Investigating the influence of mineralogy and pore shape on the velocity of carbonate rocks: Insights from extant global data sets

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Abstract

Using a variety of recent public-domain data sets comprising porosity, velocity (P- and S-waves), and, in most cases, mineralogy and petrographic data, I created an extensive global data set and evaluated the importance of mineralogy and pore type on the elastic properties behavior of carbonate core plugs. Results from this investigation clearly illuminated the potential for overinterpreting elastic properties behavior as a function of pore type(s) when mineralogy was not explicitly included in the analysis. Rock-physics analysis using a combination of heuristic and theoretical models illustrated that mineralogy exerted a significant additional variation on velocity at a given porosity. Failure to account for mineralogy exacerbated inferences about the effect of pore type(s) made using a comparison of P-wave velocity to an inappropriate empirical model (Wyllie) that did not account for pore shape(s). In this analysis, extreme variability in carbonate velocity was observed in only portions of two data sets, when mineralogy was explicitly considered and robust models that accounted for inclusion (pore) shape were used. Results from this analysis resulted in a recommended workflow, including a rock-physics template and dry-rock modulus diagnostics, for the evaluation of lab-based carbonate rock-physics data. The workflow was amenable to further integration with well-based data and other core-based petrophysical measurements (e.g., electrical properties).

Introduction

Methods for seismic-based reservoir characterization require rock-physics relationships to relate petrophysical properties (lithology, porosity, saturation) to geophysical variables (bulk density and P- and S-wave velocities), which are responsible for the recorded seismic behavior. Exploration and prospect appraisal commonly rely on amplitude variation with offset (AVO) techniques, which emphasize the importance of S-wave velocity to enhance fluid and reservoir detection. Similarly, seismic inversion using multiple seismic offset volumes uses reservoir-specific rock-physics relationships to infer reservoir properties (porosity, net-to-gross, hydrocarbon saturation) using a combination of two derived seismic property volumes (e.g., P-impedance, V_P/V_S ratio). Finally, time-lapse (4D) seismic interpretation requires the ability to model dynamic changes in reservoir stress, saturation, and fluid properties, as well as potential changes in the reservoir overburden. Tremendous effort has been made in recent decades in seismic rock physics, as noted in classic review articles (Yale, 1985; Wang, 2001), in a ubiquitous handbook (Mavko et al., 2009), and in a practical interpretation textbook (Avseth et al., 2005).

To date, considerably more attention has been devoted to the development of rock-physics relationships for siliciclastic rocks, whereas efforts focused on understanding carbonate rock properties have generally lagged behind and received comparatively less research attention. Several factors likely explain the historical emphasis on clastic (reservoir) rocks. First, early success with the direct detection of hydrocarbon using seismic (e.g., "bright spots," AVO) found ready application (and economic success) in high-porosity, acoustically "soft" unconsolidated sands and sandstones common in deltaic and turbidite environments (see the excellent summary by Forrest, 2010). Second, carbonate reservoirs (exclusive of chalk) are generally of lower porosity and acoustically "stiff," reducing or rendering, nearly nonexistent, any seismic fluid signal. Fournier and Borgomano (2007) present a compelling example from the Philippines of the use of seismic to image reservoir architecture in a carbonate buildup. Here, porosity and pore type, largely the result of diagenetic processes, control variations in (reservoir scale) acoustic impedance. Clearly, the pervasive diagenetic overprint frequently observed in carbonate reservoir rocks, resulting in complex mineralogy (calcite, dolomite, sulfate) and variable pore type(s), requires an approach to rock-physics model development that is unique from the significant experience compiled from siliciclastic reservoirs.

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Recent carbonate rock-physics results

Recent work in carbonate reservoirs has focused on the effect of pore type(s): shape, concerns about rock-fluid interaction(s) and the possible impact on fluid replacement, and the impact of texture (chalks, micritic carbonates) on elastic properties behavior. Additional studies have shown the importance of lab protocol in the measurement of velocity on carbonate samples and the role of frequency when integrating lab- and well-based data with seismic (reflection, VSP) information. The following review is provided for clarity and will help frame the subsequent data analysis and interpretation.

Carbonate pore type(s)

Observations that the nature (type) of carbonate pore(s) present in a sample exert a significant influence on velocity date to at least 1997 (Anselmetti and Eberli, 1997; Marion and Jizba, 1997; Wang, 1997). Large, equant (high-aspect ratio) pores (e.g., vugs) are seen to increase velocity, whereas thin, crack-like (low-aspect ratio) pores reduce velocity. Works by Brie (2001), Xu et al. (2006), and Sayers (2008), using two different (theoretical) models incorporating relevant pore-shape terms (aspect ratio), suggest similar effects from variable aspect ratio pores, based on a variety of lab- and well-based data sets. It should be noted that Wang (1997), and references cited therein, uses a theoretical rock-physics model (closely related to the model used by Xu et al., 2006) to describe velocity response in carbonates as a function of high- and low-aspect-ratio pores (vugs, fractures). Note that several authors (Anselmetti and Eberli, 1997; Baechle et al., 2008; Verwer et al., 2008; Weger et al., 2009) base the observation of velocity deviation (particularly to higher velocity) using a comparison of measured (lab) data to the Wyllie time average (WTA) model (Wyllie et al., 1956). In earlier works, Brie et al. (1985) also use the WTA model in an interpretation method that infers spherical porosity from well log data in which the "primary medium" is presumed to follow the Wyllie model. The suitability of that particular model for comparison with carbonate velocity data, in particular the case of P-wave velocity only, will be discussed further in a subsequent section.

Fluid replacement

Concerns about the effect of varying pore fluid type and more importantly the potential violation of one or more necessary conditions in the use of the Gassmann fluid substitution algorithm were recently highlighted in lab studies by Baechle et al. (2005) and Adam et al. (2006). Earlier works by Wang (1997) and references cited therein also make note of velocity differences between measured and Gassmann-predicted values, with the largest differences observed in P-wave velocity at low differential (effective) pressure. Baechle et al. (2005) use lab-measured (ultrasonic) data from 30 limestone (calcite) samples from Cretaceous and Miocene reservoirs, under dry and saturated conditions (typically the same sample). While many of the samples respond as per Gassmann expectation (saturated $V_P >$ dry V_P, saturated $V_S <$ dry V_S), several samples do not exhibit this behavior. A comparison of the dry and saturated shear modulus, which is a function only of measured V_S and bulk density, and predicted to be an invariant as a consequence of the Gassmann model, also showed anomalous behavior in some samples. This variability is described as either "shear weakening" or "shear strengthening." The study by Adam et al. (2006) uses nine samples (calcite and dolomite) from a single reservoir and included low-frequency and ultrasonic data. At low (seismic) frequency (100 Hz), all samples show shear modulus weakening at low (3.5 MPa) differential pressure, but significantly less at high (reservoir) differential pressure (31 MPa). Using the ultrasonic velocity data, the samples show no shear modulus effect with the data uncertainty at low and reservoir differential pressures.

Importance of lab protocol

Petrophysicists working on carbonate reservoir rocks have long understood the challenges that sample-based heterogeneity (properties) and inhomogeneity (sample condition) impose on the measurement of routine formation properties. For geophysical applications, Wang (1997) observes that sample size (plug, whole core) and the size of geologic heterogeneity (e.g., vug, mold) play an important role in geophysical measurements, particularly when making ultrasonic (i.e., 0.8–1 MHz) pulse transmission measurements. More recently, Rasolofosaon et al. (2008) made a cogent set of recommendations specific to the petroacoustic characterization of carbonate samples. Sample-specific heterogeneity that may induce acoustic scattering ("path dispersion") must be avoided by using a combination of sample selection and an alternate velocity measurement procedure. Samples with visible plug-scale heterogeneity should be discarded. Pore-scale heterogeneity that may prevent the uniform spatial saturation of a sample must also be recognized. Finally, the use of phase velocity is recommended as the best way to minimize the effect of sample heterogeneity on the acoustic velocity measurements. By following this guidance, Rasolofosaon et al. (2008) present a compelling example in which lab data demonstrate experimental verification of the Gassmann equation in (calcite) carbonate samples. Adam and Batzle (2008) further emphasize the importance of frequency and differential pressure during lab testing and suggest that bulk modulus (as shown in Rasolofosaon et al., 2008) should be preferred (over velocity) when evaluating the applicability of the Gassmann equation.

Organization of the paper

Building from the introduction, this paper next describes the data and the rock-physics models considered in the subsequent analysis. Using the global data set and a variety of rock-physics models, I critically

evaluate the importance of mineralogy and pore type on the elastic properties behavior. From this analysis, an integrated rock-physics workflow, utilizing a rock-physics template and dry-rock modulus diagnostics (Kittridge, 2006), emerges as a suggested minimum standard for the evaluation of carbonate rock-physics data. Finally, I review and comment on specific challenges in seismic petrophysics for carbonate reservoirs, particularly in the area of lab- and well-based data integration. The integrated global data set, suggested workflow, and conclusions drawn from the deliberate application of heuristic and theoretical rock-physics models should be of interest to petrophysicists and geophysicists using core, well log, and seismic data for appraisal and seismic-based reservoir characterization in carbonate reservoirs.

Data and methods

All of the data analyzed in this study are taken from published, public-domain sources. The measured data are reported in tabular form in the original source(s) and were manually transcribed from the original source. (Data from Verwer et al. [2008] were available as a digital download directly from http://www.seg.org with the full-text reference). No data were obtained indirectly from scanned data plots. When available, additional geologic information (age, mineralogy), sample analyses, and textural information (dominant pore type, digital image analyses) are noted from the original reference. Table 1 provides a summary of the core data sets considered.

Rock-physics data

Four data sets are reviewed in this study, all from geologically diverse global locations and a variety of original sample sources (well, outcrop). With the exception of one data set (Weger et al., 2009), all data sets include P- and S-wave velocities, frequently for dry and wet conditions, porosity, and grain density. The velocity measurements were made in various labs, with variables but generally comparable (isostatic) confining stress, stress path, and ultrasonic (0.7–1 MHz) frequencies. When available, dry and wet velocity data enabled the estimation of velocity differences attributable to fluid replacement and the potential issue of shear modulus variability discussed previously. Specific challenges in analysis of the Weger et al. (2009) data set, which were missing S-wave velocity and grain density, will be discussed in a subsequent section. The work reported by Weger et al. (2009) is known to have included laboratory measurements of S-wave velocity (see p. 1299 in original citation), although no data are reported and no use or evaluation of V_S data is included in this particular reference. In fact, in 2011, a direct inquiry to the lead author seeking access to those data (and measured grain density) was declined.

