The Velocity-Deviation Log: A Tool to Predict Pore Type and Permeability Trends in Carbonate Drill Holes from Sonic and Porosity or Density Logs[1]

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ABSTRACT

The velocity-deviation log, which is calculated by combining the sonic log with the neutron-porosity or density log, provides a tool to obtain downhole information on the predominant pore type in carbonates. The log can be used to trace the downhole distribution of diagenetic processes and to estimate trends in permeability.

Laboratory measurements on over 300 discrete carbonate samples reveal that sonic velocity is a function not only of total porosity, but also of the predominant pore type. In general, there is an inverse porosity-velocity correlation, but significant deviations occur from this relationship for certain pore types. Frame-forming pore types, such as moldic or intrafossil porosity, result in significantly higher velocity values at equal total porosities than do pore types that are not embedded in a rigid rock frame, such as interparticle porosity or microporosity.

The results of the laboratory measurements can be applied to expand interpretations of standard wireline-log data, as shown in this study on two drill holes through Neogene carbonates from the Great Bahama Bank. The velocity-deviation log is calculated by first converting porosity-log data to a synthetic velocity log using a time-average equation. The difference between the real sonic log and the synthetic sonic log can then be plotted as a velocity-deviation log. Because deviations are the result of the variability of velocity at a certain porosity, the deviation log reflects the different rock-physical signatures of the different pore types. Positive velocity deviations mark zones where velocity is higher than expected from the porosity values, such as zones where frame-forming pore types dominate. Zero deviations show intervals where the rock lacks a rigid frame, such as in carbonates with high interparticle porosity or microporosity. Negative deviations mark zones in which sonic log velocities are unusually low, caused, for instance, by a cavernous bore-hole wall, fracturing, or possibly by a high content of free gas. By tracing the velocity deviations continuously downhole, one can identify diagenetic zones that are characterized by these different pore types. In addition, this method can be used to observe permeability trends because pore types influence the permeability of the rock.

INTRODUCTION

Carbonate sediments and rocks are characterized by a wide variety of physical properties that are controlled by the variable depositional and diagenetic fabrics (Rafavich et al., 1984; Wang et al., 1991; Anselmetti and Eberli, 1993, 1996; Lucia, 1995). This variability makes predicting physical properties from known lithology, age, or burial depth more difficult than in siliciclastic sediments where physical properties, such as velocity and porosity, follow a more regular downhole pattern (Hamilton, 1980). Once the values and distribution of physical properties are known, however, predicting carbonate lithology is simplified due to the wide range and sensitivity of the measured parameters toward lithologic changes. Wireline logs provide the most powerful tool to predict downhole

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lithology from physical properties in drill holes that were not continuously cored. This study shows how the knowledge of the porosity-velocity correlation in carbonates can be used to improve wireline-log interpretation by predicting other parameters, such as pore type, diagenesis, and permeability trends, in addition to parameters measured by the wireline tools.

Sonic and neutron-porosity logs are common measurements in carbonate drill holes. Converting the sonic log to porosity by applying the Wyllie time-average equation (Wyllie et al., 1956) is a widely used method to produce a sonic porosity (Schlumberger, 1972, 1974; Asquith, 1985). This sonic porosity commonly is acquired because the sonic tool is less expensive and faster, and requires fewer safety precautions than the direct nuclear porosity and density tools (Paillet and Cheng, 1991). In holes where both tools were run, a comparison of the two porosity values yields differences that commonly are termed secondary porosity and quantified with the secondary porosity index (SPI™) (Schlumberger, 1972, 1974). This SPI is attributed to the presence of vugs and fractures (Schlumberger, 1972, 1974; Fertl, 1979; Asquith, 1985; Lucia, 1987; Doveton, 1994) that are not detected by the sonic signal, but are detected by the neutron-porosity log. In other cases, these differences are explained by an overprediction of the velocities from the time-average equation at porosities larger than 40% (Paillet and Cheng, 1991) or by additional parameters, such as poor compaction, free gas, and noncarbonate minerals (Hearst and Nelson, 1985). All of these interpretations were based on the assumptions that the time-average equation represents a valid model for porosity-velocity prediction, and only vugs and fractures are responsible for these deviations. Other studies indicated that the secondary porosity from the SPI is influenced mainly by pore system geometry, such as the content of spherical pores, and not necessarily by geologically secondary porosity (Nurmi and Frisinger, 1983; Brie et al., 1985). Anselmetti and Eberli (1993, 1996) and Kenter and Ivanov (1995) showed in detail that these deviations can be attributed to various pore types. Porosity and velocity values from 1-in.- (2.54-cm-) diameter minicores, in which no fractures or larger vugs are present, document that large deviations originate from carbonate-specific pore types that may have a vug-like morphology, but are neither vugs nor a product of secondary alterations (Anselmetti and Eberli, 1993). Consequently, the Wyllie equation, or any other correlation curve, cannot sufficiently describe the complex porosity-velocity relation in carbonates. Although there is a general inverse correlation of porosity and velocity, as described by the time-average equation, great scattering occurs in carbonates, reflecting the carbonate-specific fabrics that are formed by organic frameworks and by the large suite of diagenetic processes (Anselmetti and Eberli, 1993, 1996). At first, this scattering might appear as a disadvantage for lithology predictions from physical properties. Our extensive laboratory study on over 300 samples revealed, however, that this scattering is controlled by the large variety of pore types that have specific effects on the elastic moduli of the rocks. As a consequence, this complicated porosity-velocity relation in carbonates can be used to our advantage because it allows us to exploit a porosity-velocity log data set in carbonates to predict the trend of pore types and their associated diagenetic processes.

Similar to Schlumberger's SPI, we quantify the deviations in the velocity-porosity relationship between the time average and the true acoustic behavior; however, we decided to look at these anomalies more from an acoustic perspective and quantify the velocity deviations rather than the porosity deviations. The main advantage to this approach is that a velocity quantification allows a direct correlation to seismic data because the distribution of sonic velocity controls the seismic reflection pattern. This approach thus has the potential to link seismic interpretations to petrophysical analyses, such as in studies on origin of reflectivity or seismic modeling, using seismic data in a lithology-predictive fashion. In addition, because porosity is one of the controlling factors of velocity and not vice versa, it is more appropriate to quantify a velocity deviation rather than a porosity anomaly.

VELOCITY-POROSITY RELATIONSHIP IN CARBONATES

Methods

The main goal of our laboratory study was to establish the controlling factors on acoustic properties in carbonates and to relate them to depositional and diagenetic facies (Anselmetti and Eberli, 1993, 1996). Over 300 samples from two different areas were analyzed. (1) Two continuously cored deep drill holes on the Great Bahama Bank provided cores of Miocene to Holocene platform and slope carbonates of a prograding carbonate platform and its margin (Eberli et al., 1997). (2) The second area was the Montagna della Maiella, an uplifted carbonate platform with its slope and adjacent basin that crops out in central Italy ranging in age from Cretaceous to Miocene. The Montagna della Maiella provided a fossil example with similar depositional environments as penetrated by the Bahamas drill cores (Eberli et al., 1993). The wide range of the analyzed samples covers most carbonate depositional environments, such as reef, platform internal, platform marginal, slope, and basinal sediments, as well as most diagenetic types, including unconsolidated sediments, carbonates with various kinds of cementation, and completely dolomitized samples.

All samples were cut into cylindrical miniplugs of either 1 in. (2.54 cm) or 1.5 in. (3.81 cm) in diameter. Thin sections were prepared of all measured miniplugs to determine pore types, depositional lithology, and diagenetic alterations.

Fractional porosity (Φ) was calculated by measuring the bulk density of the plugs and comparing that value with the grain density obtained from helium pycnometry or XRD (x-ray diffraction) analyses (Anselmetti and Eberli, 1993). Compressional and shear-wave velocities (*Vp* and *Vs*, respectively) were measured on water-saturated samples with the pulse transmission technique (Birch, 1960) at ultrasonic frequency under independent confining and pore fluid pressures to simulate most accurately in-situ conditions of a buried sediment or carbonate rock. To compare all measurements under equal conditions, the displayed values in this study are given at an effective pressure of 8 MPa, which is an equivalent of approximately 500–800 m of burial.

Results

Vp of all analyzed samples ranged between 1900 and 6530 m/s, documenting the wide range of velocities in carbonates. Porosity values ranged between 0 and 56%. A crossplot of porosity vs. *Vp* (Figure 1) displays the distinct inverse trend; velocity decreases with increasing porosity from the pure nonporous calcite velocity of 6500 m/s at 0% porosity toward velocities around 2000 m/s at porosities of 50% and higher. The measured velocities can be compared with the time-average equation of Wyllie et al. (1956).

$$\frac{1}{Vrock} = \frac{1-\Phi}{Vmatrix} + \frac{\Phi}{Vfluid}$$

This empirical equation states that the traveltime of an acoustic signal through the rock is the sum of the traveltime through the volumetric percentage of a pore phase filled by pore fluid plus the traveltime of volumetric percentage of the solid phase represented by a matrix velocity. For this study, *Vp* of calcite (6530 m/s) was chosen as the matrix velocity, and the pore fluid is water with a *Vp* of 1500 m/s. The crossplot in Figure 1 shows that the velocities predicted by this equation seem to form a lower envelope of the measured velocities because most of the samples have velocities that are higher than those predicted by the time-average equation. The use of the dolomite velocity (7000 m/s) as matrix velocity does not change this pattern significantly, as shown by the proximity of the two plotted time-average equations for calcite and dolomite in Figure 1. Especially at high porosities, *Vp* can fall below the time-average equation, which shows that the Wyllie equation may overestimate velocities at porosities greater than 40% (Paillet and Cheng, 1991).

