PAGEOPH, Vol. 141, No. 2/3/4 (1993)
0033-4553/93/040287-37$1.50 + 0.20/0

Controls on Sonic Velocity in Carbonates

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Abstract—Compressional and shear-wave velocities (V_p and V_s) of 210 minicores of carbonates from different areas and ages were measured under variable confining and pore-fluid pressures. The lithologies of the samples range from unconsolidated carbonate mud to completely lithified limestones. The velocity measurements enable us to relate velocity variations in carbonates to factors such as mineralogy, porosity, pore types and density and to quantify the velocity effects of compaction and other diagenetic alterations.

Pure carbonate rocks show, unlike siliciclastic or shaly sediments, little direct correlation between acoustic properties (V_p and V_s) with age or burial depth of the sediment so that velocity inversions with increasing depth are common. Rather, sonic velocity in carbonates is controlled by the combined effect of depositional lithology and several post-depositional processes, such as cementation or dissolution, which results in fabrics specific to carbonates. These diagenetic fabrics can be directly correlated to the sonic velocity of the rocks.

At 8 MPa effective pressure V_p ranges from 1700 to 6500 m/s, and V_s ranges from 800 to 3400 m/s. This range is mainly caused by variations in the amount and type of porosity and not by variations in mineralogy. In general, the measured 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 2500 m/s. These deviations can be explained by the occurrence of different pore types that form during specific diagenetic phases. Our data set further suggests that commonly used correlations like "Gardner's Law" (V_p-density) or the "time-average-equation" (V_p-porosity) should be significantly modified towards higher velocities before being applied to carbonates.

The velocity measurements of unconsolidated carbonate mud at different stages of experimental compaction show that the velocity increase due to compaction is lower than the observed velocity increase at decreasing porosities in natural rocks. This discrepancy shows that diagenetic changes that accompany compaction influence velocity more than solely compaction at increasing overburden pressure.

The susceptibility of carbonates to diagenetic changes, that occur far more quickly than compaction, causes a special velocity distribution in carbonates and complicates velocity estimations. By assigning characteristic velocity patterns to the observed diagenetic processes, we are able to link sonic velocity to the diagenetic stage of the rock.

Key words: Sonic velocity, carbonates, physical properties, porosity, diagenesis, compaction.

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1. Introduction

Knowledge of the relation between sonic velocity in sediments and rock lithology is one of the keys to interpreting data from seismic sections or from acoustic logs of sedimentary sequences. Reliable correlations of rock velocity with other petrophysical parameters, such as porosity or density, are essential for calculating impedance models for synthetic seismic sections (BIDDLE *et al.*, 1992; CAMPBELL and STAFLEU, 1992) or identifying the origin of reflectivity on seismic lines (SELLAMI *et al.*, 1990; CHRISTENSEN and SZYMANSKI, 1991). Velocity is thus an important parameter for correlating lithological with geophysical data.

Recent studies have increased our understanding of elastic rock properties in siliciclastic or shaly sediments. The causes for variations in velocity have been investigated for siliciclastic rocks (VERNIK and NUR, 1992), mixed carbonate siliciclastic sediments (CHRISTENSEN and SZYMANSKI, 1991), synthetic sand-clay mixtures (MARION *et al.*, 1992) or claystones (JAPSEN, 1993). The concepts derived from these studies are however only partly applicable in pure carbonates. Carbonates do not have large compositional variations that are, as is the case in the other sedimentary rocks, responsible for velocity contrasts. Pure carbonates are characterized by the lack of any clay or siliciclastic content, but are mostly produced and deposited on the top or on the slope of isolated or detached carbonate platforms, that have no hinterland as a source of terrigeneous material (WILSON, 1975; EBERLI, 1991). They consist of over 95% of the carbonate minerals calcite (low- and high-Mg), dolomite and aragonite. These minerals have very similar physical properties, which excludes compositional variation as a major reason for the large variability in velocity of carbonates.

Theories that describe sonic wave propagation in porous media (GASSMAN, 1951; BIOT, 1956) are hard to apply in the complex system of pure carbonates because they form a variety of unique diagenetic rock fabrics with specific elastic properties. In order to quantify the physical properties, sonic velocity in pure carbonate samples from three different areas that cover a wide range of depositional environments and lithologies have been measured. Measurements of compressional-wave velocity (V_p) and shear-wave velocity (V_s) were performed under confining and pore-fluid pressures, which accurately simulate *in situ* subsurface conditions. Our study includes carbonates at all stages of diagenetic alteration and complements studies on the velocity of carbonates which were limited to highly lithified, low porosity carbonate rocks (RAFAVICH *et al.*, 1984; WANG *et al.*, 1991) or to pelagic, deep water carbonates (SCHLANGER and DOUGLAS, 1974; MILHOLLAND *et al.*, 1980; URMOS and WILKENS, 1993).

Sonic velocity measurements were done in combination with a thorough lithologic and diagenetic examination of thin sections and XRD analysis. Porosity in the samples ranges from 0 to 60% and the depositional environment varies from the protected shallow water platform over reefal and platform-marginal sediments to deeper slope deposits. The correlation of the velocity measurements with the lithology and the mineralogy data enables us to assign depositional and diagenetic stages to characteristic velocities. Furthermore it allows tracing of diagenetic evolution and velocity development from the time of deposition through different burial stages, recognizing that each diagenetic process alters velocity in its characteristic way.

2. *Sample Areas*

This study presents the correlation of physical rock properties with rock lithology based on velocity analyses of 210 discrete samples from three different areas; (1) modern carbonate mud from Florida Bay, (2) two deep drill holes in Great Bahama Bank and (3) the Maiella, an exhumed carbonate platform in Central Italy. An understanding of the geological setting of the three areas is essential in order to relate the physical properties of the carbonates to the rock lithology.

A. *Velocity Samples from Modern and Unconsolidated Carbonate Sediments: Artificially Compacted Carbonate Mud from Cluett Key, Florida Bay (South Florida)*

The velocities of 20 carbonate mud samples were measured at various stages of artificial compaction in order to determine the increase of velocity caused by the porosity reduction during pure mechanical compaction. The mud was collected with push cores of approximately 70 cm length from the interior pond of Cluett Key (Figure 1), a mangrove island in Florida Bay.

Florida Bay is a triangular shaped shallow lagoon on the southern part of the Florida peninsula. This protected bay is subdivided by a series of mudbanks with several mangrove-fringed islands (ENOS and PERKINS, 1979). The Holocene sediments on the islands overlie Pleistocene bedrock and are up to 4 m thick. The base of the Holocene is often marked by a peat layer which is overlain by a succession of dominantly mud to wackestones with few intercalations of shell-rich storm layers. Unconsolidated carbonate mud of the upper part of the Holocene section was used for the compaction-velocity experiments. The samples were taken from parts of the cores in which no roots or shell fragments disturb the homogeneous mud.

Mud from the islands and the mudbanks in Florida Bay have porosities that range from 61 to 78% (ENOS and SAWATSKY, 1981). Gamma ray attenuation measurements with cores from Cluett Key gave an average porosity for the Holocene sediments of 63% (VIDLOCK, 1983). The mineralogical composition, determined on carbonate mud from Jimmy Key, an adjacent island (BURNS and

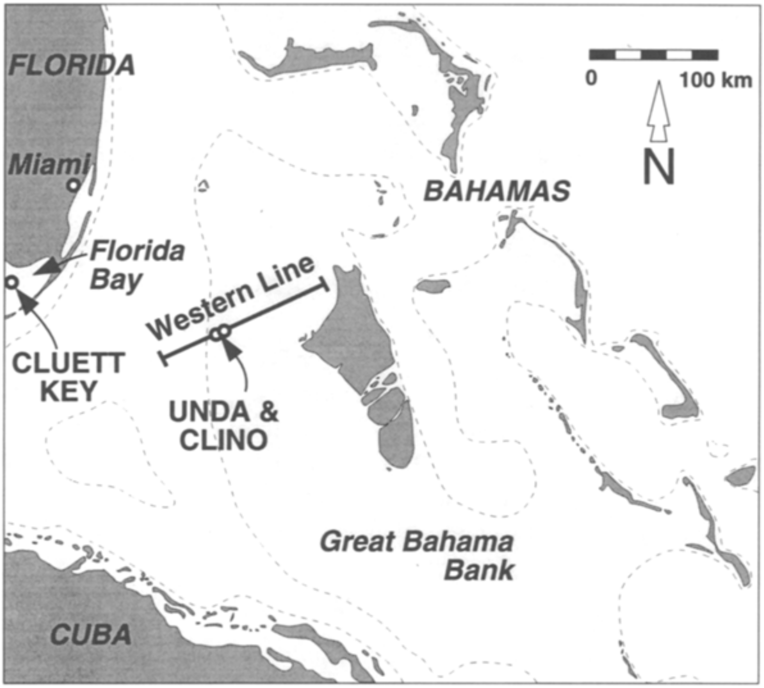


Figure 1
Location map showing the positions of the deep core borings Unda and Clino along the Western seismic line on Great Bahama Bank and the location of Cluett Key in Florida Bay.

SWART, 1992) averages 65% aragonite, 20% high Mg-calcite and 15% low Mg-calcite. These values are stable for the whole Holocene section and only traces ($<5\%$) of dolomite are observed. Between the surface and 70 cm depth, no detectable diagenetic alterations occur, although variations in pore water chemistry indicate that early diagenetic processes such as dolomitization have already started (BURNS and SWART, 1992).

B. *Velocity Samples from Cores of Deep Drillholes: Pleistocene to Miocene Carbonates from Core Borings in Great Bahama Bank (Bahamas Drilling Project)*

Two continuous core borings from the Bahamas Drilling Project, located on a multi-channel seismic line on Great Bahama Bank (Figures 1 and 2), provide an excellent opportunity to correlate the physical properties of Miocene to Pleistocene carbonate sediments with their depositional lithologies and diagenetic stages. Eighty-nine samples from both drill holes were analyzed. Unlike older and exhumed outcrop samples, the young age of the drilled sediments allows measurement of sonic velocities of carbonates that are partly unconsolidated and that are not in

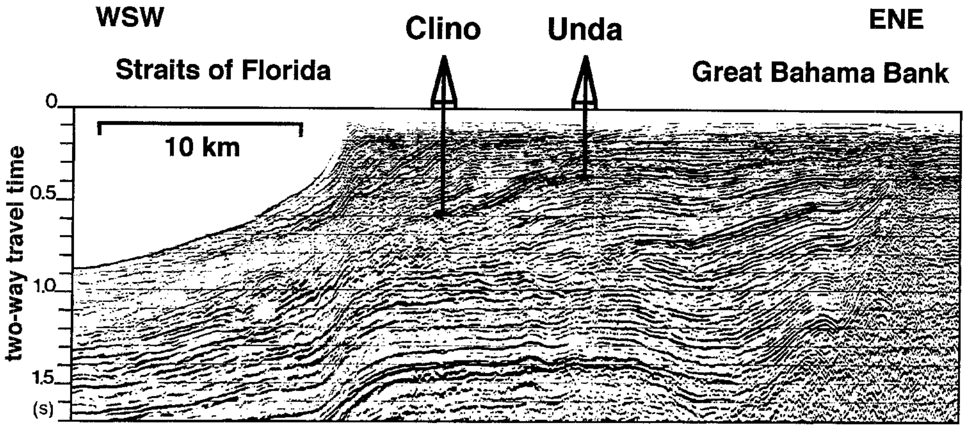


Figure 2
Part of Western line displaying modern platform margin and drill sites Unda and Clino. The succession of inclined reflectors below the modern shallow water platform document the progradation of the platform edge over inclined slope sediments for a distance of over 25 km.

their final stage of post-depositional alteration. The variety of diagenetic processes encountered enabled us to trace the velocity evolution of different carbonate sediments under different diagenetic conditions through burial history and time.

