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Velocity and Porosity from CRP-2/2A Core Logs, Victoria Land Basin, Antarctica

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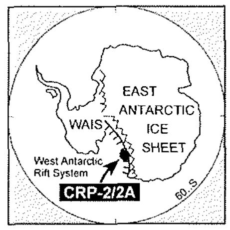

Abstract - The CRP-2/2a core is the second core drilled off-shore near Cape Roberts, Victoria Land during a three-year multi-national multidisciplinary drilling project in Antarctica 1997-1999. The CRP-2/2a core drilled in 1998 had a total length of 625 m, considerably longer than the CRP-1 core (1997). In this paper the relationship between whole-core compressional wave velocities and gamma-ray attenuation porosities of sediments cored at CRP-2/2A is examined, and compared with results from CRP-1, CRP-2/2A core-plug samples, and global models for velocity/porosity relationships of marine sediments. The high degree of data scatter observed in the velocity/porosity relationship of CRP-1 core is even larger in CRP-2/2A core. The general pattern of the velocity/porosity relationship is similar in CRP-2/2A whole core and core plug measurements. Despite scatter, all data indicate a strong primary dependence of velocity on porosity. This relationship appears to be independent of lithology except for sections with zero porosity and porosity >0.6, which are attributed to large lonestones and lapillistones, respectively. Core velocity/porosity patterns of CRP-1 and CRP-2/2A are very similar for sediments from the same age interval (19-23 Ma), both characterized by relatively low velocities (mostly between 2 and 3 km s-1) compared to porosity (0.1 - 0.4). Within this range of porosity, core velocities increase significantly up to more than 4 km s-1 below ca 440 mbsf. The change in the velocity/porosity relationship as a function of core depth is attributed to down-core increase in intergrain coupling enhanced by carbonate cementation. This is confirmed by a positive correlation of carbonate content with velocities higher or lower than empirically predicted from porosity. After removing first-order compaction control from the whole-core porosity record, no significant control by clay content can be identified (R = 0.3). This is different to the results for core from CRP-1 (R = 0.6) which is not cemented.

INTRODUCTION

The Cape Roberts Project (CRP) is investigating the Cenozoic and Cretaceous climate history of the Antarctic by coring scientific drillholes offshore Cape Roberts, Ross Sea. The first drillhole (CRP-1) penetrated 148 metres of Quaternary and Miocene sediments (Cape Roberts Science Team, 1998). The second drilling location, CRP-2/2A (77.006°S, 163.719°E), is situated in 178 m of water 14 km from Cape Roberts (Victoria Land), which is about 125 km north-north-west of McMurdo Station and 0.926 km apart from the CRP-1 location (Cape Roberts Science Team, 1999). Quaternary to Oligocene strata of the Victoria Land basin were drilled to a total depth of about 625 meters below sea floor (mbsf). The basal age of the CRP-2/2A core is approximately 35 Ma, still younger than expected from pre-drilling interpretation of the seismic stratigraphy (Cape Roberts Science Team, 1999). Three major unconformities, each including a hiatus of several m.y., are recognized at *c.* 130 mbsf (Late Oligocene/Early Miocene), 307 mbsf and 443 mbsf (Cape Roberts Science Team, 1999).

Relationships of compressional wave velocity (named velocity below) and porosity can be diagnostic tools for the interpretation of a complex imprint on the petrophysics of sediments and sedimentary rocks. Porosity and velocity of CRP-2/2A sediments are affected by both depositional conditions and post-depositional alteration such as compaction, fracturing, diagenesis and exhumation (Cape Roberts Science Team, 1999, Brink & Jarrard this volume). Velocity and porosity of CRP-2/2A were determined in three ways: by measuring *in situ* porosities and P-wave travel time in the drillhole, by measuring gamma-ray attenuation and P-wave travel time on the whole core prior to core cutting at the drill site (Cape Roberts Science Team, 1998), and by using core-plug samples (Brink & Jarrard, this volume). The aim of this paper is to discuss the relationship between velocities and porosities of sediments cored at CRP-2/2A, to compare the data with results from CRP-2/2A core-plugs, with results from CRP-1 and global models of velocity/porosity relationships for marine sediments. The goals are to examine how porosities and velocities are affected by lithology, in particular lonestone content, as well as grain size and grade of cementation. We do not compare the whole-core results to *in situ* porosities because drillhole and core porosities obtained by gamma-ray absorption were cross calibrated and therefore gave similar results. Neutron porosities measured in the CRP-2/2A drillhole respond to total hydrogen content within the bulk rock rather than simply formation porosity (Bücker et al. this volume). Thus, in clay-rich formations, neutron porosities reflect combined effects of porosity, clay content and clay type which is hardy comparable to gamma attenuation porosities in terms of velocity/porosity relationships. Also in this paper, we avoid discussing depth trends of physical properties in general which are addressed in Cape Roberts Science Team (1999) and presented by Bücker et al. (this volume).

In general, various empirical and theoretical models describe velocity/porosity relationships of rocks and sediments under different special boundary conditions (Biot, 1962; Castagna et al., 1985; Gassmann, 1951a, b; Han et al., 1986; Raymer et al., 1980; Wood, 1941; Wyllie et al. , 1956). These models hardly fit exactly conditions observed in natural marine sediments and/or depend on knowledge of various physical parameters, for example, elastic moduli (for review see Erickson & Jarrard, 1998). These are difficult to predict for sediments such as those cored at CRP-2/2A which exhibit a wide range of porosities (0-0.9) and velocities (1.5 - 7 km s^{-1}) (Niessen & Jarrard, 1998; Cape Roberts Science Team, 1999).

Recently, Erickson & Jarrard (1998) proposed global empirical relationships for predicting velocity based on porosity, sand/shale content, and consolidation history. Above fractional porosities of about 0.4 velocities of siliciclastic sedimentary rocks decrease rapidly with both increasing porosity and increasing clay content (Erickson & Jarrard, 1998). Analyses of very shallow (mostly <10 mbsf) marine sediment core samples show that initial porosity depends strongly on average grain size and sorting: well-sorted sands have porosities of only about 0.4, whereas clays have porosities of up to 0.8 (*e.g.*, Shumway, 1960a, b; Hamilton, 1976). Initial porosities are subsequently decreased by both mechanical compaction and chemical diagenesis.

At fractional porosities below about 0.4 effects of grain size on velocity/porosity may be combined with other factors like pressure-induced increase of intergrain coupling (Erickson & Jarrard, 1998). At a critical porosity of about 0.38 for highly consolidated sediments and 0.31 for normally consolidated sediments, velocities are expected to start increasing rapidly due to increasing influence of frame bulk modulus and shear modulus on velocity (Marion et al., 1992; Erickson & Jarrard, 1998). This critical porosity does not only depend on primary grain size but also on early consolidation and diagenesis and is therefore poorly predictable (Vernik, 1997; Erickson & Jarrard, 1998). Changes in elastic moduli are strongly dependent on framework stiffness which is controlled by the number and area of intergrain contacts (Stoll, 1989). The latter depends primarily on compaction due to overburden because porosity will be decreased with increased burial depth and consolidation thereby enhancing intergrain coupling. In addition to this mechanical compaction, cementation can have important effects on intergrain coupling because small amounts of cement can increase framework stiffness significantly without causing major imprint on porosity (Dvorkin et al., 1994). Thus, cementation of siliciclastic sediments will not only affect velocity but also the entire pattern of velocity/porosity relationship (Erickson & Jarrard, 1998).

In CRP-1 both core-plug and whole-core velocities exhibit a very strong dependence on porosity but are independent of lithology (Brink & Jarrard, 1998; Niessen & Jarrard, 1998). Variations in lonestone abundance have no direct influence on CRP-1 velocities and porosities, except for rare, very large lonestones (Niessen & Jarrard, 1998). On the other hand, there is a significant dependence of compaction-corrected porosities on clay content (R=0.6; Niessen & Jarrard, 1998). The effect of diagenesis on velocity and porosity is minor because core CRP-1 is hardly cemented. CRP-1 core-plug and whole-core data indicate significantly different velocity/porosity patterns (Brink & Jarrard, 1998, Niessen & Jarrard, 1998). For a given porosity, core-plug velocities are generally 0.2-0.5 km s^{-1} faster than whole-core velocities. Core-plug results from CRP-1 exhibit a better fit with the global velocity/porosity model by Erickson & Jarrard (1998). The cause of this discrepancy remained uncertain and is further addressed here using the much larger data set of CRP-2/2A.