Despite the inverse trend with a correlation coefficient of 0.93 for a linear fit, the scattering of velocities at equal porosities can be high. For example, at 40% porosity, velocities can range between 2200 and 5100 m/s, which makes a reliable velocity prediction based solely on porosity values impossible because there is no unique porosity-velocity curve in carbonates. In log studies, this pattern of a strong velocity scatter is usually attributed to secondary porosity, in particular to vugs and fractures (Schlumberger, 1972, 1974; Asquith, 1985; Doveton, 1994), which are measured by the neutron-porosity tool, but are avoided by the sonic log reading because the acoustic signal circumvents any fracture or vuggy porosity (Merkel, 1979). Our samples were chosen in a way that no open fractures or larger vugs were present in the minicores; consequently, the velocity scatter has its origin in the microfabric within the analyzed sample. Previous studies pointed out that the sonic response, as measured with the SPI, is controlled by pore geometry rather than by geological secondary porosity formed after deposition of the sediment (Nurmi and Frisinger, 1983; Brie et al., 1985). The analyzed samples offer the opportunity to investigate in more detail which pore types contribute from a microfabric point of view to the secondary porosity as measured with the SPI.

Effect of Pore Types on Velocity

Pore geometry proved to be a crucial factor in controlling acoustic properties in carbonates (Brie et al., 1985; Anselmetti and Eberli, 1993; Kenter and Ivanov, 1995). Using mainly the criteria of Choquette and Pray (1970) and Lucia (1983), we distinguished five categories of pore types in thin sections (Figure 2). Each of the pore types has a specific effect on the acoustic properties due to its geometric relationship with the solid rock phase (Figures 2, 3). The five categories of pore types are as follows:

(1) Moldic pores (Figure 2B) originate from dissolution of mineralogically metastable grains. The pores thus are integrated in a frame consisting either of micrite, cement, or just the preserved micritic rims of the grains that resisted dissolution.

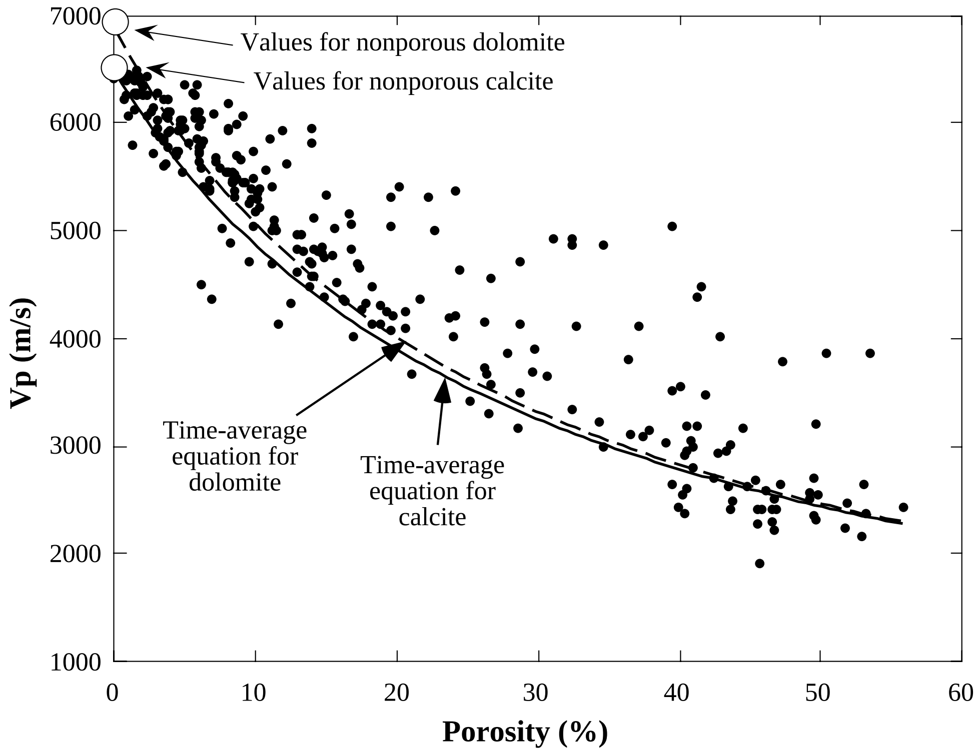


Figure 1—Crossplot of *Vp* (compressional velocity) and porosity from pure carbonate samples compared with the time-average equation for calcite and dolomite (Wyllie et al., 1956). Note the large scattering of velocity values at equal porosities, such as *Vp* at 40% porosity ranging from 2200 to over 5000 m/s. These differences are caused by the occurrence of carbonate-specific pore types that have characteristic effects on elastic properties. Note also that the use of either calcite or dolomite values for the time-average equation only results in minor changes compared to the entire velocity scattering.

(2) Intrafossil porosity (Figure 2A) is pore space that is surrounded by a biologically grown framework. This type of pore is mainly intraparticle porosity within bryozoans and corals.

(3) Interparticle porosity (Figure 2D) is defined as pore space between individual grains (intergranular) and between individual crystals (intercrystalline) (Lucia, 1983).

(4) Microporosity (Figure 2E) is defined in this study as porosity not resolvable in the optical microscope, which puts the pore size at less than 10–20 μm.

(5) Low-porosity carbonates that are intensely cemented are characterized by a small amount of porosity (approximately <10%) embedded in a cemented and, consequently, rigid frame (Figure 2C). These pores commonly are the remnants of former interparticle pore space, fully surrounded by cement. In these cases, the rock as a whole is almost completely indurated, so that the petrophysical response of these few remnant pores is independent of original pore types (e.g., mold or interparticle). We therefore categorize these samples as low-porosity, cemented lithology.

The different pore types form groups with characteristic clusters in the porosity-velocity diagram. Thus, most of the velocity scattering at equal porosities could be attributed to the occurrence of these dominant pore types. To quantify the scattering of velocities at equal porosity values, we define the term "velocity deviation" as departure of the sonic velocity from the velocity predicted by the time-average equation (Figure 1) for the same porosity value and a given lithology (in our case for calcite). Thus, a sample with positive velocity deviation has a velocity that is higher than the velocity derived from the Wyllie equation, whereas a negative deviation has a velocity that is lower than the porosity value would suggest. Part of the scattering of the velocities that yields the deviations can be related to the variable carbonate mineralogy. Dolomite and calcite have initial differences in physical crystal properties (calcite: *Vp* = 6.53 km/s, density = 2.71 g/cm^3; dolomite: *Vp* = ~7.0 km/s; density = 2.87 g/cm^3) that, when compared with the differences in a mixed-carbonate siliciclastic system, are rather small. Figure 1 displays the time-average equation for both of the major minerals in pure carbonate systems, calcite and dolomite, respectively. Note that only a minor part of the scatter in the measured velocities is a product of differences in mineralogical composition because the deviations are approximately a magnitude larger than the differences in time-average velocities between calcite and dolomite. Consequently, we did not correct the time-average value for each sample by assigning an individual matrix velocity because the difference is minor compared to the overall deviations.

