Factors controlling elastic properties in carbonate sediments and rocks
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Summary

We present an overview of petrophysical characteristics of carbonates, focused on sonic velocity and permeability. We will outline the controls of permeability and velocity in carbonates that help optimize the interpretation of seismic and log data from carbonate fields. The results are based on experimental studies of the Miami University Petrophysics Group from modern and ancient carbonate rocks.

Introduction

A seismic section is the image of the physical response of an acoustic signal to the rock, and as such not a straightforward matter of imaging depositional architecture or facies belts. The distribution of acoustic impedance and geometries define the physical characteristics of a rock section, which are converted into a seismic image by reflection seismic surveys. The acoustic impedance is the product of density times velocity. In carbonates and mixed systems, velocity is more dominant in determining the acoustic impedance. Both of these parameters are controlled by the original sediment deposition and the subsequent diagenetic alteration. Consequently, an understanding about both the depositional environment and the diagenetic alterations are needed when interpreting seismic sections. A thorough understanding of the controls on acoustic properties and impedance in carbonates is essential for refining our interpretation of existing log and seismic data. This is particular paramount when seismic attributes are used to delineate reservoir trends.

Effect of environment, compaction and mud content on velocity and porosity in carbonate sediments

Unconsolidated sediments from modern carbonate depositional environments of Florida and the Great Bahama Bank demonstrate a remarkable homogeneity in petrophysical properties (Incze, 1998). Some properties may uniquely characterize an environment and vary considerably between environmental boundaries. Mean grain size and sorting, for example, most often have standard deviations of <10% within a depositional environment, but differences across depositional boundaries up to 600%. Despite of these large differences, the acoustic velocity and acoustic velocity response to confining pressure are remarkably similar across all sampled environments (standard deviation of <6%). The homogeneity of petrophysical properties of unconsolidated sediments within a depositional environment stands in sharp contrast to the high variability found in their lithified counterparts.

Acoustic velocity (Vp and Vs) values for many unconsolidated carbonate sediments demonstrate 3-fold increase with elevated confining pressures to 80 MPa. This pressure response occurs despite pervasive grain destruction in coarse skeletal and ooid sands. Fine-grained, poorly sorted lagoonal sediments have a similar acoustic velocity response. Acoustic velocities remain high as confining pressures are reduced to 5 MPa, which suggests that grain contacts established during compaction is maintained during decompaction.

The introduction of fine-grained mud matrix into coarse carbonate sands affects porosity and acoustic velocity. Tests on a variety of grain and matrix mixtures demonstrated that maximum porosity and maximum acoustic velocity are attained with relatively small additions of fine-grained material. The response to matrix content varies with grain size and shape. Mixtures of 350 µm ooid grains achieve minimum porosity with the addition of just 10% matrix, while angular coralgal grains of 500 µm require nearly 30% matrix to provide the same response. Continued addition of matrix results in an increase in total porosity because the uncompacted matrix material has up to 70% porosity. Interestingly, acoustic velocities do not significantly decrease until 40 to 60% matrix has been added.

Role of insolubles on velocity

In addition to the investigations of unconsolidated carbonate sediments, several hundred discrete samples from cores along the Bahamas transect were analyzed to determine the role of insolubles in the velocity structure along the prograding margin and the control of sea level changes on acoustic properties. Platform-internal areas have in general higher velocities and a wider range than samples from the platform slope areas. This trend is recognized not only by higher velocities in proximal sites, but also by higher velocities at equal porosities due to the presence of constructive diagenesis. There is a strong correlation between insolubles (mainly clay content) and velocity. Fast velocities (> 4000 m/s) are only reached if clay content is below ~5%.
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Marl/limestone alternations display the effects of clay in the velocity of carbonates. Clay content in the marly intervals tend to seal the sediment from fluid flow. Consequently clay-rich layers have preserved their initial high porosity and lack major cementation. In contrast, carbonate-rich layers are usually well cemented and have a stronger diagenetic overprint. This variable post-depositional history results in a distinct cyclic pattern of acoustic properties across these lithologic cycles.

