Chapter 1:

Acoustic and elastic properties of calcareous sediments across a siliceous diagenetic front on the eastern U.S. continental slope

1.1 Abstract

The Ocean Drilling Program drilled Hole 904A on the upper continental slope offshore New Jersey through 230 m of Eocene chalks and an opal-A/opal-CT diagenetic front. In addition to a suite of standard logging tools, a dipole sonic tool was deployed to determine the *in situ* shear sonic velocity and the elastic properties of these slow, highly porous, sediments. While porosity decreases by 20% across the diagenetic front, the compressional velocity and the density are observed to increase by 30%, the shear sonic velocity and the bulk modulus by about 60%, and the shear modulus by almost 300%. It is shown that shear and compressional velocities are both controlled by porosity and consolidation, and that existing models for the prediction of elastic properties and shear velocity from standard logs are still valid through the diagenetic front. The strong effect of diagenesis on rigidity makes the shear velocity log a highly sensitive indicator of pore shape and pore filling transformations.

1.2 Introduction

The Ocean Drilling Program Leg 150 drilled and collected logging data at 4 Sites (902, 903, 904 and 906) on the eastern U.S. continental slope where it recovered a thick section of Eocene chalks [*Mountain, Miller, Blum, et al.*, 1994]. At all four sites, a diachronous high amplitude seismic reflector was recovered which had previously been identified as a siliceous diagenetic front below which biogenic opal-A has been converted to porcellanite [*Tucholke, Vogt et al.*, 1979; *Poag, Watts, et al.*, 1987]. In this paper we investigate the *in situ* elastic properties of the chalks through the diagenetic front and their relationship to porosity and consolidation.

Compressional velocity (V_p) and density (ρ) are both routinely measured *in situ* and on core samples. These data are critical for log-seismic correlation (synthetic seismograms) and for the identification of seismic sequence boundaries [e.g. *Goldberg et al.*, 1987], but in order to describe the elastic behavior of the formation, its dynamic elastic constants must also be known. The shear modulus, μ, and the bulk modulus, K, can be defined by:

$$V_p = \sqrt{\frac{1}{\rho}\left(K + \frac{4}{3}\mu\right)} \qquad \text{and} \qquad V_s = \sqrt{\frac{\mu}{\rho}} \tag{1}$$

where V_s is the shear wave velocity. Because neither of the elastic moduli can be directly measured *in situ*, the measurement of ρ, V_p and V_s is necessary for the resolution of equation (1). When using standard acoustic logging tools, however, there is no detectable shear wave in slow, poorly consolidated formations such as on the New Jersey continental slope, and it is not possible to measure V_s directly [*Toksöz and Cheng,* 1991]. Dipole sonic logging technologies, which initiate flexural waves in the formation using a directional pressure source [*Chen,* 1988], usually allow for estimates of V_s through waveform analysis, over a wide range of wave speeds and formation porosity. During ODP Leg 150, a commercial dipole tool was used in addition to a suite of standard tools which made possible the estimation of V_s and of the elastic moduli in these high-porosity sediments.

In previous work on the New Jersey continental slope at adjacent DSDP Sites 612 and 613, Poag, Watts, *et al.* [1987] and Wilkens *et al.* [1987] identified a sharp change in core and log physical properties related to the conversion of biogenic Opal-A to porcellanite. Wilkens *et al.* [1987] linked the density and porosity changes to the transformation in the micro-structure of the chalks: the re-precipitation of the dissolved biogenic silica (opal-A) into silica lepispheres (opal-CT). This diagenetic transformation cements the matrix of the sediments and partially fills the large calcareous fossils, reducing porosity by about

20% over just a few meters and without affecting the overall chemical composition of the grains or their density.

The dipole sonic tool used during Leg 150 enabled direct measurement of V_S in the chalks and through this same diagenetic front. We discuss the results at Site 904 and at nearby Site 902 and the suitability of current models for velocity-porosity relationships and sediment elastic properties.

