
Acknowledgments

AAPG and AADE thank the following for their generous contributions to
Pressure Regimes in Sedimentary Basins and Their Prediction

BP America Inc.

Knowledge Systems, Inc.

Minerals Management Service

Unocal Corporation

Contributions are applied toward the production costs of publication, thus directly reducing the book's purchase price and making the volume available to a larger readership.

19

The Future of Pressure Prediction Using Geophysical Methods

Alan R. Huffman

Conoco Inc., Houston, Texas

ABSTRACT

The technology of pore-pressure prediction has advanced significantly in recent years. In the future, new methods for pore-pressure prediction will routinely use shear-wave data gathered using multi-component seismic technology. Overburden and fracture gradient will be predicted in three dimensions using gravity and magnetic inversion technology. Seismic inversion, both prestack and poststack, will provide refined estimates of the velocity field in the subsurface, and new seismic-processing methods will allow velocity anisotropy to be predicted accurately so that it can be used to predict both pore pressure and real triaxial stress fields in the earth. These new methods will be used to make advances in the prediction of pressures in nonclastic rocks and to extract information that can be used to accurately predict structural hyperpressuring in reservoirs to assist in drilling difficult wells. Pressure prediction will become a standard tool in basin-scale and prospect-scale evaluation of the hydrocarbon system and will be used to guide the exploration process. In the production environment, pore-pressure prediction will be used routinely to provide a three-dimensional model for the pressure regime in the subsurface that will be critical to effective reservoir simulation and reservoir management.

Despite all these advances, however, pore-pressure prediction will still be limited by the quality of seismic data acquisition and processing technology that is used to prepare the data and by the structural complexity of the subsurface that is to be imaged. Predictions will continue to be limited by the lack of predrill information about the state of compaction in the subsurface that is critical to a robust pressure prediction. Lastly, prediction accuracy will continue to be limited by the presence of secondary pressure in situations where velocity reversals are difficult to detect on seismic data.

INTRODUCTION

Predrill pressure prediction using geophysical data and methods has historically been done using very simple models and overly simplistic estimates of the Earth's velocity field. The methods commonly incorporate a locally calibrated set of curves for pressure that contained imbedded assumptions about the cause of pressure in the geologic section sampled by the control wells. The advent of the effective-stress concept and the pressure-

prediction and the pressure-prediction methods that developed from that concept led to a much needed inclusion of fundamental physics into the art of pressure prediction. The use of effective-stress methods has become the standard for pressure prediction with many variants including the Eaton method (Eaton, 1975), the Bowers method (Bowers, 1994), and the Sperry Sun method (Holbrook and Hauck, 1987), to name a few. The range of software available for pressure prediction has grown significantly in recent years, along with the sophistication of the parameters used. Still, weaknesses remain because of (1) the limitations of the seismic velocities themselves, (2) the lack of understanding of the basic causes of pressure, and (3) the effects of pressure

Huffman, Alan R., 2002, The Future of Pressure Prediction Using Geophysical Methods, in A. R. Huffman and G. L. Bowers, eds., Pressure regimes in sedimentary basins and their prediction: AAPG Memoir 76, p. 217-233.

on physical properties, including velocity, density, and porosity, of the rocks. Despite the level of sophistication that is used in pressure prediction today, most practitioners are concerned primarily with predrill prediction and overlook the vast significance of pressure variations at the basin and prospect scale. This chapter discusses some of these issues and tries to put them into context.

EFFECTIVE-STRESS AND LOADING-PATH DEPENDENCY OF PRESSURE

The functional relationship between pore pressure and velocity has been generally recognized for many years. The level of understanding about the relationships between various physical properties and pore pressure, however, varies widely. Many people still are unaware that there is more than one cause of pressure and that present-day pressure regimes are the result of the complete loading path that a rock has undergone since its deposition.

The causes of abnormal pressure can be divided into two types. Undercompaction, also known as compaction disequilibrium, is related to the compaction process itself and occurs where the rates of deposition and burial are sufficiently great relative to the vertical permeability of the sediments. Where large loading rates are applied to rocks such as shales with relatively low-vertical permeability, the confined fluids in the rock mass cannot escape abruptly enough to maintain a hydrostatic fluid pressure gradient. This type of abnormal pressure is observed in many young Tertiary basins worldwide and is commonly recognized in seismic-velocity data by the slow decrease in the velocity gradient with depth.