METHODS

The drill site laboratory work included non-destructive, almost continuous determinations of wet bulk density (WBD) and velocity with 20-mm spacing. A Multi Sensor Core Logger (MSCL, Geotek Ltd., Daventry, Northamptonshire, UK) was used to measure core temperature, core diameter, P-wave travel time, gamma-ray attenuation, and magnetic susceptibility. The technical specifications of the MSCL system, core data acquisition and processing (Niessen et al., 1998; Cape Roberts Science Team, 1999) are briefly summarized below. For data Acquisition and processing of drillhole data and core plug data see Cape Roberts Science Team (1999), Brink & Jarrard (this volume) and Bücker et al. (this volume).

Velocities were calculated from the core diameter and travel time after subtraction of the travel time through the transducer caps (Cape Roberts Science Team, 1999). Resulting velocities are normalized to 20°C using the core temperature logs. For temperature logging an infrared sensor was used which was adjusted to detect temperature at the surface of the core.

Wet bulk density (WBD) was determined from attenuation of a gamma-ray beam transmitted from a radioactive source (^{137}Cs). The gamma-ray detector was calibrated using aluminum, carbon and water of known densities and specific gamma-ray attenuation coefficients. Quantification of wet bulk densities was carried out according to the following formula:

$$WBD = a + b \cdot (1/-\mu \cdot d) \cdot \ln (I/I_0) \qquad (1)$$

where a and b are instrument-specific variables to correct for count-rate dependent errors as described by Weber et al. (1997), d is core diameter, μ is specific attenuation coefficient for ^{137}Cs radiation in water, rock and calibration pieces, and $\ln (I/I_0)$ is natural logarithm of the ratio of attenuated (sample) over non-attenuated (air) gamma counts per second.

Porosity (Φ) is calculated from wet bulk density as follows:

$$\Phi = (dg - WBD) / (dg - dw) \quad (2)$$

where dg is grain density and dw is pore-water density. Grain density is assumed to be 2.70 g cm^{-3} based on the core plug measurements of Brink & Jarrard (1998), and pore-water density is assumed to be 1.02 g cm^{-3}.

CRP-2/2A core plug and core physical properties are measured at similar frequencies (Vp) and perpendicular to the core axis (Vp and density). After every 4 m of core (on average) a standard plastic cylinder was logged to check velocity and density calibrations, in total 39 and 128 standards for HQ (61.1 mm) and NQ (45 mm) core diameters, respectively (Cape Roberts Science Team, 1999). The accuracy of the measurements are described in Cape Roberts Science Team (1999). The results are summarized in table 1.

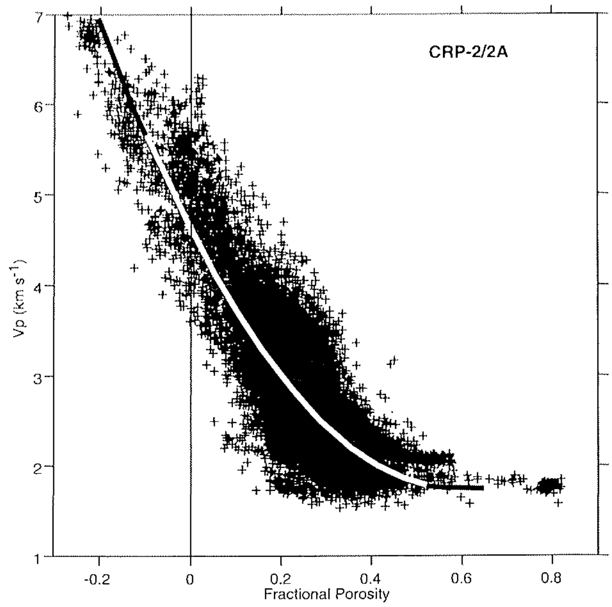

Fig. 1 - Velocity/porosity relationship including empirical 2nd order polynomial using all data from CRP-2/2A.

RESULTS AND DISCUSSION

GENERAL VELOCITY/ POROSITY RELATIONSHIP OF THE CRP-2/2A CORE

For all stratigraphic units of the CRP-2/2A core, in which velocity (v_p) and porosity (Φ) were measured (whole core), there is a clear positive correlation between the two parameters (Fig. 1). This observation is very similar to the conclusion drawn from CRP-1 data (Niessen & Jarrard, 1998). For the entire CRP-2/2A data-set including Quaternary, Pliocene, Miocene and Oligocene units, the best fit was observed for a 2nd-order polynomial function (Fig. 1):

$$v_p = 4.628 - 9.8371 \cdot \Phi + 8.4222 \cdot \Phi^2 \ (R = 0.87) \quad (3)$$

There is a relatively high amount of dispersion in the CRP-2/2A data which explains the correlation coefficient of only 0.87 (I) compared to 0.93 for CRP-1 (Niessen & Jarrard, 1998). The pattern in the velocity/porosity relationship seems to be largely independent of lithology. A differentiation after diamicts and mud-, silt- and sandstones does not exhibit distinct clustering in the velocity/porosity relationship. This implies that the large scatter in velocity/porosity has other origins than lithological composition. A similar conclusion was drawn from the CRP-1 results (Niessen & Jarrard, 1998).

For most CRP-2/2A velocities above 5.0 km s^{-1} the associated porosity is negative. Again, this is very similar to the equivalent data set of CRP-1 (Niessen & Jarrard, 1998). The reason is that porosity was calculated from bulk density (Cape Roberts Science Team, 1998), assuming a constant matrix density of 2.7 g cm^{-3}. Measured bulk densities higher than 2.7 g cm^{-3} result in negative apparent porosities. This implies that depth intervals with negative porosities have matrix densities above 2.7 g cm^{-3} and/or contain clasts of higher densities than 2.7 g cm^{-3}. Because the density determination is relatively precise (Tab. 1) only negative porosities up to -0.05 (Fig. 1) can be attributed to errors in the methodology.

THE EFFECT OF MATRIX DENSITY

Matrix densities of CRP-2/2A were determined by Brink & Jarrard (this volume) using plug samples (Fig. 2). They range from <2.5 to >2.9 g cm^{-3} but the majority of the samples cluster between 2.6 and 2.8 g cm^{-3} (mean 2.72 g cm^{-3}) (Fig. 2). Thus, using matrix density of 2.7 g cm^{-3} for porosity calculation is reasonable although some errors may result from the observed range of matrix densities.

In order to study the effect of matrix density on the velocity/porosity relationship, we have used matrix densities from 2.6 to 2.8 g cm^{-3} to calculate five data sets of CRP-2/2A core porosities (Fig. 2). These data-sets were

Tab. 1 - Velocities and densities of standard plastic cylinders used for monitoring accuracy during data aquisition of CRP-2/2A.

	Number of standards	True value	Measured mean value	Standard deviation
Vp (km s^{-1})	167	2.37	2.35	0.04
Density (HQ*) (g cm^{-3})	39	1.408	1.408	0.014
Density (NQ+) (g cm^{-3})	128	1.408	1.388	0.028

* standard diameter 61.1 mm, gamma-radiation collimator diameter 5 mm; + standard diameter 45 mm, gamma-radiation collimator diameter 2.5 mm

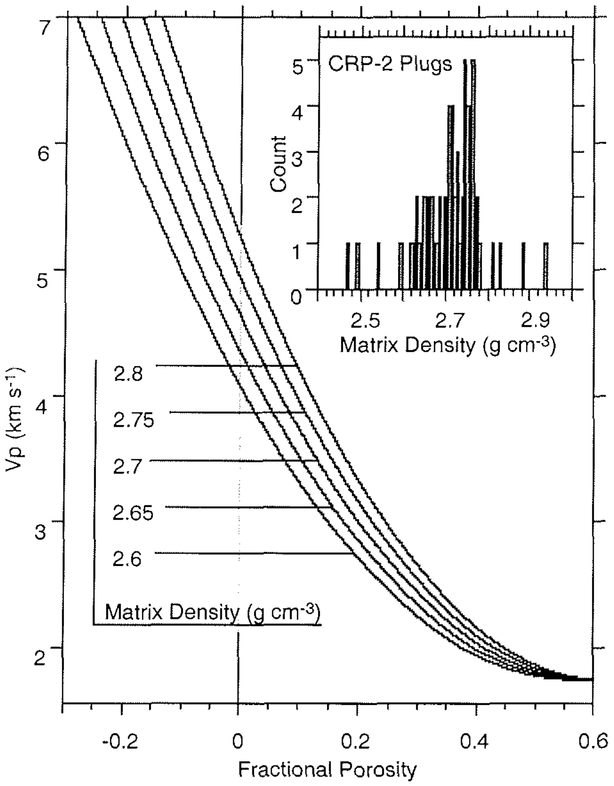

Fig. 2 - The influence of using different matrix density on empirical velocity/porosity relationships of CRP-2/2A sediments. Matrix densities of plugs are from Brink & Jarrard (this volume). The relationship using 2.7 g cm^{-3} is identical to the empirical relationship shown in figure 1.

plotted against core velocity from which five 2nd order polynomial fits were computed (Fig. 2). The centre curve (2.7 g cm^{-3}, Fig. 2) is the equivalent to equation (3) above. Effects of matrix densities are negligible for porosities of >0.6 (Fig. 2). Below 0.6 factional porosity, however, there is an increasing effect which may result in porosities of up to 0.07 higher or lower than calculated from constant matrix density of 2.7 g cm^{-3} (Fig. 2). This error may explain some of the dispersion observed (Fig. 1). However, variation in matrix density cannot explain the occurrence of negative porosities alone because a relative large number of depth intervals remain negative in porosity even if a matrix density of 2.8 g cm^{-3} is used (Fig. 2). Therefore we assume that most apparent negative porosities result from large lonestones which can have densities well above that of matrix (Niessen & Jarrard, 1998). The effect of clasts will be tested in more detail below. Because negative porosities are physically not valid we have shifted all calculated fractional porosities <0 (Fig. 1) to zero (Fig. 3).