Effect of composition, diagenesis and pore type on petrophysical properties of carbonate rocks

The effect of composition and diagenesis has been studied on the drill sites along the Bahama transect (ODP Leg 166 and BDP). The major direct controls on velocity are total porosity and the various pore types, both are mainly determined by the original composition and the subsequent suite of diagenetic events (Anselmetti and Eberli, 1993). The original composition of the sediment influences velocity in several ways. First, the grain size controls the permeability of the sediment. High permeability allows for high fluid flow and thus for rapid dissolution of metastable grains but also fast cementation of the pore space. In regards to the velocity, cementation has the stronger influence than dissolution as it increases velocity more than moldic porosity decreases it. Secondly, the original mineralogy at the time of deposition determines the amount of meta-stable aragonitic grains. These grains are likely to be dissolved during diagenesis which, similar to high permeability, accelerates diagenetic alteration.

In the investigated samples the diagenetic processes occurred in sediments that were buried between 30 and 662 m. The first process that alters velocity and porosity is early compaction of the sediment, by which we mean the process of initial consolidation, dewatering and pore space reduction but no cracking or breaking of the components. Initial values of approximately 60% porosity and 1600 m/s of Vp decrease during this first consolidation stage to values close to 40-50% and 2000 m/s.

In concert with compaction, different diagenetic processes determine the future evolution of velocity and porosity. Several stages of dissolution and cementation can be distinguished during the diagenetic history of the investigated samples. All these stages lead to different pore-types that all have their characteristic patterns in the velocity-porosity diagram (Anselmetti and Eberli, 1999). The velocity effect of this evolution, in particular the effect of the transformation of pore types, can be described by a velocity-porosity path. The timing of all these processes determines the velocity evolution of the carbonate sediments. For example carbonates with a dominant moldic porosity display a high velocity despite their high porosity. In contrast, quartzarenic dolomite with similar high porosity have a low velocity. This difference can be up to 2000 m/sec.

Early diagenetic alterations explain why shallow-water carbonates can reach high velocities already after little burial time. This dominance of early cementation over compaction is the reason why the velocities in carbonates show no clear correlation with increasing depth. Before the burial pressure compacts the rock fabric, most of the samples are cemented. Consequently, part of the porosity can survive the increasing overburden. Examination of modern beach rock samples show that cementation by intergranular and pore-filling cements is often associated with development of a rigid fabric and increased acoustic velocity. However, the type of cement is more important in early diagenesis than the total amount of cement. Acicular rim cements commonly formed in shallow marine environments do not contribute to rigidity of coarse grained-material as effectively as micritized intergranular cements. Consequently, samples with different cement types may have similar amounts of total cement, but dramatically different acoustic velocity values.

Despite the almost nonmimeric composition of the carbonates of the two BDP cores, the Vp ranges from 1700 to 6600 m/s and Vs ranges from 600 to 3500 m/sec. This range is mainly caused by variations in the amount of porosity and pore type. In general, velocities show a positive correlation with density and an inverse correlation with porosity, but departures from the general trends of correlation can be as high as 1500 m/s. The observed scattering in the velocity-porosity diagram cannot be related to compositional variations. The scattering in the velocity is an effect of carbonate specific pore types. If a dominant pore type is assigned to each sample, it can be seen that all these characteristic pore-types form clusters in the velocity-porosity diagram (Anselmetti and Eberli, 1999). The elastic properties of these different pore types explains why rocks with the same porosity can have completely different velocities. For example rocks with a dominant moldic porosity have velocities which are over 2500 m/s faster than same porous rocks with mainly interparticle porosity. Rocks with moldic and a intraframe porosity have a positive departure from the general trend, whereas rocks with interparticle, intercrystalline, or microporosity have relatively low velocities and show negative deviations (Fig. 1). The large scattering of velocities at the same porosities causes a problem for seismic inversion that attempts to produce porosity cubes from sonic velocity.

Quantifying pore types with image analysis

Assessing and quantifying pore types are difficult from rock properties measurements. Digital image analysis can quantify pore types and relate them to permeability and velocity.
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Previous observations of thin sections show that a pore structures of round pores are more likely present in low permeable samples, than a more complicated structure, dominated by branching pores. The methodology of two dimensional digital image analysis relies solely on image analysis and no knowledge of age, burial depth or diagenesis of the sample is required. Image analysis is done by using the environmental scanning electron microscope (ESEM) images in combination with the optical microscope (OM) images, from of epoxy-impregnated, polished samples and thin sections. This wide spectrum of magnifications allows to capture both the macropores and micropores. On the ESEM images, the calcite phase appears light as opposed to the pore space, which appears dark. A median filter was applied to reduce high frequency noise, before applying a threshold to the gray image. On the OM images, the separation between pore space (blue) and the framework was achieved by setting up a threshold a blue filtered gray-scale image.

