Seismic petrophysics: An applied science for reservoir geophysics

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Modern computational power and processing schemes have liberated reflection seismology from its primary purpose, structural mapping. It is now fairly routine to produce a number of seismic attributes, using either prestack or poststack data, or even both in combination. With these attributes, the geophysical interpreter can now make maps and look for geologically-meaningful trends in the data...or correlate them with well observations and use them in geostatistical models...or perhaps try to use them directly to solve for the rock types and fluids in a deterministic manner. These processes can be performed carefully, with checks and redundance, or sloppily, using only the interpreter's intuition and, perhaps, wishful thinking, as a guide.

This short paper introduces a new term "seismic petrophysics" to refer to the careful and purposeful use of rock physics data and theory in the interpretation of seismic observations. It also points out a number of pitfalls in their misuse, and provides suggestions for future efforts.

Reservoir geophysics — going beyond structure. From the 1940s through the present time, the main use of reflection seismic data in the oil industry has been to map structure surfaces. Once a time-depth relationship can be established, whether through logs, check shot surveys, or other means, the depth of reflecting surfaces can be determined, the closure determined, and the resources evaluated. These concepts are not new. Some date back more than half a century. See "The history and development of seismic prospecting" by B. B. Weatherby which appeared in the July 1940 issue of GEOPHYSICS. (It may be of interest to note that the famous paper on wavelets by Norman Ricker appeared in the following issue.) In 1942, B.G. Swan described, again in GEOPHYSICS, depth conversion from knowledge of "Velocities in the Texas Gulf Coast." Techniques to enhance the imaging capabilities of reflection methods have improved steadily over the years, including the CDP stack and digital processing to remove unwanted effects. Modern methods, such as prestack depth migration, have virtually eliminated the need to produce a time section before depth conversion, and the confidence in structural positioning can be very high indeed.

Modern seismic methods provide us with extremely high-quality data — data in which there is far more information that just the time (or depth) of a reflection. We now can have sufficient confidence in the nature of the reflected wavelet that we can use it to provide insight into the nature of the reflector itself. Realization of the importance of bright spots on true-amplitude sections in the1970s was perhaps industry's first realization that we could look beyond structure in the data.

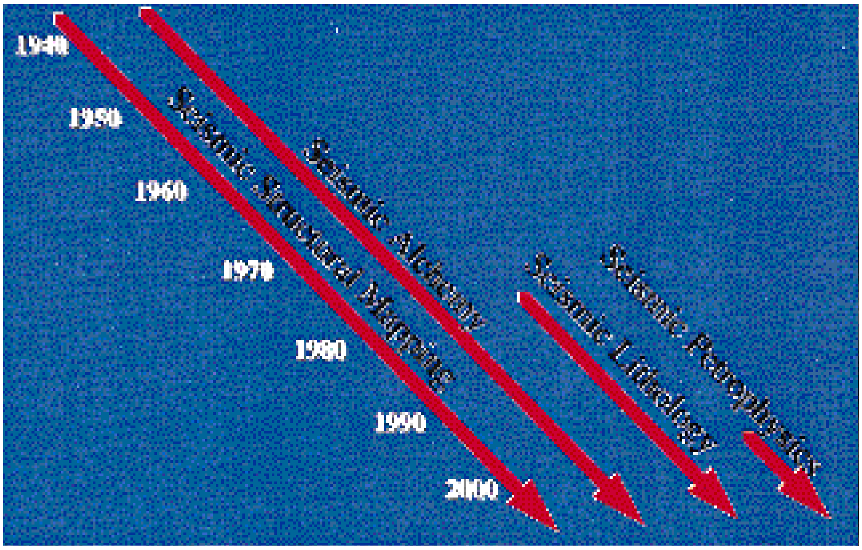


Figure 1. Time lines.