COMPARISON OF CORE AND CORE-PLUG DATA

Whole-core data is compared with results from plug measurements and different models (Fig. 3). Despite the relatively large dispersion in the whole-core data, significant differences between the different data are evident. Except for one sample, core-plugs are within the area where 90% of the core velocity/porosity are plotted (Fig. 3) although

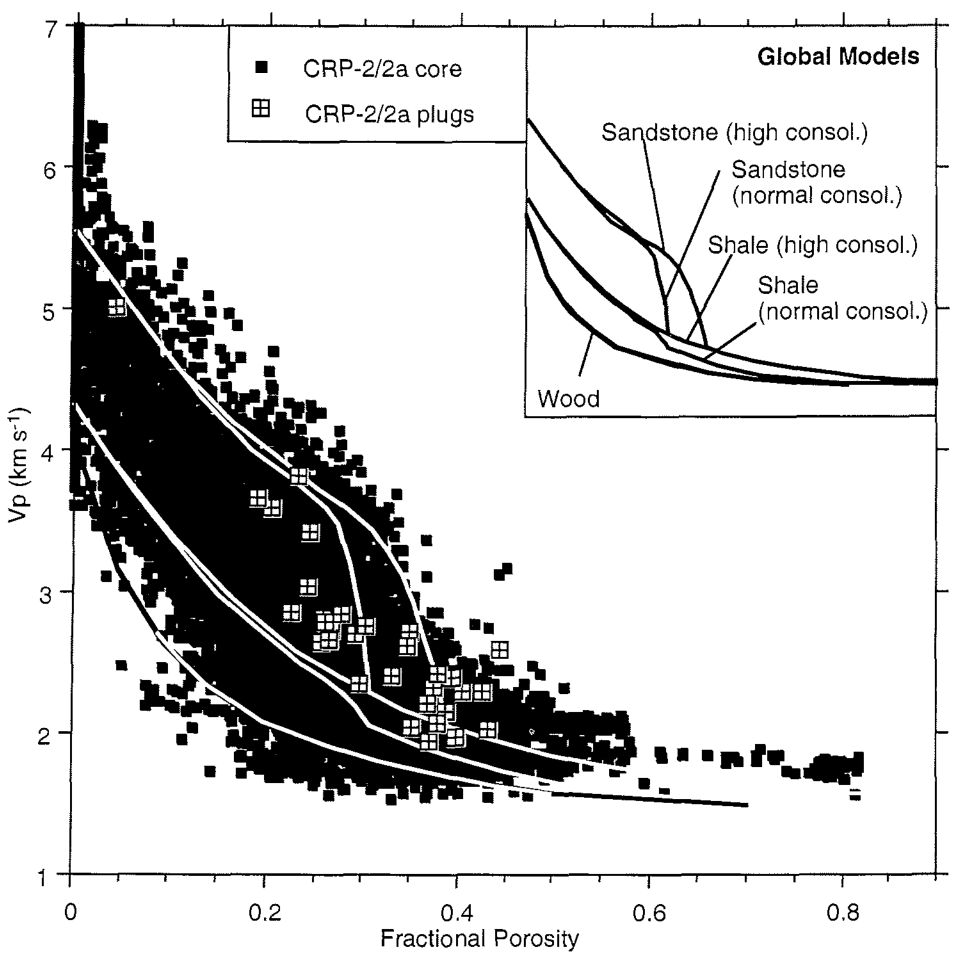

Fig. 3 - Comparison of velocity/porosity relationships of CRP-2/2A core and plug data. Global models are from Wood (1941) and Erickson & Jarrard (1998).

plug velocities tend to be slightly higher compared to core velocities below fractional porosities of 0.3.

Data of very high velocity/low porosity and very low velocity/high porosity are underrepresented in the plug data because low porosity/high velocity results are at least partly attributed to large clasts in the core which were not sampled as plugs. The other extreme of very high porosities above 0.6 are almost entirely restricted to lapillistone layers of core CRP-2A (Cape Roberts Science Team, 1999, Fig. 4, unit 7.2). Again, no plugs were analysed from this lithology. Thus extremes on both ends of the velocity/porosity relationship of CRP-2/2A are indicative for specific lithologies whereas there is no such indication for the rest of the plot (Fig. 3).

An additional reason for the observed descrepency between whole-core and plug results may be core alteration. It is interesting to note that the discrepancy in the velocity data is largely restricted to Miocene units (Fig. 5), which in both CRP-1 and 2 are generally more strongly fractured than Quaternary units (Wilson & Paulsen, 1998) and underlying Oligocene Units (Cape Roberts Science Team, 1999). Miocene units are uncemented or cementation is minor (Cape Roberts Science Team 1998, 1999). This implies lower rigidity. In addition, lack of cement makes the core more vulnerable to drilling-induced cracks. Indeed numerous small cracks are described in the lithology logs of CRP-2/2A above 120 mbsf. Possibly some of the cracks may contain air which can explain velocities even lower than predicted by the Wood (1941) model. This phenomenon is not evident in plug samples. Plugs are generally drilled from intact, unbroken and unfractured core intervals, and broken plugs are not measured. Thus, plug velocities are more consistent with global models but do not represent the broad range of physical state which is observed in the CRP cores.

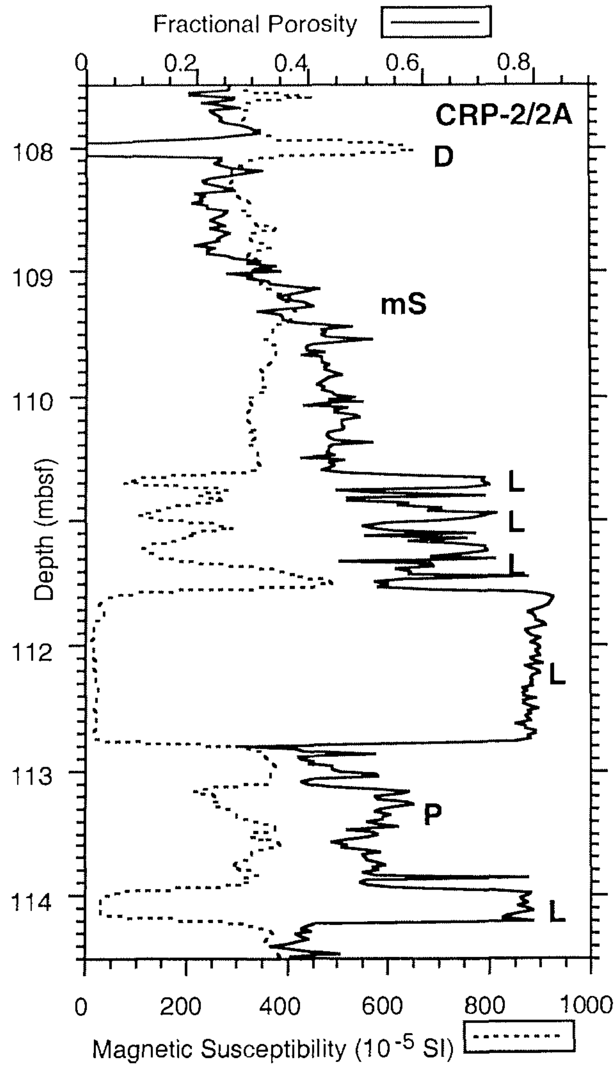

Fig. 4 - Fractional porosity and magnetic susceptibility of unit 7.2 (Lapillistones). Units of Lappilistones (L) and dispersed Pumice (P) are characterised by high porosity and low magnetic susceptibility compared to muddy sandstone (mS) and diamict (D). For a detailed lithological description of the section see Cape Roberts Science Team (1999, Fig. 4.2).