Data 1 — Miocene outcrop, Mallorca

The data are from outcrop and surface-drilled boreholes (3) of a Miocene outcrop in Mallorca. Data are not identified in any manner that enables determination of the outcrop or (surface) borehole source for the

Table 1. Summary of core data sets analyzed.

Source	Location(s)	Type	#Spl	V_P	V_S	ρ_g	Lab velocity	Geology	Additional descriptor(s)
Verwer et al. (2008)	Cap Blanc of the Llucmajor Platform, Mallorca	Outcrop and surface borehole (3)	250 (131)	Yes	Yes	Yes	Wet (deaired brine 35% NaCl) and dry; Peff 10 MPa; Ppore 0.1 MPa; 1MHz	Miocene; low- and high-Mg calcite, dolomite, aragonite. Mostly dolomitic.	XRD, petrography, texture (granular, crystalline)
Weger et al. (2009)	Middle East (Shu"aiba); southeast Asia (Miocene); Marion Plateau (Miocene)	Wells	120	Yes	No	No	Wet (distilled H20); Pconf 20 MPa; Ppore 2 MPa; 1 MHz	Limestone or Dolomite (<2% noncarbonate)	Dunham texture; pore type (dominant, minor); Digital image analysis
Bakhorji (2010)	Arab-D reservoir (Saudi Arabia) from seven wells	Wells	37	Yes	Yes	Yes	Wet and dry; Pconf 5-25 MPa (increasing, decreasing stress); ~1 MHz	Limestone or Dolomite (<1% noncarbonate)	Samples characterized as macro, micro, dual porosity. Petrography, SEM, mercury porosimetry
Fournier et al. (2011)	Four outcrop locations, southeast France	Outcrop	80	Yes	Yes	Yes	Dry; Pconf 2.5, 5, 10, 20, and 40 MPa; Ppore 0.1 MPa; 1 MHz	Lower Cretaceous platform; microporous limestone	All grainstone texture, absence of intergranular, intercrystal-line, or moldic porosity

individual sample. Very few permeability data are reported and are not further considered in this analysis. The original data set was edited to include only samples with wet and dry velocities and measured mineralogy and in which mineral-based grain density agreed with the reported grain density. Subsequent rock-physics analysis on the edited data set (Figure 1) is based on calcite ($n = 16$) and dolomite ($n = 115$) end-members (>0.9 v/v), with average grain densities of 2.72 and 2.857 g/cm^3, respectively.

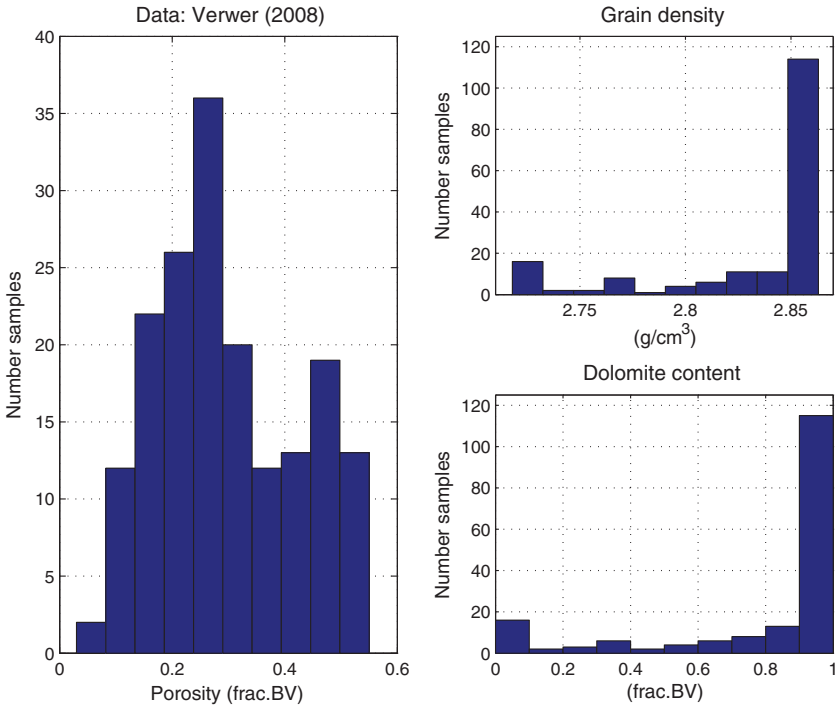

Figure 1. Basic petrophysical properties for data compiled by Verwer et al. (2008). Mineralogy (dolomite, calcite) based on reported XRD data.

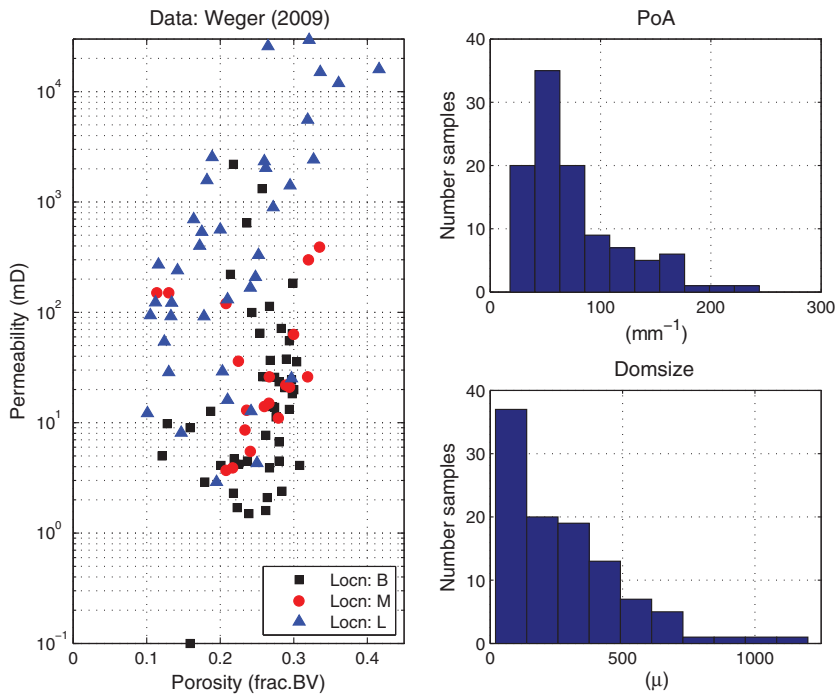

Figure 2. Basic petrophysical properties for data compiled by Weger et al. (2009). Digital image analysis was used to generate DomSize and PoA data.

Data 2 — Global cored wells

The data are from cored wells at three different sites (Middle East, Southeast Asia, Australia), and all samples are either limestone or dolomite, with less than 2% noncarbonate minerals. Data are identified in a manner that enables discrimination into one of three data groups (B, L, and M) that reflect location (Figure 2). One of the locations is documented as the Marion Plateau (Australia) with data acquired during ODP leg 194 (Ehrenberg et al., 2003). Further analysis and evaluation of specific data from the three locations is described below as part of the rock-physics analysis. Minimum reported permeability is 0.1 mD, and entries with zero permeability ($n = 2$, Location L) were assigned a permeability of 0.01 mD. No further editing of the original data set was made. Two pore shape parameters from digital image analysis are reported and used in the rock-physics analysis: perimeter over area (PoA) and dominant pore size (DomSize). The interested reader is referred to the original publication for further details on these parameters.

Data 3 — Arab-D reservoir, Saudi Arabia

The data are from seven cored wells in the Arab-D from a reservoir in Saudi Arabia. Data are identified in a manner that enables discrimination by well. Using reported mineralogy data, samples are grouped based on mineralogy (Figure 3). Subsequent rock-physics analysis is based on calcite ($n = 26$) and dolomite ($n = 6$) end-members (>0.9 v/v), with average grain densities of 2.714 and 2.839 g/cm^3, respectively. Velocity data (dry and wet) are at 20 MPa and are taken from the increasing confining stress cycle. Minimum reported permeability is 0.01 mD, with individual samples reported as 0.1 and 0.01 mD.

Data 4 — Outcrop grainstone, France

The data are microporous limestone samples from four different outcrop locations in southeast France. Data are identified in a manner that enables

discrimination by (outcrop) locale. All the samples are grainstones and are well-sorted and medium- to very coarse-grained. The intergranular and intraskeletal space is almost completely filled with calcite cements. The average micrite content is 0.656 v/v ($\sigma = 0.11$), and the average grain density is 2.705 g/cm^3 (Figure 4). Velocity data (dry) are at 20 MPa (using $V_{S1}$for shear velocity). No permeability data are reported.

A variety of additional carbonate velocity data sets are reported and known from the public domains, which are not included here. Sayers (2008) analyzes a single published data set, and I did not repeat that analysis in this study. Several other data sets are omitted because of mineralogical complexity (varying carbonate and sulfate fraction, admixtures with quartz), no reported S-wave velocity, and/or concerns about measurement protocol and sample viability. The data considered here enable a detailed evaluation of generally monomineralic samples for carbonate (calcite and dolomite) reservoir end-members.

Rock-physics models

Numerous rock-physics models exist for a wide variety of lithologies that are relevant to subsurface petroleum exploration and production (e.g., Mavko et al., 2009). Model details and formulas may be found in Mavko et al. (2009) and the original references cited therein. The discussion that follows will use the general classification of rock-physics models described in Avseth et al. (2010). Of paramount importance in the analysis of the carbonate data sets reported here is the distinction between models that explicitly include factor(s) related to pore shape(s) and those (often frequently used) models that actually have no pore-shape (or texture) parameter(s) at all in the (often empirical) model. Furthermore, the rock-physics analysis that follows incorporates three novel features: (1) deliberate evaluation of the influence of mineralogy (calcite and dolomite) on the interpretation of measured velocity data; (2) application of a variety of (heuristic, theoretical) models to the measured data (including dry-rock modulus diagnostics [Kittridge, 2006]), often applying one or more models not used by the original authors; and (3) integration between data sets, seeking insights into mineralogically and/or textural behavior consistent across multiple (global) data sets.

