difference, the mean P-wave velocity of the outcrop scale 3 is very close to the one acquired at seismic scale (Figure 15b), suggesting that a medium of 40 cm in length is representative of the seismic scale. This finding is of importance for upscaling procedures because it shows that sonic measurements (here of 54 kHz) may better

correspond to seismic velocities (here of 100 Hz), while ultrasonic measurements on plugs and outcrops (respectively of 500 kHz and 250 kHz) do not fit with seismic acquisition.

This brings the usual question of the representativeness of plug measurements for reservoir characterization (Ringrose et al., 2008; Corbett et al., 2015). Indeed, by analogy, several authors show that multi-scale geological medium implies different fluid-flow properties that has to be related to multiscale REV's (Nordahl & Ringrose, 2008; Ringrose et al., 2008; Corbett, 2009; Claes, 2015; Ringrose and Bentley, 2015). Similarly here, the upscaling of elastic properties of lacustrine carbonates shows that we need to take into account several scales of rock heterogeneities, from microscopic to megascopic scales, including pores, cracks and fractures, following thus the early works of Stierman and Kovach (1979) as well as Moos and Zoback (1983). The present work highlights the need to interpret and model multiscale elastic data with regards to the different length scales related to geology (Figures 1 and 12). This is of importance for linking high frequency and low frequency elastic moduli because an elastic wave with different frequencies will not necessarily characterize the same geological object. This fact goes against the assumption often made that the drained moduli (equal to the dry elastic moduli) is the same whatever the frequency. Indeed, the geological medium is not homogeneous with scale, implying that it does not necessarily have the same multi-scale elastic properties (Figure 15).

Figure 15. Upscaling of (a) the wavelength size (REV), (b) P-wave velocity, (c) major controlling factors and (d) porosity versus arbitrary scale of measurements. The curve starts from the pure calcite value and fluctuates with scale changes. For the REV, the descriptive statistics introduced in Figure 9 are used to symbolize the variability. Then, for P-wave velocity and porosity, each fluctuation of the curve represents 10 % of the dataset (deciles), until arriving on the median value symbolized by a plateau.

Conclusion

This multi-scale geophysical characterization enables the linkage of elastic properties of dry lacustrine carbonates to relative proportions of crack/fracture porosity. If upscaling of the elastic properties is largely discussed in the literature, there is a paucity of multi scale acoustic field datasets. Indeed, the originality of this work is to compare different scales of acoustic measurements, from ultrasonic to seismic frequency, acquired on the same geological object, keeping in mind the size of the elastic REV - the wavelength size - induced by the used geophysical tools. The large dataset acquired at all scales allow us to have an approach which is statistically effective. Results show that P-wave velocities decrease with decreasing frequency, so that the acoustic measurements are related to the REV evolution and thus to the size of geological features. Indeed, upscaling of elastic properties from ultrasonic (microscopic scale) to seismic (megascopic scale) frequencies means increasing the REV, from pluri-millimetric to pluri-metric. Furthermore, results also show that acoustic measurements done at a frequency of 54 kHz (scale of ~ 40 cm) are really close to the one acquired at 100 Hz, suggesting that sonic velocities can be extrapolated to the seismic frequencies at least for the study site that we investigated. Using effective medium theory, a model based on the comparison of the multiscale datasets is presented (concept of multi-scale REVs). It aims to upscale P-wave velocity assuming that inclusions with different aspect ratios ($\alpha_{matrix\ pores} = 0.15$ and $\alpha_{crack-fractures} = 10^{-3}$) control the elastic behavior of the studied lacustrine carbonates. In our study, model-based results suggest that the crack density/porosity becomes the main controlling factor of P-wave velocity at seismic scale. Finally, the inherited different scales of geological heterogeneities (pores, cracks, fractures) impact differently the elastic properties. This implies that the common matrix porosity control on ultrasonic wave velocities may be lost with upscaling because of the presence of larger structural features (cracks, fractures and bedding planes), a result that is of importance for the understanding of subsurface reservoir properties (*i.e.* porosity and permeability) using solely sonic and seismic data.