COMPARISON WITH GLOBAL MODELS

The majority of the CRP-2/2A core and plug velocity/porosity data is consistent with the range suggested by global models (Fig. 3) for normal and high consolidated shales and sandstones (Erickson & Jarrard, 1998). However, some core of CRP-2/2A indicate that there are higher velocities than predicted from velocity/porosity models. Also, a considerable number of core data exhibit lower velocities than predicted for normally consolidated shales. Some velocities are even as low as the Wood (1941) model, implying no rigidity (Fig. 3). These surprisingly low velocities were also observed in CRP-1 core data (Niessen & Jarrard, 1998).

The velocity/porosity relationship of CRP-2/2A is compared to CRP-1 (Fig. 5). The down-core gradient of velocity (Cape Roberts Science Team, 1999) clearly indicates that much of the high velocity data of CRP-2/2A comes from deeper parts of the core which are older than CRP-1 sediments. Therefore, it is not valid to compare the entire data set of CRP-2/2A with CRP-1. In figure 5, we compare only those units from both cores which are of similar age. Chrons C6, C6A, C6AA and C6B are present in both CRP-1 and CRP-2/2A cores and comprise a time range from about 19 to 23 million years (Cape Roberts Science Team, 1998, 1999). Data from these chrons fall in the same range in both cores. Like CRP-1 results, most CRP-2/2A data indicate velocities lower than predicted from global models (*e.g.* lower as would be expected in 100% shale according to Erickson & Jarrard, 1998) and lower than measured in plugs.

For the CRP-1 data, various possibilities were discussed by Niessen & Jarrard (1998) to explain the discrepancy between the core data and the plugs and global models. These include undetected bias in the velocity measurements, non-representation of *in situ* conditions in the core or plugs, lack of rigidity in the core, and diagenetic change in the plugs. The fact that the general velocity/porosity pattern of CRP-1 core is repeated for CRP-2/2A rules out an undetected bias caused by core logging because the logging system was frequently tested using standards during CRP-2/2A field season (Cape Roberts Science Team, 1999). Non-representation of *in situ* conditions is of no importance because nearly all *in situ* velocities are <4% higher than those measured at

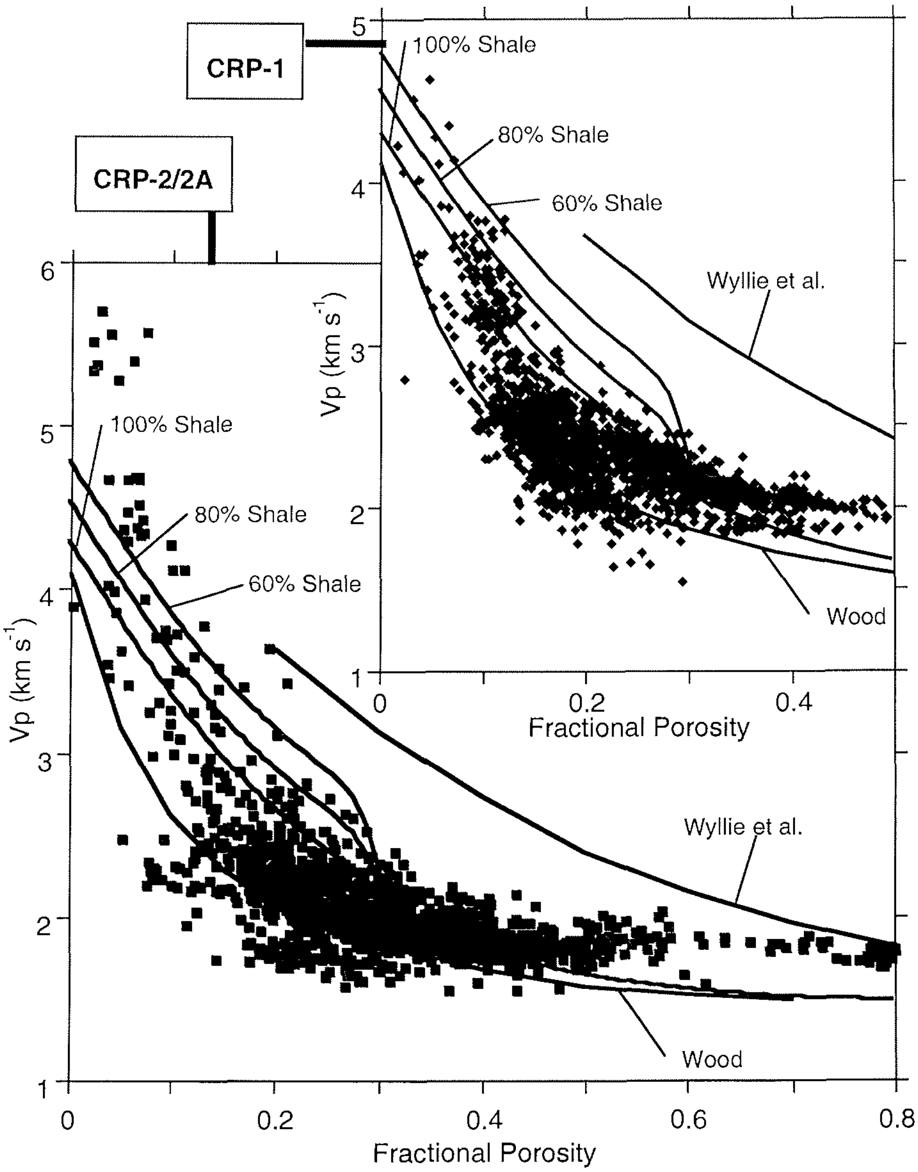

Fig. 5 - Velocity/porosity relationships of sediments of Chrons C6, C6A, C6AA and C6B age for CRP-1 (Cape Roberts Science Team, 1998) and CRP-2/2A (Cape Roberts Science Team, 1999). The data is compared with theoretical and empirical models (normal consolidated sediments) from Wood (1941), Wyllie et al. (1956) and Erickson & Jarrard (1998).

atmospheric pressure, and most are only 0-2% higher (Brink & Jarrard, this volume). This suggests lack of core rigidity as one of the most probable reasons.

Loss of rigidity could have occurred due to either *in situ* brecciation (Passchier et al., this volume), *in situ* exhumation (Jarrard & Erickson, 1997), core rebound (Hamilton, 1976), or - at least in some sands - core disturbance. Stress relaxation, whether *in situ* or coring-induced, can generate and open microcracks (*e.g.* Nur, 1971). Initial microcrack porosities <0.005 are sufficient to cause pressure-dependent velocity variations of 5-50% (Walsh, 1965; Nur & Murphy, 1981). Exhumation can decrease velocities by as much as 1 km s^{-1} due to microcrack opening (Jarrard & Erickson, 1997). Seismic profiles across CRP-1 and 2/2A demonstrate that some exhumation has occurred (Cape Roberts Science Team, 1998). The CRP-1 compaction trends suggest that an overburden between 300 and 650 m of sediments were removed above the present location of CRP-1 (Niessen et al., 1998). Using the longer record of CRP-2/2A, Brink & Jarrard (this volume) suggest an exhumation of about 250 m.

Is there any systematic clustering in velocity/porosity data of CRP-2/2A within the range of global model predictions? We have used the 4 m core description logs (Cape Roberts Science Team, 1999) to select clast-free depth intervals of mudstone and sandstone. In figure 6, whole-core data from widely distributed mudstone sections are compared to trends empirically determined for highly consolidated shaly sediments (Erickson & Jarrard, 1998). Results correlate with trends observed for shale contents of 20 to 100%. In this relationship the critical porosity, a kink where velocities increase rapidly, is located at about 0.38. This implies most mudstones of CRP-2/2A are highly consolidated. The distinct clustering of the different units between the lines of 20 to 100% of shale may imply different grain size of these units. The effect of grain-size on porosity and velocity is analyzed in more detail below.