Mineral-specific rock properties and rock-physics parameters are summarized in Table 2. Average calcite and dolomite mineral-based end-member grain density

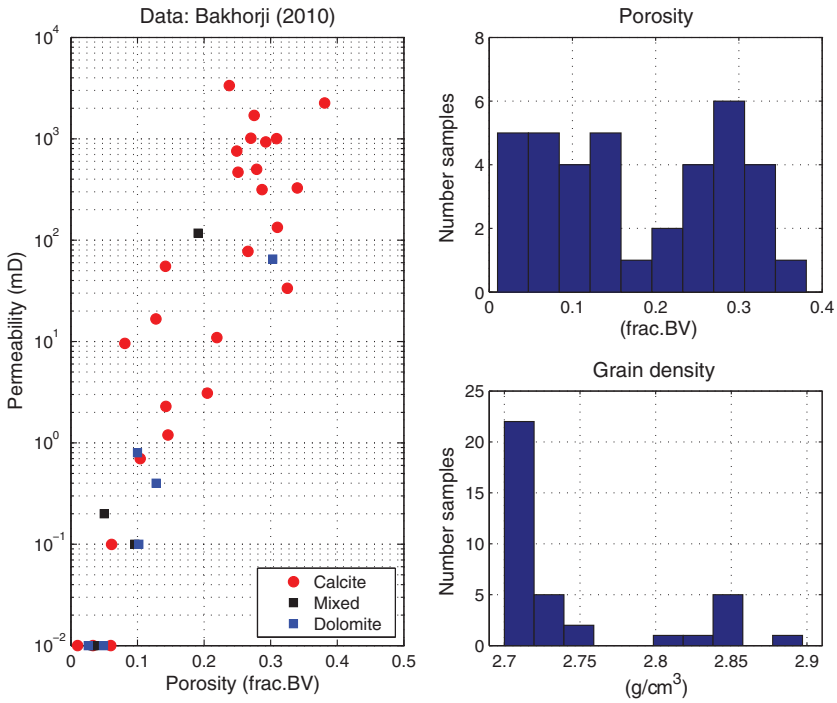

Figure 3. Basic petrophysical properties for data compiled by Bakhorji (2010).

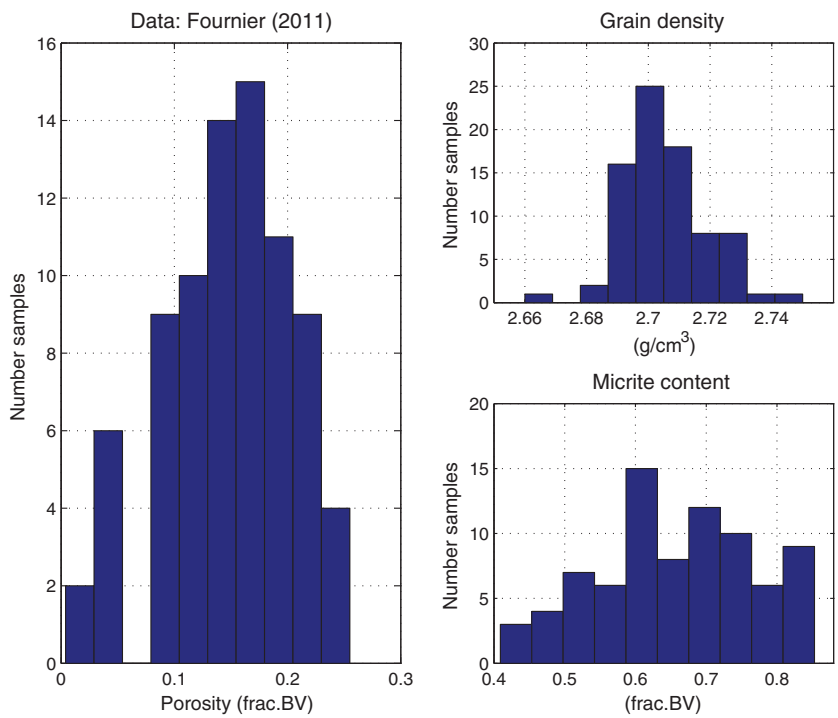

Figure 4. Basic petrophysical properties for data compiled by Fournier et al. (2011).

values from the data of Verwer et al. (2008), Bakhorji (2010), and Fournier et al. (2011) agree with values reported in Table 2. Note that other sample-based (e.g., Sayers, 2008; Verwer et al., 2008) and computational rock-physics studies (Dvorkin et al., 2012; Andra et al., 2013) use mineral values that are consistent with individual mineral (e.g., calcite) values given in Mavko et al. (2009). The rock-physics models described in the following section use the average properties (grain density, moduli, velocity) for calcite and dolomite (Table 2) determined from data reported in Mavko et al. (2009).

Table 2. Reported mineral-specific properties and rock-physics parameters.

Mineral	ρ_g	K_g	μ_g	V_P	V_S	φ_c	Source
Calcite	2.708	70.8	30.3	6.41	3.35	0.4	Mavko et al. (2009). Avg. value (five samples)
Calcite	2.71	73.3*	32	**6.41**	**3.44**		Bakhorji (2010). * value unique from Mavko et al. (2009). V_P and V_S computed.
Dolomite	2.873	80.2	48.8	7.11	4.12	0.6	Mavko et al. (2009). Avg. value (three samples)
Dolomite	2.84	94.9	45.7*	**7.41**	**4.01**		Bakhorji (2010). * value unique from Mavko et al. (2009). V_P and V_S computed.

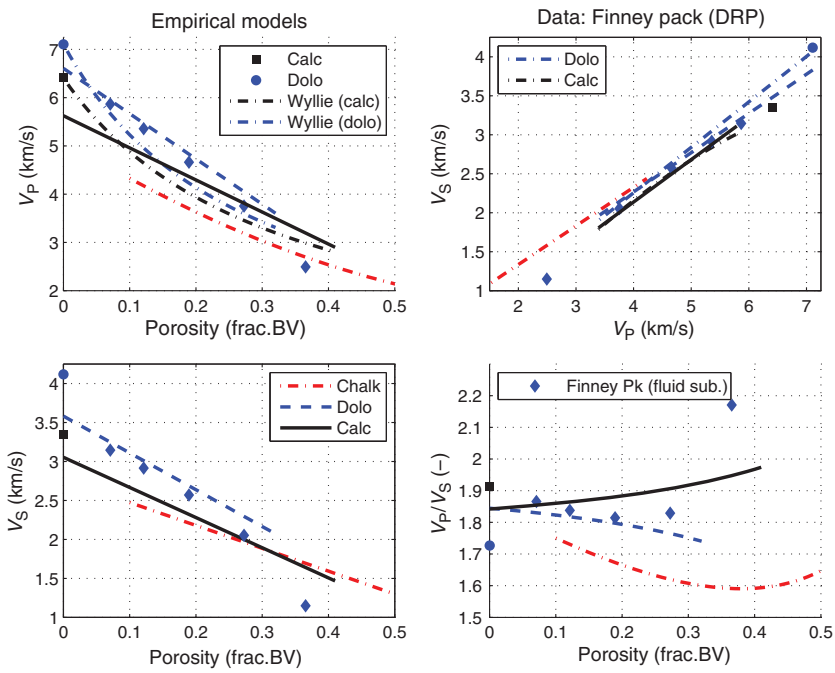

Figure 5. Empirical relationships for calcite, dolomite, and chalk as reported in Mavko et al. (2009). All models are for brine-filled conditions. Data are for calcite, using computational results reported in Dvorkin et al. (2012).

Empirical models

A variety of mineral-specific (calcite and dolomite) empirical transforms are known (Mavko et al., 2009) and commonly applied in carbonate rocks. In general, these relationships are direct (regression) fits to data, using functional forms relating velocities (V_P and V_S) to porosity and V_S to V_P (Figure 5). The models may not agree with the data, are often inconsistent with pure mineral end-point V_P and V_S (Table 2), and generally have very limited predictive capability (or possibly no predictive capability). It should be readily apparent that none of these empirical models will be able to model the effect of varying carbonate pore(s) on velocity (Brie [2001] reports an empirical model for calcite that includes a "spherical pore" fraction as a variable in the relationship).

As noted previously, several authors make use of the empirical Wyllie relationship (Table 3), in which departure from the behavior expected by the WTA model is cited as evidence for pore-shape effects on carbonate velocity. Two important observations on the Wyllie model are evident (Figure 5): (1) Calcite and dolomite show very little V_P differences at a given porosity and (2) the model calcite data ($\varphi < 0.3$) are faster (higher V_P) than WTA model predictions for calcite (and also dolomite). Mavko et al. (2009) provide a useful reminder about the inadequacies of the WTA as a credible rock-physics relationship.

Theoretical models

A variety of theoretical models relevant to carbonate rock physics are used, including bounds, inclusion models, and computational models. Bound models (e.g., Voigt, Reuss) are rigorously correct, are generally free from (geologically) idealized behavior, and find great utility in placing limits on realistic behavior, which often facilitates measurement quality control (QC). Although a variety of inclusion models are available, I restrict my use to the self-consistent approximation (SCA), in which pores and grains are considered to be (idealized) ellipsoidal inclusions in the composite (Table 3). Additionally, I utilize the model of Xu et al. (2006) (XuP) as it handles variable mineral-specific pore shapes and has been applied (Xu et al., 2009; Xu and Payne, 2009) to reservoir and lab data comparable to those data analyzed in this study. Although Avseth et al. (2010) would likely describe the Xu et al. (2006) model as an "empirical

relationship sometimes disguised as theoretical," I include it here given that it relies on an inclusion model (Kuster-Toksoz) to describe the effect of variable pore shape(s) on moduli and velocity. XuP model properties (calcite, dolomite) were calculated using commercial software. The Kuster-Toksoz inclusion model has been avoided, given the constraint on dilute (noninteracting) inclusions (see Wang, 1997). With the emergence of computational (digital rock physics) approaches to rock physics (Xu et al., 2006; Dvorkin et al., 2012), 3D image-based computed rock-physics properties (moduli, velocity) extend and improve our understanding of the elastic behavior, particularly in which lab-based methods are difficult or prone to measurement irregularities.