$$\frac{1}{V_p} = \frac{1-\phi}{V_{matrix}} + \frac{\phi}{V_{fluid}}$$

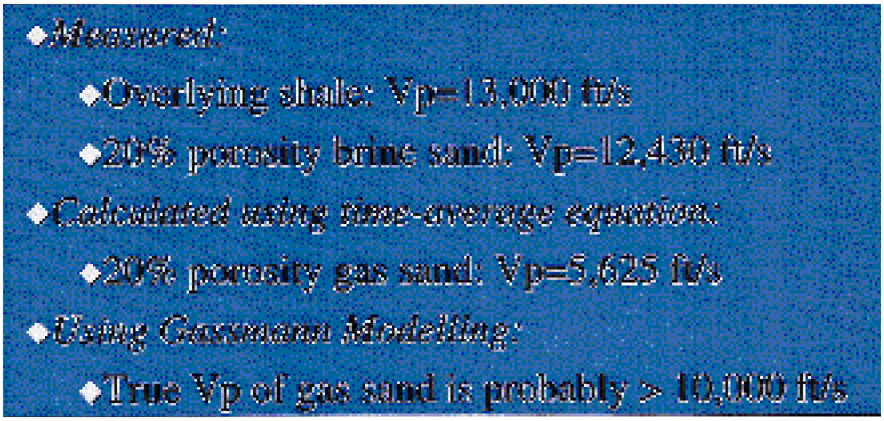
Figure 2. Wyllie's equation.

The quality of prestack data continually improved, and amplitude variation with offset has become a household term (at least in some unusual households). The term "seismic lithology" has been used to describe inversion of seismic data for impedance (as it is used in Sheriff's 3rd edition of the *Encyclopedic Dictionary of Exploration Geophysics*) or as the interpretive stage of processing and analyzing AVO data (as it is used in Hilterman's article in the June 1990, issue of *TLE*, where he asked the question "Is AVO the seismic signature of lithology?"). In the broader sense, what we now think of as seismic lithology has been practiced since the mid-1970s.

Seismic alchemy. Seismic applications, as functions of time, are shown on the time lines displayed in Figure 1. Here, you can see that seismic structural mapping has been used continuously since the 1940s, and continues today. You can also see that, in this interpretation, seismic lithology started in the mid 1970s and continues today. On this chart, I have included a new term, 'seismic alchemy" and have assumed that this practice has coexisted with other seismic applications for all time. One dictionary includes in its definition for alchemy "the seemingly miraculous change of a thing into something better" (*Webster's New World Dictionary, 2nd College Edition*). We have all seen examples of this, and we continue to see it every day. Some forms of alchemy actually work: A good example is that of imaging beneath salt, where the transformation of seismic data into a useful image when proper prestack depth migration is applied is nothing short of “seemingly miraculous.” But we also have seen examples of sloppy science or downright charlatanism, the equivalent to pulling a rabbit out of a hat — we would like to believe that somehow it can really work, but, perhaps, we are just being fooled, or we are fooling ourselves.

A good example of (often inadvertent) seismic alchemy can be found in the simple prediction of reflection amplitudes from gas sands, using the well-known Wyllie time-average equation, shown in Figure 2. In the original paper by Wyllie, Gregory, and Gardner (GEOPHYSICS, 1958), the authors noted that the formula held only if the velocity of the saturating fluid exceeds that of water. In other words, the use of gas velocities in the equation is not valid. Yet workers in the industry (including, alas, academia) continue to make the mistake of applying this equation to conditions of partial saturation. Let’s see just how bad that mistake can be, by looking at Figure 3. In this (artificial) example, the reflection coefficient at an interface is found to be -.02. The interval consists of a shale over a brine sand, with the velocities as indicated. If we mistakenly apply the time-average equation, having calibrated the constants from the logging, but now substituting a low velocity for the fluid (gas), we would find a reflection coefficient of -.40, a truly remarkable bright spot. But we would be mistaken; and if we search for such a large reflection coefficient in our data, we may never find it, even if gas is in fact present. The use of the more appropriate Gassmann theory (with assumptions for shear modulus or dry frame properties) will yield a reflection coefficient of -.13, and a much more modest bright spot effect.

A more subtle form of seismic alchemy can be found in experiments run over existing, producing fields. Take, for example, an exploration program in an existing play (see Figure 4). In order to “calibrate” the seismic observations to known lithologies and fluids, the ambitious geophysicist runs a new seismic line over an existing field, taking care to pass near wells in which logs have already been obtained. The seismic data then show a distinctive character, perhaps a particular AVO behavior that can be related to the existence of hydrocarbons, or reservoir-quality sand. The conservative management of the geophysicist’s company is convinced of the value of seismic, and agrees to pay for a large 3-D survey over a neighboring area of interest — and they never see another similar AVO anomaly like the one over the producing field. Based on other information, the geologists are certain that another large field is in the survey area, but they cannot get approval to drill an exploration well, because the seismic data shows that they are wrong. But are they? The seismic “calibration” line was run over a producing field. That field has probably been produced under artificial lift (pump) for some time, and gas has been liberated from the oil, forming a partial-saturation gas cap. The AVO anomaly, so carefully observed from seismic, is responding to the gas, and there is no free gas present in an unproduced field in this play. Perhaps some other seismic characteristic would have been useful, but the calibration over a depressured, producing field has overwhelmed it.