The other class of abnormal pressure mechanisms is not associated with the compaction process, and occurs where the pressure of the fluid in the rock mass is allowed to increase relative to hydrostatic pressure through one of several mechanisms (Plumley, 1980). These mechanisms include (1) aquathermal fluid expansion (Magara, 1975), (2) hydrocarbon source maturation and fluid expulsion (Spencer, 1987), (3) clay diagenesis (Bruce, 1984), (4) fluid pumping from deeper pressured intervals during fluid migration, and (5) decreases in overburden caused by tectonic activity. Although each one of these mechanisms are distinctly different in their behavior, they all produce a similar effect in pressured rocks in that they work to cause a decrease in the effective stress on the formation for a given porosity. In particular, clay diagenesis, aquathermal expansion, and source maturation occur at elevated temperatures so that cold sediments should not be affected by these mechanisms. In contrast, fluid pumping and overbur-

den decreases can occur in any sediments. Where secondary pressure occurs, it is commonly manifested through a reversal in the velocity trend with depth without an increase in porosity. Although not all velocity reversals are caused by secondary pressure, it is important to remember that reversals caused by secondary pressure contain some of the most severe pressure increases. Thus, it is prudent to treat velocity reversals as if they are caused by secondary pressure unless there is clear evidence from well data that the velocity reversals are due to undercompaction, lithology changes, or other possible causes. Also, velocity reversals, if not recognized as being due to secondary pressure, overestimate porosity if it is assumed that the rocks are simply undercompacted.

To understand the relationships between effective stress, porosity, and velocity, consider the concept of critical porosity that was first defined by Marion et al. (1992). Figure 1 shows the relationship between porosity and velocity for clastic materials from laboratory experiments. The boundary between Wood's equation behavior and the loading-bearing behavior occurs at porosities of 38 to 50% and is defined as the critical porosity. The trend of velocity with porosity shows two dominant trends that follow (1) Wood's equation (Wood, 1941) at porosities above the critical porosity and (2) a modified Voigt-Reuss behavior at porosities below the critical porosity (Nar et al., 1991). The Wood's equation behavior is characteristic of slurries, and the modified Voigt-Reuss behavior is characteristic of frame-bearing solids, including clastic rocks under significant effective-stress conditions. Figure 1 shows how velocity increases as porosity decreases. This trend correlates with the degree of compaction that the material has undergone and is part of the reason that some pressure methods use porosity as a proxy in determining the compaction state of a material.

We must also consider the relationship between velocity and effective stress that defines the normal compaction trend. Tosaya (1982) performed experiments on clastic rocks to demonstrate the critical factor of the effective stress. Figure 2 shows that the velocity of the material follows the effective stress nearly perfectly regardless of the total overburden stress that is applied. This experimental result is an excellent demonstration that Terzhagi's effective-stress relationship is valid and can be correlated with velocity changes in clastic materials.

One way to think about the two causes of abnormal pressure is to recognize that the velocity of any rock in the subsurface is a direct function of its depositional and burial history. Figure 3 shows a hypothetical loading path for a rock in a clastic basin in porosity-velocity-effective-stress space. This diagram is a three-