1.3 Logging Results

In Hole 904A, an extensive suite of logs was run over a 230 m-thick calcareous chalk section, including porosity (Φ), ρ, V_P and V_S measurements. The borehole conditions were excellent over this interval and the data clearly show the opal-A/opal-CT diagenetic front penetrated at 525 meters below seafloor (mbsf). In Figure 1.1 porosity (Φ) decreases by 20 % across this boundary, density and V_P increase by about 30% and V_S by 60%. Mountain, Miller, Blum, *et al.*, [1994] observe that the grain density in core samples remains unchanged, or even decreases slightly, below 525 mbsf, which suggests that the increase in bulk density and compressional velocity are controlled uniquely by changes in the porosity and the nature of the pore space.

The strong correlation between velocities and porosity in Figure 1.2a and 2b underlines the velocity dependence on porosity. The chalks drilled in Hole 904A have been divided into three distinct subunits, identified by Mountain, Miller, Blum *et al.*, [1994]: above (+) and below (o) an abrupt drop in clay content at 419 mbsf; and below (•) the diagenetic boundary at 525 mbsf (see Figure 1.1). Least square regressions distinguish different trends between these three groups of data (Table 1.1). The increase in slope with increasing depth and decreasing porosity can be attributed mainly to compaction. Part of this increase between (+) and (o) may also be attributed to a clay content reduction which increases the contribution of higher-velocity calcite and silica minerals. Data recorded below the diagenetic front (•) are particularly distinct, showing reduced scatter (increased correlation coefficients in Table 1.1), but no significant change in chemical composition. This behavior is interpreted to be characteristic of the change in mechanical state of the sediments.

In the past, a lack of direct V_s measurements has precluded the development of empirical relations between V_s and porosity. The shear velocity and the rigidity of marine sediments have not been easily computed from their physical components and properties because of the diversity in grain sizes, shapes, and other parameters affecting particle interlocking and sediment rigidity [Hamilton, 1971]. Figure 1.2b shows, however, that a consistent correlation exists between Φ and V_s. Least square regressions for the same three subunits described above appear in Table 1.1. The relationships for $1/V_s$ and $1/V_p$ vs. Φ through the chalks and the diagenetic front are similar with a reduction in scatter and a steepening of slopes as Φ decreases with depth (Table 1.1). Figures 2a and 2b show that V_s increases faster than V_p with decreasing porosity, although this is more apparent in the evolution of their ratio V_p/V_s as a function of depth. Figure 1.3 (column a) shows V_p/V_s, representative of the Poisson's ratio and of the stiffness of the material, steadily decreasing with depth as a result of compaction, and dropping sharply from 3.0 to 2.5 at the diagenetic front. This change is consistent with the stiffening of sediments during the early stages of diagenesis also observed by Wilkens *et al.*[1992].

Having acquired log data for V_p, V_s and ρ, equation (1) can be used to estimate μ and K, the shear and bulk moduli, as a function of depth. Figure 1.3 (column b) illustrates the sharp increase in the two moduli and the mechanical change occurring through the diagenetic front at 525 mbsf. The relative increase in bulk modulus is about 60%, and the shear modulus increases by about 300 %. Therefore a five times greater relative increase in rigidity than in incompressibility results from diagenesis in these sediments.

1.4 Velocity-Porosity Models

1.4.1 Models description

Several models have been proposed for the determination of elastic moduli in sediments from porosity, in the absence of shear velocity measurements. Particularly, Wood [1941] and Gassmann [1951] derived equations that have been used by different authors to address the changes in elastic properties of marine sediments through consolidation. Wood assumes that the shear modulus of unconsolidated sediments, considered to be high porosity aggregates of fluid and grains, is zero and that the bulk modulus is the geometric average of the bulk moduli of the grains (K_s) and of water (K_w):

$$\frac{1}{K_{Wood}} = \frac{\Phi}{K_w} + \frac{(1-\Phi)}{K_s} \qquad \text{and} \qquad V_p = \sqrt{\frac{K_{Wood}}{\rho}} . \tag{2}$$

Hamilton [1971], Hamilton *et al.*[1982] and Wilkens *et al.* [1992] suggest that this formulation is not valid for marine sediments, which have some rigidity, but still can be used to obtain a maximum estimate of the shear velocity. Assuming that the difference between compressional velocities estimated from Wood's equation and measured velocities can be attributed to non-zero rigidity, the dynamic shear modulus predicted by Wilkens *et al.*[1992] is $\mu = 3/4(\rho V_p^2 - K_{Wood})$.