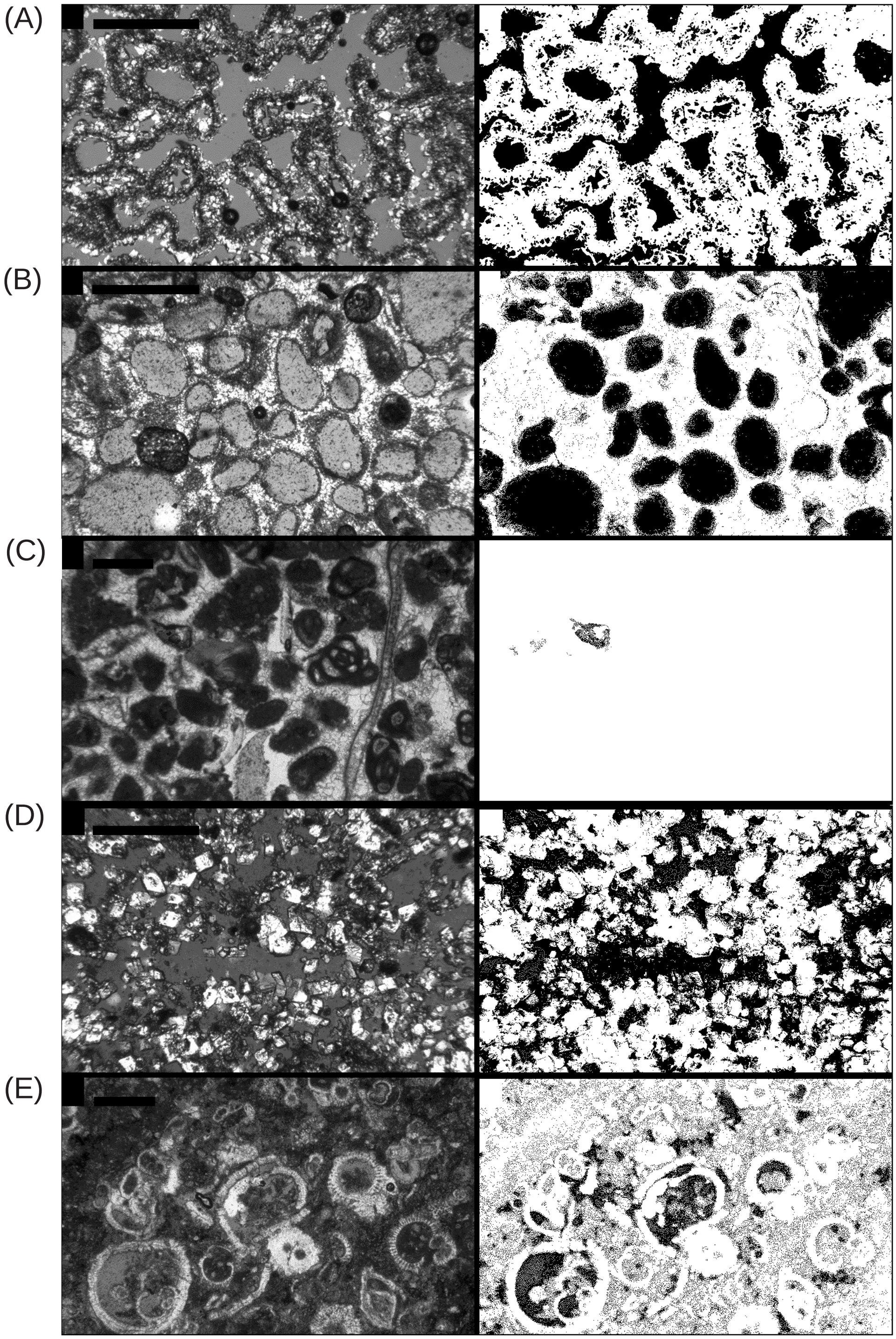


Figure 2—Photomicrographs of samples showing observed major pore types with a binary pore image from image analyses in right column (porosity = black, solid phase = white). Scale bar = 0.5 mm. (A) Sample with intrafossil porosity from the Unda drill hole at 302 m bmp (below mud pit). The coral has a porosity that is integrated in the construction of the framestone. Plug porosity is 43%. (B) Sample with moldic porosity from the Unda drill hole at 65 m bmp. All components of this grainstone were dissolved during and after cementation of the interparticle pore space. Plug porosity is 37%. (C) Sample with low-porosity cemented lithology from the Unda drill hole at 358 m bmp. The mainly skeletal grainstone is cemented with a blocky calcite that almost completely fills the former interparticle pore space. Plug porosity is 3%. (D) Sample with intercrystalline porosity from the Unda drill hole at 286 m bmp. The sediment is completely altered to microsucrosic dolomite. Plug porosity is 49%. (E) Sample with high microporosity from the Clino drill hole at 510 m bmp. The slope deposit is rich in globigerinids and micritic matrix, has almost no diagenetic alterations, and has only minor compaction visible. Plug porosity is 35%.

In our data set, some samples show positive deviations as high as +2230 m/s, whereas negative deviations reach values down to –800 m/s. A previous study of the same set of samples showed that a large part of the scattering can be related to the occurrence of different pore types (Anselmetti and Eberli, 1993). Figure 3 shows the velocity deviations from the Wyllie equation for the five pore type categories. Largest deviations are measured in samples in which intrafossil porosity dominates (Figure 3A). All deviations are larger than +950 m/s and reach up to +1830 m/s, averaging +1320 m/s. The constructional framework surrounding intrafossil porosity enhances the elastic

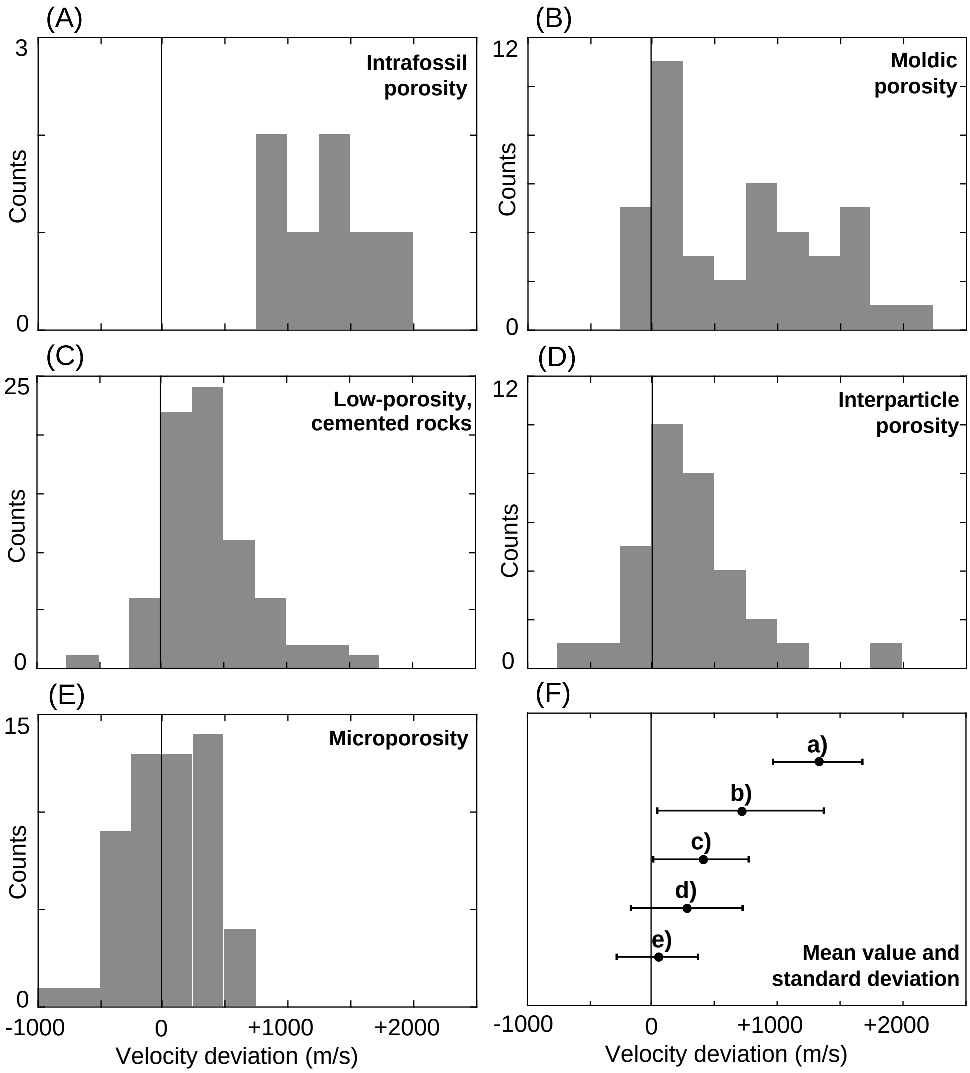


Figure 3—(A–E) Velocity deviations of pore type categories shown in Figure 2. Porosity-velocity values of samples with zero deviation (marked by a vertical line) are exactly described by the empirical time-average equation for calcite. (F) Mean values and standard deviations of all five pore types. Note different mean values for all observed dominant pore types.

properties, which results in relatively high velocities. A similar pattern is recognized in samples with dominant moldic pores, which reach deviations of +2230 m/s, with an average deviation of +710 m/s (Figure 3B). Only a few rocks of this category show negative deviations (greater than −170 m/s). Similar to intrafossil porosity, moldic porosity is well embedded in a rock frame that can preserve its high elastic properties despite the partly high total porosity.

Samples with low-porosity cemented lithology also display positive deviations (Figure 3C), which average +390 m/s and thus are much lower than deviations in intrafossil and moldic porosity types. In these samples the cement provides a framelike backbone of the rock. Total porosities, however, are lower, so that the higher time-average velocity yields only low positive deviation values.

In contrast to these three pore types, the two remaining pore types (interparticle porosity and microporosity) are characterized by much smaller and partly negative deviations. Samples with interparticle (intergranular or intercrystalline) porosity show velocity deviations that range from −670 to +1120 m/s (Figure 3D), with one exception reaching +1800 m/s. Because rocks with interparticle porosity have an ideal fabric to be described by the time-average equation, it is not surprising that the average deviation of those samples is small at +275 m/s and thus close to ideal time-average behavior. In a similar way, the deviations of all samples with high microporosity scatter from −800 m/s to +630 m/s, averaging +42 m/s (Figure 3E). This pattern is a result of the lack of major connections between the grains, which would enhance elastic properties and thus velocities. The fabric and the pore texture of these samples resemble more closely siliciclastic sediments, which generally are better described by the time-average equation than carbonate rocks.