Acknowledgments, Samples, and Data

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<i>Thickness (m)</i>	<i>Laboratory dataset</i>					<i>Outcrop dataset</i>		
	<i>Sample name</i>	<i>Density dry</i>	<i>Porosity</i>	<i>Vp dry 500 kHz</i>	<i>Vs dry 500 KhZ</i>	<i>Vp 250kHz Horizontal</i>	<i>Vp 54kHz Horizontal</i>	<i>Vp 54kHz Vertical</i>
0.2	RE001	2.15	0.206	4192	2264	1986	1267	2090
0.4	RE002	2.34	0.137	4744	2889	3945	1793	1779
0.6	RE003	2.017	0.256	3504	2259	2160	1406	1306
0.8	RE004	2.34	0.136	4523	2752	2766	3033	1149
1	RE005	2.288	0.155	4566	2575	3161	1870	1263
1.2	RE006	2.164	0.201	4166	2451	2919	3030	1457
1.4	RE007	2.124	0.216	3802	2200	3546	3443	1449
1.6	RE008	2.283	0.157	4802	2803	3175	3478	2550
1.8	RE009	2.322	0.143	4385	2554	3328	3443	1698
2	RE010	2.329	0.141	4545	2775	2964	2278	2401
2.2	RE011	2.284	0.156	4550	2717	2660	2338	2166
2.4	RE012	2.334	0.137	4564	2743	2941	2365	2533
2.8	RE014	2.358	0.129	4959	2864	4348	1309	998
3						3140	2366	2067
3.2	RE015	2.194	0.19	4139	2502	2151	1489	2053
3.4	RE016	2.092	0.228	3789	2264	3373	3429	2768
3.6						3333	2412	3419
3.8	RE018	2.391	0.118	4892	2767	3333	2703	2180
4	RE019	2.201	0.188	4232	2437	3195	2881	2727
4.2	RE020	2.208	0.186	4315	2477	3774	2331	1753
4.4	RE021	2.14	0.211	4019	2333	4141	2576	2117
4.6	RE022	2.252	0.17	4234	2226	2597	2959	3014
4.8	RE023	2.223	0.181	4369	2500	3636	2064	2566
5	RE024	2.349	0.136	4709	2690	3215	1860	1278
5.2	RE025	2.476	0.083	5164	2992	2558	2902	890
5.4	RE026	1.94	0.285	3623	2229	3610	2549	1934
5.6	RE027	1.938	0.285	4025	2270	2090	1461	1875

5.8	RE028	1.917	0.294	3749	2141	2695	3030	1775
6						3759	2901	1412
6.2	RE029	2.34	0.137	4980	2759	3690	2466	2003
6.4	RE032	1.86	0.313	3965	2292	3610	3036	2634
6.6	RE030	2,00	0.262	4172	2373	2594	2096	2340
6.8	RE031	1.988	0.267	4333	2527	1222	1308	
8.2	RE037	1.922	0.284	3249	1996	2717	2812	1630
8.4	RE038	1.844	0.318	3470	2049	2152	1498	2703
8.6	RE039	1.808	0.331	3482	2068	2664	2296	2904
8.8	RE040	2.195	0.191	4166	2519	2845		
9	RE041	2.225	0.176	4528	2724	2284	2998	
9.2	RE042	2.174	0.2	4193	2410	1751	1518	
9.4	RE043	1.911	0.292	3545	2128	2532	1724	2703
9.6	RE044	1.957	0.278	3615	2142	2320	1208	
9.8	RE045	1.951	0.278	3712	2181	2421	1331	
10	RE046	2.296	0.154	4552	2509	1591		
10.2	RE047B	1.817	0.329	3137	1891	2500	597	
10.4	RE048	1.77	0.346	3082	1888	2963	2817	
10.6	RE049	1.784	0.342	3362	1996	3846		
10.8	RE050	2.181	0.197	4101	2419	2733		
11						3409		
11.4	RE053	2.358	0.133	3830	2291	0		
11.8	RE054	2.467	0.093	4228	2581	4375		
12	RE055	2.416	0.111	4690	2802	4400		
12.2	RE056	2.533	0.068	5016	2945	0		
12.6	RE057	2.128	0.215	4235	2387	0		
12.8	RE058	2.29	0.153	4719	2719	0		
13.2	RE059	2.175	0.199	3983	2364	3750		
13.4	RE060	2.207	0.187	4323	2677	2848		
13.6	RE061	2.323	0.144	4871	2870	1452		
13.8	RE062	2.122	0.218	4020	2572	4531		
14	RE063T	2.018	0.254	3910	2263	4437		
14.2						3614	1031	
14.4	RE064	2.31	0.149	4473	2621	2759	1391	2794
14.6	RE065	2.371	0.127	4766	2790	4389		
23.4						4107	3374	3340
23.6	RE106	2.25	0.167	4608	2626	3987	3468	2118
23.8	RE107	2.31	0.143	4713	2687	3830	2238	2661
24	RE108	2.485	0.073	5601	3077	4319	2946	2517
24.2	RE109	2.221	0.182	4711	2483	2381	1121	1499
24.4	RE110	1.998	0.263	3821	2213	2419	912	1426
24.6	RE111	2.304	0.148	4958	2674	2512	995	989
24.8	RE112	2.371	0.123	4693	2800			
25						2365	2196	
26.6	RE066	2.408	0.114	4613	2770	4854	2785	