In this image analysis methodology the two dimensional pore shape is assumed to give an indication of the connectivity of the pores. But it is recognized that the connectivity can only be measured directly from a three dimensional volume. The two dimensional perimeter/area value is thought to be related to the connectivity in carbonate rocks. This value is defined as:

$$\gamma = \frac{P}{2\sqrt{\pi A}}$$

where

\(P\) = Perimeter [mm], \(A\) = Area [mm\(^2\)] and \(\gamma\) = pore type factor [-].

By using the square root of the area, the pore type \(\gamma\) becomes a dimensionless parameter, thereby allowing us to normalize it. For a perfectly round shape, the \(\gamma\)-value is one and any derivation from this form will result in an increase of the \(\gamma\)-value.

No smaller values are possible, although in practice they occur due to the discrete nature of the digitized image. The average value of \(\gamma\) of one sample is calculated by weighing the individual \(\gamma\) by the pore size:

$$\gamma = \frac{\sum (A_i \gamma_i)}{\sum A_i}$$

This procedure avoids a high number of insignificant, small pores with specific geometries dominating a few larger pores with a different geometry, which, due to their size, are much more important for the properties of the whole rock.

Three data sets have been selected to compare the pore type factor \(\gamma\) with petrophysical data. One data set of samples contains extreme textures, which represent the end members of the pore type \(\gamma\). Another data set are Cretaceous samples of the CSL database and the third and most extensive data set is from ODP Leg 194. These data show a weak relationship between permeability and porosity. Samples of the same porosity exhibit a variation in permeability up to 6 orders of magnitude.

The pore type factor \(\gamma\) of samples with two different pore textures is shown in optical and binarized images. Without any change in total porosity, the effective porosity decreases from a bioclastic grainstone with well connected interparticle porosity to a bioclastic grainstone characterized by interparticle porosity that is reduced by cementation. A moldic grainstone where most of its porosity is accounted for in round moldic pores will exhibit a lesser effective porosity. The \(\gamma\)-value reveals a positive correlation with permeability in this sequence.

A positive correlation of permeability and macro pore shape \(\gamma\)-value has been established on selected samples of specific pore texture (Anselmetti and Eberli, 1998). In their study Anselmetti and Eberli used pore type end members from smooth spherical pores to rough jagged and branching pores. In another study randomly chosen samples from the ODP Leg 194 and various Cretaceous samples re-confirmed previous results.

**Conclusion**

Carbonate sediments display a good correlation between porosity and depositional environment, while this trend is not present for velocity. In carbonaceous grain-mud mixtures a critical porosity is found at 40 % for ooid sands and at 50 % for coralgal sands.

Carbonate rocks, unlike siliciclastic sediments, show no direct correlation between acoustic properties and age or burial depth of the sediment. Sonic velocity in carbonates is rather controlled by the combined effect of depositional lithology and several post-depositional processes, such as cementation, dissolution or recrystallization. This diagenesis creates carbonate specific rock-fabrics and porosity which have a major control on velocity.

Total porosity alone, however, does not sufficiently determine velocity. In addition, the geometrical distribution of pores and solid phase is important for the velocity. Porosity occurring in a rigid rock framework results in higher velocities than interparticle porosity. Compaction increases velocity when the sediment does not undergo intense diagenetic alteration after deposition. The susceptibility of carbonates to diagenetic changes, which occur much more quickly than compaction, causes a special velocity distribution in carbonates, complicating downhole velocity estimations. As a result velocity inversions with increasing depth are common.
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Quantification of pore type is possible with digital image analysis. A pore type factor $\gamma$ shows a good correlation to permeability in carbonates.

References


Figure 1: Velocity versus porosity crossplots with categories of different pore types. The large scattering of velocities at the same porosities is a result of different predominant pore types. Rocks with moldic (red dots) and intraframe (green squares) porosity have a positive deviation from the general trend, whereas rocks with interparticle (unfilled dots) and microporosity (blue rhombs) have relatively low velocities and show a negative deviation.