The two holes (Unda and Clino) penetrated to depths of 442 and 662 m below seafloor, respectively. The continuous cores had an average recovery of over 80%. The top of the rock section in both holes is of Pleistocene age. The oldest drilled sediments are dated as Middle Miocene at the bottom of Unda, whereas the bottom of Clino reaches an age of Late Miocene (Figure 3). The retrieved lithologies range from platform-interior to platform-margin and slope carbonates; there is no siliciclastic sediment on this isolated carbonate platform (KENTER *et al.*, 1991).

Hole Unda, located 10 km from the modern platform edge, is characterized by three successions of shallow-water platform sands and reefal deposits that alternate with fine-sand and silt-sized deeper marginal deposits. The two intervals of deeper-water sediments record periods of rapid rise of sea level and probable backstepping of the platform and reefal units. Hole Clino, 7 km closer to the modern platform edge, penetrated a single interval of shallow platform and reefal sediments overlying a thick succession of slope sediments. The nearly 500 m of fine-sand to silt-sized slope sediments below 200 m have a variable amount of planktonic foraminiferas and are, except for some intervals with coarse-grained, mainly skeletal sands, remarkably poor in coarser material.

This succession of depositional environments (Figure 3) shows the progradation of the whole platform over the underlying slope sediments. The platform rim prograded over 25 km to the west into the Straits of Florida (EBERLI and GINSBURG, 1989).

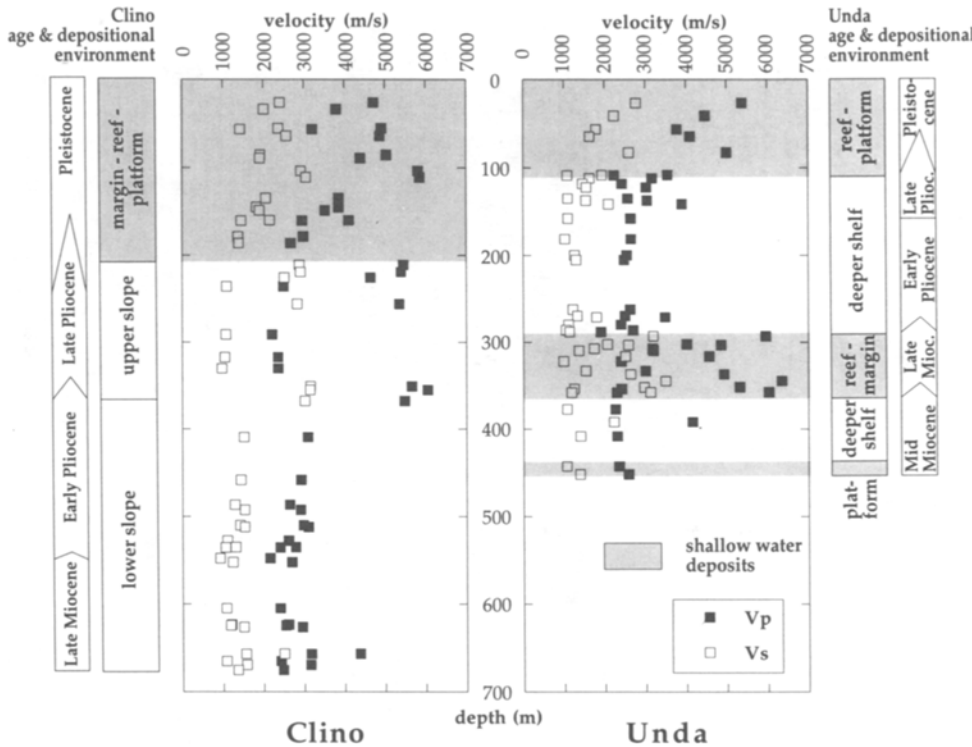


Figure 3

Correlation of V_p and V_s (at 8 MPa effective pressure) with depth, depositional environment and age of the drilled sediments from the two drill holes Unda and Clino on Great Bahama Bank. Velocity inversions are common in both holes and show that the effect of diagenetic alterations and sediment type dominate over the velocity effect of depth. Velocities of carbonates that were deposited on the shallow water platform (shaded areas in graph) have larger variability and higher velocities than velocities from deeper water samples.

Not only the depositional lithology, but also the diagenetic overprinting changes several times downhole. The upper parts of both holes are characterized by early marine and subsequent intense freshwater diagenesis. Many samples show intense dissolution features, as well as extensive cementation, which led to specific rock fabrics with characteristic elastic properties. In the lower part of Clino, the periplatform slope sediments show no major alterations and only the platform derived turbidite layers are more cemented. Little dolomite occurs below a hard-ground at 536 m. Dolomitization in Unda is considerably more pervasive and forms either a fabric destructive sucrosic dolomite or a crystalline mimetic dolomite (Dawans and Swart, 1988), depending on the precursor. In the lowest part of Unda, dolomite disappears and the rocks again show intense dissolution features.

C. *Velocity Samples from Outcrops: Montagna della Maiella (Abruzzi, Italy)*

The Maiella is an uplifted and exhumed carbonate platform in Central Italy (Figure 4) that is exposed in several valley flanks. The exposed platform and slope carbonates range in age from the Lower Cretaceous to the Upper Miocene. One hundred and one samples were collected and velocities were determined. The knowledge of the physical properties in combination with the assessment of the large-scale geometrical pattern of the outcropping rock formations enables us to calculate synthetic seismic sections using computer simulations in order to see the seismic response of a particular geological setting (ANSELMETTI and EBERLI, 1991).

The margin of the Maiella carbonate platform is characterized by a steep escarpment during Early Cretaceous time that became buried during the Late Cretaceous and developed into a low-angle ramp in the Paleogene. The sediments of the external platform are mostly rudist biostromes and carbonate sandbodies whereas the platform interior is mainly made of limestones deposited in a shallow subtidal to supratidal environment, such as wackestones and fenestreal mudstones (CRESCENTI *et al.*, 1969; SANDERS, 1994). A distinct mid-Cretaceous, karstic unconformity separates the Cretaceous platform section into an upper and a lower unit. On the adjacent slope, several mega-breccias onlap this platform margin (EBERLI *et al.*, 1993; VECSEI, 1991). They were deposited during sea-level lowstands that caused the exposure of the platform top and the erosion and downslope

Figure 4
Map showing the location of the Montagna della Maiella, in the Abruzzi, Central Italy.

transport of platform fragments. These breccias are intercalated with calcareous turbidites and pelagic carbonates that form the normal background sedimentation. In the lower Paleogene, a relative deepening of the platform resulted in a backstepping of the platform margin and the steep escarpment was slowly infilled. Finally, during the Oligocene, reefal units of the platform margin prograded over the former deeper shelf and slope deposits and formed a wide and shallow shelf. This general evolution of backstepping and prograding of an isolated carbonate platform has striking similarities with the evolution of the modern Great Bahama Bank.

Unlike the Great Bahama Bank, the Maiella platform shows almost no signs of dolomitization. This explains why, despite their older age, most samples are better preserved than many dolomitized Bahamas carbonates. Some of the bioclastic sands of the Upper Cretaceous still have porosities of over 30%, whereas most of the platform deposits are densely cemented.

3. *Methods*

A. *Sampling Technique*

The samples used for velocity determinations are cylindrical miniplugs 2.5 or 3.8 cm in diameter. The miniplugs of unconsolidated mud from Florida Bay were sampled from short push cores 7.6 cm in diameter. So as to avoid compaction and fabric destruction during sampling, a thin-wall tube with a diameter of 3.8 cm was used to cut the miniplugs vertically out of the cores. The 2–4 cm long cylinders were compacted longitudinally by a hydraulic press with a uniaxial pressure of up to 170 MPa. The velocities of the mud samples were measured at variable degrees of compaction. The maximum compaction reached was approximately 50% so that the initial porosity of 63% was reduced to 26%.

The samples from the Bahamas deep drillings were cored horizontally, or occasionally vertically, into the 7.6 cm diameter cores. Plugs from the Maiella were cored from hand samples collected in outcrops. All rock cores were trimmed to a length between 1.5 and 5 cm. The end surfaces were polished to make them flat and parallel in order to allow a good transmission of the acoustic signal.

B. *Velocity Measurements*

The velocities from all Bahamas samples and from 29 of the Maiella samples were measured applying a pulse transmission technique (BIRCH, 1960) with an apparatus shown in Figure 5. The velocity samples were water saturated and jacketed in rubber or heat shrink tubing which seals the pore fluid from the confining oil in the pressure vessel. Confining and pore-fluid pressures are chosen

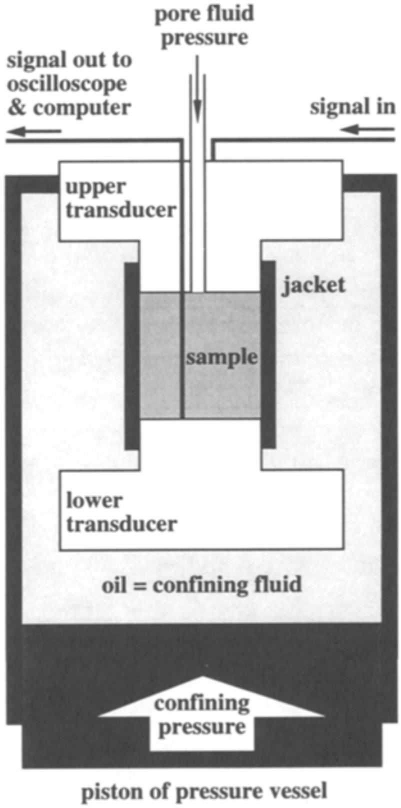


Figure 5
Schematic cross section of ultrasonic velocity meter.

independently to simulate most accurately *in situ* conditions of a buried sediment. Pore-fluid pressures as high as 50 MPa can be obtained but most experiments were run at 2 MPa. Confining pressure is varied between 3 and 100 MPa, resulting in an effective maximum pressure (confining pressure minus pore-fluid pressure) of up to 98 MPa. However, many samples collapsed and failed at pressures below 100 MPa.

Within the end caps, piezoelectric crystals create a signal with a center frequency of 0.6 to 1.2 MHz. The same pair of transducers generates one compressional-wave signal (V_p) and two orthogonally polarized shear-wave signals (V_{s1}, V_{s2}). The transducers are arranged so that the waves propagate along the core axis. The electrical signal produced by the receiver crystal is amplified, filtered, and fed into a digital oscilloscope. The oscilloscope digitizes the ultrasonic signals and transfers the digitized waveforms to a Macintosh Quadra computer for display and time series analysis. A customized analysis software package collects the data as a function of effective pressure, and calculates the travel times of the signals as well as the three velocities (V_p, V_{s1}, V_{s2}) at every pressure step. The V_s used for the calculation of the V_p/V_s ratio is the mean V_s of the two measurements.

The velocities of the compacted mud from Florida Bay were measured with the same set of transducers but with a benchtop measuring system not under confining pressure. This measuring system allows recognition of compaction due to the axial pressure of the transducers during the measurement. The two transducers were pressed together with a piston at an axial pressure of 0.1–1 MPa. This relative low pressure allowed the transmission of the signal from the transducers into the mud but did not compact drastically the still deformable mud samples. Some measurements were performed on uncompacted mud, however the minimal required transducer pressure reduced the sample length by a few percent. Corrections for length change are made so as not to produce errors in the velocity determination.

