Do not believe in anything simply because it is found written in your books. But after observation and analysis, when you find that anything agrees with reason and is conducive to the good and benefit of one and all, then accept it and live up to it. **The Buddha**

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Preface

Every year finding new oil is harder, riskier, and more expensive – a natural consequence of its finiteness. As dictated by M. King Hubbert's "peak," declines in discoveries and production are inevitable. Yet demand continues, forcing us to deeper water, more complex reservoirs, and smaller, more subtle oil fields.

A key to managing this complexity and risk has always been effective integration of the diverse petroleum technologies. Workstations, visualization software, and geostatistics have contributed to integrating the vast amounts of *data* that we sometimes drown in. Perhaps more important are the asset teams that exploit diverse data by *integrating expertise*. Our goal, in preparing *Quantitative Seismic Interpretation*, is to help illustrate the powerful role that rock physics can play in integrating both the data and expertise of geophysics and geology for reservoir characterization.

Our objective for this book is to help make the links between seismic and reservoir properties more *quantitative*. Most of our examples use amplitude signatures and impedances, but we consider quantitative seismic interpretation to include the use of any seismic attributes for which there are specific models relating them to the rock properties. Our approach is to introduce fundamental rock physics relations, which help to quantify the geophysical signatures of rock and fluid properties. Since rock properties are a consequence of geologic processes, we begin to quantify the seismic signatures of various geologic trends. We also fully embrace probabilistic and geostatistical tools, as quantitative means for managing the inevitable uncertainty that accompanies all quantitative methods. Quantifying, managing, and understanding the uncertainties are critical for survival in a risky environment.

For many years, rock physics focused on *physics*. We carefully measured wave propagation under a variety of laboratory conditions, and we developed marvelously clever acoustic analogs of rocks, finding ways to model grains and pores, and the fluids that sit inside them. We know how to parameterize seismic velocities in terms of mineralogy, porosity, aspect ratios, and grain contacts. We understand how pore pressure and stress affect velocity, attenuation, and their anisotropies. We have a sense for why (high-frequency) laboratory velocities differ from (low-frequency) field velocities. And we can make excellent predictions of how velocities change when pore fluids change.

Surprisingly, some of the most important breakthroughs in rock physics during the past decade have come not from additional mathematics, but from rediscovering the physics of rock geology. Our rock textural parameters that control elastic response can now be related to depositional maturity, and the overprint of compaction and diagenesis. Pore aspect ratios have given way to parameters such as grain sorting; linear impedance–porosity trends have given way to sand-shale "boomerang" plots in the velocity–porosity plane, reflecting depositional cycles. Quantitative geologic constraints can define the relevant trajectories through geophysical planes (velocity versus porosity; V_P versus V_S), which physics-based models can only parameterize.

One of the most powerful uses of rock physics is for *extrapolation*. At a well – assuming that data quality is good – we pretty much know "the answer." Cuttings, cores, and logs tell us about the lithology, porosity, permeability, and fluids. The problem is, often, knowing what happens as we move away from the well. This is the role of the rock physics "*What if?*" Using rock physics, we can extrapolate to geologically plausible conditions that might exist away from the well, exploring how the seismic signatures might change. This is particularly useful when we wish to understand the seismic signatures of fluids and facies that are not represented in the well. For statistical methods, such as clustering analysis or neural networks, such extrapolations are critical for extending the training data. What if the pore fluids change? What if the lithology changes? What if the depositional environment changes?

Another exciting development is the appearance of *statistical rock physics*. Simulation-based quantitative interpretation is one of the main messages of statistical rock physics. Geophysicists and geologists have tended to shy away from (even scorn) statistics. We have somehow felt that statistical methods were giving up the physics, even getting sloppy. But stochastic methods do not throw away the physics. They just put in some of the realities and heterogeneities that are not modeled by the idealized physics. When was the last time you saw a seismic section with error bars? Not long ago one of our colleagues, after hearing a presentation on stochastic simulation, remarked "You mean that you just make up random numbers?" Thankfully, these misconceptions are (slowly) melting away. Just because we do not yet have the perfect imaging and velocity estimation algorithm does not mean we should stop making interpretations and wait for perfect data. Decisions need to be made in the face of uncertainty, with imperfect and incomplete data. As better-quality data become available, one can update prior interpretations and reduce the associated uncertainty. One of the complaints about statistical methods is that they require lots of data. It is true that more data help the statistics. But scenarios with scarce data are the ones where the uncertainty is the greatest. It is these situations with few data that benefit the most from stochastic methods for quantifying and reducing the uncertainty.

"Quantitative" does not mean without uncertainty. We also stress that uncertainty estimates and probabilities are always subjective. Subjective information plays an important role in quantitative interpretation. "Subjective" and "quantitative" are not mutually exclusive.

Uncertainty and risk pervade our decisions on reservoirs. One source of uncertainty is model approximations of a hopelessly complex Earth. Rocks are neither linear nor elastic nor isotropic. Yet much of seismic analysis assumes so, leaving imperfections in our seismic images. Another source of uncertainty is the fundamental nonuniqueness of interpretation. The most perfect seismic inversion assuming isotropic linear elasticity yields at best three parameters: V_P, V_S, and density. We're still struggling to get even these three. In addition to V_P, V_S and density, perhaps we might be able to estimate something about Q and anisotropy with appropriate models. The wave equation that we base most of our work on depends only on these few parameters. Yet there are many more rock unknowns: mineralogy, porosity, pore shapes, grain size distributions, angularity, packing, pore fluids, saturations, temperature, pore pressure, stress, etc. So even with perfect data we have a tremendous uncertainty that needs to be described and reduced by optimum use of geology.