While comparing whole-core data from sandstone

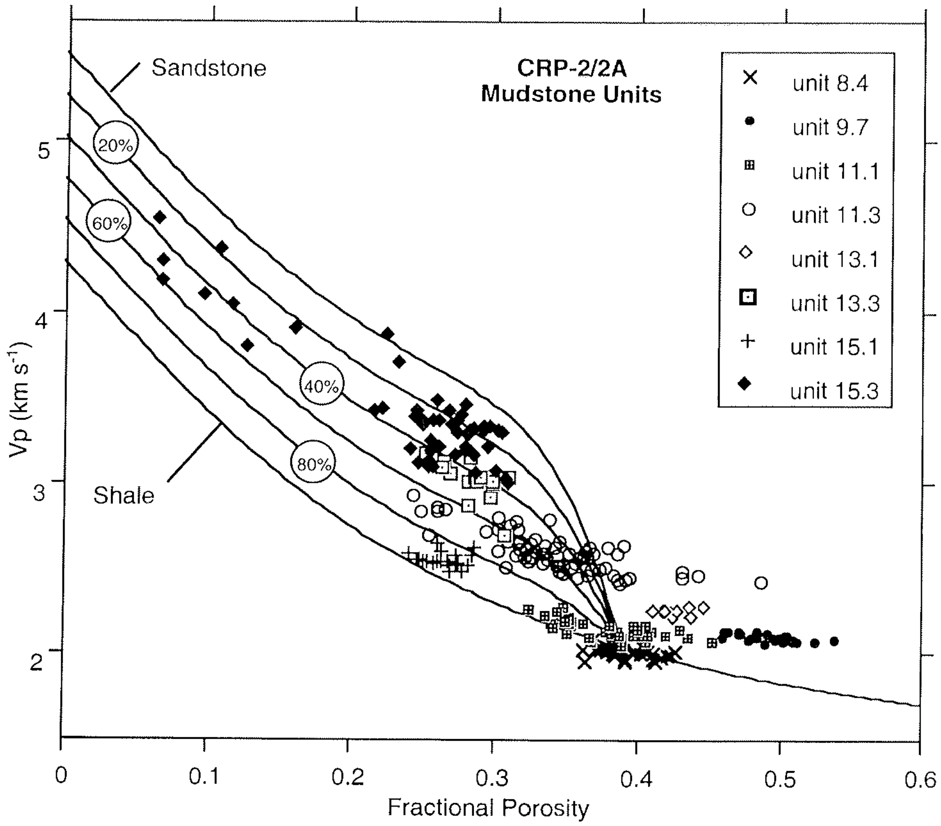

Fig. 6 - Velocity/porosity relationship of selected mudstones from CRP-2/2A compared to global models for high consolidation sandstone, 20 to 80% of shale and shale (Erickson & Jarrard, 1998). For stratigraphy of units and grain size see figure 9.

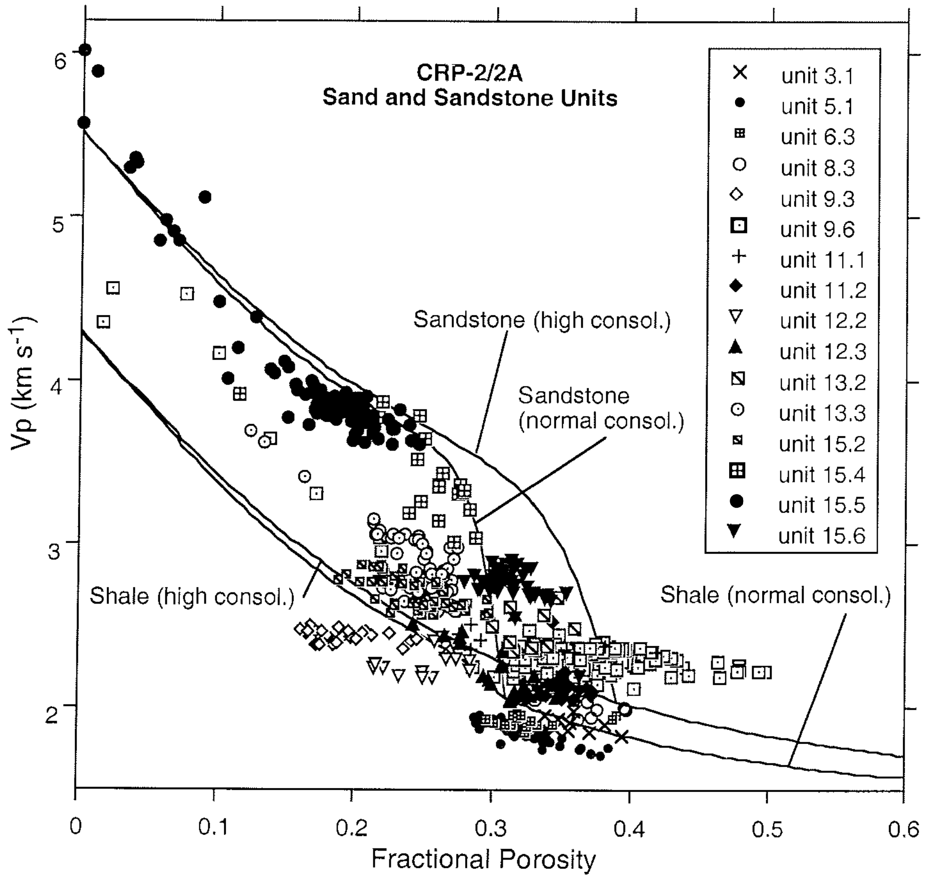

Fig. 7 - Velocity/porosity relationship of selected sandstones from CRP-2/2A compared to global models for sandstones and shales (Erickson & Jarrard, 1998). For stratigraphy of units and grain size see figure 9.

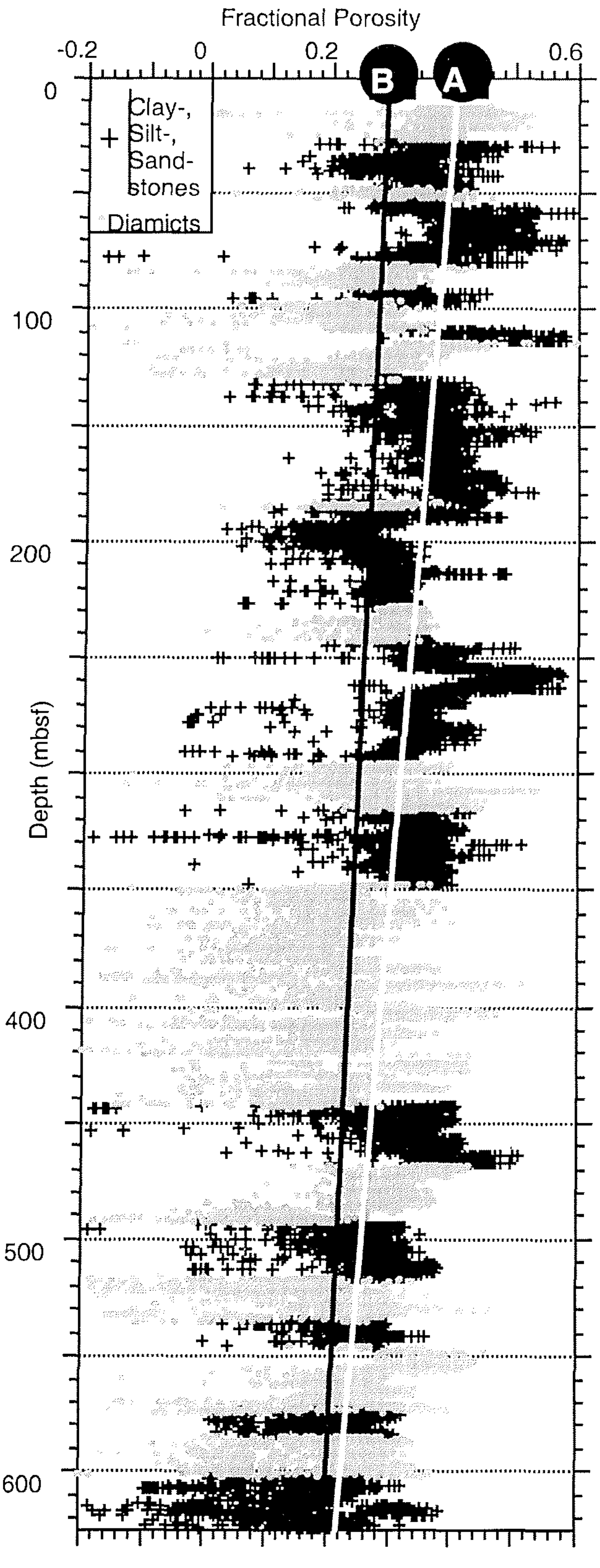

Fig. 8 - CRP-2/2A porosity and linear compaction trends of diamicts (A) and mud- and sandstones (B) as a function of depth.

sections to trends empirically determined for highly consolidated and normally consolidated sandstone and shales (Erickson & Jarrard, 1998) (Fig. 7) most of the data correlate well with global trends. However, none of the sandstone trends fits to all data presented from CRP-2/2A sandstone units. For example units 3.1, 5.1, 6.3, 12.3 and 15.4 suggest normal consolidation whereas units 8.3, 9.6, 11.2, 13.2 and 15.6 point to higher consolidation. In addition, units 9.3, 9.6, 12.2, 13.3, 15.2 correlate with trends more typical for shale or mixtures of sand and shale. Units 5.1, 6.3, 9.3 and 12.2 have lower velocities than suggested from global models which is similar to observations from CRP-1 (Niessen & Jarrard, 1998). Some velocities of unit 15.5 are higher than suggested from model trend for sandstone. It is interesting to note that the degree of dispersion and deviation from global models is more common in the sandstones than in mudstones. Therefore, the large range of Vp found at low porosity levels is probably more related to different characteristics of sandstones than mudstones. Grain-size differences may account for some of the dispersion. More likely however, there is a large variability of frame bulk modulus and shear modulus on velocity. Elastic moduli can be strongly controlled by cementation (Dvorkin et al., 1994). The effects of grain size and cementation on CRP-2/2A porosity and velocity are analyzed in more detail below.