Bound-filling models

Of several bound-filling models, two are used in the subsequent analysis: Modified Voigt and the modified upper Hashin-Shtrikman (HSM) models (Table 3). Both of these models use the critical porosity (φ_c) concept to modify original Voigt and upper HSM bounds. The bound-filling models do not explicitly use any pore-shape parameters; rather, the critical porosity is seen to be the adjustable model parameter, perhaps with a connection to geology (perhaps the texture?).

The theoretical and bound-filling models for calcite are shown in Figure 6 using a graphically robust rock-physics template, which I will use in my subsequent analysis. The models describe bulk (Kd) and shear (Gd) modulus as a function of porosity and mineralogy. From the dry-rock moduli, fluid-filled V_P and V_S are calculated using Gassmann's relationship. Fluid replacement (Gassmann) and dry-rock moduli determination follow the procedures described in Wang (1997) and Smith et al. (2003). The free parameter in the bound models (Voigt, HSM) is critical porosity (no pore-shape information), whereas the theoretical models (XuP, SCA) use one (or more) pore shape(s) to be modeled using variable aspect ratio(s). For reference, I used the computational results on the Finney Pack, with matrix properties for calcite, as reported by Dvorkin et al. (2012). The Finney Pack is a reference (computational) media in which all pore spaces are found between uniform-sized spheres; porosity is varied in the Pack by changing the sphere size. As such, all porosity is interparticle, and this (numerical) configuration includes no anomalous pore shape(s) as may be found in natural carbonate core material. The computed properties are comparable with the "reference" interparticle pore ($\alpha = 0.15$) of, for example, Xu and Payne (2009). The models and computational results (Figure 6) enable the following observations: Computed moduli are between the bound-filling models and generally consistent with all models; pore-shape models, using similar aspect ratios, yield very similar results and are close to the (HSM) bound model; bound and theoretical model performance varies when compared to data in bulk and shear modulus space; and both models and data yield higher V_P than Wyllie model predictions at a given porosity.

Results: Analysis of carbonate rock-physics data

In this section, I analyze each of the individual core-based velocity data sets previously described. The analysis necessarily treats calcite and dolomite as distinct, given the differences in matrix moduli, and I rely on a combination of heuristic and theoretical models, some (XuP, SCA) including variable pore-shape parameters.

The theoretical and bound-filling models used in the subsequent analysis share three important advantages: (1) Dry-rock modulus behavior (bulk and shear) is predicted as a function of porosity and mineralogy, (2) the models are assured to honor mineral-based moduli and velocity at the matrix (zero porosity) point, and (3) they readily facilitate evaluation of dry and saturated laboratory-measured velocity data. None of the models are regressed to the data; the only adjustments are for mineralogy (grain moduli at zero porosity, Table 2), critical porosity (bound-filling models), and pore aspect ratio (SCA model). The models and the associated

Table 3. Summary of rock-physics models and input parameters.

Model type	Model name (figure legend)	Critical porosity, φ_c	Pore aspect ratio	Comment
Empirical	WTA	N/A	None	Matrix V_P for calcite and dolomite from Table 2 (Mavko et al., 2009).
Bound-filling	Modified Voigt (Voigt)	0.42, 0.44, 0.5	None	Matrix K_g and μ_g for calcite and dolomite from Table 2 (Mavko et al., 2009).
Bound-filling	Modified upper Hashin-Shtrikman (HSM)	0.42, 0.44, 0.5	None	Matrix K_g and μ_g for calcite and dolomite from Table 2 (Mavko et al., 2009).
Theoretical	Xu-Payne (XuP)	N/A	0.15	Constant "reference" pore aspect ratio for calcite and dolomite.
Theoretical	Self-consistent approximation (SCA)	N/A	Variable	Reference aspect ratio 0.2. Varied aspect ratio cases with single (0.1, 0.175, 0.25, 0.3, 0.45, 0.8), and dual (0.3, 0.8) aspect ratio pores.

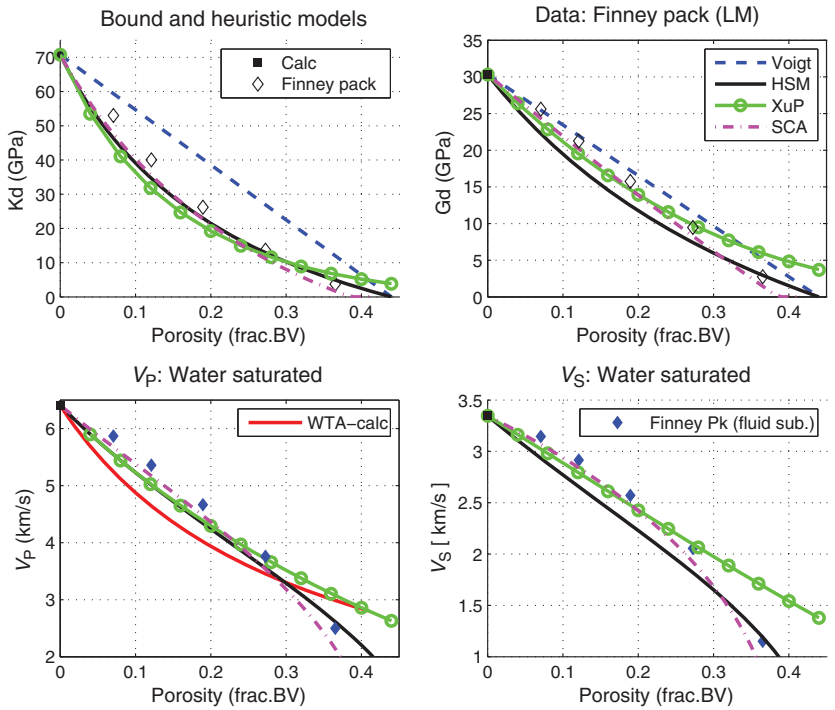

Figure 6. Theoretical and bound-filling relationships for calcite. Critical porosity (φ_c) is 0.44 and single pore aspect ratio is 0.15 (XuP) and 0.2 (SCA). Data are for calcite, using computational results reported in Dvorkin et al. (2012).

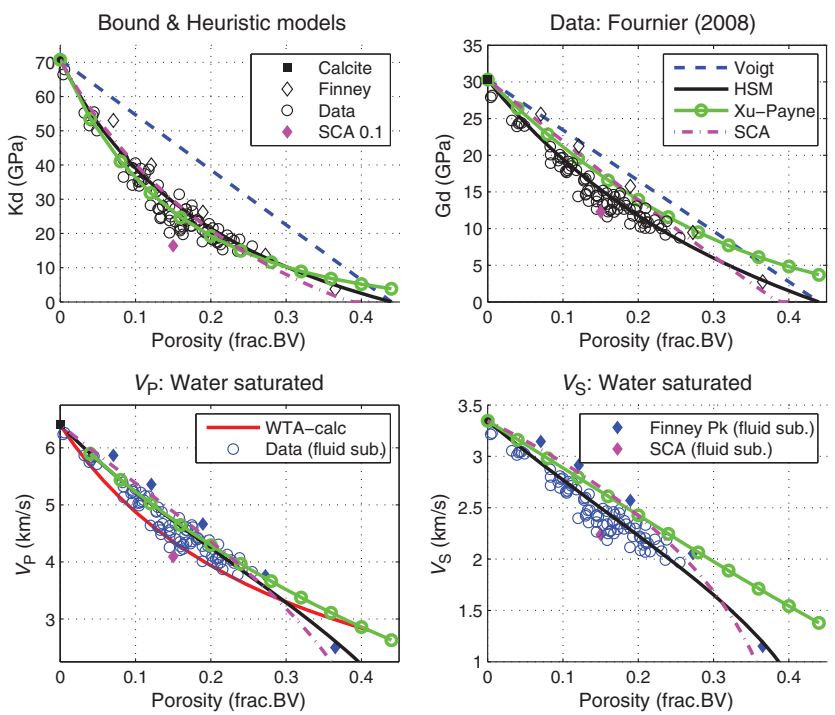

Figure 7. Theoretical and bound-filling relationships for calcite. Data are calcite samples reported in Fournier et al. (2011). SCA single pore aspect ratio $\alpha = 0.1$ ($\varphi = 0.15$) model (magenta symbol). See the caption in Figure 6 for additional details.

(graphical) rock-physics template provide a sound heuristic basis from which observations about mineralogy and pore-shape-based variability may be credibly evaluated from lab-measured velocity data.

Single mineralogy (calcite)

First, I examine the monomineralic data reported by Fournier et al. (2011). All of the samples are calcite, and the results are shown in Figure 7. The dry velocity-derived moduli are consistent with bounds, computational results on the Finney Pack, and the zero porosity matrix point for calcite. Moduli are generally well described by the HSM bound and pore-shape models (XuP, SCA), with both using a single pore aspect ratio (0.15, 0.2, respectively). In fact, all data are generally within a very narrow SCA aspect ratio range of 0.1–0.2, implying very little pore-shape variability across the data set. As such, optimal matching to the total data set would involve empirical adjustments to φ_c (HSM) and sample-specific variations in pore aspect ratio (XuP, SCA), possibly using a distribution of more than one aspect ratio. The fitting with variable pore aspect ratio(s) leads to a nonunique result. Fluid-replaced V_P data are all generally faster than the WTA model prediction, but they are compatible with results from the Finney Pack.

Mixed mineralogy (reservoir samples)

To extend the analysis for a single mineral, I next examine the Saudi Arabian oilfield data reported by Bakhorji (2010). Measured sample grain density, supported by petrographic evidence, enables a clear distinction between calcite and dolomite samples. Dry-rock moduli inferred from the (dry) measured velocities are consistent with bounds for calcite and dolomite (Figure 8). Note that the large separation in shear moduli makes the distinction between carbonate minerals more diagnostic. The computed moduli for the (assumed calcite) Finney Pack are also compatible with bounds for calcite, particularly for the narrowly separated shear moduli. The Voigt bound also suggests the potential for sample QC, particularly for the single high-porosity calcite sample ($\varphi = 0.381$ v/v). Modeling with SCA

at $\varphi = 0.375$ v/v and a significant fraction ($\varphi = 0.15$ v/v) of large aspect ratio ($\alpha = 0.8$) pore space does not adequately describe the measured data point.