In Gassman's equation [1951], the bulk modulus is considered as the combination of three moduli: K_s, K_w and the frame bulk modulus (K_f) which represents a rigidity component introduced by grain-to-grain contacts:

$$K = K_s \frac{K_f + Q}{K_s + Q} \quad \text{with} \quad Q = \frac{K_w(K_s - K_f)}{\Phi(K_s - K_w)} . \tag{3}$$

Hamilton [1971] and Hamilton *et al.*[1982] defined an empirical relation between K_f and Φ for calcareous sediments similar to those encountered on the eastern U.S. continental slope:

$$\log(K_f\,(\mathrm{Pa}) \times 10^{-9}) = 1.87355 - 3.41062\Phi . \tag{4}$$

Once K has been estimated from porosity using equation (2) (Wood's model) or using equations (3) and (4) (Gassmann-Hamilton's model), μ and V_s can be deduced from V_p and ρ measurements.

Using the logging data recorded at Site 904, we have compared the results of these two models to the V_s log data in Figure 1.3 (column c). Both models assume a grain bulk modulus $K_s = 74.74 \times 10^9$ Pa (mostly calcite) and $K_w = 2.25 \times 10^9$ Pa (after Hamilton *et al.*, [1982]). As expected, the shear velocity estimated from Wood's model is higher than the log data, while on average the results from the Gassmann-Hamilton model agree with the log data within 10 %. In the absence of other *in situ* measurements of V_s, this observation supports the prediction of V_s in these sediments using the Gassmann-Hamilton model. We use this model for the estimation of V_s in adjacent Hole 902D, where no direct shear waves were recorded.

1.4.2 Hole 902D

Hole 902D was drilled 7 km upslope from Site 904 through similar, uniform lithologies and with good hole conditions. Only a monopole sonic tool was used in this hole and measured V_p, but no direct shear waves were detected. The second arrival detected was almost invariably the fluid wave at a constant velocity of V_f=1.6 km/s, as shown in Figure 1.4. In order to estimate V_s at this site, we applied the Gassmann-Hamilton model using the density, V_p and Φ logging data measured in Hole 902D. The results are also shown in Figure 1.4. Based on the comparison with Hole 904A, this estimate reasonably represents the shear velocity in Hole 902D because: (1) the limited range of ρ, Φ or V_p data is similar at Site 904; (2) V_s is clearly less than V_f and could not have been measured with a monopole source in this hole; and (3) in one interval where V_s is higher than V_f (at about 613 mbsf), a refracted shear wave was measured and agrees with the model.

A limitation of this method for estimating V_S is that it requires similar lithologies. When direct V_S measurements are not available, however, a reasonable estimate can be provided from standard logs by a well-constrained formulation. With more direct measurements of V_S (in combination with V_p, ρ and Φ) in different types of sediments, the empirical parameters in equations (3) and (4) could be defined broadly over a wide range of minerals and porosity, which could eventually allow for estimates of V_S in any environment using conventional logging data.

1.5 Elastic Moduli and Porosity

Figure 1.5 displays the relationships between porosity and the bulk and shear moduli calculated from logging data at Site 904, and the curve representing the Gassmann-Hamilton model in calcareous sediments. The same symbols are used as in Figure 1.2, except for μ below the diagenetic front (■). The bulk moduli data agree reasonably well with the model and confirm its validity at this site, even through the diagenetic front. In itself, such a strong correlation points to the porosity as a dominant parameter in the elastic properties of the chalks.

Figure 1.5 also illustrates the difference in the elastic moduli across the diagenetic front. While K and the gradient $\partial K/\partial \Phi$ increase progressively with decreasing Φ, μ increases steadily and $\partial \mu/\partial \Phi$ changes sharply at $\Phi = 45\%$, from 2.19 to 8.37 (Table 1.2).

1.6 Discussion

The discontinuity in rigidity may be explained by the formation of silica lepispheres in open pore space due to diagenesis. The abrupt increase in stiffness at the diagenetic front is clearly illustrated by the increase in V_p/V_S ratio (Figure 1.3a) and the discontinuous change in $\partial \mu/\partial \Phi$ suggests a coincident discontinuity in the mechanical properties of the chalks and in the lithification process. Whether this process is actually discontinuous or not, however, the increase in rigidity is the most significant change in the elastic properties of the chalks through diagenesis.