THE EFFECT OF GRAIN SIZE

In order to analyse effects of grain size on porosity and velocity pattern first-order control of down-core porosity trends introduced by compaction have to be removed (*e.g.* Niessen & Jarrard, 1998). For CRP-2/2A we have analyzed the depth gradient of porosities for two lithologies: (i) mud-, silt- and sandstones and (ii) diamicts because diamicts are often characterized by slightly lower porosities compared to the other lithologies (Fig. 8). This is enhanced by single large lonestones as indicated by very low or even apparent negative porosities in figure 1. Because diamicts are ice proximal deposits (*e.g.* Powell et al., 1998) they may have poorer sorting resulting in lower porosities compared to sand and mud. In addition, diamicts may be overconsolidated by glacier load as discussed by Niessen et al. (1998) for some very low porosity diamicts of CRP-1. For CRP-2/2A the compaction trend of diamicts is lower and less steep than for other lithologies, probably as the result of a combination of these various effects discussed above. Therefore we assume that the porosity gradient of mud- and sandstones is a better reflection of the first order compaction trend as a function of depth than is the more complex diamict trend. Analysis of compaction and exhumation of the CRP-2/2A sediments is beyond the scope of this paper. For a detailed discussion see Brink & Jarrard (this volume). The compaction trend of mud- and sandstones as observed in the CRP-2/2A core (Fig. 8) can be described by a linear regression:

$$f = 0.40404 + -0.000298 \cdot Z; (R = 0.5) \qquad (4)$$

where f is fractional porosity and Z is depth (mbsf). We have removed this first-order control from the entire porosity data, resulting in porosity residuals, here defined as the differences between observed porosities and those predicted from depth. If plotted versus depth (Fig. 9) some correlation of residual porosities with lithology is apparent. Some mudstone units show significantly higher porosity residuals than sandstone units. This is particularly valid for the mudstone units 5.1, 8.4, 9.7, 11.3 and 13.1, all

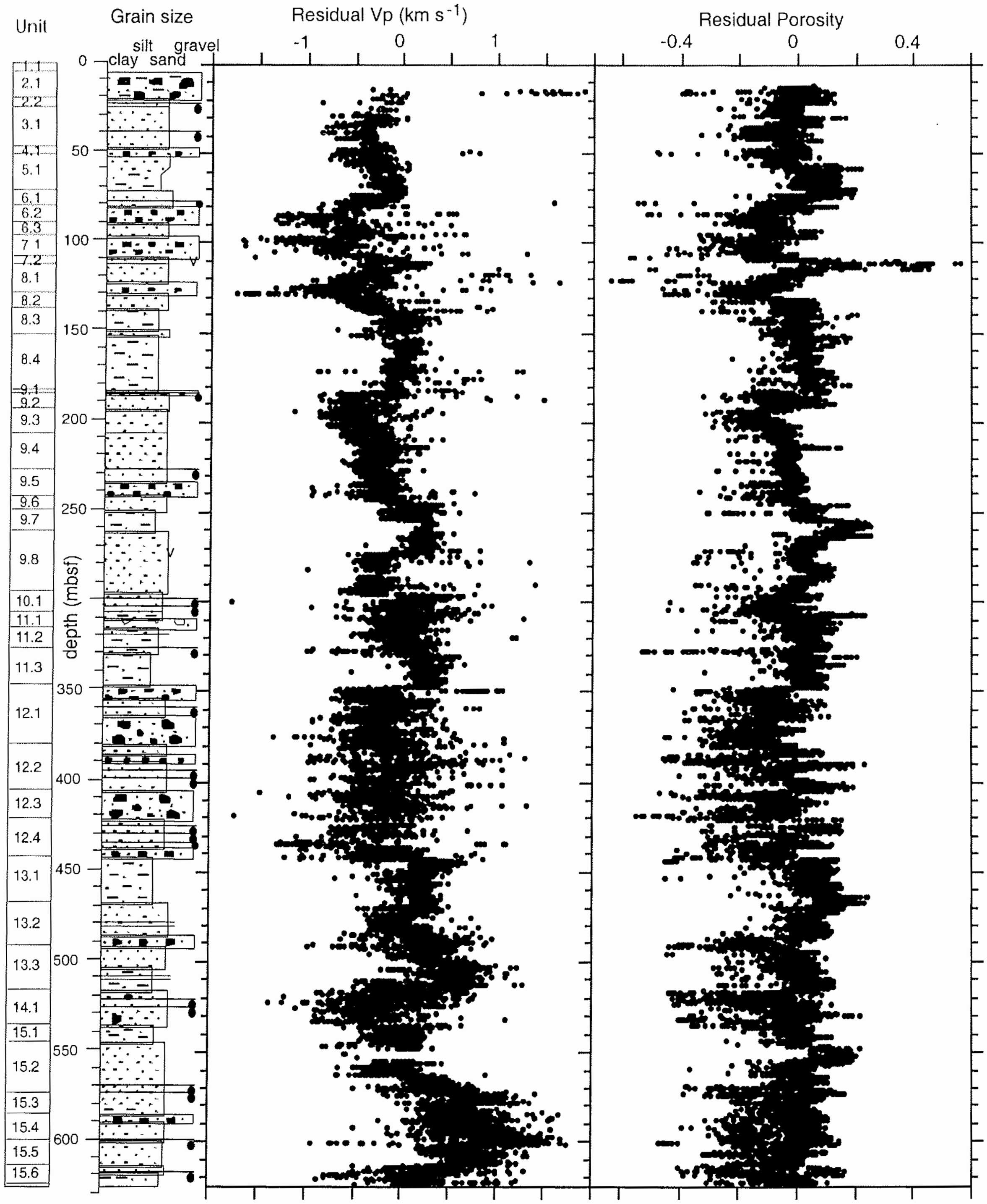

Fig. 9 - Residual velocity and residual porosity as a function of depth and compared with lithology (Cape Roberts Science Team, 1999).

above 350 mbsf (Fig. 9). Most diamicts show negative residual porosities, because we used the mud and sandstone depth-trend of porosity and not the lower and slightly steeper diamict trend to calculate porosity residuals.

Porosity residuals were compared with grain size using data of clay and sand content from Ehrmann (this volume) and Neumann & Ehrmann (this volume), respectively. There is some poor positive correlation of residual porosities with grain size which is statistically not significant (R=0.36 for clay, R=0.2 for sand) and lower than observed for CRP-1 (R=0.6, Niessen & Jarrard, 1998). Because the clay content ranges between 0 and *c.* 25 % in both cores CRP-1 and CRP-2/2A, differences in lithology in both cores cannot account for the reduced influence of clay and sand on porosity in CRP-2/2A. We assume that secondary effects such as pore volume reduction by cementation has to be considered as an important process in CRP-2/2A. Also, the porosity difference between clay and sand is expected to be greatest at shallow depth, and CRP-2/2A is mostly deeper than CRP-1.

In order to compare CRP-2/2A velocity data with grain size, we have calculated residual velocities, here defined as the difference between measured velocities and those predicted from porosity according to equation (3). The comparison of residual velocities with grain size data from Ehrmann (this volume) and Neumann & Ehrmann (this volume) indicates no correlation with clay and sand content, respectively. These trends are not consistent in sign with global models because sandstones should have higher velocities at a given porosity level than shales (Fig. 3; Erickson & Jarrard, 1998). Also, Brink & Jarrard (this volume) detected no correlation between velocity/porosity patterns and grain size.

THE EFFECT OF CEMENTATION

Brink and Jarrard (this volume) suggested that the CRP-2/2A velocity/porosity pattern change with depth is due to cementation. Carbonate cementation is minor in the upper part of CRP-2/2A, increases with depth, and becomes extensive in some sandstone units below 400 mbsf (Aghib et al. this volume). Indeed, the velocity/porosity relationship for selected mud and sandstone units from CRP-2/2A core measurements suggests that there is some systematic trend in the data depending on the unit and depth where the data were measured (Fig. 6 and 7). This trend cannot be explained in terms of grain size.