A part of the Maiella miniplugs (72 samples) was measured with a similar apparatus in the petrophysics laboratory at the University of Geneva, Switzerland. The transducer pair of this machine only creates a p-wave signal. Measurements were performed dry without pore-fluid pressure and under confining pressures varying up to 400 MPa.

The precision of the velocity measurements is mainly a function of the quality of the sample. In well cemented, high velocity samples, the lower transducer receives a clear peak as first break which allows measurements of velocity with an error of less than 1%. Friable, unconsolidated samples tend to compact and reduce their sample length by up to 5%. In addition, they sometimes produce only a moderate first break signal, especially for V_s, so that the error of velocity determinations in these difficult samples probably amounts to approximately 5%.

C. *Additional Properties*

In addition to the velocity determinations, several other analyses were performed. Dry bulk densities were calculated by weighing the oven dried rock plugs and calculating the volume by measuring diameter and length. XRD analyses were performed on the cut-offs of drilled plugs from the Bahamas samples. Calibration with carbonate-standards allowed determination of the percentage of calcite, dolomite and aragonite. Because these almost pure carbonates consist dominantly (>95%) of three carbonate minerals, the percentage of the minerals determines a theoretical grain density:

$$\rho_{\text{grain}} = \frac{\%\text{calcite} \cdot \rho_{\text{calcite}} + \%\text{dolomite} \cdot \rho_{\text{dolomite}} + \%\text{aragonite} \cdot \rho_{\text{aragonite}}}{100}$$

$$\rho_{\text{calcite}} = 2.71 \text{ g/cm}^3; \quad \rho_{\text{dolomite}} = 2.87 \text{ g/cm}^3; \quad \rho_{\text{aragonite}} = 2.93 \text{ g/cm}^3.$$

The rock porosity is calculated by comparing the calculated grain density with the measured dry or saturated bulk density

$$\frac{\%\text{porosity}}{100} = \frac{\rho_{\text{grain}} - \rho_{\text{bulk}}}{\rho_{\text{grain}} - \rho_{\text{fluid}}}.$$

This easy way to determine rock porosity in pure carbonates was compared with the results from other techniques such as helium densitometry and Archimedes principle. Our porosity values are systematically 0–3% higher than porosities obtained by the other methods. The difference is caused by the fact that the helium densitometry as well as the Archimedes method are based on penetration of a pore fluid or gas (water, and helium respectively) into the pore space and therefore are a function of permeability. In addition, isolated and closed porosity is not penetrated by the pore fluid and is therefore not detected, whereas our method based on the density and X-ray analyses also considers this closed porosity.

Cut-offs of the mini-plugs were also used to make thin sections from most velocity samples. Thin sections were examined in order to determine factors such as sediment type, composition, grain size, porosity type and diagenetic alterations. These examinations enable us to correlate the physical properties with the lithological parameters.

4. *Velocity Data*

A. V_p *and* V_s

In the following descriptions and correlations, velocities at a confining pressure of 10 MPa and a pore-fluid pressure of 2 MPa are discussed. The resulting effective pressure of 8 MPa (10 MPa for dry samples) is high enough to allow a good signal transmission but does not cause significant fracturing in the high porous samples. The V_p measurements on dry samples are also presented here because major differences between dry and saturated V_p only have to be expected in rocks with a dominant crack porosity (NUR and SIMMONS, 1969), whereas the saturation of round-shaped pores, abundant in our samples, does not influence V_p drastically.

Despite the limited variability in mineralogy, the measured carbonates have an extraordinarily wide range in velocities. V_p varies between 1700 and 6500 m/s, V_s between 700 and 3400 m/s. The three different data sets have different ranges in V_p and V_s (Figure 6). The unconsolidated mud samples from Florida Bay have the lowest velocities with a minimum V_p and V_s of 1700 and 700 m/s, respectively. The Bahamas and the Maiella samples reach velocities of up to 6500 m/s (V_p) and 3400 m/s (V_s). Unlike siliciclastic sediments, where variations in mineralogy (e.g., clay-content) can cause large velocity contrasts, the different carbonate minerals, calcite, dolomite and aragonite, have very similar physical properties so that

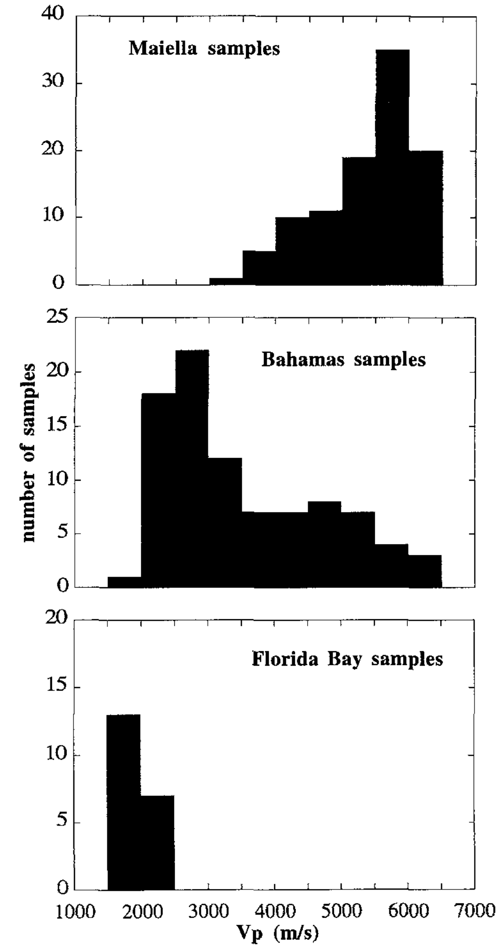


Figure 6

Range of V_p for the three investigated areas (at 8 MPa effective pressure). The Maiella samples have a higher average velocity than the Bahamas samples. The artificially compacted mud samples from Florida Bay have, despite compaction of up to 50%, only low velocities. The large range of velocity in all samples is remarkable for the restricted mineralogy of the pure carbonates.

differences between them cannot be responsible for the large variability in velocities. Consequently, the wide range of V_p and V_s in carbonates has to be explained with different fabrics and textures and not with the different minerals of the rocks.

B. *Acoustic Impedance*

The observed range in V_p and V_s and therefore the large contrasts in acoustic impedance (Figure 7) can explain the excellent seismic reflectivity of many seismic

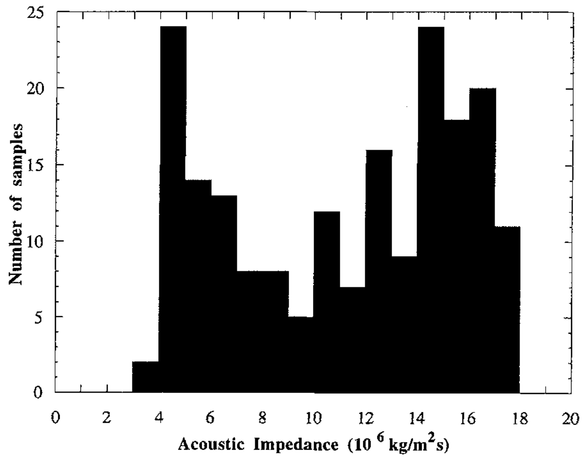


Figure 7
Range of acoustic impedance of the Bahamas and Maiella samples (at 8 MPa effective pressure). Impedances of high velocity and dense rocks are over five times higher than impedances of low velocity rocks. These impedance variations in the pure carbonates are caused by differences in fabric and not by differences in composition. The large range explains the good reflectivity observed in many seismic sections of carbonates.

sections in pure carbonates. The two drillholes in the Bahamas, for instance, have acoustic impedance values that range from $3.8-17.4 \cdot 10^6$ kg/m^2 s. The observed good reflectors on seismic sections, often believed to be caused by intercalations of noncarbonate sediments, can in fact be explained by variations in the fabric of the carbonates.

C. V_p/V_s

Similar to V_p and V_s, the V_p/V_s, which was only measured under saturated conditions, also has a wide range. The cross plot of V_p/V_s with V_p (Figure 8) shows that the ratio in indurated rocks with high V_p normally falls between 1.8 and 2. At lower V_p, the V_p/V_s ratio can reach substantially higher values of up to 2.6. These higher V_p/V_s ratios reflect the fact that in general V_s is more affected by the highly porous fabric of the low-velocity carbonates than V_p. It must be taken into account that some readings of the shear wave velocity and thus the V_p/V_s ratio might have a large error, due to a bad V_s-signal quality, e.g., when a low shear wave amplitude is combined with a high background noise. Therefore some of the extreme V_p/V_s values might be unreliable; however, these few values do not change the general pattern of the V_p/V_s range. The artificially compacted samples from Florida Bay have an extreme range of V_p/V_s from 1.7 to 2.8 within a narrow range of V_p from 1700 to 2300 m/s. The uncompacted mud-fabric with a porosity of approximately

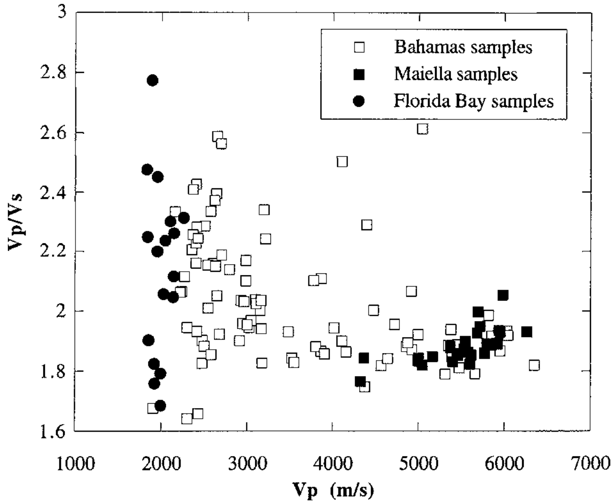


Figure 8

V_p/V_s as a function of V_p (at 8 MPa effective pressure). The wider range of V_p/V_s towards higher values in low velocity rocks shows that shear waves are more affected by high porosity fabrics than compressional waves. Some of the extreme low and high values might be caused by a questionable registration of the arriving V_s signal, in particular in high porosity rocks.

63% is not strong enough to sustain shear stresses (LAUGHTON, 1957) and inhibits transmission of the shear-wave signal. The little compacted mud samples have high V_p/V_s of up to 2.8. With increasing compaction, the V_p/V_s of these Florida Bay samples approach more "normal" values around 2.2.

5. *Factors Affecting Velocity*

In many sedimentary rocks, the concept of grain and matrix supported fabric with a critical porosity is able to explain the variations in velocity (NUR *et al.*, 1991) and to relate them to differential composition. The high susceptibility of carbonates towards diagenetic changes however, causes cementation, dissolution and recrystallization processes that form rock fabrics unique to carbonates with velocity patterns that do not simply reflect the compositional variations of the sediment.

Acoustic velocity in carbonates is a complex funciton of several factors. We can distinguish between rock-intrinsic and rock-extrinsic parameters. Intrinsic parameters, such as porosity, pore type, composition or grain size, are factors that are connected with the lithology and thus, with the physical properties of the rock fabric. Rock-extrinsic parameters are factors that are not physically connected to the rock fabric, but are determined by external boundary conditions. Examples of rock-extrinsic parameters are burial depth, confining pressure and age of the sediment. It will be shown that in carbonates the rock-intrinsic factors are more important than the extrinsic ones.