Keep in mind that the pore types were determined only semiquantitatively and based on thin-section observations. In addition to the dominant pore type, most samples contain other pore types as minor pores. Interference of the minor pore type with the dominant pore type might partly explain the large scattering of the deviations for one individual pore type.

VELOCITY-DEVIATION LOG

The knowledge of the porosity-velocity relation in carbonates obtained on discrete samples in the laboratory can be applied to the continuous record of downhole wireline logs. The basic idea is to calculate the velocity deviation, as described in the methods section, as a continuous, synthetic downhole log. The main advantage in applying the laboratory results to log data is that, unlike analyzing only discrete samples, whole packages that represent specific pore types and their related rock fabrics can be mapped in a drilled sequence; consequently, depositional and diagenetic zones can be recognized that would not have been detected by solely looking at the sonic log or the porosity or density logs.

The velocity-deviation log is calculated by comparing porosity and velocity information from wireline-log data. Velocity data are obtained from the sonic log that measures transit times through a short vertical interval of rock, usually 40–100 cm. Porosity values are obtained from the neutron-porosity log or by the density log. In the following section we explain both methods for calculating the velocity-deviation log.

Calculation from Neutron-Porosity and Sonic Logs

A standardized synthetic velocity log is calculated from the porosity values measured by the neutron-porosity log (Figure 4). These velocities represent values that are expected from the porosity value, depending on the porosity-velocity conversion being used. The porosity values are generally converted to velocity by applying the time-average equation (Wyllie et al., 1956). Alternatively, another porosity-velocity equation, such as a best-fit curve through any given data set, can be used. Using the time-average equation for the conversion is advantageous despite its simple theory of adding traveltimes and its lack of consideration of the variable rock fabrics. The time-average equation represents a widely used conversion which, for carbonates, gives a lower envelope of velocity values (Figure 1). As has been explained, we did not account for differences in the physical matrix properties (calcite vs. dolomite) (see Figure 1), so that for this study only the time-average values for calcite were used.

The calculated synthetic velocity log can be compared with the true velocities obtained from the sonic log. The velocity deviations are obtained by subtracting the velocity values of the synthetic sonic log from the velocity values calculated from the true sonic log (velocity deviation = sonic log velocity – velocity calculated from neutron-porosity or density log).

These velocity deviations can be plotted as normal log data in plots of deviation vs. depth. The best graphical displays were made by filling the deviations in regard to the zero-deviation line (Figure 4).

Calculation from Density and Sonic Logs

In cases where the neutron-porosity log is not available, the density log can be used to create the synthetic velocity log. In our case study, this procedure had to be done in zones in which the neutron-porosity log showed erroneous readings. Usually, the combination of neutron-porosity and porosity from density logs is used to determine lithology; e.g., sandstone vs. carbonates (Schlumberger, 1972, 1974). In carbonates, however, the density-porosity conversion can be simplified assuming one grain density, for example calcite density. Grain densities in a system dominated by calcite and dolomite vary between only 2.71 and 2.86 g/cm^3, or by 5%. In sections where significant amounts of dolomite or aragonite are present, a higher grain density could be used. Although a single grain density will result in some error for the calculated velocity log, these errors are small compared to the variations in velocity. As a result, the deviation log contains some minimal errors, but still clearly displays the trends. Once the conversion to porosity is performed, the procedure is the same as that previously described. The porosity values are converted to expected velocities, and the difference to the true sonic log represents the velocity deviation.

A comparison of the two methods is shown in Figure 5, which displays the velocity-deviation log for the same drill hole using either the porosity or the density logs. This comparison shows that in all sections of the hole the trends of velocity deviations remain the same for both methods. Differences on the order of less than 200 m/s appear mainly as a shift toward lower deviations when the density log is used. This offset occurs mainly in the interval between 100 and 380 m depth, and is caused either by too high log densities, resulting in smaller velocity deviations, or by

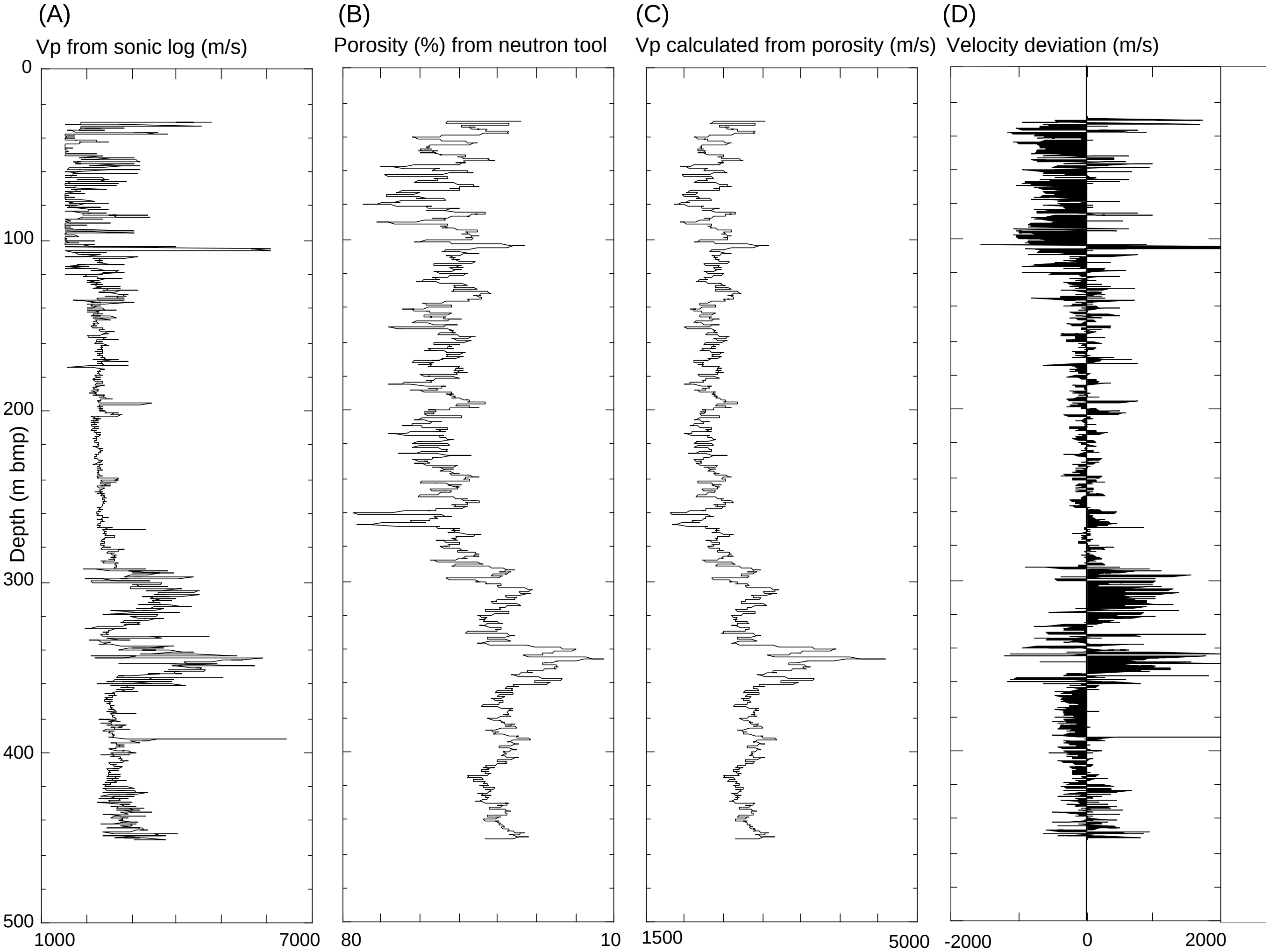


Figure 4—Calculation of a velocity-deviation log (drill hole Unda, Great Bahama Bank). (A) The sonic log provides the true downhole velocity distribution. The (B) neutron-porosity log is converted into a (C) synthetic velocity log. The difference between the two defines the (D) velocity-deviation log, which is plotted with positive and negative fill around the zero-deviation line. Depth is in meters below mud pit (m bmp).

too high neutron porosities, resulting in larger deviations. These differences in deviations, however, are small compared to the full range of values and justify the use of both methods, depending on quality and availability of neutron-porosity and density log data.