Chapter 1 gives a brief introduction to rock physics, the science aimed at discovering and understanding the relations between seismic observables (velocity, impedance, amplitude) and rock properties (lithology, porosity, permeability, pore fluids, temperature, and stress). We introduce the concepts of bounds on elastic properties, and show how they also can serve as powerful interpolators when describing depositional and diagenetic trends in the velocity–porosity plane. We give an extensive discussion of fluid substitution, and explore the special role that shear wave information plays when separating lithologic, pressure, and saturation effects. We also discuss some of the effects that pore pressure has on seismic velocities.

Chapter 2 focuses on the rock physics link to depositional and diagenetic trends of sands, shales, and shaly sands. We introduce a number of specialized models that describe the velocity–porosity behavior of clastics, and illustrate these with a number of field examples. We establish important links between depositional facies and rock physics properties, investigate depth trends in the rock physics of sands and shales as a function of diagenesis, and finally put it all together in basin-specific rock physics templates (RPTs) which can be used both for well-log and seismic data analysis.

Chapter 3 focuses on statistical rock physics. It gives brief introductions to various statistical classification techniques, and shows how combining rock physics models with modern computational statistics helps us to go beyond what is possible using either statistics or physics alone. We show how Monte Carlo simulations help us to quantify uncertainties in rock physics interpretation of seismic attributes. We also discuss the concept of derived distributions to extend and extrapolate training data. MATLAB™ functions for Monte Carlo simulation and statistical classification techniques described in Chapter 3 may be downloaded from the website for our book. Two excellent texts that we recommend for elaborate discussions on statistical classification techniques are *The Elements of Statistical Learning: Data Mining, Inference, and Prediction* (Hastie, Tibshirani and Freidman, 2001) and *Pattern Classification* (Duda, Hart and Stork, 2001). *Decision Making with Insight* (Savage, 2003) highlights in an entertaining manner the pitfalls of ignoring uncertainty in quantitative modeling.

Chapter 4 provides a compilation of the most common techniques used for quantitative seismic interpretation, including the new contributions made by the authors of this book. We start with explaining some common pitfalls in qualitative seismic interpretation, and how quantitative techniques can solve important ambiguities, and improve the detectability of hydrocarbons. Amplitude variation with offset (AVO) analysis is the most common quantitative technique used in the industry today, and we give an overview of the many aspects of AVO, ranging from wave-propagation theory, processing and acquisition effects, and different ways to interpret the AVO information. This chapter also includes an overview on various methodologies to extract rock properties from near and far impedance inversions. We stress the many pitfalls associated with the various techniques, but also the great potential to obtain rock and fluid properties. We extend the discussion from deterministic techniques to probabilistic AVO analysis as a technique for seismic prediction of reservoir properties. The new techniques of AVO constrained by rock physics depth trends and seismic applications of RPT analysis are also presented. Finally, we give a brief overview on forward seismic modeling as a technique to quantify subsurface reservoir properties.

Chapter 5 describes different case studies where the concepts described in the previous chapters are used systematically for quantitative prediction of lithology and pore fluids from seismic data. Although our examples are drawn from siliciclastic depositional systems, the methods and workflows can be applied to other problems, such as carbonates, gas hydrates, fractured reservoirs, and shallow hydrologic site characterization. Moreover, we discuss only static reservoir characterization, but the methods can be extended to include time-lapse seismic.

Chapter 6 recommends specific workflows for applying the methodologies of quantitative seismic interpretation at various stages of reservoir exploration, appraisal, development and management. By including these workflows, we hope to make the methodology appealing to everyone who routinely interprets geophysical data.

Chapter 7 provides problem sets and an extended reservoir characterization project based on an example seismic data set and well logs provided at the website. We emphasize the value of working through the problems. The best way to learn is by doing. We hope the exercises, example data set, and MATLAB functions will help the reader to understand the techniques better by providing practical hands-on experience. We believe the resources at the website (*http://srb.stanford.edu/books*) will make this book suitable for teaching.

Quantitative Seismic Interpretation is complementary to other works. For in-depth discussions of specific rock physics topics, we recommend *The Rock Physics Handbook* (Mavko *et al.*, 1998); *Acoustics of Porous Media* (Bourbié *et al.*, 1987); and *Introduction* *to the Physics of Rocks* (Guéguen and Palciauskas, 1994). We also draw your attention to *3-D Seismic Interpretation* (Bacon *et al.*, 2003), and *Interpretation of Three-Dimensional Seismic Data* (Brown, 1992). More geologic discussions can be found in *Principles of Sedimentology and Stratigraphy* (Boggs, 1987). Excellent discussions of AVO technology can be found in *Offset-Dependent Reflectivity: Theory and Practice of AVO Analysis* (Castagna and Backus (eds), 1993) and discussions of inversion methods in *Global Optimization Methods in Geophysical Inversion* (Sen and Stoffa, 1995). We found especially useful the works of Yoram Rubin, including *Applied Stochastic Hydrogeology* (Rubin, 2003).

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We hope you find this book useful.