- *Measured:*
  - Overlying shale: Vp=13,000 ft/s
  - 20% porosity brine sand: Vp=12,430 ft/s
- *Calculated using time-average equation:*
  - 20% porosity gas sand: Vp=5,625 ft/s
- *Using Gassmann Modelling:*
  - True Vp of gas sand is probably > 10,000 ft/s

Figure 3. Modeling a gas sand.

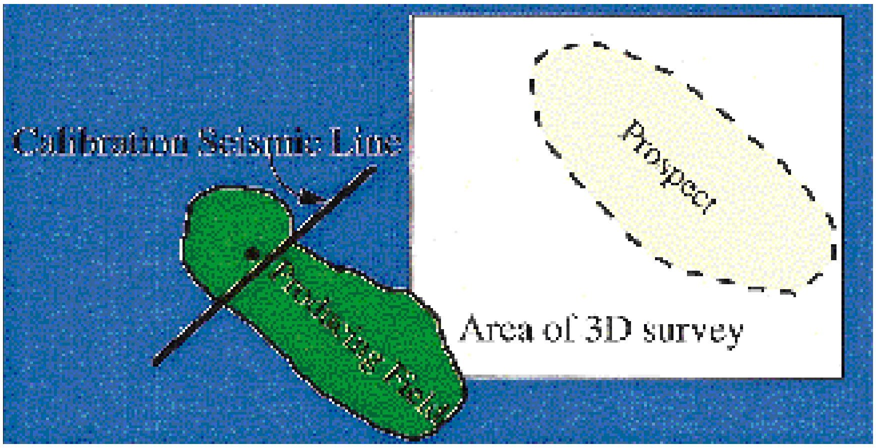


Figure 4. A common situation.

The Development and Production Forums

The inspiration for the ideas presented in this paper came from presentations made by many participants of the 1996 D&P Forum, held last summer in Vail, Colorado, and chaired by Hai-Zui Meng. All of the other papers in this special issue of *TLE* (except the regular features) are themselves derived from presentations made at that meeting. If you are interested in attending the 1997 D&P Forum, 13-18 July, to be chaired by John Eastwood, see the application form and call for participation in this issue, find them on the SEG home page of the World Wide Web, or contact the SEG headquarters.

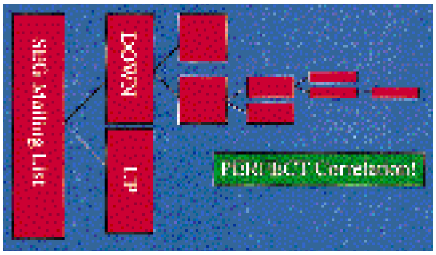
Here, seismic alchemy has failed due to a misconception concerning the cause of the anomaly. In this case, the seismic characteristic observed would have been more useful for reservoir geophysics, within the producing field, than for exploration.

Finally, we will take a look at an extremely subtle form of seismic alchemy, based on spurious correlations. (This is closely related to an example using a stock-sales scam outlined in a box nearby, and is also related to the subject of additional papers in this special issue of *TLE*.) Imagine you have run a very good seismic survey, and you are able to extract a large number of seismic attributes from it, including the usual Hilbert transform ones, several attributes from AVO, and perhaps others that are favorite proprietary attributes in your own company. You then search for correlations with reservoir properties as known from wells. You are careful to avoid going outside of your field, and you intend to use this correlation only to control stochastic modeling within the one reservoir, thereby avoiding the pitfall described above. If your suite of attributes is sufficiently large, and your set of wells sufficiently small, you can be virtually guaranteed of finding at least one attribute that correlates extremely well (as documented in the paper by Kalkomey in this issue of *TLE*), and you are likely to act on that correlation to drill wells in other parts of the field. This would be a mistake, unless you are convinced that there is a good rock-physics-based explanation for the correlation, or the correlation is so statistically robust that there can be little room for error. (The paper by Hirsche and others in this issue provides good arguments for the rock-physics basis.) Why? Because the correlation may be spurious, given many possible attributes and a scarcity of wells! This is seismic alchemy, as defined, because, in the absence of good rock physics support or overwhelming statistical power, the transformation from "attribute" to "indicator" is indeed "seemingly miraculous."