A. *Velocity as a Function of Rock-extrinsic Parameters*

The effect of mechanical compaction

The compaction experiments and the velocity measurements on modern carbonate mud from Florida Bay were performed to determine the change in velocity due to a porosity reduction from solely mechanical compaction. The samples are pure carbonate mud and have a special lithology that is rarely encountered in the other measured carbonate samples. However, most of the measured samples have, together with the coarser grain fraction, a large amount of micrite in the matrix. Therefore, we suspect that compaction in our other samples would have a similar effect on velocity as in the compacted mud.

It is known that porosity has a major influence on velocity and a porosity decrease usually produces a velocity increase. The Florida Bay samples show a relatively subtle increase in velocity with increasing compaction or decreasing porosity (Figure 9). At porosities close to 60%, poorly compacted samples have a V_p of 1700 m/s and no measurable V_s. The samples had to be compacted by 10–15% in order to receive a V_s signal. This corresponds well with the measurements of LAUGHTON (1957) who only detected shear waves in unconsolidated

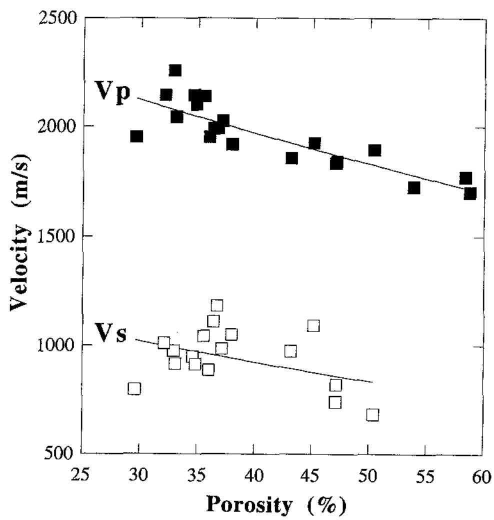


Figure 9
Increase of V_p and V_s at decreasing porosities in the differently compacted Florida Bay samples. The velocity increase is the effect of pure compaction. Initial porosity of the carbonate mud is on average 63%. The little compacted samples with porosities above 50–55% could not transmit a V_s signal.

ocean sediments above a compacting pressure of 5 MPa. At maximum compaction with porosities of 29%, V_p increases to 2200 m/s and V_s lies around 900–1100 m/s. The gradient of the measured increase in velocity of the compacted mud is significantly lower than the observed gradients in the other Bahamas and Maiella samples (Figure 10). The mud samples display, due to their low shear modulus, a behavior similar to material that has no rigidity as suggested by HAMILTON (1971). He showed that, unlike liquids, most unconsolidated marine sediments do possess rigidity (shear modulus > 0) and have a definite structure. The Wood equation (WOOD, 1941), valid for mediums without shear modulus or rigidity, can be used to compare the observed porosity-velocity relation of the artificially compacted sediments.

$$V_p = [(\Phi\beta_{\text{fluid}} + (1 - \Phi)\beta_{\text{solid}})(\Phi\rho_{\text{fluid}} + (1 - \Phi)\rho_{\text{solid}})]^{-1/2}$$

Φ = fractional porosity; β = compressibility; ρ = density.

The Wood equation was calculated using values for water ($4.06 \cdot 10^{-10}$ m^2/N) and for calcite ($1.34 \cdot 10^{-11}$ m^2/N) compressibility, because the elastic properties of aragonite are not well-known. The comparison of the calculated with the measured velocities reveals that the measured velocities of the mud samples are in fact only slightly above the values predicted by the Wood equation, whereas all other samples that were altered during diagenesis show much higher velocities (Figure 10). The

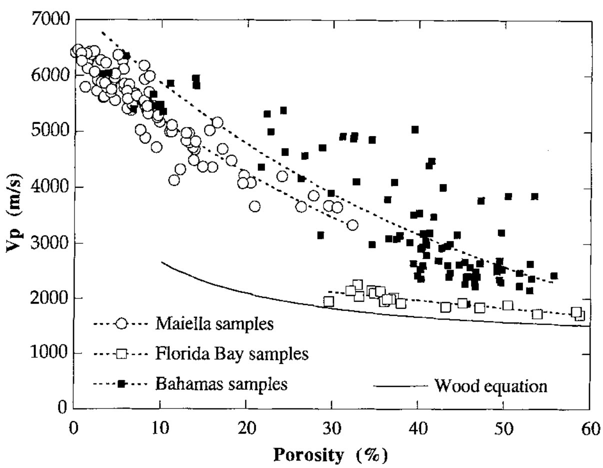


Figure 10
Velocity as a function of porosity for the three data sets. V_p and porosity show clearly an inverse correlation, but the gradient of increasing V_p at decreasing porosity is much lower in the compacted Florida Bay samples than in the natural rocks of the Bahamas and the Maiella. Velocities of the mud samples are only slightly higher than velocities of mediums without rigidity, calculated using the Wood equation (WOOD, 1941). This shows that porosity reduction due to mechanical compaction has only a minor effect on V_p, whereas porosity reduction due to diagenetic processes (e.g., cementation) can increase rigidity which results in higher velocities.

lower gradient for the mud samples can thus be explained by the absence of additional processes that increase the rigidity of the rock and normally accompany the compaction of sediments. The artificial compaction experiments happen so fast that no diagenetic alterations are initiated. Normally, the effects of diagenetic processes, such as recrystallization or cementation, are superimposed on the effect of porosity reduction. The velocity, therefore, represents the combined effect of these different processes. The difference between the velocity-porosity correlation in natural rocks and in the artificial compacted rocks demonstrates how much diagenesis contributes to the observed velocity increase. In fact, our samples document that diagenetic alterations are more effective in increasing velocity than compaction, because they significantly increase the rigidity of the rock.

With a uniaxial pressure of 170 MPa, the porosity could not be reduced to under 29%, indicating that the microfabric of the rock, consisting of 65% aragonite needles, is close to the densest packing that can be reached just by mechanical compaction. This experimental compaction also shows that pure mechanical compaction only plays a minor role in carbonates. Samples with porosities between 0 and 25 percent can only reach their actual porosity with the aid of diagenetic closing (cementation) of part of the pore space.

Burial depth and age of the sediment

The measured samples taken from the two core borings of the Bahamas Drilling Project clearly show that in these carbonates, velocity is neither primarily a function of the sediment age, nor of the burial depth. In contrast to the usual assumption that velocity increases with depth (HAMILTON, 1980; JAPSEN, 1993), the depth plots of V_p and V_s (Figure 3) in the two drillholes display velocity inversions that make velocity predictions, based only on depth, impossible. Both holes display a pattern of high variability of velocity in the carbonates that were deposited in a shallow-water environment like sediments from the reef, platform margin or platform interior. These high velocity zones, in Clino above 220 m and in Unda between 290 and 370 m and above 120 m, overlie zones of low velocities that cause the observed velocity inversions. The distinct jump to higher velocities at Unda 293 m, for instance, marks the transition from a fully dolomitized carbonate sand to a dolomitized reefal unit. Below the reefal unit, both V_p and V_s decrease again, resulting in a velocity inversion. Rocks of the low velocity zones are mostly carbonates that were deposited in deeper water and underwent less diagenetic alteration than the shallow-water carbonates. The inverse trend with decreasing velocities at greater depths indicates that diagenetic processes other than simple compaction substantially control the velocity evolution. In the young sediments of shallow Clino and Unda, high velocities are attained due to intense diagenetic alterations which occur much faster than compaction due to an increased overburden.

The Maiella carbonates also demonstrate that depth, or in this case age, does not necessarily influence velocity. Some of the Upper Cretaceous rudist sands are among the oldest but also have the slowest velocities of the measured samples from this data set. The V_p of 3300 m/s is remarkably low for Cretaceous carbonates, documenting again the insignificance of absolute age for velocity evolution in these samples. The reason for this low velocity is the preserved high porosity and the associated interparticle pore type.

As a consequence, the depositional environment and the diagenetic alteration is much more important for velocity evolution than age or depth. Velocity predictions cannot be made solely with the knowledge that a carbonate sediment has a certain age and/or is at a certain depth, rather the acquisition of some additional, intrinsic rock parameters is necessary to produce a reliable velocity estimation.

Effective pressure

To investigate the pressure dependence of V_p and V_s, sonic velocities of the Bahamas and Maiella samples were measured under varying confining and pore-fluid pressures. Sonic velocity in rocks is a function of the differential pressure, or effective pressure, which is the difference between the confining and the pore-fluid pressure. Minor departures from this relation are caused by changing pore-fluid properties at different pressures (COYNER, 1984).

At low pressures, all samples show an increase in velocity with increasing effective pressure due to better grain contacts, changing pore shapes and closing of microcracks (GARDNER *et al.*, 1974). This increase is large for slow, unconsolidated samples, whereas the velocities of indurated, dense samples are usually less affected by higher pressures. All velocity-pressure traces of the Bahamas samples plotted in the same graph (Figure 11) display a systematic pattern with higher gradients for low-velocity samples and lower gradients for fast samples. A minor part of the observed velocity increase is an artifact because compaction at increasing pressures reduces the sample length which is used to calculate the velocities.

A characteristic of many samples is that both V_p and V_s reach a maximum during increasing pressure and suddenly begin to decrease above a critical pressure. This velocity decrease is caused by a continuous disintegration and collapse of the sample in the pressure vessel, which progressively destroys the partly cemented grain contacts that supported the transmission of the acoustic signal. Eventually, velocity can increase again (e.g., sample Unda 141 m, Figure 12d) because the newly formed fractures that reduced the velocity can close by a further increase in confining pressure. In these samples, velocities that are measured under decreasing pressure at the end of a hysteresis loop (Figures 12d,e) are much lower than at the same pressures in the first part of the loop, because the fractured plugs completely fall apart and form an unconsolidated fabric with loose fragments. V_p/V_s increases dramatically above the critical pressure (Figure 12f) and continues to increase with decreasing pressure in the hysteresis loop. Shear-wave velocity is extremely affected

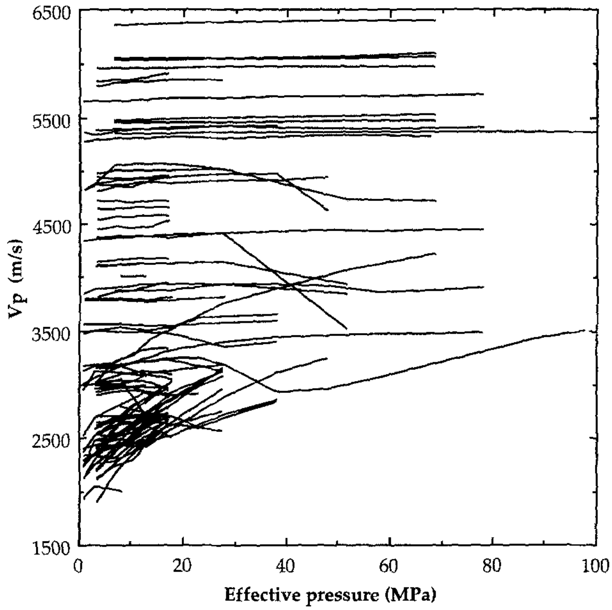


Figure 11
Velocity evolution of the Bahamas samples at increasing effective pressure. Each trace represents the velocities for one sample at different pressures. The gradient of low-velocity samples is higher than the increase of velocities in samples with high velocities. Decreasing velocities at higher pressures mark a critical pressure at which the samples are intensely fractured and collapse. A minor part of the velocity increase is an artifact caused by compacted sample length, that is used for velocity calculation.

by the destroyed fabric that results in a nonelastic behavior. A similar behavior with decreasing velocity during increasing pressure was also observed in some Cretaceous samples from the Maiella, indicating that age or burial depth is not a guarantee for consolidation and lithification of a carbonate sediment.