The Gassmann-Hamilton model accurately predicts shear sonic velocities through the entire chalk interval and through the diagenetic front in the absence of direct V_S measurements. This suggests that there is no major change in the nature of the consolidation process, or in the grain structure, due to silica diagenesis. If there is a change, its quantitative effect on the elastic properties of the sediments is limited, so that they remain predictable by the same algebraic formulation shown in equations (3) and (4).

Wood's model, by comparison, predicts velocities less satisfactorily than observed by Wilkens *et al.* [1992] for the same lithological formation a few miles downslope at Site 613, and the velocities which result from using this model are much higher than the velocities measured *in situ* by the dipole sonic tool. However the difference between the model and the V_S log increases with depth, or greater consolidation, as also observed by Wilkens et al. [1992]. The greater burial depth and higher consolidation of the chalks at Site 904 than at Site 613 may partially explain the difference in the application of Wood's model at the two sites. There is also a considerable difference between the results of the inversion described by Wilkens *et al.* [1992] and the V_S logging data, particularly above the diagenetic front where the inversion process produces shear velocity values much higher than the present logging data. Wilkens *et al.* [1992] note that the inversion process breaks down at very low shear wave velocities (i.e. lower than about 800 m/s) which accounts for most of the interval above the diagenetic front both at Sites 904 and 613. Consequently we suggest that the results of the inversion study overestimate V_S at Site 613 above the diagenetic front, and that Wood's model overestimates V_S at both sites. Dipole log measurements and alternatively the Hamilton-Gassmann model are more representative of V_S in these marine sediments.

1.7 Conclusion

The primary role of porosity on the evolution of the mechanical properties of carbonates has been here observed and documented over an intermediate porosity range from 30 to 65% on the eastern U.S. continental slope. The Hamilton-Gassmann model provides a reliable empirical estimation of elastic moduli and V_S from porosity and conventional logs and agrees well with the dipole sonic log data. More *in situ* shear velocity measurements are needed to calibrate similar models in a variety of sedimentary environments.

At Site 904, the infilling of foraminifer chambers by diagenetic re-precipitation of Opal-CT from dissolved Opal-A generates a noticeable change in the lithification process, whose most apparent mechanical effect is a sharp increase in sediment rigidity. Shear velocity logs can indicate, and to some extent quantify, this specific diagenetic transformation in the absence of sediment core analyses. With adequate data for calibration, these observations could be extended to other mechanical or geochemical processes that affect grain-to-grain contacts and alter the pore space and the matrix through different types of transformations, such as the formation of ice (gas hydrates) or the precipitation of diverse types of minerals. The shear velocity log is a highly sensitive indicator of such processes that primarily affect the sediment rigidity.

References

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Tables

Table 1.1: Linear regressions for slowness vs. porosity (with correlation coefficients).

Unit	$1/V_p$	$1/V_s$
+	$0.475 + 0.159\Phi$ (0.441)	$1.217 + 1.079\Phi$ (0.404)
o	$0.378 + 0.310\Phi$ (0.636)	$0.621 + 2.064\Phi$ (0.586)
•	$0.231 + 0.586\Phi$ (0.817)	$-0.324 + 3.897\Phi$ (0.855)

Table 1.2: Linear regressions for elastic moduli vs. porosity (with correlation coefficients in brackets).

Unit	Bulk Modulus (K, in 10^9Pa)	Shear Modulus (μ, in 10^9Pa)
+	$7.21 - 4.50\Phi$ [0.410]	$1.05 - 0.95\Phi$ [0.429]
o	$10.31 - 10.17\Phi$ [0.642]	$1.73 - 2.19\Phi$ [0.636]
•	$15.26 - 19.76\Phi$ [0.777]	$4.69 - 8.37\Phi$ [0.821]