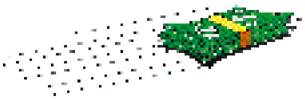
Seismic petrophysics. At the risk of applying too many terms to the seismic lexicon (my apologies to our modern Webster of geophysics, Bob Sheriff), I must ask the reader, "Which would you prefer, metaphysics or petrophysics?" Metaphysics, like alchemy, allows the seemingly miraculous; it permits one to develop, from initial assumptions, grand schemes of nature or reality. It is not scientific, in that it requires no checking or testing of hypotheses before an assumption is regarded as fact. Unfortunately, much of the application of seismic attributes falls into the category of metaphysics, in that relationships are assumed to be valid, rather than tested and either confirmed or rejected.

May I sell you some stock?

A parable to illustrate spurious correlations, appropriate for retelling at management conferences and cocktail parties.



Let's say that I decide to make a lot of money from my colleagues in SEG. I decide to use the SEG mailing list (against policy), and mail a letter to all the thousands of members on the list. To the members whose last names begin with A through M, I send a letter predicting that, next week, the stock of a certain company will go down; to the others, the letter predicts that the stock will go up. Next week, the stock either goes up or down — let's say that it goes down. So, that week, I send out two new sets of letters, but I only send them to those with last names A-M, because I had sent them a successful prediction the previous week (N-Z are simply ignored). In those new letters, I predict, for A-G, that the stock of some other company will go down, and for H-M, that it will go up. Next week, it goes either up or down — it doesn't matter; let's say it goes up. So I discard the mailing list for A-G, and send new letters to the remaining group: for H-J, I predict the stock of some company will go up, and for K-M that it will go down. And so on... you get the idea. By the end of a few weeks, I will be down to a very few individuals who have observed what they think is a flawless record of predictions on my part. My final letter to these individuals is an offer to invest in stock for them — all they have to do is send me $10 000 each, and they should be able to double their money in months! Of course, they are more than happy to borrow against their 401ks and send me bundles of cash. And I move to a Caribbean island to live out my days in splendor. What went wrong? These hapless investors witnessed a perfect correlation of stock predicting; but the correlation was perfectly meaningless! It was a subset of a random suite of predictions — I simply exploited the emotional response that blinds us to recognizing that a correlation will occur within any large random set of events (a Type I error in the terminology used in the paper by Kalkomey in this issue). It is no different with seismic attributes; calculate enough of them, and, with sparse well control, you will find the correlation that is bound to exist... even though it may be meaningless.



The solution to this problem is to incorporate the use of rock physics knowledge, locally calibrated and properly applied, to the interpretation of seismic data. To avoid confusion with existing usage of the terms rock physics, petrophysics, and the like, I would like to suggest that we refer to the purposeful application of rock physics theory, as calibrated by laboratory and well measurements, to the interpretation of seismic data, as "seismic petrophysics."

Several advances in recent years enable us to consider seismic petrophysics a scientific endeavor, rather than an art or alchemy. These include the truly astonishing improvements in seismic imaging, the development of new or improved wellbore measurements, and significant advances in rock-physics theory. We are still somewhat short of making the best use of seismic petrophysics, however, because the techniques required for application are not well-established, and the fundamentals are understood only by a handful of experts in some cases. In the following, I briefly outline those advances and the improvements I think are required for widespread application.

Seismic imaging. Readers of *TLE* are well aware of the improvements in seismic imaging that have occurred over the past several years. These include, but are not limited to, an increased number of recording channels, the widespread use of 3-D seismic acquisition and processing, processing that includes prestack depth migration, and the phenomenal improvements in computing power that enable the application of these techniques. As a byproduct of these improvements, the nature of the wavelet has been enhanced, and is much more robust, with surface effects removed or balanced. This, in turn, is what enables the use of seismic data, both poststack and prestack, for petrophysical interpretation.