In contrast to the nonelastic behavior, the hysteresis loops of fast, more lithified samples (e.g., sample, Clino 657 m (Figures 12a–c) show a gentle increase in velocities with increasing pressure. V_p, V_s and also V_p/V_s eventually reach a plateau at high pressures and they nearly reach the former velocities at decreasing pressures. In these cases, the plugs are perfectly intact when they are removed from the pressure vessel, documenting the elastic behavior of the high-velocity rocks.

The critical pressure at which the first velocity decrease occurs varies with the different lithologies. Dense, indurated rocks display no evidence of fabric destruction up to the highest measured pressures of 100 MPa, whereas soft, unconsolidated samples show signs of velocity decrease already at 5 MPa. These low critical pressures demonstrate that some carbonates, especially most slope deposits or sucrosic dolomites, became buried without being progressively indurated. Under hydrostatic conditions, an effective pressure of 5 MPa is equivalent to a burial of

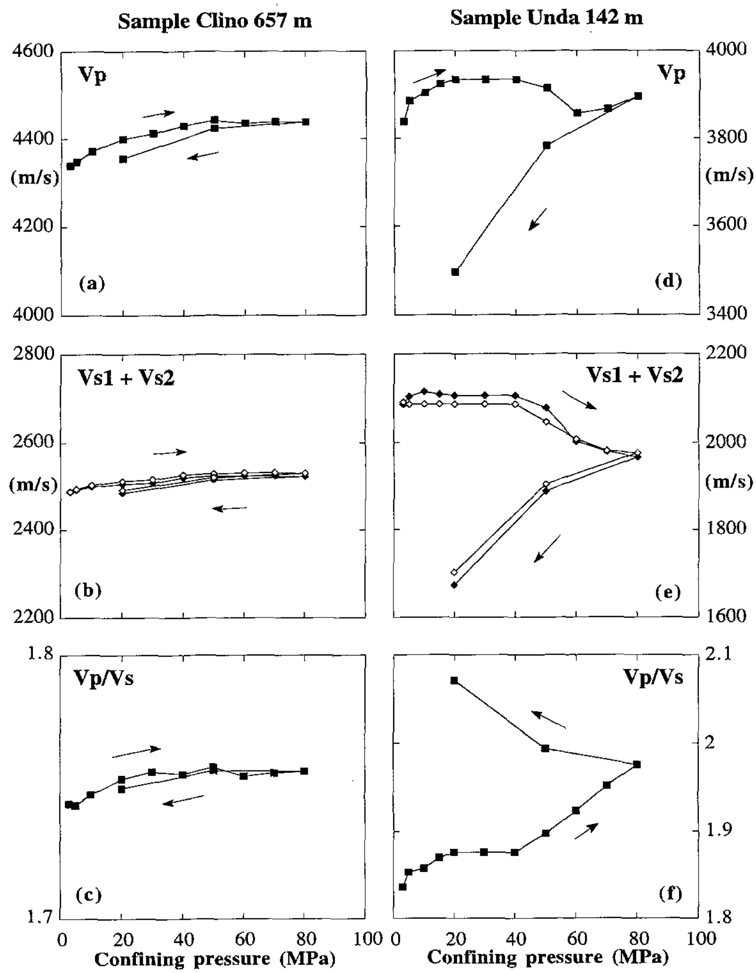


Figure 12

Two examples for elastic and nonelastic behavior: Sample Clino 657 m shows a steady increase in V_p (a) and V_s (b); this increase is mainly caused by the closing of microcracks at elevated pressures. The increasing V_p/V_s (c) shows that V_p increases more than V_s. The values reach a plateau at high pressures and approach starting conditions at the end of the hysteresis-loop. After the experiment, the plug shows no signs of damage. Sample Unda 142 m shows a similar increase in V_p at low pressures but at a critical pressure of 40 MPa, V_p and V_s start to decrease (d and e). This decrease is the result of fabric destruction in the pressure vessel. The plug is fractured and cemented grain contacts are destroyed so that velocities decrease. Above 60 MPa, V_p starts to increase again (d) because the newly formed fractures are progressively closed. With the release of pressure, V_p and V_s decrease dramatically because the fractured plug disintegrates. The V_p/V_s increases remarkably above the critical pressure (40 MPa) and becomes even higher at the end of the hysteresis-loop (f). Pore-fluid pressure equals 2 MPa for all samples.

less than 500 meters. Therefore, some parts of the drilled cores must have *in situ* conditions that cause development of cracks and fractures. This observation coincides well with open or partly cemented fractures that are visible in part of the cores. Also remarkable is that many samples show no signs of fabric destruction up to high pressures, demonstrating that porosity within partly cemented rocks can be preserved, even at pressures of 100 MPa or at depth of approximately 5 km.

B. *Velocity as a Function of Rock-intrinsic Parameters*

Depositional lithology

The lithology of a carbonate sediment at the time of deposition has strong influence on the evolution of velocity, in that it controls future alterations of the rock. At the time of deposition all unconsolidated sediments have similar velocities between 1550 and 1800 m/s. The different lithologies have, despite their similar velocities, different susceptibilities to diagenetic alteration that will change the physical properties and thus the velocities. The diagenetic susceptibility of special sediment types causes fast or slow alterations of the rock fabric, depending on the diagenetic potential of the sediment (SCHLANGER and DOUGLAS, 1974) and on the diagenetic regime.

The diagenetic potential in carbonates is mainly a factor of the grain size and the amount of metastable minerals. A high content of fine-grained micritic material, as found in mud or wackestones, results in a low permeability. The resulting low fluid flow inhibits or slows diagenetic alterations that rely on transport of chemical components in the water. In contrast to fine-grained rocks, sediments with a grain-supported fabric and a low content of micrite (grain- to packstone) have a higher permeability and, as a consequence, a higher fluid flow. This accelerates diagenetic processes and the sediment is quickly altered and consolidated. Thus, original coarse-grained rocks can reach higher velocities after a short time of burial, whereas fine-grained rocks tend to preserve their unaltered fabric and their slow velocity for longer burial durations.

In addition to grain size, the amount of metastable minerals, such as aragonite or high-magnesium calcite controls the diagenetic potential (SCHLANGER and DOUGLAS, 1974). A high amount in metastable components causes a high diagenetic potential and leads to a rapid dissolution or recrystallization of the sediment. This alteration can enhance the elastic properties and increase permeability, resulting in accelerated lithification.

The comparison of the velocity range with the depositional environment confirms these relationships. For example, if the Maiella samples are grouped into two categories of depositional environment, (1) platform deposits and (2) basin, slope and deeper shelf deposits (Figure 13), the velocity range of the two categories form two different clusters that only overlap in the high velocity area. The platform

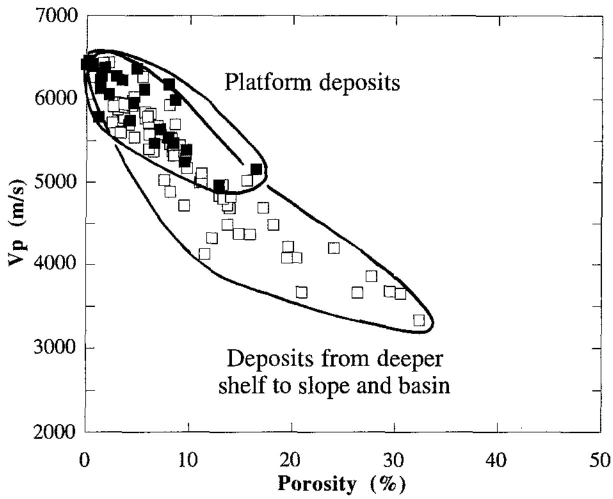


Figure 13
Velocity vs. porosity (at 8 MPa effective pressure) compared with depositional environments from the Maiella samples. Carbonates deposited on the shallow-water platform have a narrow range with high V_p and low porosities. Sediments from the deeper shelf, slope or basin show a higher variability towards lower V_p, but maximal V_p are the same as in the platform rocks.

carbonates have a significantly higher average velocity than the basin and slope carbonates. In the Bahamas cores, the relation between shallow water deposits and deeper water deposits is slightly different with an overlap of velocities of the two categories in the low velocity area (Figure 3). The majority of the Bahamian slope carbonates are unconsolidated and thus slow, whereas the platform carbonates show a larger range towards higher velocities, but have similar minimal velocities.

The explanation for these observed velocity patterns is that the platform carbonates are usually high in coarse-skeletal grains or non-skeletal grains (ooids, peloids). They consist predominantly of aragonite which is metastable in sea water. Slope or deeper water deposits are normally characterized by a high micritic grain fraction and by a higher content in pelagic calcareous organism (foraminiferas, coccolithes) and consist mainly of more stable low-Mg calcite shells. Therefore, shallow-water carbonates fulfill both conditions for fast diagenetic alterations: coarse grain size and a high amount of metastable minerals. Some turbidites deposited on the slopes, that contain many skeletal and aragonitic fragments from the platform top, are similar to platform deposits (EBERLI, 1988), and thus different from the normal background slope deposits. The differential depositional lithologies explain the different ranges of the velocity measurements in the different sediment types. In the older Maiella samples, most of the platform carbonates had enough time for diagenetic alterations to reach their high, final velocities, and as a consequence cluster at higher values than the slope sediments (Figure 13). In the

Bahamas cores, which are younger than the Maiella samples, not all the platform deposits reach high velocities, but both the average velocity and overall velocity range are much higher than in most of the slope samples. Only the few turbidites in the slope section containing platform derived material have high velocities resulting in some velocity variability (Figure 3).

The data strongly suggest that the depositional environment of a carbonate sediment affects the starting conditions under which a sediment undergoes diagenetic alterations. This indirect influence controls direct, rock-intrinsic parameters such as porosity, pore type, density and mineralogy.

Mineralogy

In siliciclastic rocks, the physical variety of minerals is large (e.g., quartz and clay), and mineralogy has more influence on sonic velocity than in carbonates (CHRISTENSEN and SZYMANSKI, 1991). The minimal influence of mineralogy on velocity in carbonates can be partially explained by the small velocity contrasts of the two dominant carbonate minerals calcite (6500 m/s) and dolomite (6900 m/s). Pure carbonates have little initial velocity differences due to mineralogy. The measured samples from the Bahamas cores are comprised >95% of minerals calcite, dolomite and aragonite and the Maiella carbonates consist almost purely of calcite.

Our data suggest that changes of this mineralogical composition have no major influence on velocity. A plot of the dolomite content versus velocity of the Bahamas samples clearly shows that there is no correlation between dolomite content and velocity (Figure 14). This lack of correlation is also shown by two measured plugs of Unda, only 7 m apart and both made of 100% dolomite: sample Unda 286 m has a V_p of 2697 m/s and a V_s of 1052 m/s, whereas sample Unda 293 m has a V_p and V_s of 5953 m/s and 3187 m/s, respectively. The high-velocity sample is a "reefal"-dolomite with a fabric preserving dolomitic cementation resulting in a total porosity of 14%, whereas the low-velocity sample is a sucrosic dolomite with high interparticle porosity of 49%. This example demonstrates that velocity depends on the type of dolomite and thus the associated porosity and pore type, and that mineralogy alone is not a characteristic parameter for determination of velocity in carbonates.