Brine-saturated velocity data, measured wet and the dry data (fluid) substituted to wet, are shown for calcite and dolomite samples in Figure 9. Separation between values for a given sample might be a suggestive of Gassmann fluid replacement issues and/or original sample measurement QC. In general, the data are consistent with bound (constant φ_c) and theoretical models (single aspect ratio), particularly when mineralogy is accounted for. Velocity deviation (s) is generally small and can be seen to be faster and slower than a given model across the sample suite. In particular, dolomite samples are generally consistent with bound and theoretical models, but they are faster than Wyllie (WTA) model prediction and would be consistently faster (most notably in shear velocity) than any of the calcite models, at a given porosity.

Mixed mineralogy (outcrop samples)

I further our evaluation of the role of mineralogy and pore shape(s) now evaluating the outcrop data reported by Verwer et al. (2008). In contrast to the reservoir data reported by Bakhorji (2010), the outcrop data set is dominated by dolomite samples, and the dolomite samples extend to significantly higher porosity ($\varphi > 0.5$ v/v). Dry-rock moduli inferred from the (dry) measured velocities are compared with bounds, and XuP (Figure 10) and SCA models (Figure 11) for calcite and dolomite. Calcite sample data are consistent with bounds and computational model results; theoretical model performance is variable, with XuP (single pore) calcite performance in better agreement than dolomite, whereas the SCA model, using (single) variable aspect ratios, is in much better agreement with data, particularly for calcite (Finney Pack and outcrop data). The high-porosity ($\varphi > 0.46$ v/v) dolomite data exceed relevant bounds and are stiffer than SCA model prediction using a large ($\alpha = 0.8$) single aspect ratio pore. Properties of these samples may be unique and a result of the (outcrop) nature of the original sample.

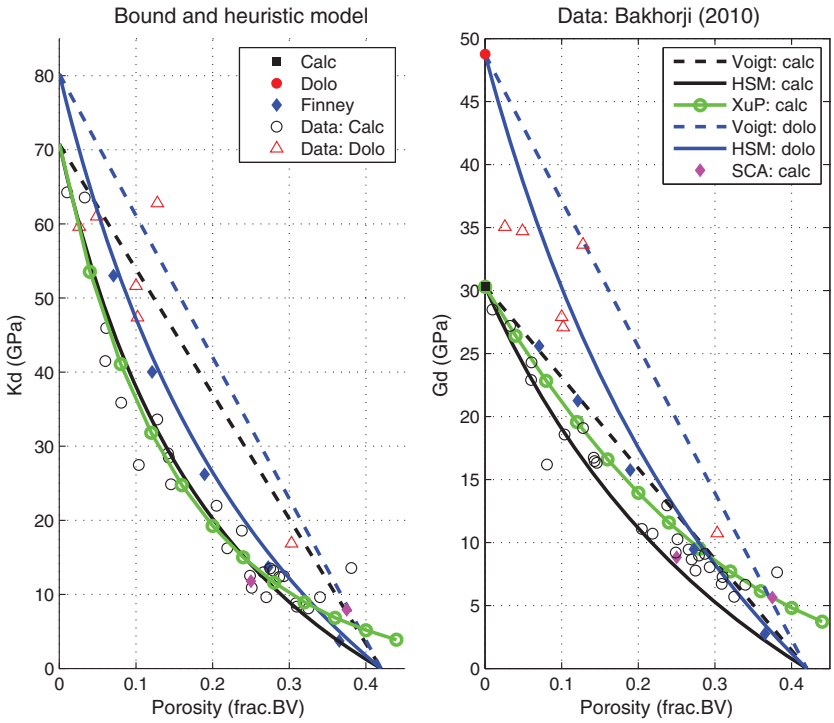

Figure 8. Dry-rock moduli inferred from (dry) measured velocities for data compiled by Bakhorji (2010). Critical porosity (φ_c) is 0.42, SCA single pore aspect ratio is 0.175 ($\varphi = 0.25$), and two pore aspect ratios $\alpha = 0.3$ ($\varphi = 0.225$) and $\alpha = 0.8$ ($\varphi = 0.15$) for the high-porosity ($\varphi = 0.375$) model (magenta symbols). See caption in Figure 6 for additional details.

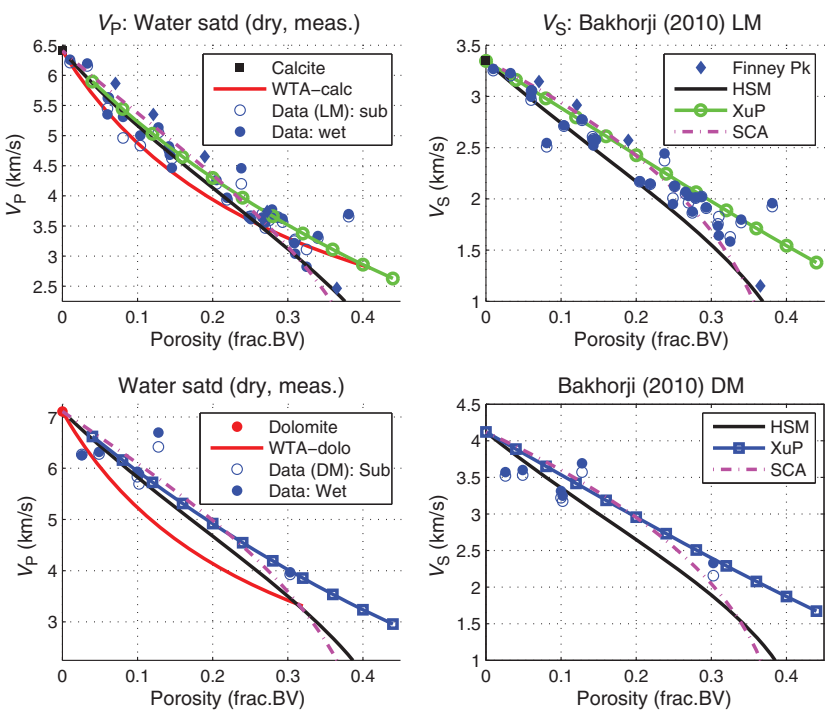

Figure 9. Theoretical relationships for calcite and dolomite. Data are calcite (top) and dolomite (bottom) samples reported in Bakhorji (2010). Critical porosity (φ_c) is 0.42; see the caption in Figure 6 for additional details.

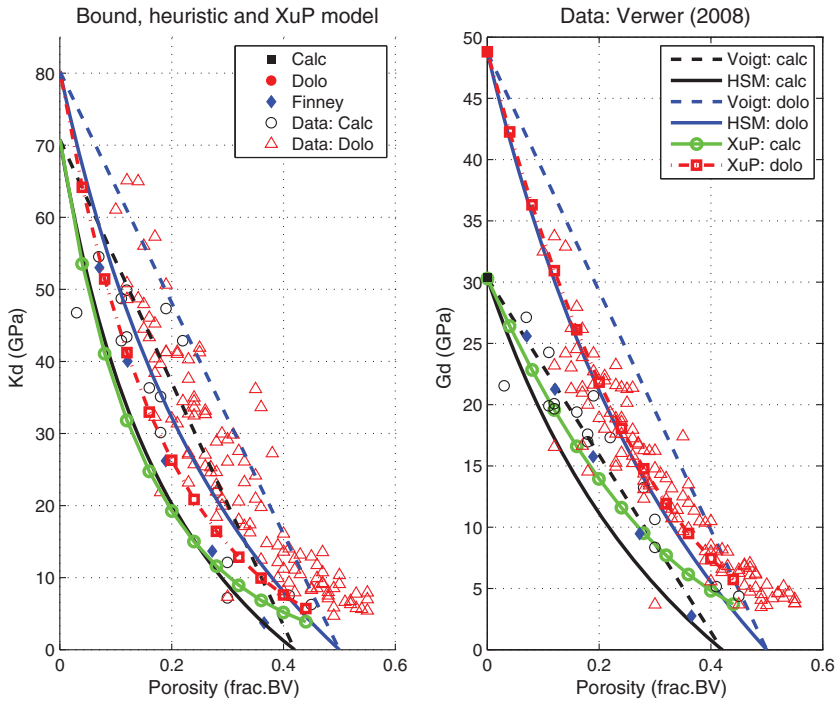

Figure 10. Dry-rock moduli inferred from (dry) measured velocities for data compiled by Verwer et al. (2008). Critical porosity (φ_c) is 0.42 for calcite and 0.5 for dolomite. XuP single reference pore aspect ratio is 0.15 for calcite and dolomite. See the caption in Figure 6 for additional details.

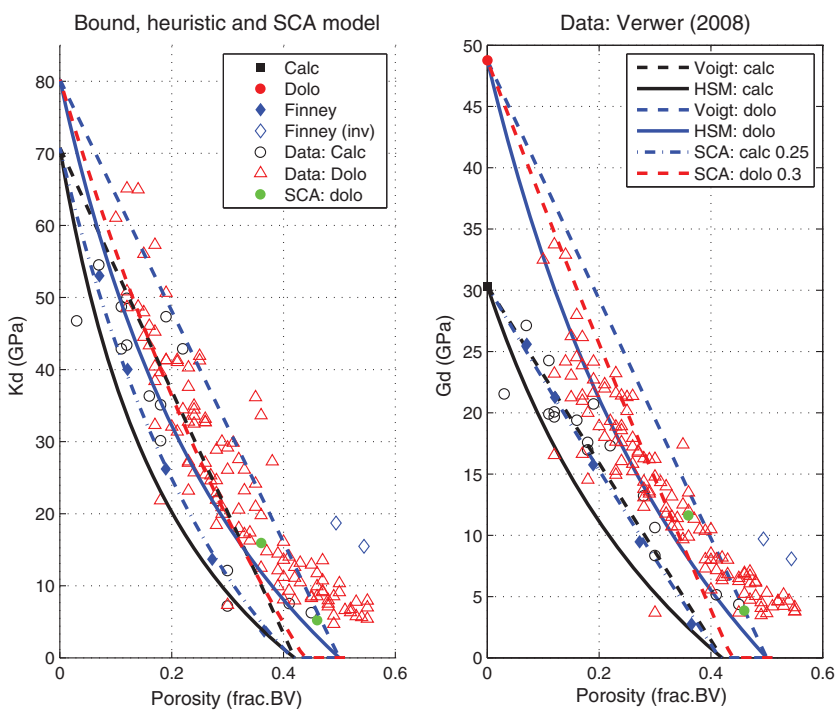

Figure 11. Dry-rock moduli inferred from (dry) measured velocities for data compiled by Verwer et al. (2008). SCA single pore aspect ratio is 0.25 for calcite and 0.3 for dolomite. SCA single pore aspect ratio $\alpha = 0.45$ ($\varphi = 0.36$) and $\alpha = 0.8$ for the high-porosity ($\varphi = 0.46$) model (green symbols). See the captions in Figures 6 and 10 for additional details.