26.8						3431	1814	1518
27	RE067	2.185	0.194	4298	2489	3096	1662	1021
27.2	RE068	2.424	0.104	4948	2808	3745	2037	990
27.4	RE069	2.317	0.144	4465	2651	4415	3219	2721
27.6	RE070	2.376	0.123	4990	2613	4914	3904	
28.6	RE071	2.453	0.08	5403	2796	4415	2765	
28.8	RE072	2.409	0.112	4713	2643	4515	3330	
29	RE073	2.412	0.11	4933	2643	3974	4204	2006
32						2432	1496	
32.2	RE074	2.092	0.229	4070	2515	3257	1627	1081
32.4	RE075	2.154	0.205	4346	2538	3257	2440	3053
32.6	RE076	2.195	0.191	4430	2607	4073	2946	
32.8	RE077	2.32	0.141	4881	2708		3337	
33	RE078	2.175	0.199	4391	2299	3731	2682	2466
33.2	RE079	2.096	0.226	4010	2379	3552	562	
33.4	RE080	1.931	0.288	3523	2066	3552	1297	3234
33.6	RE081	2.323	0.144	4782	2639		2577	944
33.8	RE082	2.438	0.097	4990	2653	3906	1692	1372
34.2	RE083	2.46	0.094	5197	2809	2571		
34.4	RE084	2.336	0.14	4488	2717	4762	1645	
34.6	RE085	2.399	0.116	5164	2931	4787	1255	
34.8	RE086	2.316	0.146	4865	2663	4219	1859	
35	RE087	2.01	0.259	3588	2072	2109	1498	
35.2	RE088	2.572	0.054	4837	2727	3221		
35.4						1127		
35.6	RE089	2.396	0.117	5322	2850	1270		
35.8	RE090	2.276	0.162	4632	2521			
36	RE091	2.583	0.048	4565	2867	3712		
36.2						2913		
37.2	RE093	2.064	0.24	3124	1792			
37.4	RE094	2.088	0.23	3091	1888			
37.6	RE095	2.007	0.26	2877	1784			
38	RE096	2.094	0.231	3773	2026	1462		
38.2						3425	4663	
38.4							2872	2491
38.6	RE098	2.202	0.189	3993	2444	3236		
38.8	RE099	2.318	0.146	4127	2390	1950	1064	
39						2941		
39.2	RE101	2.15	0.208	3135	1986	2005		
40	RE102	2.029	0.253	3070	1736	2120		
40.2	RE103	2.036	0.251	3167	1886	3604	2283	2003
40.4	RE104	1.848	0.319	2859	1755			
40.6	RE105	2.195	0.192	4025	2272			

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