While the mineralogical composition in carbonates has little influence on velocity, the processes that alter mineralogy, such as sucrosic dolomitization or dolomitic cementation, have a strong influence on velocity. These processes also alter, in concert with changing mineralogy, porosity and porosity type. For example, fabric destructive dolomitization also destroys most of the earlier cementation, creating an undercemented and loose dolostone with petrophysical characteristics similar to a semi-lithified carbonate sand.

Porosity and pore types

Velocity is strongly dependent on the rock porosity (WANG *et al.*, 1991; RAFAVICH *et al.*, 1984). A plot of porosity versus velocity displays a clear inverse

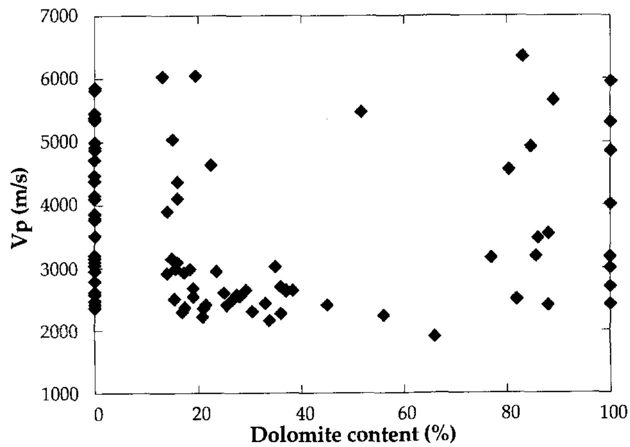


Figure 14

Velocity at 8 MPa effective pressure as a function of dolomite content in the Bahamas samples. There is no correlation between these two factors. Different dolomite types, such as sucrosic dolomite or dolomitic cement have totally different effects on velocity, therefore dolomite content alone cannot be used as an indicator for velocity.

trend; an increase in porosity produces a decrease in velocity (Figure 15). The general trend of the Bahamas and Maiella samples has correlation coefficients of 0.94 for V_p and 0.92 for V_s. Nevertheless, the measured values display a large scatter around this inverse correlation in the velocity-porosity diagram. Velocity differences at equal porosities can be over 2500 m/s, in particular at higher porosities. For example, rocks with porosities of 40% can have velocities between 2100 m/s and 5000 m/s, which is an extraordinary range for rocks with the same chemical composition and the same amount of porosity. This discrepancy is caused by the ability of carbonates to form cements and special fabrics with pore types that can enhance the elastic properties of the rock without filling all the pore space. The high elastic moduli result in velocities that are higher than velocities predicted by theoretical equations, such as the time average equation (WYLLIE *et al.*, 1956), as shown in Figure 15.

In other data sets, such as synthetic sand-clay mixtures (MARION *et al.*, 1992) or siliciclastic sediments (VERNIK and NUR, 1992), a similar scattering in the velocity-porosity diagram is observed. But unlike carbonates, the scattering in these rocks can be explained by compositional variations, in particular by changes in clay content. WILKENS *et al.* (1991) noticed that velocities of low-porous basalts are very dependent on the pore shapes. Samples containing pores with low aspect ratios (cracks) are associated with lower velocities, compared to samples with round pores or high aspect ratios. As a result, high velocity contrasts are observed between rocks without large variations in total porosity. The pores in our high porosity

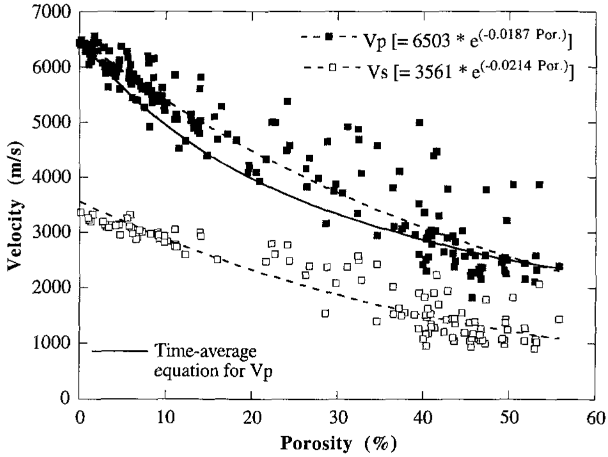


Figure 15

V_p and V_s from the Bahamas and the Maiella samples at 8 MPa effective pressure as a function of porosity with exponential best fit equations (dashed lines). Both V_p and V_s demonstrate the trend of decreasing velocities with increasing porosities, but scatter, especially at higher porosities, around the dotted best fit lines. The scattering is a result of special fabrics and pore types that enhance the elastic moduli of the rock without filling all the pore space. As a consequence, measured V_p are higher than V_p predicted by theoretical equations such as time-average-equation (WYLLIE *et al.*, 1956).

carbonates generally have high aspect ratios. In this case, the high velocity contrasts between rocks with similar total porosity can be related to specific pore types resulting in characteristic and very different elastic properties. Based on thin section observations, the Bahamas samples can be grouped into five categories of predominant pore types which all have characteristic clusters in the velocity-porosity diagram (Figure 16). The five dominant pore types that can be distinguished are:

(1) *Interparticle and intercrystalline porosity (Figures 17a,b):* The porosity between the components of a sediment is the interparticle porosity. This porosity predominates after deposition of a sediment when grains form a loose package with little cementation. Intercrystalline porosity develops at a later stage during diagenesis, when newly crystallized minerals such as dolomite rhombohedra form a loose aggregate. It has a similar petrophysical behavior as interparticle porosity. The accumulation of unconnected grains without cement or matrix results in a low velocity because the rock has low elastic moduli due to the lack of a rigid framework. Most of these samples therefore show a negative departure from the average velocity-porosity correlation (Figure 17c).

(2) *Micro-porosity:* Micro-pores ($<10\ \mu$m) are abundant in carbonate mud, either in a micritic grain or in the micritic matrix. High micro-porosity is thus expected in carbonates with a high micritic content. Due to the lack of cementation that results in an unconnected grain fabric, micro-porosity has a similar effect on

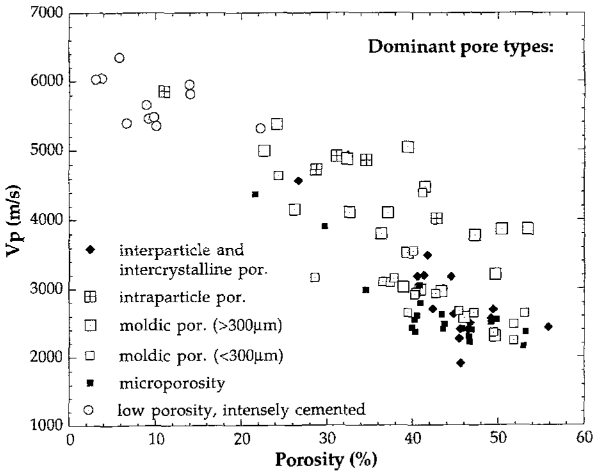


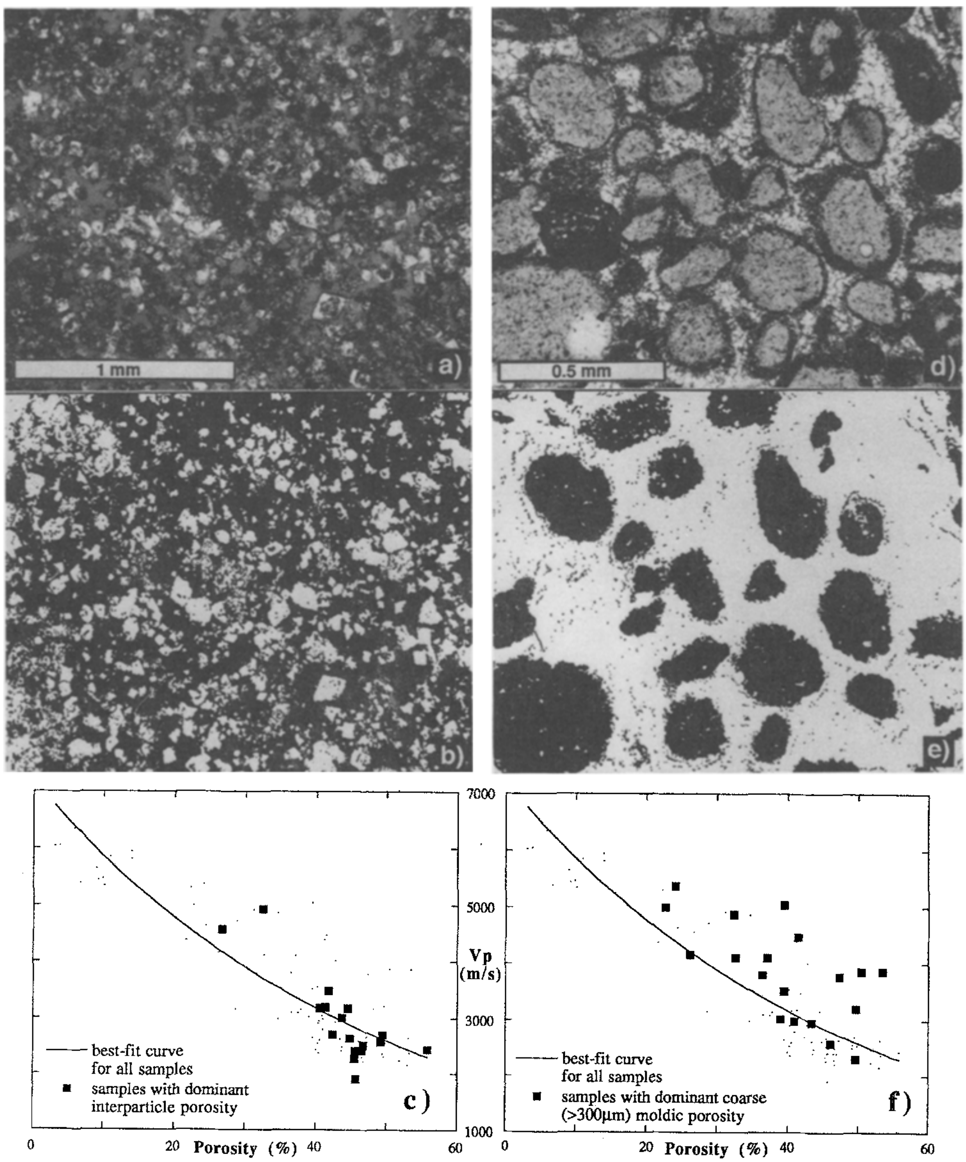
Figure 16
Velocity vs. porosity diagram from the Bahamas samples, with observed categories of different pore types. The large scattering, e.g. velocities from 2200 to 5000 m/s at porosities of 40%, are a result of different predominant pore types in the analyzed samples. Rocks with moldic or intraparticle porosity have positive departures from the general trend whereas rocks with interparticle, intercrystalline or micro-porosity have relatively low velocities and thus show negative departures. Velocities are taken at an effective pressure of 8 MPa.

velocity as fine-grained, interparticle porosity and also shows a negative departure from the average velocity-porosity trend.