Interpretation

The resulting velocity-deviation log can now be interpreted by applying the porosity-velocity relations that were recognized in the laboratory study. Keep in mind that all laboratory velocities were measured on discrete plugs of 2–5 cm in length under ultrasonic frequencies (1 MHz), whereas the following log interpretations use sonic log velocities measured with a signal frequency of approximately 1–100 kHz and with a resolution of 40–100 cm. The dispersion effect between ultrasonic and log frequencies is difficult to assess, but is believed to be less than 3–5% (Wang and Nur, 1990). Thus, the frequency difference should not be a source of large offset between laboratory and log data. This effect of dispersion, although insignificant, was also confirmed by directly comparing log and laboratory data (Rafavich et al., 1984; Anselmetti and Eberli, 1993). The frequency dependence, combined with the smaller resolution of drilled miniplugs that better represent thin, fast layers, results in the tendency of laboratory velocities being slightly faster than log velocities. This discrepancy would cause smaller velocity deviations in the logs than seen in the laboratory samples. The

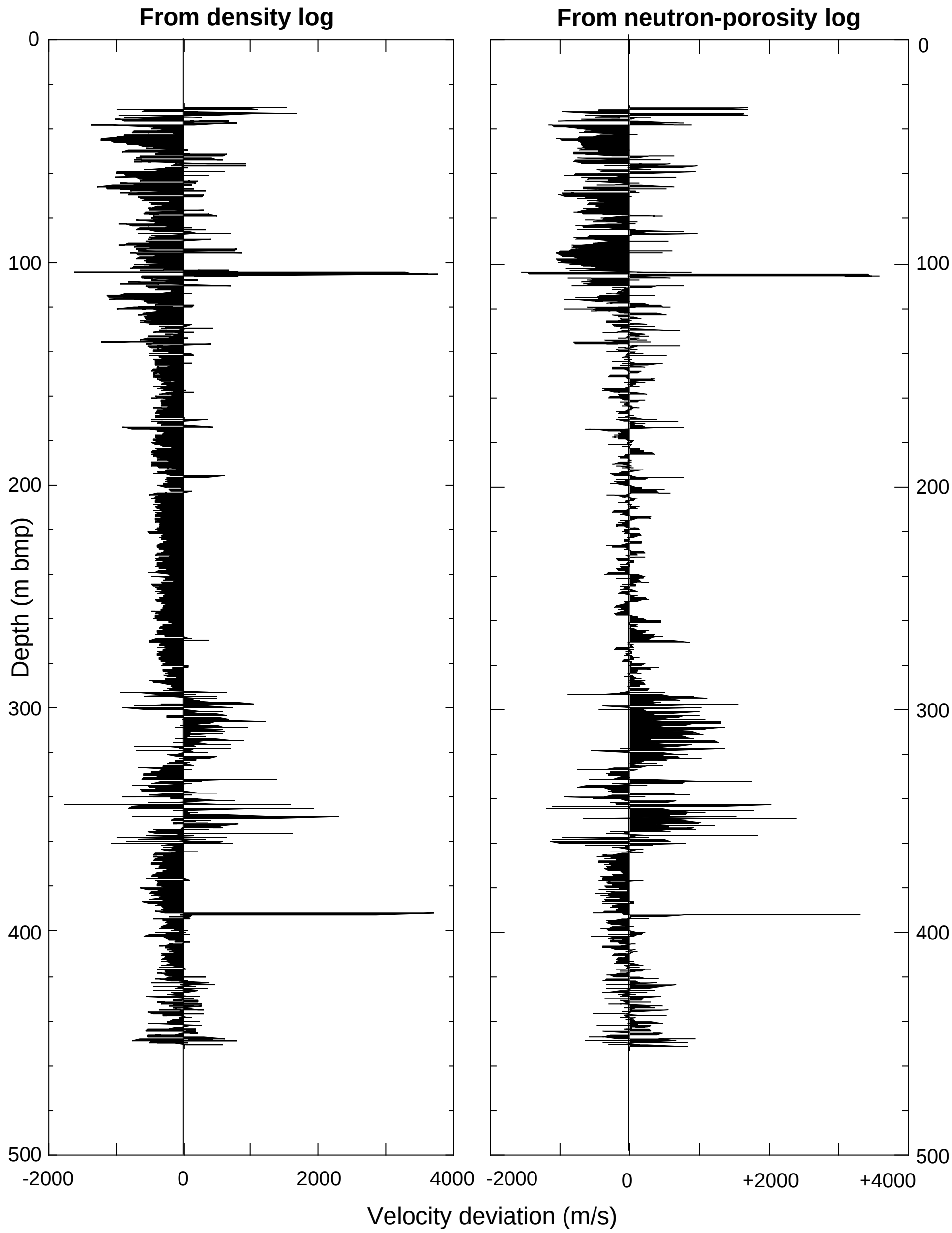


Figure 5—Comparison of velocity-deviation log from drill hole Unda on Great Bahama Bank calculated by the density log or by the neutron-porosity log. Differences are minimal; however, the deviations calculated with porosities from density values are consistently lower than those calculated by neutron porosities. This difference indicates that either the neutron-porosity readings were too high or the density log values were too high. Depth is in meters below mud pit (m bmp).

slight offset can be tolerated because the velocity deviations have a wide range between –1000 and +2250 m/s.

Based on the pore type dependence of velocity deviations, the following predictions can be done by interpreting a downhole velocity-deviation log showing zones with various characteristic patterns.

Zones with Positive Deviations

Positive deviations indicate relatively high velocities in regard to porosity, and are caused mainly by porosity that is integrated in a framelike fabric of the rock, such as in intrafossil or moldic porosity. In moldic porosity, porosity deviations indicate intense diagenetic alterations, such as dissolution or precipitation, yielding moldic porosity and favoring reprecipitation of the dissolved material as pore-filling cement. The fabrics of these rocks thus have high porosities and high velocities, and are displayed on the deviation log by their positive values. The deviation log, consequently, can be used not only to detect the rock frame–integrated porosity, but also to suggest their associated diagenetic processes.

In general, positive deviation zones are characterized by pores within a dense, cemented matrix, where the pores commonly are not connected. A positive deviation thus also may indicate low permeability.

Zones with ± Zero Deviations

Zones with small deviations (±500 m/s or less) represent sections that follow the predictions by the time-average equation. These zones are dominated by either interparticle, intercrystalline, or high microporosity. All of these pore types are particularly predominant in a sediment just after deposition, when original grains or micrite are simply packed together. Most of the zones with small velocity deviations thus indicate zones with little diagenetic alterations. These small velocity deviation zones contrast sharply with the intense diagenesis of the zones with large velocity deviations. One exception is sucrosic dolomite, which is characterized by intercrystalline porosity between the diagenetically formed dolomite rhombohedra (Figure 2D) and thus is a diagenetic product of intense dolomitization.

Unlike the pore types resulting in positive deviations, these pore types are usually well connected and yield high permeability, unless only microporosity is abundant, which results in low permeability.

Zones with Negative Deviations

According to the empirical concept of the time-average equation, which adds traveltimes of solid and fluid phases (Wyllie et al., 1956), no rock should have a velocity below the prediction based solely on the porosity of the microfabric. Only the velocity in high-porosity rocks (>40% porosity) may be overestimated by the equation (Paillet and Cheng, 1991); however, the studied velocity-deviation logs show zones where deviations were consistently negative, indicating factors other than lithology to control the velocity deviations. There are three possible explanations. (1) Caving or irregularities of the borehole wall, for example irregularities caused by a karstic overprint, yield unfavorable wall conditions, resulting in artificially low velocities on the sonic log. In this case, the sonic tool would not be coupled to the wall, whereas the porosity tool reaches farther and reads a more reliable value. Correct porosity and too low a velocity can produce a negative deviation. (2) Despite the fact that fracture porosity has always been included in the secondary porosity, which is an equivalent of too high velocity or positive deviations (Schlumberger 1974), several studies showed that fracturing decreases velocities on both a small scale (Gardner et al., 1974; Anselmetti and Eberli, 1993) and on a large scale (Guadagno and Nunziata, 1993). The larger scale fractures can be detected with the logging tools and yield lower velocities than the undisturbed rock. In addition, buried fractures are normally closed or, in regard to total porosity, are relatively insignificant, so that the neutron porosity is not significantly reduced. As a result, fracturing produces negative deviations. (3) Negative deviations also could be caused by a high content of free gas. Free gas would have a strong negative effect on the deviation log because gas drastically reduces *Vp* (Nur and Simmons, 1969) and results in a reduced neutron-porosity reading due to the lower content of hydrogen in the fluid phase (Hilchie, 1982). Both of these effects theoretically cause a strong negative signal in the deviation log.