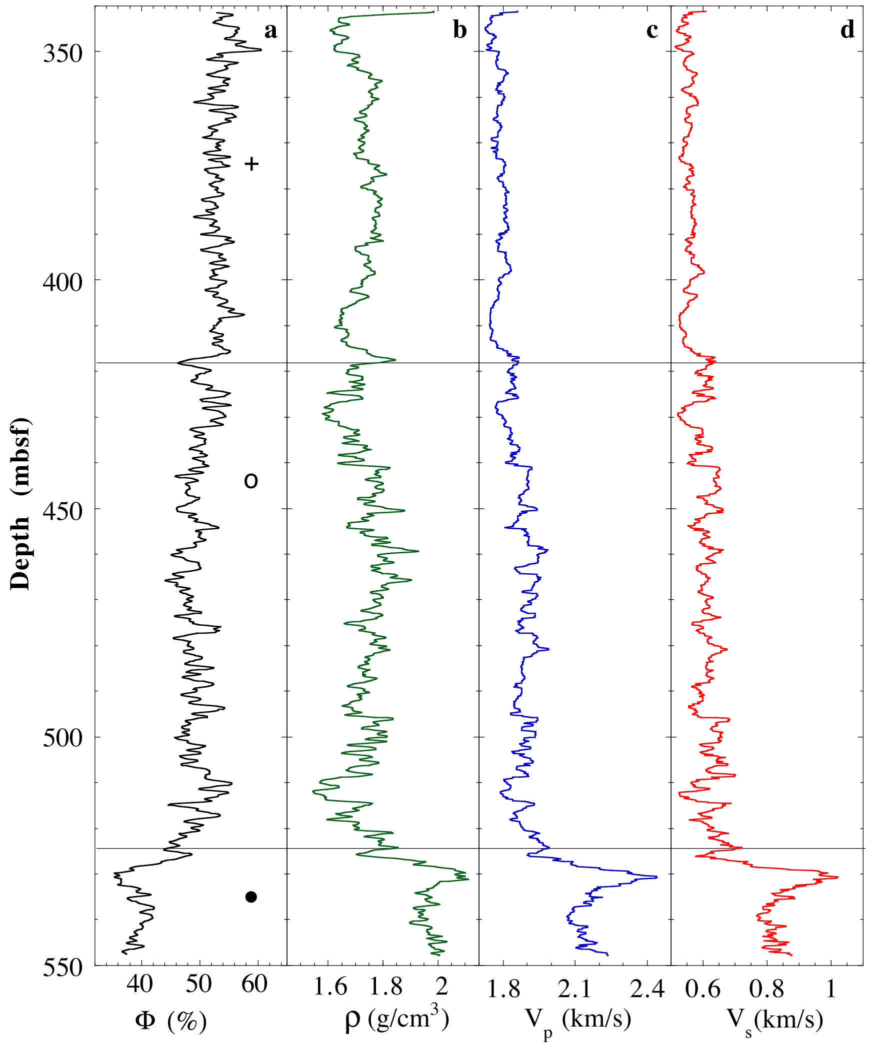

Figure 1.1: Logs measured in hole 904A (a) F, (b) r, (c) Vp and (d) Vs. The interval logged is divided into three subunits (see text). The sharp change in all the measurements at about 525 mbsf corresponds to the diagenetic change from Opal A to Opal CT.

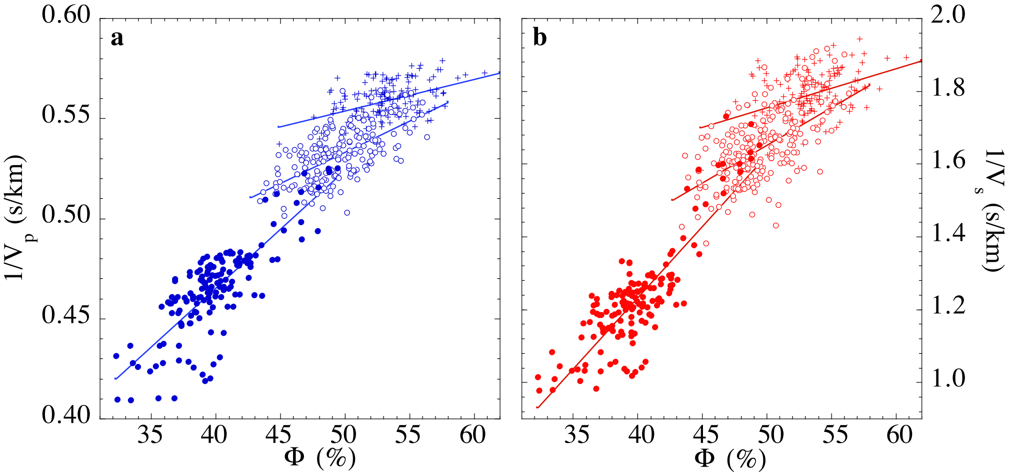

Figure 1.2: Relationship between porosity (Φ) and **(a)** $1/V_p$ and **(b)** $1/V_S$ in Hole 904A. Least square linear regressions are displayed for each lithologic subunit (same as in Figure 1.1: cross above 419 mbsf, holow circle above the diagenetic front and filled circles below).