(3) *Moldic porosity (Figures 17d,e)*: Moldic porosity develops by dissolution of grains with a metastable mineralogy (e.g., grains of aragonite and high Mg-calcite). Selective dissolution can occur before, after or during cementation of the interparticle pore space. After dissolution, the rock consists mainly of molds and the partially cemented former interparticle pore space which is a fabric type with high elastic properties. Samples in which moldic porosity predominates, have higher

Figure 17
Two examples for pore types with characteristic clusters in the V_p-porosity diagram: a) Photomicrograph of sample Unda 286 m as an example for a rock with intercrystalline porosity. The rock consists completely of micro-sucrosic dolomite. Plug-porosity is 49%. b) Computer scan of photomicrograph above (porosity black, particles white) with characteristic pattern of loose particles (dolomite rhombohedra) surrounded by connected pore space. c) V_p-porosity diagram of all samples with dominant interparticle and intercrystalline porosity. V_p are in general below average trend due to the lack of connections between the grains. d) Photomicrograph of sample Unda 65 m as an example for a rock with coarse moldic porosity. All grains were dissolved after cementation of the interparticle pore space. Plug-porosity is 37%. e) Computer scan of photomicrograph above (porosity black, particles white). The nonconnected molds are integrated in a framework of sparry cement. f) V_p-porosity diagram of all samples with dominant coarse moldic porosity. V_p are significantly above average V_p-porosity trend due to the rigid framework of the rocks.

velocities than expected from their total porosities, and therefore a positive departure from the best fit curve (Figure 17f). These high velocities are caused by the self-supporting framework made of cement and micrite surrounding the molds. The travel time through this framework is faster than through grains that are only connected by point contacts, as found in rocks with interparticle porosity. In



addition, velocity is dependent on the diameter of the molds. Velocities are higher in coarse moldic rocks, whereas fine-moldic samples are relatively slower.

(4) *Intraparticle porosity:* Framestones and boundstones, formed by organisms such as corals or bryozoans, consist of a constructional framework with a porosity that is embedded in the solid frame. Therefore, these samples show a similar velocity-porosity pattern to rocks with coarse moldic porosity that also have a framework with high elastic rigidity, resulting in high velocities. The samples with predominant intraparticle porosity all show positive departures from the general trend in the velocity-porosity diagram.

(5) *Low porosity samples with dense cementation:* These samples show an extensive, blocky cementation with porosities of 20% or less. They are close to the final stage of diagenetic evolution. Velocities are high and close to the intrinsic velocities of the minerals calcite (6500 m/s) and dolomite (6900 m/s). These samples form the upper part of the velocity-porosity correlation line.

As discussed above for the case of the Bahamas samples, the specific effects of the various pore types on elastic properties of rocks explain why rocks with the same porosity can have extremely different velocities. The most significant velocity contrasts at equal porosities are measured between coarse moldic rocks and rocks in which interparticle porosity predominates (Figures 17 and 19). Moldic rocks with 40–50% porosity can have velocities up to 5000 m/s, whereas rocks with interparticle or intercrystalline porosity can have velocities that are up to 2500 m/s or 50% lower for the same porosities. This relationship between pore type and velocity can also be seen in the samples measured from the Maiella. The Cretaceous rudist sands, consisting of individual, not connected rudist fragments with only little cementation, have a predominant interparticle porosity and have therefore very low velocities around 3000 m/s.

As a consequence, velocity estimation for a given carbonate sample should not be performed using only the porosity values, but in combination with an assessment of the pore type. The observed complicated velocity-porosity pattern, which causes a similar impedance-porosity pattern, implies that an impedance contrast between two layers can occur even without a porosity change, due only to different pore types.

Density

Seismic reflection patterns are a function of acoustic impedance and therefore the combined products of velocity and bulk density. In many case studies, only one parameter, either velocity or density, is known and the other factor has to be estimated with empirical correlations. Because density is closely related to porosity, velocity shows a good correlation with density (Figure 18). Despite the good correlation coefficients of 0.94 for V_p and 0.93 for V_s, the data in a plot of velocity vs. density scatters around a best-fit curve which also reflects the carbonate specific pore types. Using the general velocity-density trend in our data set, we can improve

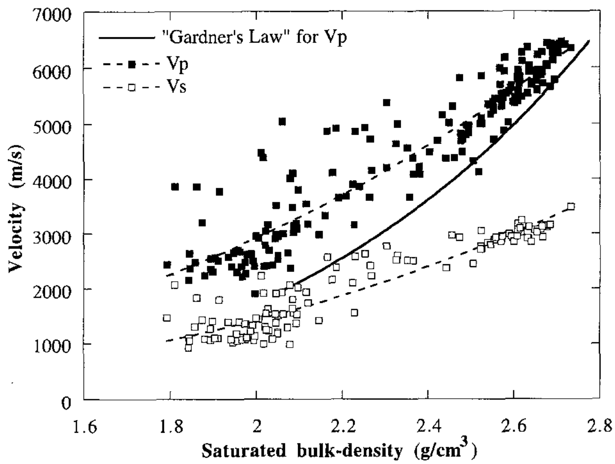


Figure 18
Velocity as a function of density in the Bahamas and Maiella samples at an effective pressure of 8 MPa. The solid line represents V_p calculated by "Gardner's Law" [density(g/cm^3) = $0.23 \cdot V_p$(ft/sec)$^{1/4}$], an empirical formula for all sedimentary rocks, which is often used to calculate impedance values only from velocity or density data (GARDNER *et al.*, 1974). The velocities of the measured carbonates are all higher than the Gardner velocities. The equation has thus to be modified towards higher velocities in order to produce more reliable velocity-density pairs in carbonates (for suggested equations see text).

the velocity-density correlations for pure carbonate rocks because most empirical formulas, such as Gardner's Law (GARDNER *et al.*, 1974), are mainly valid in siliciclastic rocks. Gardner's Law is an empirical equation for sedimentary rocks relating V_p to density.

$$\text{density(g/cm}^3) = 0.23 \cdot [V_p(\text{ft/sec})]^{1/4} \quad \text{or} \quad V_p(\text{m/s}) = 108.9 \cdot [\text{density(g/cm}^3)]^4.$$

This formula is mainly used to calculate impedance values from either density or velocity data so as to make impedance estimations for seismic models in sedimentary sequences. However, all our measured velocities are higher than the Gardner equation predicts. This implies that Gardner's equation, which is an average formula for all sedimentary rocks, requires a modification for carbonates towards higher velocities to predict reliable velocity-density pairs. Based on the data from the Bahamas and the Maiella samples, we suggest these empirical correlations

$$V_p(\text{m/s}) = 524 \cdot [\text{density(g/cm}^3)]^{2.48} \quad V_s(\text{m/s}) = 199 \cdot [\text{density(g/cm}^3)]^{2.84}.$$

These correlations, specific for carbonates, show a better fit and describe more accurately the velocity-density relation, but should not be applied in siliciclastic or mixed carbonate-siliciclastic rocks.

6. *Velocity Evolution during Diagenesis*

Diagenesis is a very important process in carbonates that can transform a lithified sediment into a rock with completely different physical properties. These post-depositional processes can alter porosity and cause transformations into different pore types that produce characteristic patterns in velocity evolution.

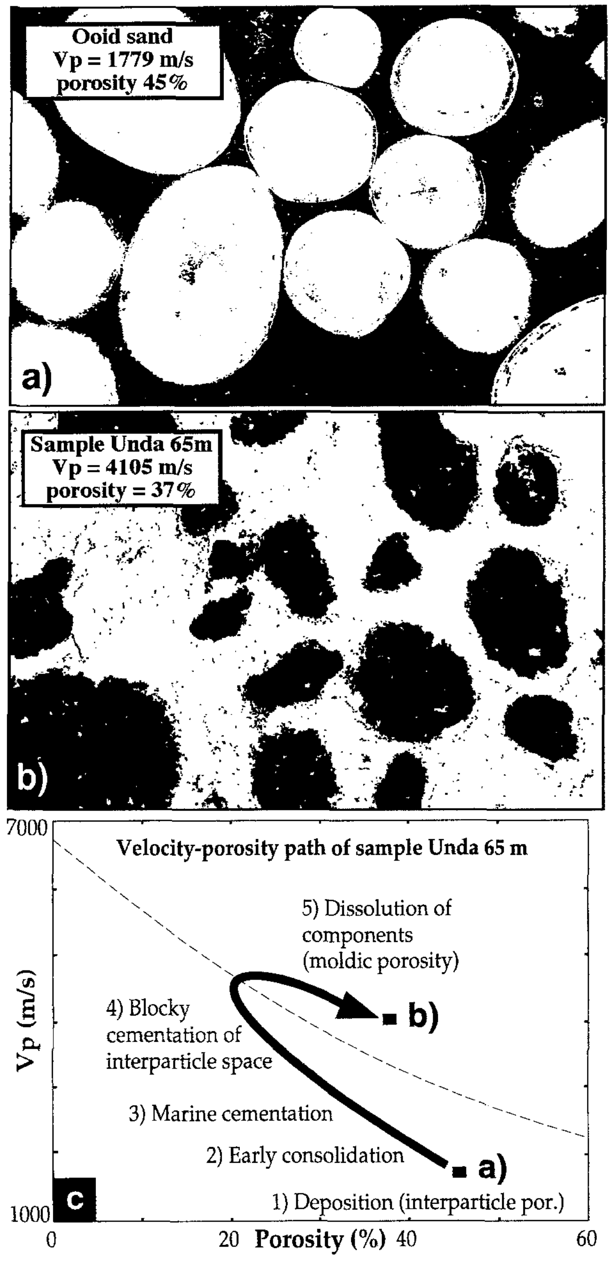
The first process that alters velocity and porosity is early compaction of the sediment: initial consolidation, dewatering and grain rearrangement with no cracking or breaking of the components. Initial values of approximately 50–60% for porosity and 1600 m/s for V_p, change during this first consolidation stage to values close to 40–50% and 2000 m/s respectively (Figure 20a). At this early stage, the sediments are characterized by an interparticle porosity (grainstones) or a high micro-porosity (mud to packstones).

Different diagenetic processes will also affect the future evolution of porosity. The velocity effect of this evolution, in particular the effect of the transformation of pore types, can be described by a velocity-porosity path (Figures 19 and 20). During its burial history, every sediment undergoes such a specific velocity-porosity path, which starts at deposition and ends at the measured velocity-porosity values of the last diagenetic stage. This path is not necessarily a straight line because different pore types are created and eventually destroyed during diagenesis. To pass the different clusters in the velocity-porosity diagram caused by the specific pore types, the shape of the path is rather a curved line which depends on the timing of the diagenetic events.

A good example for a loop during the velocity-porosity path is the fabric inversion of a grainstone to a coarse moldic rock. A clean unconsolidated ooid sand from Cat Cay (Bahamas), that has a depositional, mainly interparticle porosity of 40–50% (ENOS and SAWATSKY, 1981), has a V_p of 1779 m/s at 8 MPa effective pressure (Figure 19a). The "same" rock (sample Unda 65 m), but after cementation of the interparticle pore space and after the dissolution of the ooids and peloids (Figure 19b), has a completely inverted fabric with a porosity of 37% (mainly moldic) and a V_p of 4105 m/s. During the fabric inversion, the rock must have

Figure 19

Example for reconstruction of a porosity-velocity path. Figures (a) and (b) are porosity scans (porosity = black; particles = white) of photomicrographs, short side equals 1 mm. a) Ooid-grainstone at time of deposition (Cat Cay, Bahamas) with interparticle porosity, representing starting conditions of the path; por. = 45%, V_p = 1779 m/s. b) Sample Unda 65 m (also shown in Fig. 17d), por. = 37%, V_p = 4105 m/s, V_s = 1640 m/s. Former ooid(?)-grainstone with coarse moldic porosity. After a few marine alterations and an intense blocky cementation, all grains were dissolved and left molds behind (black). c) Reconstructed velocity-porosity path for a nonskeletal grainstone from deposition (a) to the diagenetic stage observed in (b). The transformation of pore types together with the dissolution of grains that took place after cementation led to a fabric inversion, which resulted in a characteristic loop of the path. The moldic framework (b) provides high elastic rigidity and thus high velocity at high porosity.