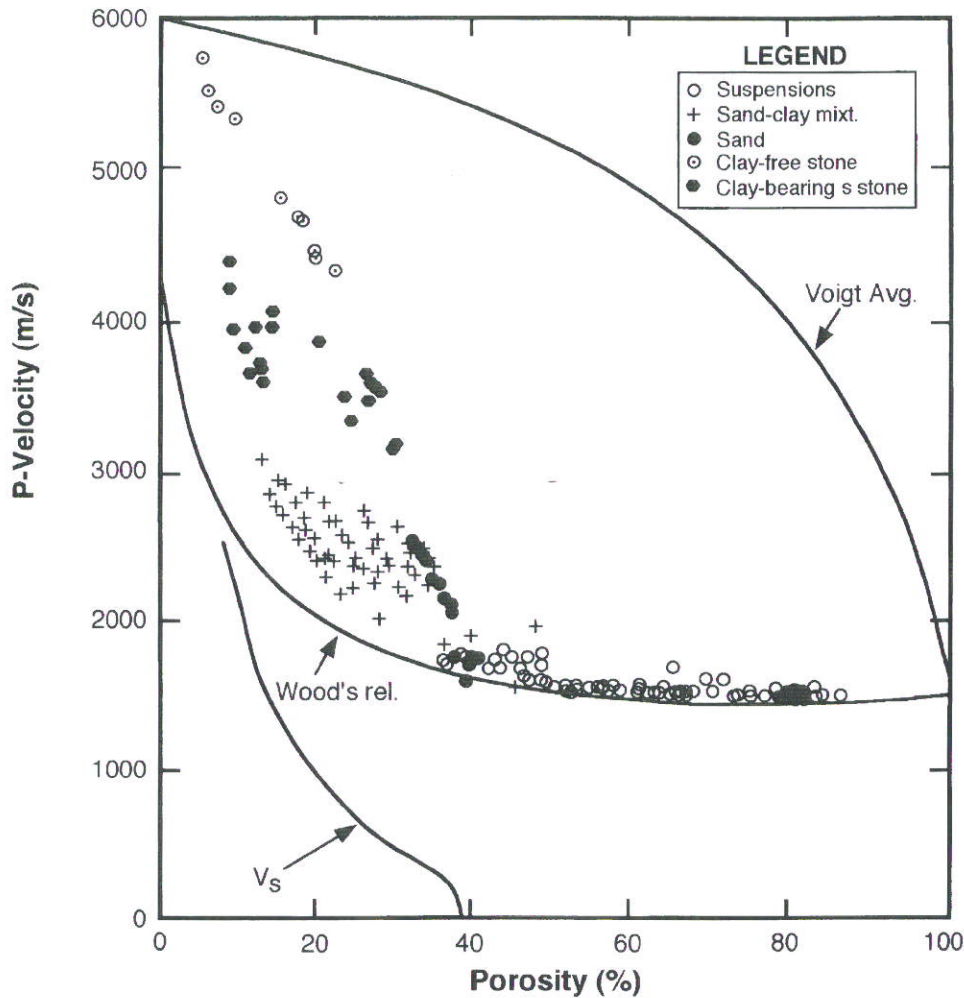


Figure 1. Velocity-porosity relationships in clastic sedimentary materials. Note the change in behavior caused by the inception of load-bearing capability at the critical porosity point (about 40% porosity). At porosities less than critical porosity, the material behaves like a Voigt-Reuss material. Also note the shear-wave behavior and how abruptly it changes from zero to nonzero as you pass the critical porosity. Figure modified from Marion et al. (1992).

dimensional composite of Figures 1 and 2 that demonstrates the interplay between velocity, porosity, and effective stress. The loading path starts at an effective stress of zero, and the velocity increases and porosity decreases until the material changes over from a Wood's equation material to a frame-bearing clastic rock that can support an effective stress on the grains. The Wood's equation part of the loading path (blue curve) occurs as the material is initially deposited and compacted near the surface. Once the critical porosity is reached, the material follows the primary compaction curve (black curve), achieving either a compacted or undercompacted state. If allowed to compact normally with fluid draining out of the pore spaces, a rock continues up the normal loading path, velocity increases, and porosity decreases. Both of these properties are dependent on the effective stress on the grains that are bearing the external load. If at some point the fluid is prevented from escaping, the rate of ascent up the normal pressure curve decreases so that the rock has a lower velocity and effective stress

than would be expected at normal pressure conditions at a given depth of burial. This condition is known as undercompaction or compaction disequilibrium. The key to understanding undercompaction is to recognize that a rock under these conditions still remains on the normal compaction trend, only it is not as compacted as you would expect it to be at that depth of burial under normal hydrostatic pressure.

Unlike undercompaction, a rock subjected to secondary pressure cannot stay on the normal compaction curve. Where fluid is pumped into a rock or expands within the pore spaces in the rock, the compaction process is arrested, and the rock begins to display a form of hysteresis behavior in velocity-effective-stress space. Where this occurs, the porosity essentially does not change except for some minor elastic rebound (Moos and Zwart, 1998), and the velocity behavior is strictly controlled by the contact area and the grain-to-grain contact stresses in the rock. Because there is essentially no porosity change, the net effect is to flatten out the velocity-effective-stress trend and produce an unload-