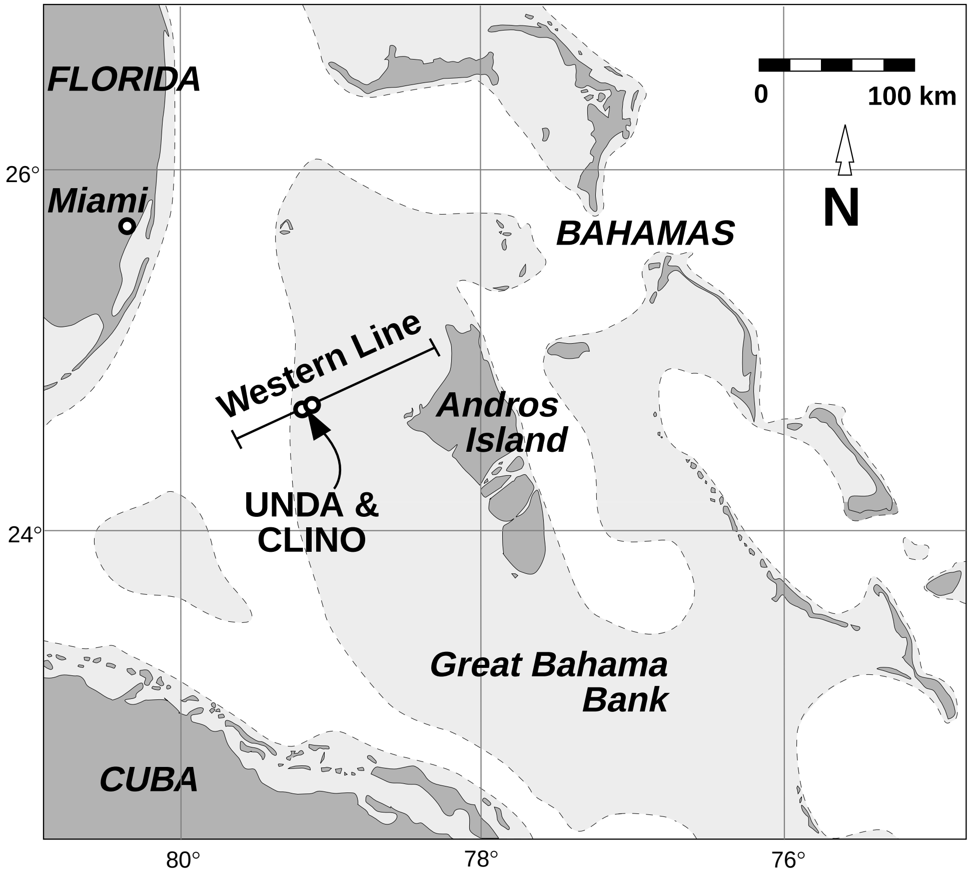
CASE STUDY

Bahamas Drilling Project

We developed the method of the velocity-deviation log while we were studying the cores and wireline logs of the two deep drill holes on the Great Bahama Bank. These holes were cored as part of the Bahamas Drilling Project (BDP) (Eberli et al., 1997) and were named Unda and Clino. These drill holes are located on the shallow Great Bahama Bank (Figure 6) and reach depths of 500 m (Unda) and 672 m (Clino) (Figure 7). All depths are reported as meters below mud pit (m bmp). For Clino, sea level was 7.3 m bmp and the sea floor was 14.9 m bmp; for Unda, sea level was 5.2 m bmp and the sea floor was 11.9 m bmp. Both sites are positioned on a multichannel seismic line (Western Seismic Line) that images the geometry of the prograding carbonate platform margin (Eberli and Ginsburg, 1989). The continuously cored holes provided a unique opportunity for a multidisciplinary study to assess lithology and depositional processes, chronostratigraphy, diagenesis and fluid flow, physical properties, and sequence stratigraphic architecture [for a BDP synthesis see Eberli et al. (1997)].

Drill hole Clino, located approximately 3 km east of the modern platform margin, penetrated a lithologic succession that displays an overall shallowing-upward trend (Figure 7) produced by the westward progradation of the platform margin. The lower part of Clino penetrated fine-grained periplatform sediments and turbidites deposited on the lower and upper slopes. Upsection, the depositional environment becomes gradually shallower and, finally, the uppermost 200 m are reefal and shallow-water deposits. Several thin, pelagic-rich intervals interrupt this facies succession. Many of these interruptions are marked by distinct

Figure 6—Map of Great Bahama Bank with locations of drill holes Unda and Clino.



diagenetic changes with characteristic effects on petrophysical properties. In addition, the most prominent interruptions coincide with layers that were interpreted as sequence boundaries on the seismic section (Eberli et al., 1997).

Drill hole Unda, 5 km farther from the modern margin than Clino, consists of two intervals of deeper water carbonates sandwiched between three zones of shallow-water carbonates (Figure 7). The upper and the middle shallow-water sections are dominated by reefal rocks, whereas the bottom of the hole is made of cross-bedded coarser carbonate sands typical of a platform margin. The two deeper water intervals are characterized by finer grained slope deposits. The lower part of Unda, in particular between 250 and 370 m, is dominated by an intense and partly complete dolomitization.

Correlation of Velocity-Deviation Logs with Lithology

The available wireline logs of the two drill holes provide an opportunity to compare the velocity deviation of a continuous downhole section (Figure 8) with the lithological data obtained from the cores (Figure 7). The two following sections describe the relation between lithology and velocity-deviation log for each of the two drill holes.

Drill Hole Unda

Unda is characterized in the upper part down to 100 m depth by a mainly negative velocity-deviation trend, which is likely the result of a strong karstic overprint resulting in a cavernous borehole wall that prevented reliable sonic log readings. Few strong positive spikes in the velocity-deviation log document the reefal and intensely cemented lithologies within this shallow-water carbonate section. From 100 to 290 m, Unda consists of unconsolidated, peloidal-skeletal sands, that are dolomitized in the lower part. The velocity-porosity values of these sands and the sucrosic dolomites are well described by the time-average equation because intergranular and intercrystalline porosity dominates. Consequently, the velocity deviations are close to zero in this entire interval (Figure 8). This trend changes sharply at 292 m, where the boundary to an underlying reef unit occurs (Figure 7), which drastically changes the lithologic and diagenetic signature. From 300 to 350 m, velocity

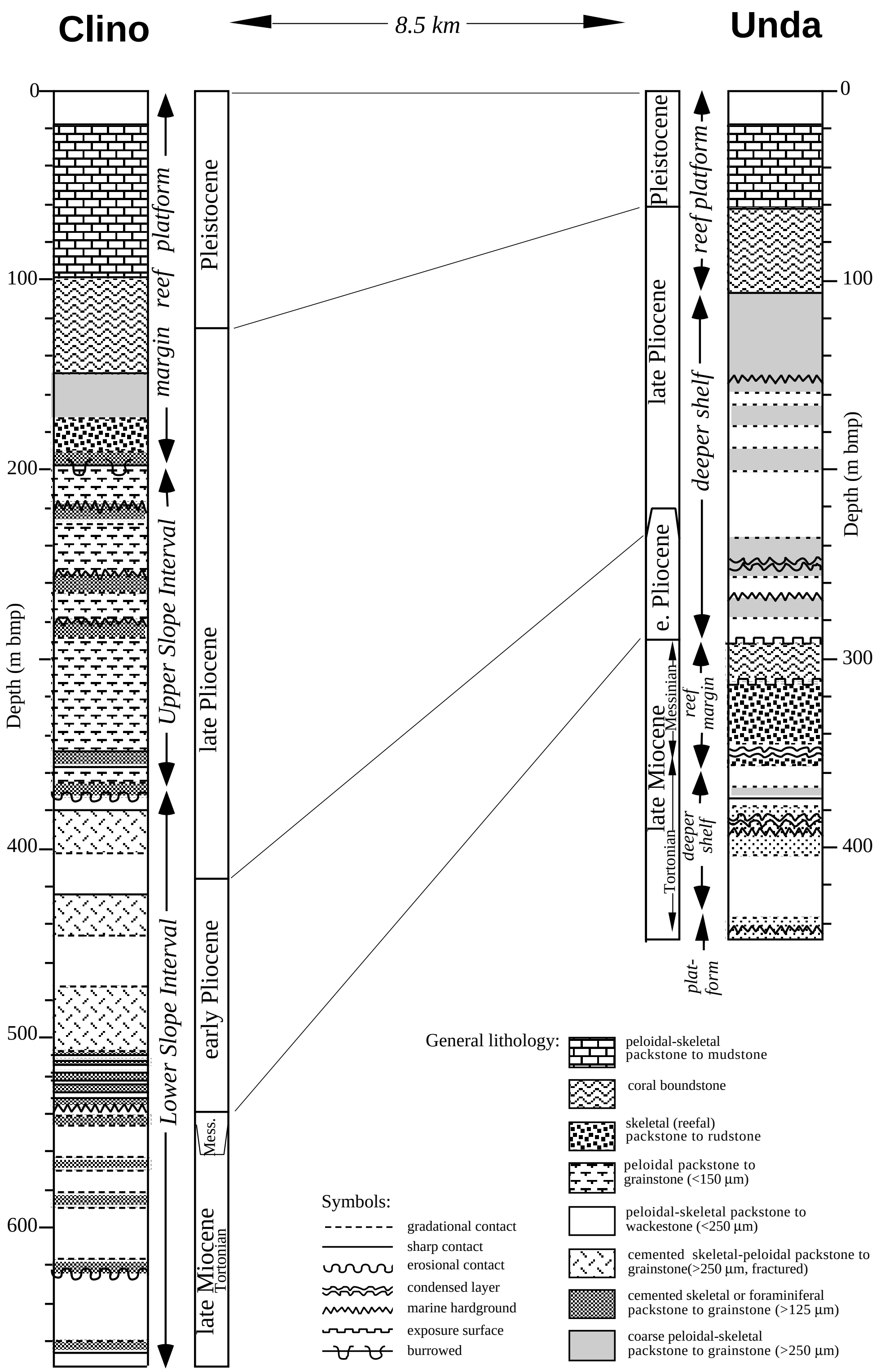


Figure 7—Facies successions, depositional environments, and ages of the cores from the two drill holes Unda and Clino (from Kenter and Ginsburg, in press). See Figure 6 for drill hole locations.