Computational results on the inverted Finney Pack (Dvorkin et al., 2012) structure at comparable porosity (using calcite matrix moduli) are higher than the high-porosity (outcrop) dolomite samples.

Brine-saturated velocity data, both measured wet and the dry data (fluid) substituted to wet, are shown for calcite and dolomite samples in Figure 12. In general, sample velocities are faster than the WTA model for calcite and dolomite, but deviations from a theoretical (SCA) single pore model, accounting for matrix mineralogy, are much reduced (100 sm/s). Samples with notable deviation from SCA model velocity (more prevalent in dolomite samples than calcite) also frequently show the largest difference between wet- and fluid-replaced velocity, which may be indicative of Gassmann fluid replacement issues, original sample measurement QC, or pore-type variability. Velocity variability in the low ($\varphi < 0.4$ v/v) ratio is consistent with a larger (e.g., $\alpha = 0.45$) single pore aspect ratio (SCA model); in contrast, all of the high-porosity ($\varphi > 0.46$ v/v) dolomite samples are significantly faster than SCA model predictions with a single, large aspect ratio pore ($\alpha = 0.8$), as expected from dry-rock moduli (Figure 11) behavior.

Finally, note that the need to invoke a larger (single) aspect ratio pore to explain dolomite sample velocities is a function of (high) porosity and is a nonunique (and sample-specific) determination. For dolomite samples with $\varphi <$ ~0.38 v/v, a single larger aspect ratio can explain the measured data. Dolomite samples with a larger porosity are not well described by an inclusion model using a single large aspect ratio pore.

Mixed mineralogy (no shear velocity)

The preceding analyses clearly illustrate the importance of mineralogy and the utility of dry-rock modulus diagnostics in the evaluation of carbonate velocity data. Challenges arise in the analysis of data reported by Weger et al. (2009), as I have only P-wave velocity data (wet) and no direct sample-specific mineralogy information.

One of the three data sets (Marion Plateau) is specifically identified, and references therein further identify that

the data are from ODP Leg 194. Original sample data, including porosity, permeability, and mineralogy (calcite and dolomite), are available in an earlier reference (Ehrenberg et al., 2003). Using those data, in particular the reported permeability (detailed to as many as five significant digits), I can uniquely identify (38 of 52) well "L" samples as the ODP data (Figure 2). All but five of the well "L" samples are dolomite. The permeability data tabulated in Weger et al. (2009) at or below 2 mD cannot be uniquely matched with data reported in the original ODP-194 compilation (original with three significant digits). Although I can match permeability data "exactly," I also note that porosity values reported in Weger et al. (2009) vary from those given in the original ODP-194 data compilation.

The remaining data sets (referenced as wells "B" and "M," Figure 2) are from the Middle East and Southeast Asia. Middle East samples are from the Shu'aiba Formation and are Aptian in age. A general search in the open literature indicates that this formation is limestone (calcite) in, for example, the Bu Hasa field. Data from the Southeast Asia source are from an isolated platform of the Miocene age. The Malampaya field (Fournier and Borgomano, 2007) may be such an example of the Southeast Asia data set. Core-based results in Fournier and Borgomano (2007) and additional references cited therein indicate that the Malampaya reservoir is limestone (calcite). In the following analysis, all data identified as wells "B" and "M" are treated as calcite.

The measured (wet) P-wave velocity data are shown in Figure 13 (calcite) and Figure 14 (dolomite). As in previous examples, nearly all the samples are faster (significant departure in dolomite samples) than the WTA model prediction for calcite and dolomite. Data are generally well described by models using a single pore aspect ratio (XuP, SCA), with deviations to lower and higher velocities on the order of the 100 sm/s. The dolomite samples are in very good agreement with the (single pore) SCA model, with a few notable departures at higher porosity ($\varphi >$ 0.3 v/v). Samples with larger (positive) velocity deviations tend to have larger pores (DomSize), but there are samples

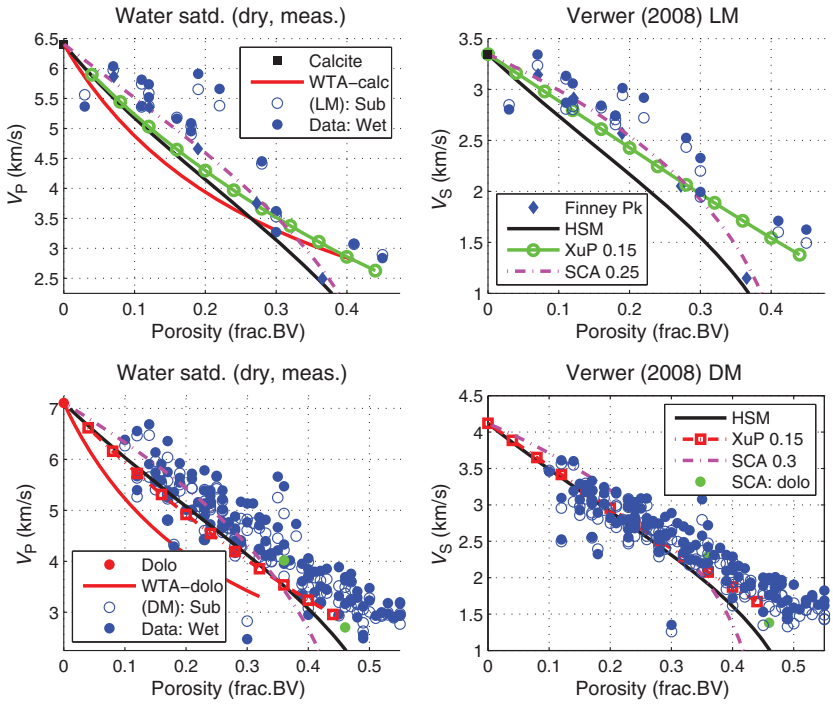

Figure 12. Theoretical relationships for calcite and dolomite. Data are calcite (top) and dolomite (bottom) samples reported in Verwer et al. (2008). See captions in Figures 6, 10, and 11 for additional details.

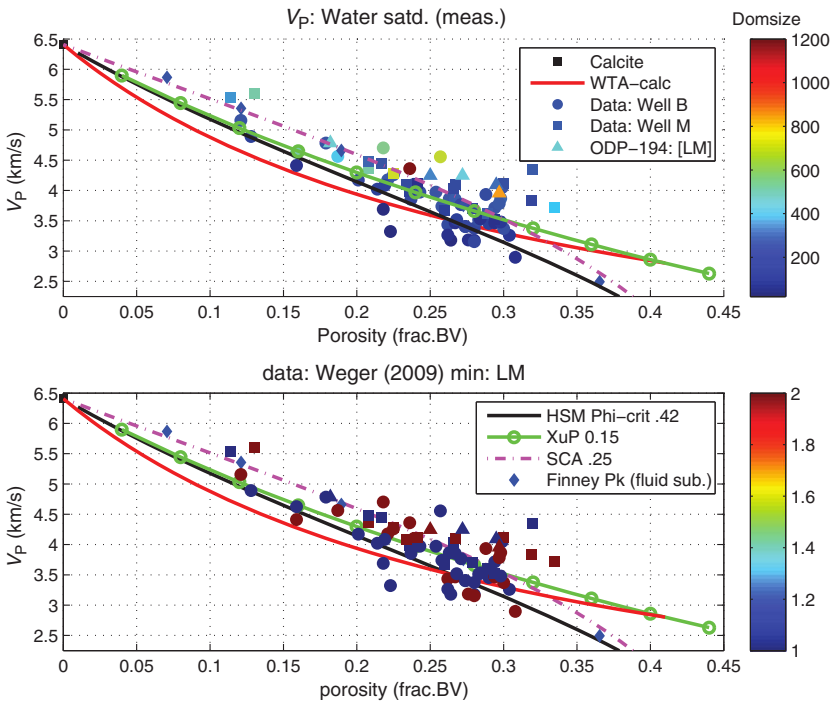

Figure 13. Measured P-wave velocities for calcite sample data compiled by Weger et al. (2009). Color scale is DomSize (image analysis) in the upper figure and dominant pore type (1 = interparticle, intercrystalline and 2 = moldic, vuggy, intraframe, and micromoldic) in the lower figure. See caption in Figure 6 for additional details.

that deviate with small pores and samples with larger pores that show minimal velocity deviation. Similarly, the nature of the dominant pore type (interparticle versus "vuggy") does not consistently explain velocity deviations nor is it a useful discriminator for samples that are in good agreement with a single aspect ratio "reference" model (XuP, SCA). Notable positive velocity deviations in several dolomite samples (Figure 14) are consistent with a dual-pore aspect ratio SCA model, in which a large fraction (>50%) of the total porosity is a large aspect ratio ($\alpha = 0.8$) pore. In this instance, the nature of the dominant pore type is not always consistent with this (nonunique) modeling choice; two high-porosity dolomite samples with positive velocity deviation are dominated by interparticle porosity. It is likely that this is an indication of the need for a quantitative description of carbonate texture (pore shape(s), rock fabric) that is consistent with the effective media model(s) that includes a term to describe pore shape(s).

Discussion on the application of seismic petrophysics workflows to carbonate reservoir rocks

Seismic petrophysics

Seismic petrophysics is an integrated workflow to integrate lab- and well-derived rock-physics data. Although the analyses described here focus exclusively on lab-based measurements, I include comments that are particularly relevant for the application in well-based studies of carbonate reservoirs. For workflow details, the interested reader will find (siliciclastic) examples in Kittridge et al. (2008) and Smith (2011). Comments that follow reference, the two-part workflow of Kittridge et al. (2008), and emphasize work elements in which challenges and aspects unique to carbonate reservoirs are likely.