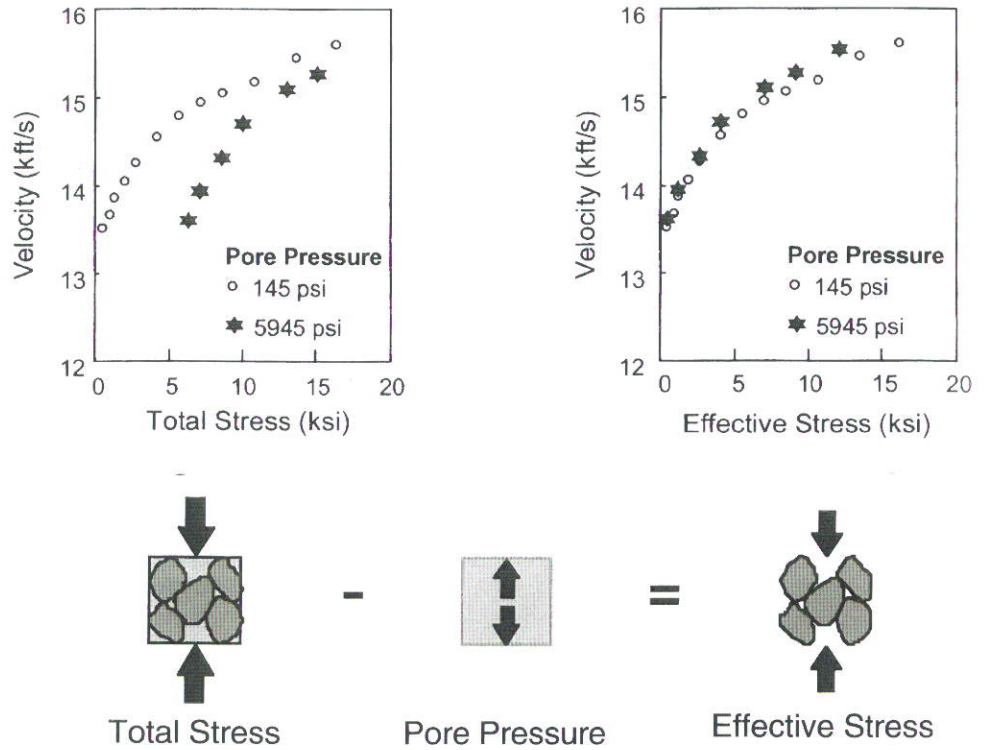


Figure 2. Experimental results from Tosaya (1982) demonstrating the relationship between effective stress and velocity in a granular material of approximately constant porosity. The schematic equation below the diagrams represents the observed stresses that are applied to the grains where total stress is applied as an external force to the rock volume, and pore pressure counteracts the total stress resulting in a net grain load that is equal to the effective stress.

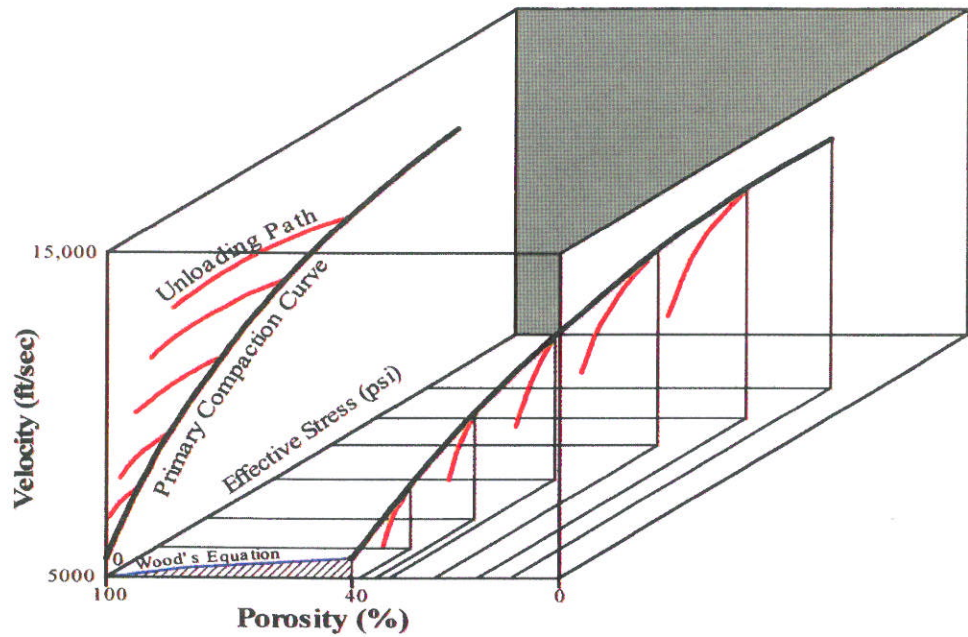


Figure 3. A three-dimensional diagram showing the loading history of a hypothetical shale material in terms of effective stress, velocity, and porosity. The actual three-dimensional normal compaction trend and unloading limbs are projected into the velocity–effective stress plane to the left, which is the same display shown in Figure 4B.

ing trend that is different from the primary compaction trend. The unloading curve must start from the velocity–porosity–effective stress point on the primary compaction curve where the unloading begins (Bowers, 1994). This is why unloading (red curves on Figure 3) always starts from a porosity–velocity–effective stress point on the primary compaction curve. Note that the

unloading paths occur essentially in the velocity–effective stress plane as the porosity decrease associated with compaction is arrested during unloading and very little elastic rebound (less than 1 porosity unit) occurs during the unloading process. As the effective stress decreases because of higher fluid pressures at fixed overburden, the velocity decreases in direct relation to