deviations are positive, caused by the framelike fabric of the reefal sediments and the complete mimetic dolomitization that preserves the original fabric of the rock and creates a frame with high elastic rigidity consisting of 100% dolomite. Some zones of sucrosic dolomites within and below the reef, however, result again in zero to negative deviations, as does the lower part of Unda below 350 m, where

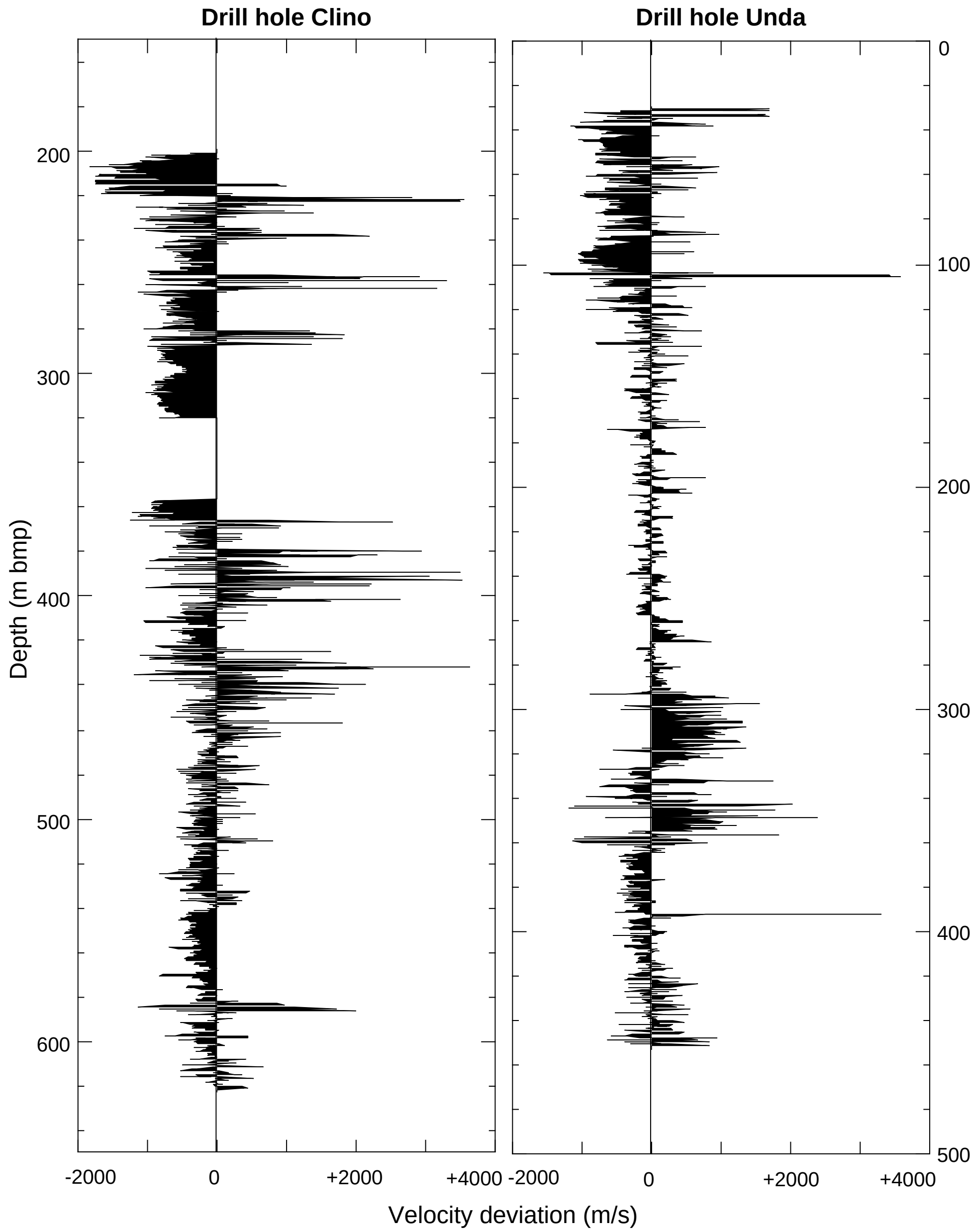


Figure 8—Velocity-deviation log for drill holes Unda and Clino (see Figure 6 for drill hole locations). Due to the low quality of the neutron-porosity log in Clino above 213 m bmp (below mud pit) and between 260 and 412 m bmp, the density log was used to calculate the deviations instead of the neutron-porosity log. See the text for explanations and interpretations.

the depositional environment shifts from shallow water again to the deeper shelf, and where diagenetic alteration is low and limited to some dissolution and little cementation. The lowermost part of Unda, composed of cross-bedded sands deposited on the platform, is imaged in the deviation log by slightly higher and positive values than the deeper water deposits above.

Drill Hole Clino

Because casing remained in the hole, logs for Clino are available only below a depth of 200 m. The section between 200 and 300 m depth is characterized by a succession of four marine hardgrounds, which are coarse-grained and show intense submarine cementation (Figure 7). All of these hardgrounds are imaged in the velocity-deviation log by a strong positive spike, whereas the background sediments between the hardgrounds have negative deviations. This pattern reflects the occurrence of cemented fabrics with pore types integrated in a frame at and below the hardgrounds, which contrast sharply to the mainly microporous and interparticle porosity in the fine-grained peloidal packstones in between. Farther downhole, two intervals of cemented skeletal-peloidal sands at around 400 and 440 m are characterized by a succession of several marine hardgrounds and result in positive deviations, indicating the increased alterations in those sections. The remainder of Clino generally is characterized by zero to little negative deviations, documenting the absence of major diagenesis. Surprisingly, a thick condensed interval above a hardground between 500 and 540 m does not result in increased deviations, and only the hardground itself at 540 m has a weak positive signature in the deviation log. Unlike the hardgrounds previously described, this hardground is not characterized by intense dissolution or cementation processes, but rather by a thin layer of phosphatic mineralization; the overlying condensed section is almost unaltered. Below, only few coarse-grained turbidite layers (580 m) cause positive velocity deviations because the coarse grain size in those layers resulted in higher original permeability and thus accelerated dissolution of platform-derived skeletal grains and consecutive cementation.

VELOCITY DEVIATIONS AND PERMEABILITY TRENDS

Permeability in carbonate rocks is more affected by pore types and their connectivity than by the total amount of porosity (Lucia, 1987; Melim et al., in press). The large variety of pore types in carbonates results in highly variable permeability values. Because pore types in carbonates have a major control on both velocity deviation and permeability, it seems appropriate to investigate whether the velocity-deviation log can be used to trace permeability trends downhole.

We showed that most of the positive deviations are a result of intrafossil and moldic pores or of low-porosity cemented lithologies, which are all pores that are embedded in a rigid rock frame (Figure 2A–C). Most of these pores are not connected, but rather are separated by a densely cemented matrix inhibiting major fluid flow through the isolated pores. Consequently, rocks with positive velocity deviations show generally low permeability values. In contrast, interparticle (intergranular and intercrystalline) porosity is characterized by well-connected pores and thus by high permeability. Our laboratory analyses revealed that samples with these pore types showed low positive or negative velocity deviations; consequently, we can postulate that a large velocity deviation may indicate low permeability, whereas small or negative deviations may indicate high permeability. Such an indirect correlation is simplified and does not cover all carbonate lithologies. For instance, microporosity does not necessarily follow this pattern because it results in small velocity deviations, but also might cause low permeability. To test this inverse correlation of permeability and velocity deviation, we used a short-spaced permeability data set consisting of minipermeameter readings that were measured directly on the split cores from the BDP (Melim et al., in press). For a detailed comparison between the permeability data and the velocity-deviation log, we selected two intervals that had permeability data measured with a higher sampling rate than the bulk of the cores (Figure 9). Both intervals are lithologically characterized by intercalations of zones with strong diagenetic overprint and zones with little diagenetic alterations. The first interval (Clino from 200 to 320 m depth, Figure 9A) shows the postulated inverse correlation between velocity deviation and the trends in permeability. Three marine hardgrounds at 220, 255, and 280 m depth were recognized in the cores (Figure 7). These hardgrounds all are characterized by strong positive peaks in the velocity-deviation log. Above the hardgrounds, velocity deviations abruptly decrease to small or even negative values and gradually increase toward the next higher overlying hardground surface. This observed trend is well matched by an upcore decrease in average permeability and an abrupt upcore increase in permeability across the hardgrounds. Small-scale variations in permeability seem to increase upward toward those hardgrounds. The hardgrounds display permeability values of less than 1 md, whereas the intercalated zones of slope deposits have permeability values of 1–100 md.