Reservoir petrophysics

This segment of the seismic petrophysics workflow includes data QC; evaluation of local pressure, temperature, and (effective) stress; fluid acoustic properties determination; and quantitative reservoir petrophysics. Given the importance of carbonate mineralogy in the understanding of velocity, it is imperative that the reservoir petrophysical evaluation include a quantitative determination of mineral volumes. Water saturation determination is often problematic in carbonates, the combined result of reservoir heterogeneity (variable cementation exponent, "m"), temporal changes in formation of water salinity (waterflood), and complex saturation distribution (transition zone, residual hydrocarbon saturation). The use of NMR data in carbonates, particularly for porosity partitioning, may provide unique in situ information that would enhance the evaluation of pore type(s) and their potential impact on measured velocity.

Rock physics

This segment of the seismic petrophysics workflow includes shear log QC and estimation, fluid replacement modeling, and the development of end-member rock-physics relationships. Although the general approach to shear log QC and estimation would not be different, the choice of appropriate model(s) is critical. The results developed in the preceding section suggest a workflow that is amenable to velocity log QC and estimation in carbonates using porosity and mineralogy, forward model V_P and V_S using one or more theoretical models, and compare to measured well data. This is similar to the view advocated by Xu et al. (2009). Challenges for fluid replacement modeling in carbonates with Gassmann were discussed briefly in the Introduction. When working with well data, additional issues may include invasion effects (see the example suggested in Xu et al., 2009) and the choice of a fluid-mixing model. A complex in situ fluid distribution may require an alternative fluid-mixing model to correctly infer dry-rock moduli from hydrocarbon-saturated log

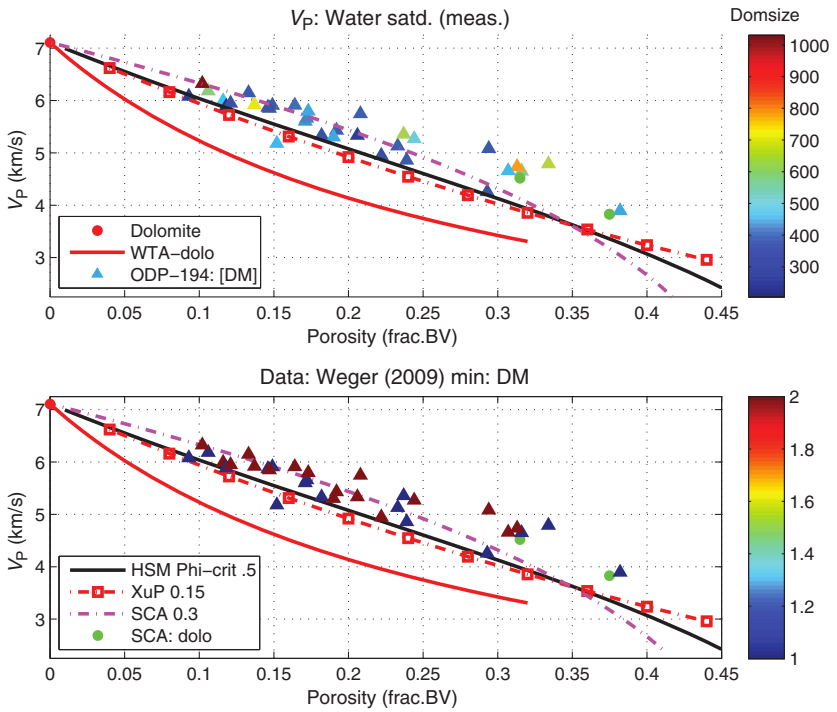

Figure 14. Measured P-wave velocities for dolomite sample data compiled by Weger et al. (2009). Color scale is DomSize (image analysis) in the upper figure and dominant pore type (1 = interparticle, intercrystalline and 2 = moldic, vuggy, intraframe, and micromoldic) in the lower figure. SCA pore aspect ratio $\alpha = 0.3$ (yy$\varphi = 0.125$) and $\alpha = 0.8$ ($\varphi = 0.19$, $\varphi = 0.25$) for the two porous ($\varphi = 0.315$, $\varphi = 0.375$) model cases (green symbols). See caption in Figure. 6 for additional details.

data. Rock-physics model development should necessarily integrate lab- and well-based data, using appropriate (heuristic, theoretical) model(s) and the rock-physics template approach employed in the preceding data analyses. Additional comments on a proposed workflow for carbonate rock-physics model development follow in a subsequent section. Finally, the integration of well-based data will necessarily require the (vertical) upscaling of well log data. The use of mineral- and pore-based classification scheme(s) would naturally facilitate the rock-physics analysis. For example, averaging by petrophysically determined reservoir rock types particularly those based on capillary pressure or other pore-type-based (NMR) methods would obviously enable and enhance elastic properties modeling as described in the previous examples.

A workflow for carbonate rock-physics model development

The data analyses and results presented for the four public-domain data sets naturally suggest a preferred workflow (Figure 15) for the development of a carbonate rock-physics model. As a minimum standard, the following analytical elements are required:

1) Using analytical (e.g., XRD) and/or descriptive (petrographical) methods, characterize sample mineralogy. Validate sample mineralogy with measured grain density, using published mineral values (Table 2).
2) Core-based measurements should include V_P and V_S, and preferably measurements of dry and saturated velocities.
3) QC sample-based velocity measurements using dry-rock modulus diagnostics (Kittridge, 2006) and relevant mineral-specific theoretical and heuristic bounds on dry-rock moduli.
4) Use a rock-physics template in the analysis of carbonate velocity behavior. Samples should be evaluated using relevant, mineral-based heuristic, and theoretical models. Moduli and velocity behavior are linked, and additional interpretive insight is realized from the analysis of corendered moduli and velocity data and models.
5) Wet and dry data should be compared, and samples with large velocity deviation should be examined further.
6) Sample(s) with anomalous behavior can be tested using theoretical model(s) and varying pore aspect ratio values in an iterative attempt to reproduce measured behavior. Digital rock-physics results are a natural addition to this evaluation.

The suggested workflow is amenable to integration of lab- and well-based data and computational (digital) results. Additional value is derived from the iterative application of the workflow, particularly with dry-rock moduli, rock-physics template(s), and the testing of variable (single, multiple) aspect ratio pores.

Limitation of empirical models

As noted previously, several authors (Anselmeti and Eberli, 1997; Verwer et al., 2008; Weger et al., 2009) have used sample-based (P-wave) velocity deviations from the WTA model as an indication of the presence of anomalous carbonate pore type(s). The WTA model has no theoretical justification and includes no information about pore shape(s). Further, several authors (Anselmeti and Eberli, 1997; Weger et al., 2009) use the WTA model to make the fatuous claim that mineralogy does not matter, as the model predicts very similar V_P for calcite and dolomite at a given porosity. Though the argument is numerically correct, the use of an inappropriate model leads to an erroneous conclusion about the role of mineralogy.

Returning to the data of Weger et al. (2009) to examine and deconstruct this misleading interpretation, results are presented in Figure 16. The upper figure reproduces what was shown by the original authors (their Figure 3). The lower figure captures the results of the mineral-based interpretation, using a credible theoretical rock-physics model (including pore-shape parameter). In their analysis, Weger et al. (2009) attribute all of the (positive) P-wave velocity deviation, when compared to WTA model, as evidence of pore-shape effects. Results after application of the preferred workflow described in the previous section are substantially different: (1) Mineralogy (calcite, dolomite) exerts a significant control on carbonate velocity and (2) for a given mineral, velocity variation at a given porosity is much reduced, with significant portions of the data set (particularly the dolomite samples) well described by a theoretical model using a single ("reference") pore shape. Note that much of the velocity departure in the calcite samples is to lower V_P at a given porosity, suggesting a lower aspect ratio than the reference ($\alpha = 0.25$) used in the SCA model.

A second example of an empirical carbonate model is the one presented by Brie (2001). Using computed

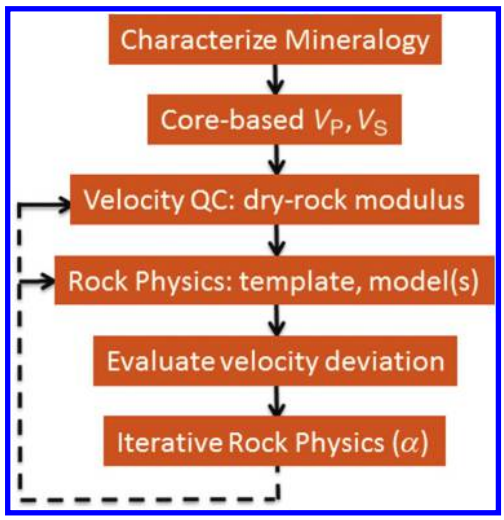

Figure 15. An iterative workflow for the evaluation and development of carbonate rock-physics model(s).

results from an effective media (Kuster-Toksoz) model, Brie (2001) fits an empirical (linear) relationship to the model (dry) V_P/V_S ratio, including a "spherical pore factor" term. As used, this term represents the fraction of the porosity that is "spherical" porosity, presumably the equant larger aspect ratio pores. In Figure 17, I compare this empirical approximation to the measured (dry) rock sample data and the theoretical results using the SCA model. In this instance, the empirical fit is in very good agreement with the theoretical model and computed results (to $\varphi \sim 0.31$v/v). Measured sample data (none were available to the original author) are also in reasonable agreement with the empirical fit. One potential use of such an empirical model would be as a constraint or external input to the Gassmann-fluid-replacement modeling, particularly for the case of log-based fluid substitution in the absence of a measured shear log.