The velocity scatter is largest at the level of 0.2 fractional porosity (Fig. 1). If some of the dispersion in the data is controlled by cementation, then velocity at this porosity level should follow increasing cementation as a function of depth. Indeed, velocities from the 0.2 porosity level (selected range: 0.19-0.21) plotted versus depth are consistent with the cementation trend (Fig. 10). Above about 400 mbsf, most velocities range between 1.5 and 3.0 km s^{-1}. Below 400 mbsf the velocities increase significantly and become as fast as 4.5 km s^{-1} near the bottom (Fig. 10). Velocity scatter on the 0.2 porosity level is introduced by mainly two effects: (i) The steep down-core gradient of velocities seems to be controlled by intensive cementation in the lower part of the core ; and (ii) there is an increase of velocity fluctuations in the lower part of the core probably controlled by strongly cemented units intercalated with less cemented units.

Fluctuations of velocities between cemented and uncemented layers are reflected in the downcore pattern of residual velocities (Fig. 9). Most sandstone units above 450 mbsf have residual velocities between -1 and 0. In contrast, some sandstone units below 450 mbsf show significantly higher residual velocities up to 1.5 km s^{-1}, thus significantly higher than suggested by the empirical relationship between porosity and velocity (Fig. 1). This is in particular true for units 13.3, 14.1, 15.3 and 15.5 , for which extensive cementation is described by Cape Roberts Science Team (1999). These units intercalate with units of negative residual velocities (such as 15.2). The latter are characterized by loose sands. Bücker et al. (this volume) interprete the sands as aquifers. Percolation of water probably enforced dissolution of cement resulting in strong reduction of framework stiffness and consequently reduction of velocity. Thus, differences in cementation can explain most of the dispersion observed for sandstone velocity/porosity relationships (Fig. 7). It may also explain some dispersion in the mudstone data (Fig. 6) because in the lower part of the core cementation is evident in mud- as well as sandstones (Cape Roberts Science Team, 1999).

An additional test of the influence of cementation on velocity can be carried out by comparing residual velocities to carbonate contents. Carbonate is the prominent cement observed in CRP-2 (Aghip et al., this volume) and carbonate content is largely controlled by degree of cementation (Dietrich this volume). Carbonate content is mostly below 2 % above 300 mbsf, increases between 300 and 400 mbsf, and increases to 6 % at the bottom of the core (Dietrich this volume, Fig. 11). Because samples of carbonate content and core velocity measurements represent slightly different depths and volume sizes, we re-sampled residual velocities in 0.1 m intervals based on linear interpolation. The resulting fluctuations of residual velocity as a function of depth (Fig. 11) correlate well with the carbonate content except for a few relatively high carbonate values below 300 mbsf where no specific peaks in residual velocities are observed. Thus most fluctuations towards higher residual velocities can indeed be explained by more intense carbonate cementation.

Brink & Jarrard (this volume) observe that porosities near the bottom of the core CRP-2/2A are lower than suggested from an exhumation depth of 250 m. They conclude that, in places, cementation has reduced porosities by further 0.05 to 0.1. Cementation may also account for the missing correlation between clay and sand content and fractional porosity of mudstones, because primary porosity effects by grain size can be reduced by cement during diagenesis. Thus, it may be possible that excursions towards higher residual velocities and lower residual porosities in the entire core (Fig. 9) may be related to either cementation or occurrence of large lonestones.

The large degree of dispersion observed in the entire dataset (Fig. 1 and 3) is significantly reduced if the data set is split at a depth of 440 mbsf (Fig. 12). The upper part is interpreted to represent largely uncemented sediments of normal or reduced framework stiffness resulting in relatively low velocities. The lower part represents sediments that underwent intense cementation should thus be typical for rock types of increased framework stiffness and relatively high velocities. The entire velocity/porosity pattern is shifted up by about 1 km s^{-1} for cemented sediments compared to the non-cemented sediments in the upper part of the core. This is consistent with the results and interpretation of velocities measured on core-plug samples of CRP-2/2A (Brink & Jarrard, this volume).

THE EFFECT OF LONESTONES

Most of the clasts in the CRP cores are derived from granites, granitoids, granodiorites and dolerites (Cape Roberts Science Team, 1998). These rock types are normally characterized by relatively high densities up to 3.0 g cm^{-3} and P-wave velocities from well above 5 to more than 6 km s^{-1} (*e.g.*, Schön, 1998; Niessen & Jarrard, 1998). If large clasts are drilled their high densities will result in zero or negative apparent porosities as discussed above.

The effect of large clasts on velocity can be tested by examining p-wave data for depth intervals with apparent

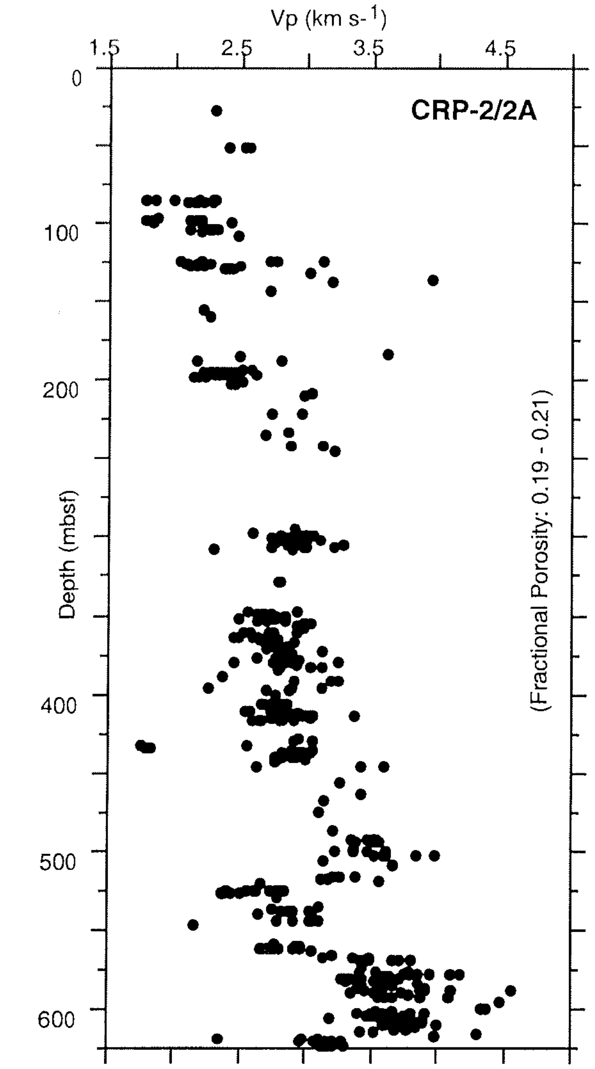

Fig. 10 - Velocity from the porosity range of 0.19 to 0.21 (Fig.1) as a function of depth.

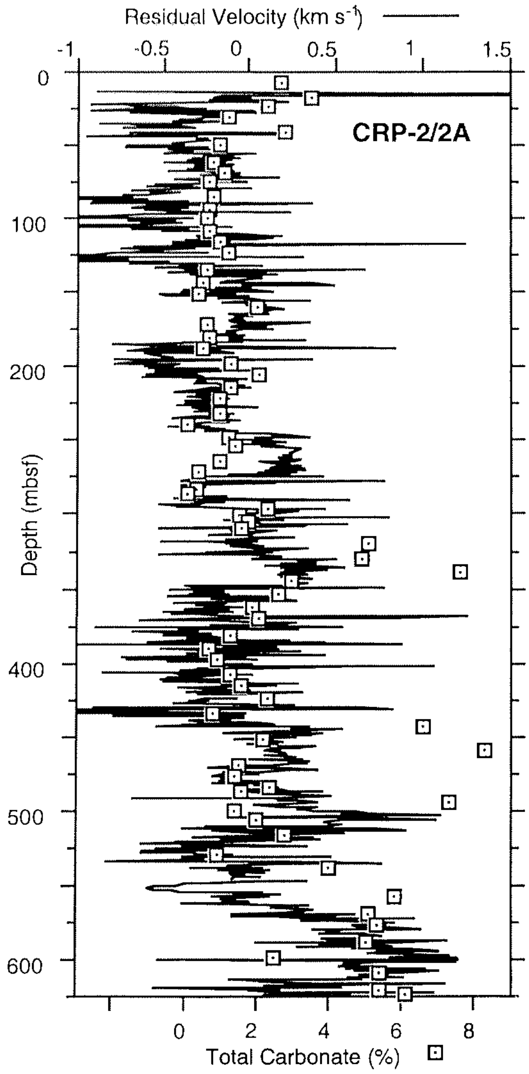

Fig. 11 - Residual velocity compared with total carbonate content (Dietrich this volume) as a function of depth.