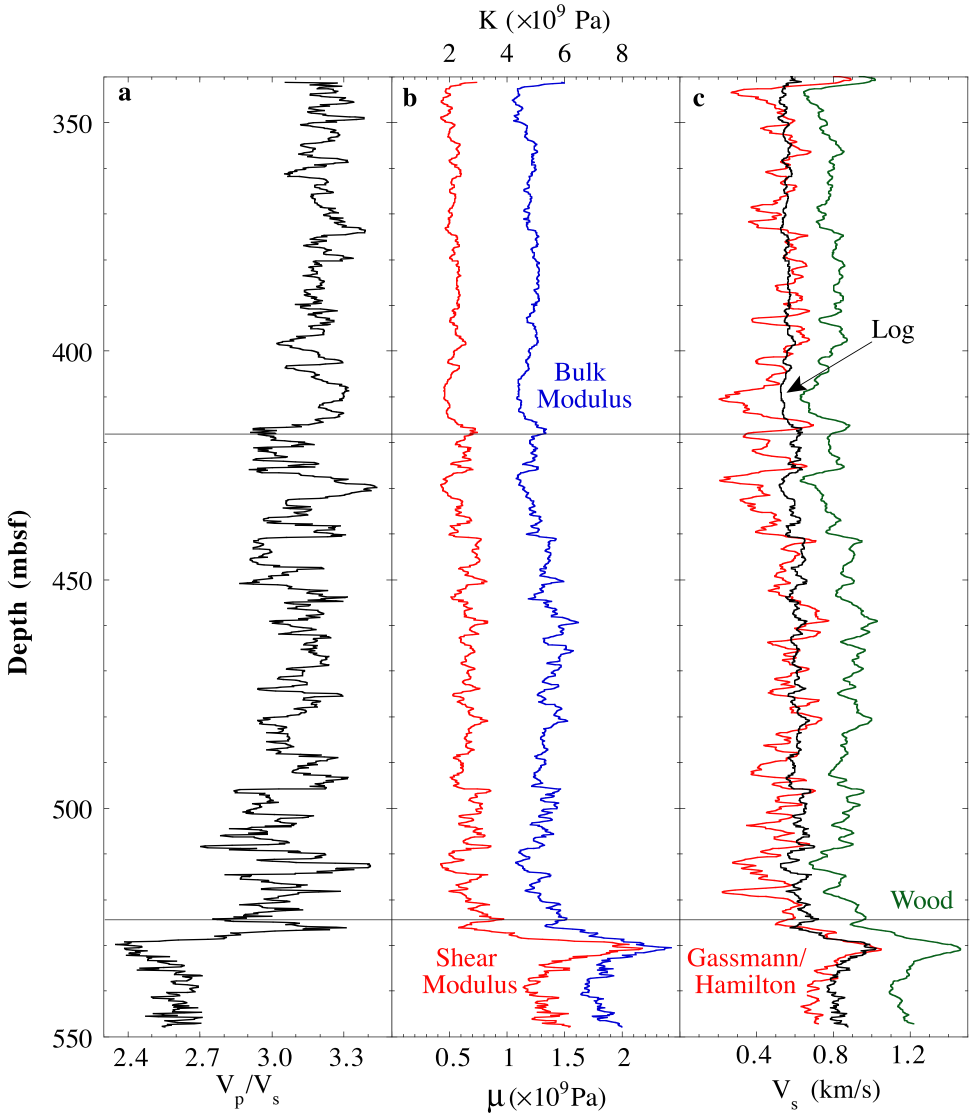

Figure 1.3. (a) In situ V_p/V_s from logging data in Hole 904A. (b) Bulk and shear moduli calculated from ρ, V_p and V_s logs in Hole 904A. (c) Comparison between direct V_s measurements in Hole 904A and the Wood and Gassmann-Hamilton models.