Ooid sand
Vp = 1779 m/s
porosity 45%
a)
Sample Unda 65m
Vp = 4105 m/s
porosity = 37%
b)
Velocity-porosity path of sample Unda 65 m
5) Dissolution of components (moldic porosity)
4) Blocky cementation of interparticle space
3) Marine cementation
2) Early consolidation
1) Deposition (interparticle por.)
a)
b)
c
7000
1000
Vp (m/s)
0
20
40
60
Porosity (%)

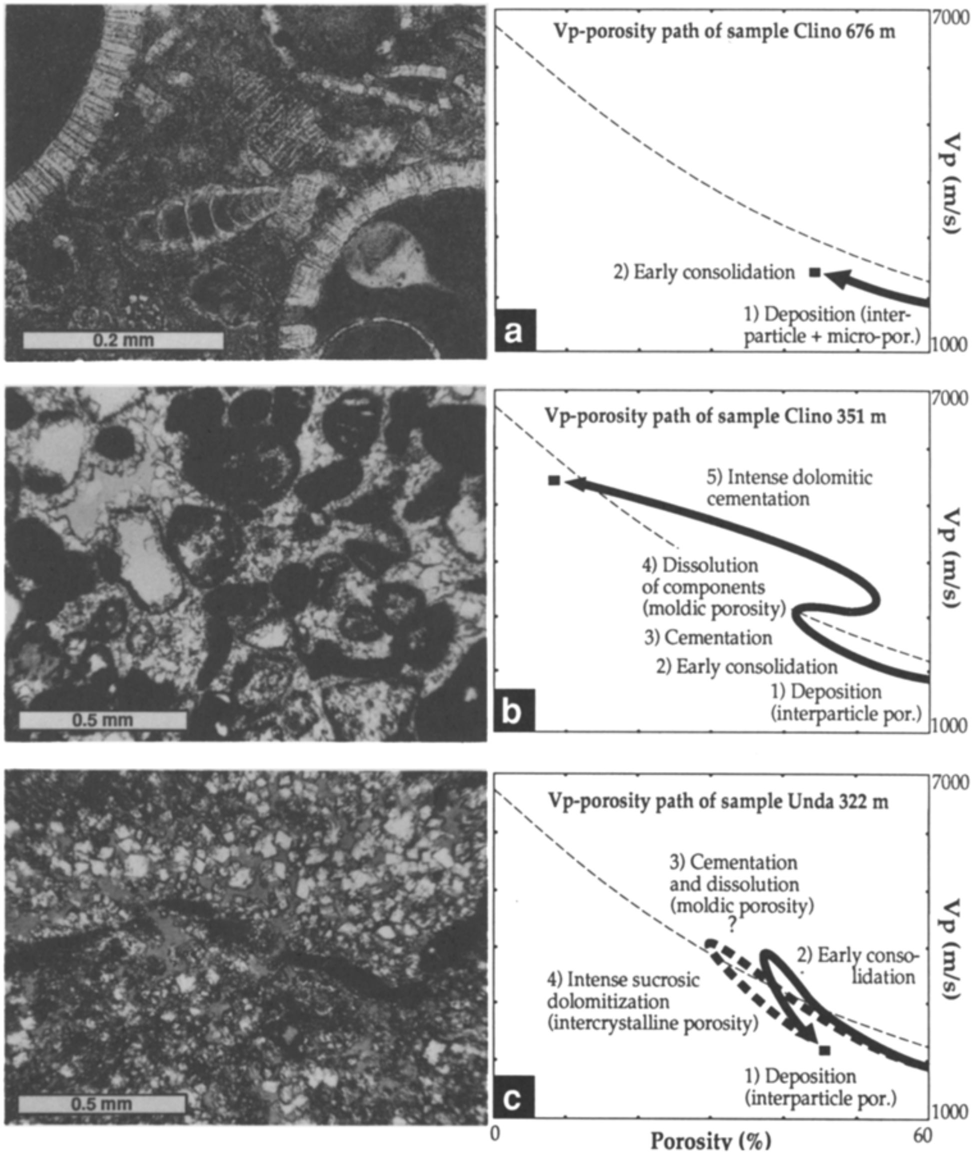


Figure 20

Examples of inferred V_p-porosity paths for specific Bahamas samples from different depths, shown in photomicrographs (left). The black square in the V_p-porosity diagram (right) marks the measured values. The arrow path is constructed by observing the different diagenetic stages of the sample and by relating them to V_p-porosity values. a) Clino 676 m, por. = 44%, $V_p = 2478$ m/s, $V_s = 1356$ m/s. Periplatform slope sediment with globigerinas. Despite the burial depth (deepest sample of both cores) only minor compaction and matrix recrystallization can be observed. The V_p-porosity path is thus a short, straight line from conditions at deposition to present times. b) Clino 351 m, por. = 9%, $V_p = 5661$ m/s, $V_s = 3158$ m/s. Densely cemented grainstone. Similar evolution as in sample of Figure 19, but an additional cementation after dissolution filled the earlier created moldic pore space, resulting in reduced porosity and increased velocity. c) Unda 322 m, por. = 46%, $V_p = 2405$ m/s, $V_s = 991$ m/s. Sucrosic dolomite with few relicts of redalgaes. The sedimentary fabric has been completely destroyed by sucrosic dolomitization that created a dominant intercrystalline porosity.

undergone a stage with a considerably lower porosity, because cementation occurred before dissolution. This stage marks the turning point of the loop in the velocity-porosity path (Figure 19c). This evolution clearly documents how diagenesis can invert the fabric and change the elastic properties of the rocks, even without changing total porosity.

Some samples undergo, in addition to a dissolution stage, a subsequent intense cementation of the newly created moldic pore space (Figure 20b). The beginning of the velocity-porosity path is, in this example, the same as in the example described above, but the last stage of cementation reduces porosity, increases velocity and creates a much denser rock fabric. In contrast to cementation, fabric destructive processes, as shown with the example of sucrosic dolomization (Figure 20c), can decrease velocity and increase porosity of an already altered sediment.

In siliciclastic sediments, the diagenetic potential is much lower than in carbonates, and increasing burial pressure leads to an increase in velocity at greater depth (JAPSEN, 1993). All the described diagenetic processes occur much faster than compaction and the carbonate sediments are quickly dissolved, cemented and recrystallized. These processes control and alter the velocity before compaction can play a significant role. The dominance of lithification by diagenesis over lithification by compaction is the reason why the velocities of carbonates show no clear correlation with increasing depth. Before burial pressure compacts the rock fabric, the sediment is already altered and the cemented fabric, as well as part of the porosity, survives the increasing overburden.

7. *Summary and Conclusions*

The measured velocities in carbonate rocks have a remarkably wide range of over 4500 m/s for V_p and over 2500 m/s for V_s. The maximum velocities (V_p 6500 m/s, V_s 3400 m/s) are four times higher than the minimum velocities (V_p 1700 m/s, V_s 800 m/s). These velocity contrasts cause, together with the density variations, large impedance differences that explain the excellent seismic reflectivity of pure carbonates observed in seismic sections.

The performed analyses document that the variability in velocity of carbonates is a product of several factors that have different relevances and effects:

(1) Changes in mineralogy are not a reason for the large variability in velocities, because all measured samples contain only carbonate minerals that have very similar physical properties. Fully dolomitized rocks can be extremely fast but also extremely slow, demonstrating the insignificance of mineralogical composition.

(2) Carbonates that are deposited in shallow water generally have a higher average velocity than carbonates from the deeper shelf, slope or basin. This relation can be explained by the higher diagenetic potential of shallow-water carbonates.

(3) The comparison of the velocity with burial depth or age shows that neither one has a major control on the velocity evolution and that velocity inversions with increasing depth or age are common. In fact, a velocity increase, caused only by pure mechanical compaction, as measured in compacted carbonate mud, is lower than the observed velocity increase with decreasing porosities in natural rocks. This difference in velocity increase shows clearly that velocity is mainly influenced by other post-depositional, diagenetic processes and not just by pure compaction at increasing burial.

(4) Increasing effective pressure can lead to a fracturing of the rock and thus to a dramatic decrease in velocity. The critical pressure, at which fractures are first formed, varies substantially and can be as low as 5 MPa.

(5) Porosity is the most important physical factor that influences velocity. V_p and V_s increase with decreasing porosity, but there are large departures from this general trend.

(6) Different velocities in rocks with equal porosities are the result of different pore types. Rocks with frame-forming pore types, such as moldic or intraparticle porosity, can have very high velocities even at high-porosity fabrics, whereas rocks with interparticle, intercrystalline or high micro-porosity have, at the same porosities, much lower velocities,

(7) The high elastic properties of self-supporting framework fabrics enable the rock to maintain its extensive porosity even at a high overburden pressure. In particular the cementation-dissolution processes, that are in this extent unique in carbonates, create during early stages very stable rock fabrics with high velocities. As a consequence, commonly used velocity-density or velocity-porosity correlations, such as Gardner equation or time-average equation, have to be modified towards higher velocities in order to produce reliable velocity data in carbonates.

In summary, it is impossible to make a velocity prediction for carbonates based solely on depth or age data. High susceptibility towards diagenetic alterations distinguishes carbonates from other sedimentary rocks. Diagenetic processes, such as dissolution, cementation or recrystallization, take place so fast and in such shallow depth of burial, that the rock fabric is completely altered before compaction becomes effective. The sediment is mainly lithified by diagenesis and to a lesser degree by increased overburden, which explains the lack of correlation between velocity and age or depth.

Most of the physical properties are a combined result of (1) the initial sediment type and (2) the diagenetic alterations. The initial lithology determines the diagenetic potential and controls, together with the succession of diagenetic processes, the post-depositional history of the carbonate sediment. The timing of the different diagenetic events controls the porosity evolution and thus the velocity development. Our analyses suggest characteristic signatures in the porosity-velocity evolution to the specific diagenetic processes.

Acknowledgments

Many of the samples are from the cores of the Bahamas Drilling Project which was sponsored by the American National Science Foundation grant OCE-89117295 and by contributions from several industrial sponsors and the Swiss National Science Foundation. The geologic background information was produced by and with our collaborators Robert Ginsburg, Peter Swart, Jeroen Kenter, Donald McNeill and Leslie Melim. Flavio Anselmetti thanks Jaap Focke and Volker Vahrenkamp from the production research laboratory at Shell Holland (K.S.E.P.L.) for financial support. Gregor Eberli was supported by DOE grant DE-FG05-92ER14253. Collection and initial measurements of Italian samples were supported by Daniel Bernoulli through Swiss National Science Foundation grant 20-27457.91. Part of these samples were measured at the petrophysics laboratory at the University of Geneva, Switzerland; we thank Souad Sellami and Jean-Jacques Wagner for access and help. Karl Coyner from Verde GeoScience manufactured and installed the ultrasonic velocity meter in Miami. Phil Kramer provided the boat and helped us to take samples from Florida Bay for the compaction experiments. Lisa Dell'Angelo improved the English and Urs Gerber made the photographic figures. Roy Wilkens and an anonymous reviewer made useful suggestions and important comments.

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(Received April 14, 1993, revised October 1993, accepted November 1993)