The second interval (Clino from 350 to 470 m depth, Figure 9B) consists of a series of cemented skeletal-rich packstones to grainstones intercalated by peloidal-skeletal wackestones to packstones. These cemented layers stand out in the velocity-deviation log by sharp spikes reaching values of greater than +2000 m/s. Most of these positive excursions in the velocity-deviation log correlate with low-permeability peaks with values of less than 1 md. In contrast, the wackestones to packstones in between the cemented layers have velocity deviations averaging ±0 m/s and permeabilities of 1–500 md.

The coincidence between velocity deviation and permeability trends indicates that both parameters in this succession are controlled by similar parameters. Thin sections indicate that these controlling parameters are the pore types of the different lithologies. The marine hardgrounds and the cemented layers have mainly isolated pores (molds) that are integrated in a rigid, submarine-cemented matrix, whereas the less altered carbonates between those layers are characterized mainly by intergranular pores.

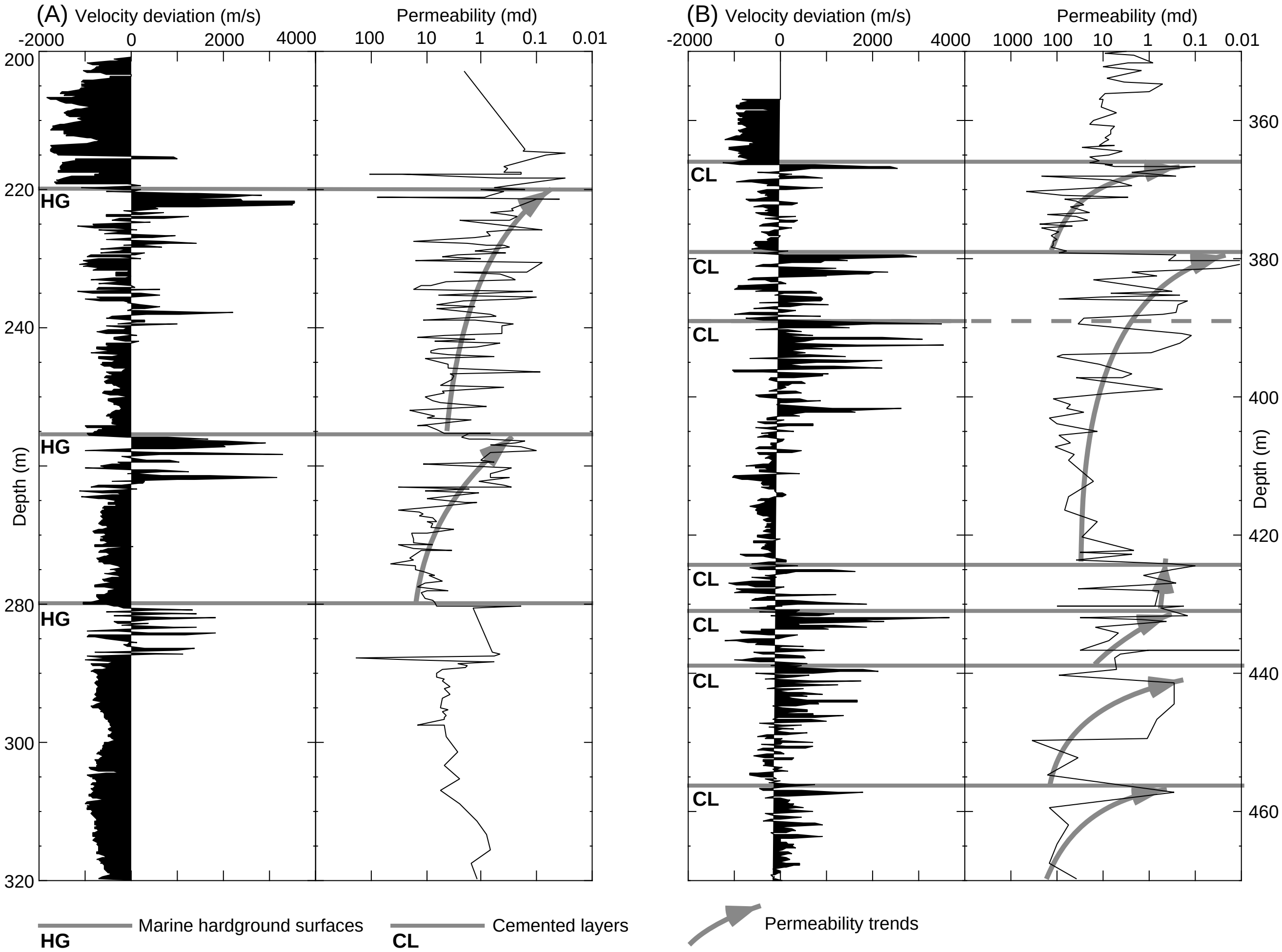


Figure 9—Correlation of velocity-deviation log and permeability data in two intervals in drill hole Clino (see Figure 6 for drill hole location). Permeability was measured with a helium minipermeameter on split cores. Permeability is plotted in reverse to match trends in velocity-deviation log. (A) This interval at 200–320 m bmp (below mud pit) consists of fine-grained slope deposits intercalated by three marine hardgrounds (HG). Velocity deviation increases upcore and decreases abruptly above the surfaces. This signature correlates inversely with upcore-decreasing permeability values that increase sharply above the hardgrounds. (B) This interval at 350–470 m bmp consists of peloidal-skeletal lower slope deposits intercalated by skeletal-rich cemented layers (CL). Most of the positive peaks in the velocity-deviation log are matched by lows in the permeability data and vice versa. The similarity of the trends in the deviation log and the permeability data indicates a significant link between velocity deviation and trends in permeability.

These examples show that the velocity-deviation log has the potential to partly mimic the permeability pattern and that the log might be used to predict trends in downhole permeability distribution in a carbonate setting; however, because permeability is influenced by more parameters than just the porosity-velocity signature, the deviation log can be used to predict trends and not absolute values of permeability. Additional parameters, such as sediment type, amount of microporosity, or pore throat sizes, have to be included to obtain a more reliable proxy for the permeability value in a carbonate drill hole.

SUMMARY AND CONCLUSIONS

An extensive laboratory study on over 300 carbonate samples revealed that the acoustic velocity in carbonate rocks is a complex function of porosity and pore types, which are controlled by the combined effect of depositional lithology and by the succession of diagenetic alterations. Different pore types in the carbonates cause significant scattering in the velocity-porosity diagram, so that most samples show deviations from an average velocity-porosity trend. We defined the term "velocity deviation" as the difference from the measured acoustic velocity to the velocity calculated from the porosity value by applying the commonly used empirical time-average equation. As with the secondary porosity index (SPI™), this approach quantifies the difference between the true acoustic and the theoretic time-average behavior of carbonate sediments and rocks. Because porosity controls velocity, and not vice versa, we quantify the resulting velocity deviations rather than the porosity anomalies. This approach offers the potential to relate any seismic data set, which is mainly controlled by the velocity distribution, directly to the petrophysical data. Using this approach, the classic interpretation of the deviations from the time-average equation as a result of secondary porosity from vugs and fractures was refined by relating the pore characteristics from the microfabrics observed in the minicores to the measured plug velocities. The velocity deviation is zero for lithologies with intergranular or intercrystalline porosity, which the time-average equation describes best. Positive deviations, which are a result of higher velocity values than expected from porosity, are caused by pore types that are integrated in a rock frame and that yield high elastic properties of a rock. All of those pore types are related to the depositional and, to a greater extent, the diagenetic overprint.

This concept of velocity deviation can be applied to the continuous velocity-porosity record obtained by wireline logs. A velocity-deviation log can be established by calculating the velocity deviations from the sonic log and the neutron-porosity log. Because density and porosity are closely related in pure carbonates, the density log also might be used to obtain a porosity data set. The resulting velocity-deviation log displays a continuous record of velocity-deviation values, which allows us to recognize the predominant pore types downhole. Because most pore types can be related to the diagenetic overprint, this log can be used to trace associated diagenetic processes downhole and to predict microfabrics, which would not be predictable from velocity, neutron-porosity, or density logs alone. In addition, the velocity-deviation log can be used to predict trends in permeability because permeability also is controlled by the occurrence of the various pore types. Absolute downhole permeability predictions, however, need additional information on lithologies from cores, cuttings, or additional lithology logs.

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Flavio Anselmetti obtained a diploma in geology at the University of Basel in 1990, and a Ph.D. at the Swiss Federal Institute of Technology in Zürich (ETH) in 1994. His thesis linked lithological, petrophysical, and seismic records of carbonates. He then spent three years at the University of Miami processing and interpreting seismic data from a Bahamian platform margin. Since June 1997, he has been a research associate at the ETH Zürich focusing on high-resolution seismic surveys, petrophysical characterizations, and seismic modeling of lacustrine and marine systems.

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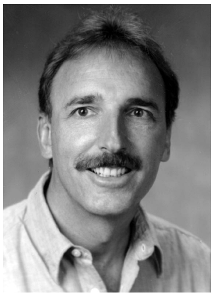

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