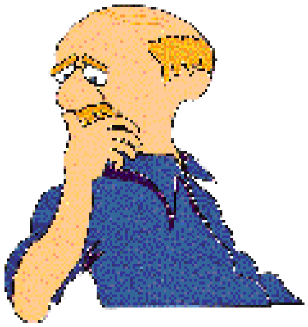
In-situ calibration. Even with increased confidence in the nature of the seismic wavelet, we still need to locally calibrate the seismic response to observations made in nearby wells, or to core taken from those wells. Many new logging tools have made our interpretation of well data more reliable, but most significant for seismic petrophysics have been the improvements in sonic-log acquisition and processing, vertical seismic profiling, and borehole imaging. Although there may be some room for continued improvement in readily-available commercial tools, the data provided from the current generation of monopole and dipole digital sonic logs is itself a tremendous improvement over the previous generations. When a modern tool is run and the data processed properly, there should not be need to rely on trends or "rules of thumb" for compressional and shear-wave velocities unless the hole was in very bad shape. These data are, typically, at a lower frequency than the tools of the past, and should more closely resemble the velocities at seismic frequencies. Additionally, the use of calibrated shear velocities in Gassmann-equation fluid substitutions should yield a much more reliable estimate for reservoir properties than empirical trends observed in wells in other areas or in laboratory data. It is a shame that this fact is not more-widely recognized and modern digital sonic logs not run in more wells as a routine matter. The calibration to seismic frequencies is best accomplished through the use of VSPs, as is the unambiguous association of reflections with beds. Borehole imaging data, providing detailed information on fractures, vugs, and other medium-scale features, may be required for the proper application of scaling laws and rock physics theories to reservoirs containing those features.

Rock physics theories. Over the past few decades, the advances in rock physics theories have far outpaced our ability to make use of them in seismic interpretation. A large number of theories have been advanced to account for "soft" pore space, such as that occupying compliant cracks, the presence of clays, and the existence of fine layering. These theories appear complicated, and can be confusing to most people; debate of the fine points by the experts themselves has helped to lend an aura of mystery and incompleteness to them as well. But the fact is, most of these theories are different ways of looking at the same phenomena, and often can be shown to reduce to the same relationships in simple cases. They are, in fact, appropriately applied to observations of seismic in many cases, although this has been largely confined to a research mode to date. The Gassmann model should be applied routinely to data obtained from dipole sonic logs to predict seismic response away from the well, where the saturation may be different from that in the logging environment. The Backus-layering model should be applied to all sonic logs to account for the effect of thin layers (on a seismic wavelength) in the generation of synthetic seismograms. And the Kuster-Toksoz crack model should be applied when additional information regarding the density of fracturing or jointing is available. You can substitute other specific models for any of those mentioned, depending on your preference, but in any case, your interpretation of seismic data will be greatly improved.

A word of caution is warranted here: I do not feel it is valid to calibrate seismic observations from ultrasonic measurements on core plugs, without the use of full-waveform sonic log data and vertical seismic profiling. There are many aspects of rock physics that operate on an ultrasonic scale, such as "squirt flow", that are not significant at lower frequencies, and the direct application of laboratory observations to seismic interpretation is not straightforward. On the other hand, I do feel laboratory investigations are extremely important in understanding the physics of elastic-wave propagation in specific rocks; if the physics is understood, the application of appropriate theories is warranted, and the combination can enhance our understanding of the phenomena we mean to interpret.

How can we use seismic petrophysics? There seem to be three hurdles to the widespread use of seismic petrophysics rather than seismic alchemy: (1) the infrequent use of proper wellbore measurements; (2) the lack of understanding of rock-physics theories at an appropriate level; and (3) a shortage of clear case histories to follow. These three hurdles must be overcome simultaneously. Modern sonic-logging tools should be run in far more wells than is currently the case, and the interpreter must pay attention to the quality of the data in various intervals, to avoid misleading results. Papers should be written by the experts in rock physics that present the theories in comprehensible forms and make their application clear. And, perhaps most difficult, the case histories of application of seismic petrophysics should be widely published, charting a course for others to follow. The problems remaining are actually those that require technology transfer, not fundamental advances in the science itself.

Metaphysics* or *Petrophysics



When the techniques of seismic petrophysics become routinely available, their results will probably be used by specialists and nonspecialists alike, much in the same way that seismic interpreters do not all know how to process seismic data. But these nonspecialists must still be familiar with the basic aspects of the science and with pitfalls (for example, see the paper by Francis in this issue). They may or may not actually be geophysicists; they may be petrophysicists, or geologists, or even engineers. The customers of these technologies, our clients, will likely be reservoir engineers, because the main application of these technologies will be to fill in the gaps between wells in order to construct improved reservoir models, often for simulation purposes. We can think of these technologies as being deterministic, but they are likely to become uncertainty-reducing techniques in a stochastic-modeling scheme, where geophysical data is interpreted in terms of rock and fluid properties, and these properties are then used as "soft" data between wells. We should expect to significantly reduce the uncertainty from brute-force correlations that may result from spurious factors or chance, and greatly enhance the reliability of interpretations. The range of stochastic models should be narrowed, and improvements in economic field development may be profound.

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