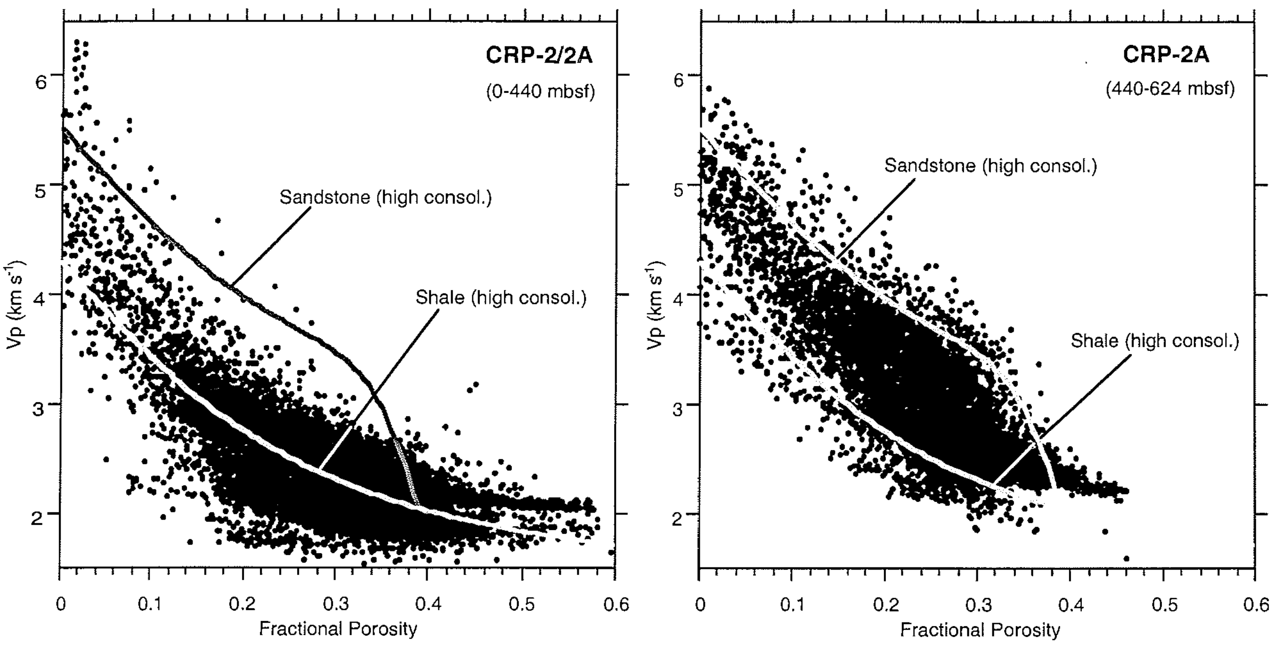

Fig. 12 - Velocity/porosity relationships above (left) and below (right) 440 mbsf. Global trends for Sandstone and Shale are from Erickson & Jarrard (1998).

porosities of < 0. A plot of velocities versus depth (Fig. 13) and comparison with lithology (Fig. 13) shows that more than 90% of velocities higher than 3.6 km s^{-1} occur in diamict and diamict dominant units. This indicates that most data of zero porosity (or apparently negative) and velocity of 3.6 or above are related to single large lonestones in the core. The individual relationships of velocity to porosity for different clast types is probably the reason for the relatively large scatter in the velocity/porosity plot above 4.5 km s^{-1}.

Niessen & Jarrard (1998) combined Vp and magnetic susceptibility data to distinguish between clasts derived from dolerite and granite rocks in CRP-1. Velocities near or above 6 km s^{-1} are associated with magnetic susceptibilities above 400 10^{-5} SI and are indicative of dolerite clasts. In contrast, velocities between 5 and 6 km s^{-1} are associated with relatively low susceptibilities. This is indicative of granite clasts because granite has velocities in this range and is low in magnetic minerals (Niessen & Jarrard, 1998). For CRP-2/2A, magnetic susceptibility of sections with zero porosity are plotted versus depth and compared to velocity (Fig. 13). A clear separation of different clast types from magnetic susceptibility and velocity is not possible. Magnetic susceptibility as low as 10 10^{-5} SI and as high as 1000 10^{-5} SI suggest granite or dolerite sourcerocks, respectively. However, most data are between these extremes. Thus, for most larger clasts physical property data are not indicative for source rock origin. Also, there is no clear trend in the depth plot. This is surprising because clasts from below 320 mbsf are dominantly doleritic, whereas clasts from above 320 mbsf are mostly granitic (Cape Roberts Science Team, 1999).

CONCLUSIONS

Primary control on compressional wave velocity of CRP-2/2A is porosity. The large scatter in the velocity/porosity relationship of the CRP-2/2A core below porosity 0.4 is attributed to various secondary controls on velocity:

1) Increased intergrain coupling as a function of depth is strongly enhanced by carbonate cementation, thereby enlarging elastic moduli resulting in higher P-wave velocities. This is particularly important in the lower part of the core (440-624 mbsf). The influence of cementation on velocity is significantly larger than cement-induced reduction of porosity by further 0.05. Consequently, intensive cementation of CRP-2/2A may result in both very low porosity and very high velocity which, in the case of the uncemented CRP-1, was restricted to large single lonestones in the core.
2) Stress relaxation, whether *in situ* or induced by coring (probably more important), is associated with formation of cracks on various scales, thereby reducing framework stiffness and resulting in lower velocities. This is particularly important in the upper part of the core (0-440 mbsf). Again the influence on velocity is larger than on porosity. The velocity/porosity pattern of the upper part of CRP-2/2A is similar to that of CRP-1 and probably caused by the same processes.

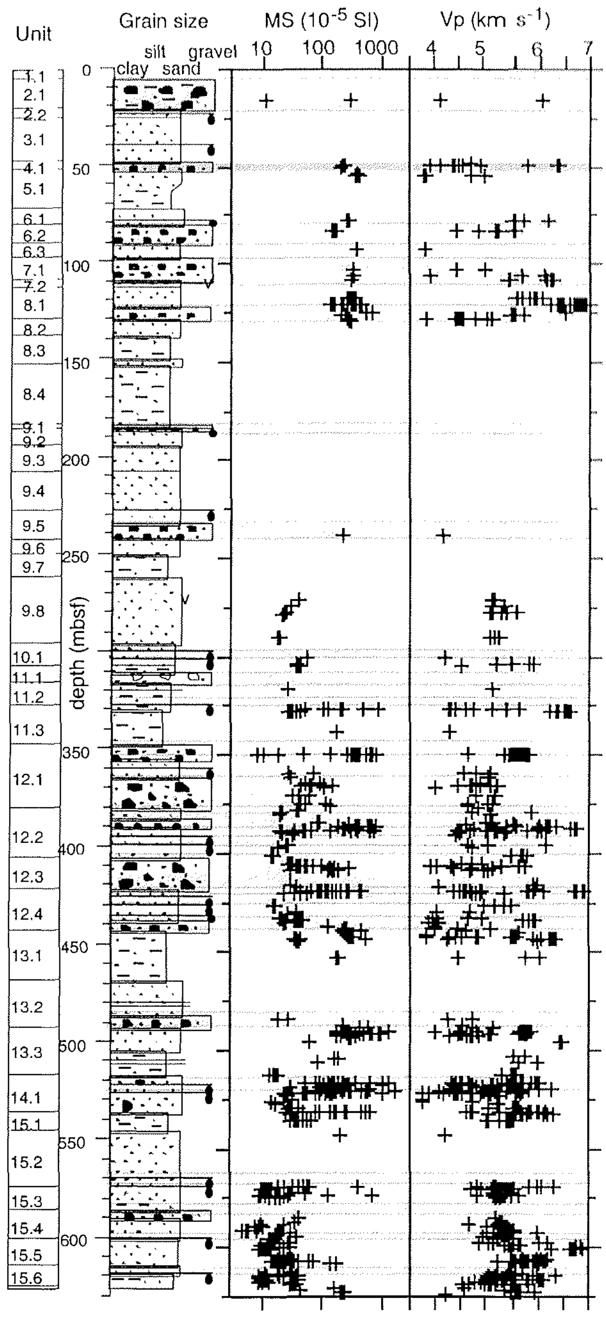

Fig. 13 - Magnetic susceptibility (MS) and velocity (Vp) data from depth intervals with negative apparent and zero porosity (Fig.1) as a function of depth and compared with lithology and grain size (Cape Roberts Science Team, 1999). Note that most data cluster in diamict units (shaded areas)

3) Intercalation between cemented and uncemented units of CRP-2/2A cause velocity/porosity scatter among sandstone and mudstone units which is significantly larger than suggested by global models for siliclastic marine sediments.
4) At the level of zero-porosity, velocities between 3.8 and 7 km s^{-1} reflect the characteristics of single large lonestones (sedimentary rocks, basement granites, granitoids, granodiorites and dolorites).
5) The influence of grain size on CRP-2/2A velocity/porosity relationship is insignificant based on

correlations of residual porosities and velocities with grain-size data.

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