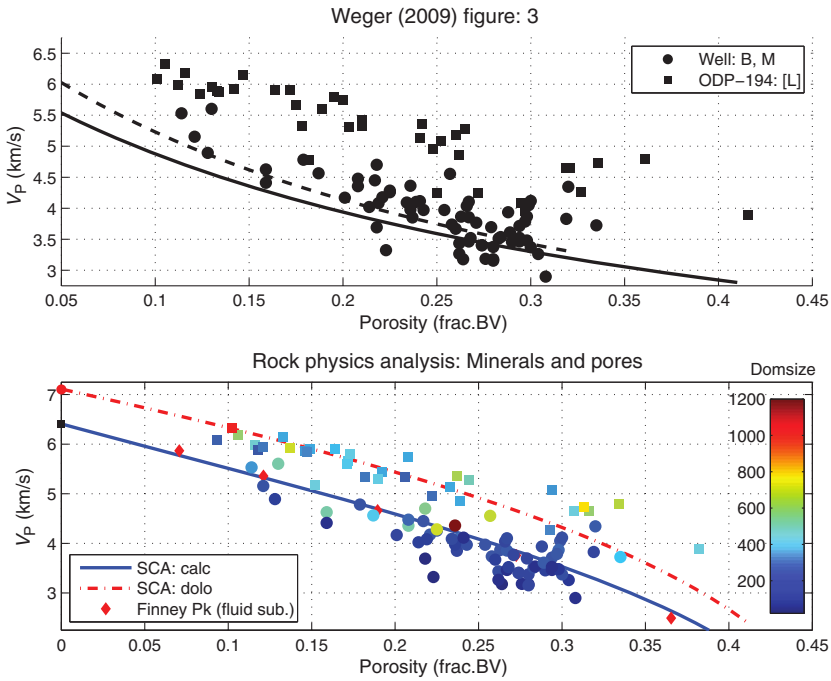

Figure 16. Carbonate P-wave velocity versus porosity. Data are from Weger et al. (2009). Upper figure shows a completely empirical approach, with no distinction made for sample mineralogy. Lower figure shows samples by mineralogy (circles: calcite and squares: dolomite) and with pore information (color scale is DomSize from image analysis). See the captions in Figures 13 and 14 for additional details.

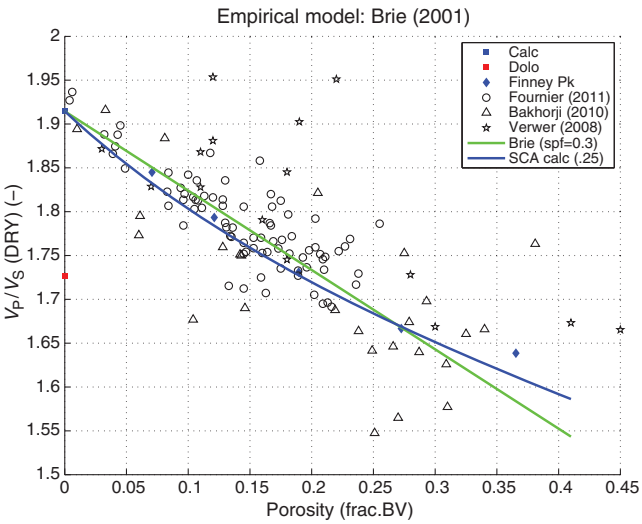

Figure 17. V_P/V_S ratio versus porosity, dry calcite sample data. The empirical model of Brie (2001) with a spherical pore factor of 0.3 is shown (green) and compared with the theoretical results from the SCA model ($\alpha = 0.25$).

Linking pore-shape effects on electric and elastic properties

Petrophysicists working in carbonate reservoir formation evaluation have long understood the challenges for resistivity log interpretation. Variable carbonate pore types particularly vuggy and moldic (large aspect ratio) pores are known to result in higher formation resistivity factor (FRF) and implied (Archie) m exponents. Herrick and Kennedy (1995) describe a model and present data from a MidEast oomoldic carbonate reservoir. Ragland (2002) presents a comprehensive globally distributed data set and statistical analysis, suggesting an average m exponent of 1.93 and 2.46 for intercrystalline and moldic-dominated samples, respectively. More recently, computational methods have been used to determine FRF for carbonate samples. Knackstedt et al. (2007) present directional (x, y, and z) results for four sucrosic dolomite samples. Andra et al. (2013) give computational results for Grosmont carbonate, using a variety of numerical solution algorithms. Digital rock physics provides a unique and complementary data source for the joint evaluation of electrical and elastic properties in carbonate samples (e.g., Knackstedt et al., 2008).

As an example of the combined evaluation of electrical and elastic properties, I utilized the data of Verwer et al. (2011). Data and interpretive results are shown in Figure 18. Using specific data from digital image analyses (DomSize and PoA) and reported permeability, I was able to uniquely identify 19 samples in Verwer et al. (2011) that have velocity (V_P only) results given in Weger et al. (2009). The well L samples are all known to be dolomite, whereas the well B samples are all assumed to be calcite (see the Discussion in the preceding section).

Well B samples show variability in FRF with implied m between average intercrystalline ($m = 1.93$) and average moldic ($m = 2.46$) bounds. All of the samples

are small DomSize, with a large range in PoA. Velocity data are very consistent with XuP and SCA calcite models for a single reference pore type, suggesting little elastic impact from anomalous (large aspect ratio) pores. In fact, velocity data for these samples are more consistent with a smaller pore aspect ratio (lower velocity than the model), which is in agreement with image analysis results. The range in FRF and implied variability in m seem greater than indications that may be inferred from elastic behavior alone.

Well L samples show significant variability in FRF with nearly all samples that are at or higher than the average moldic reference trend. In fact, at least three samples have reported FRF values that seem substantially out of range, based on the analog core measurements and DRP results, suggesting a measurement QC issue. It is important to note that the porosity value reported in Verwer et al. (2011) for well L data differs from the value given in Weger et al. (2009) and in the original ODP-194 data table (Ehrenberg et al., 2003). Choice of porosity value does not change the observation about anomalous (high) FRF values. All of the samples are large DomSize, with a small (limited) range in PoA. Velocity data are very consistent with the SCA dolomite model for a single reference pore type, suggesting little elastic impact from anomalous (large aspect ratio) pores. As such, this makes the disconnect between electrical and elastic behaviors more pronounced for the (well L) dolomite samples than for the (well B) calcite samples. Even though there is nothing that would require the electrical and elastic properties to behave similarly, it is instructive to note the variations demonstrated in this relatively small, but well characterized, sample set. Further work, particularly with computational rock physics and perhaps alternate methods to characterize pore space morphology, seems necessary to provide a causal explanation for this particular data set.

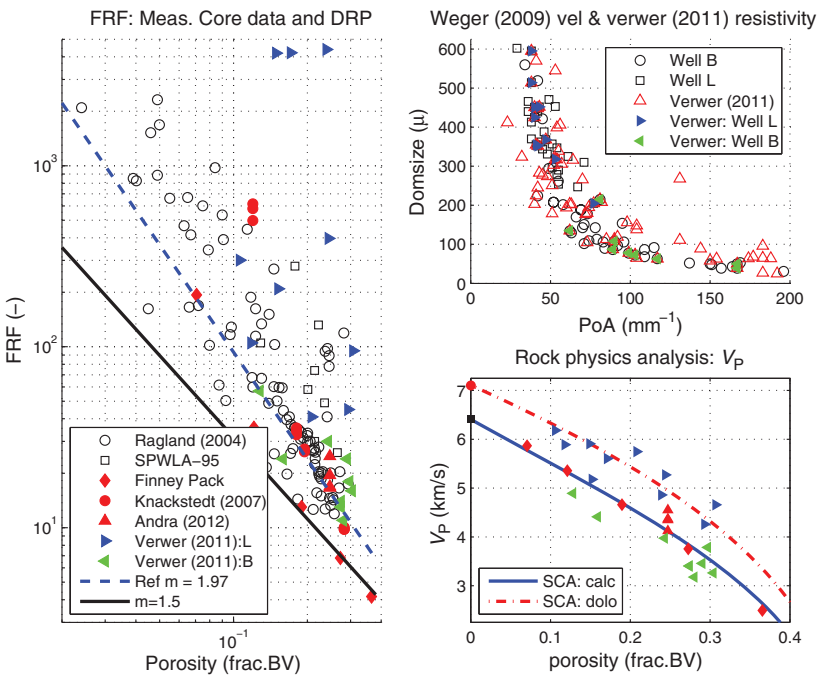

Figure 18. Joint evaluation of carbonate resistivity and elastic properties data. FRF data include measured data and digital rock-physics results. Velocity samples are those uniquely identified as also having FRF measurements (Verwer et al., 2011). See text for additional comments.

Conclusions

Using a variety of recent public-domain data sets comprised of porosity, velocity (P- and S-waves) and, in most cases, mineralogy and petrographic data, I create an extensive global data set and evaluate the importance of mineralogy and texture (pore type) on the elastic properties behavior. Results from this investigation clearly illuminate the potential for overinterpreting elastic properties behavior as a function of pore type (s) when mineralogy is not explicitly included in the analysis. Inferences of this type are exacerbated by the application of an inappropriate (WTA) model that has neither theoretical justification nor the ability to model variable pore type(s). With a diverse set of lab-based rock-physics data and a combination of heuristic and theoretical rock-physics recipes, I developed the following results:

1) Mineralogy (calcite and dolomite) exerts a significant, first-order control on elastic properties. Failure to account for the differences in mineralogy could lead to erroneously attributing velocity variation, at a given porosity, to pore shape(s).
2) For a known monomineralic sample, several theoretical models (XuP, SCA) describe the measured velocity data using (total) porosity and a single ("reference") pore aspect ratio. The heuristic models used here (Voigt, HSM) do not include an explicit pore–shape variable. These models may often describe the measured velocity data with comparable accuracy as the commonly applied theoretical (effective) media models that use a variable pore-shape factor.
3) The effective media model(s) commonly used in carbonates is nonunique and is frequently applied using pore-shape parameters (aspect ratio) as "fitting parameters." With such a technique, some data are shown to be consistent with a dual-pore system, in which large aspect ratio pores form a large portion of the (total) porosity. Even though the physics underlying the model(s) certainly has appeal, inappropriate application may create a false sense of geologic security in the (inferred) aspect ratio data.

I also examine the role of seismic petrophysics in integrated studies of lab- and well-based carbonate rock-physics data. I describe a minimum standard (iterative) workflow for those modeling elastic properties data from carbonate reservoirs. Although the specific interpretation of the four data sets described here seems conclusive, I advocate continued studies that bring together quantitative petrology, sound analytical data, and complementary digital rock-physics results that seek a causal explanation for rock the physics behavior in these important reservoir rocks.

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