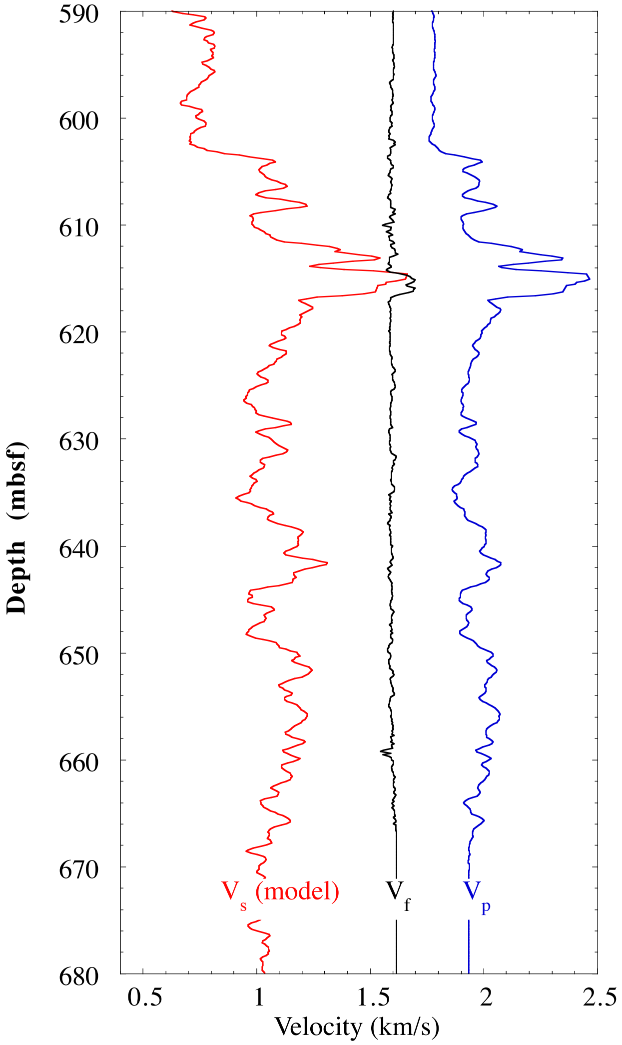

Figure 1.4: In situ velocity measurements in Hole 902D (similar lithology as Site 904) and V_s estimated by the Gassmann-Hamilton model. A direct refracted shear wave measurement around 613 mbsf matches the model results.

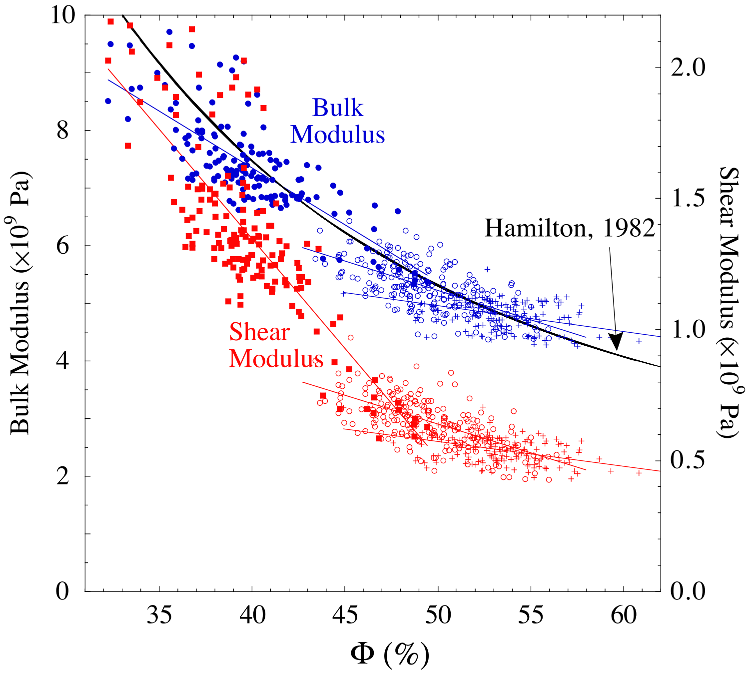

Figure 1.5: Relationships between porosity and bulk and shear moduli in Hole 904A. The symbols are the same as in Figure 2. The measurements of K compare well with the Gassmann-Hamilton model.