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Seismic Reflections of Rock Properties

Key global geophysical applications, such as prospecting for oil and gas, require interpretation of the seismic response from the subsurface to assess rock properties and conditions behind the observed seismic reflection (amplitude), and to create an accurate geological subsurface model. This book now provides an accessible guide to using the rock-physics-based forward modeling approach, systematically linking the properties and conditions of rock to the seismic amplitude.

Providing a number of practical workflows, the book shows how to methodically vary lithology, porosity, and rock type, as well as pore fluids and reservoir geometry; calculate the corresponding elastic properties; and then generate synthetic seismic traces. These synthetic traces can then be compared to actual seismic traces from the field: the practical implication being that, if the actual seismic response is similar, the rock properties in the subsurface are similar as well. The book catalogues various cases, such as siliclastic and carbonate natural rocks, and time-lapse seismic monitoring, and also discusses the effect of attenuation on seismic reflections. It shows how to build earth models (pseudo-wells) using deterministic as well as statistical approaches, and includes case studies based on real well data.

This is a vital guide for researchers and petroleum geoscientists in industry and academia, providing sample catalogues of synthetic seismic reflections from a variety of realistic reservoir models with direct application to oil and gas exploration and reservoir characterization and monitoring.

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To our families

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Color plates appear between pages 126 and 127.

Preface

Rock physics is the part of geophysics concerned with establishing relations between various properties of rocks. Because the elastic radiation is the main agent that allows us to illuminate the subsurface, the primary emphasis of rock physics has been to relate the elastic properties of rock, including the *P*- and *S*-wave velocity, *P*- and *S*-wave impedance, and Poisson's ratio to porosity, lithology, and pore fluid. A significant number of such rock physics models (transforms) have been developed based on experimental data or physical theories or both. These models enable us to forward model the elastic properties of rock as a function of porosity, rock texture (arrangement of grains or cavities at the pore-scale level), mineralogy, and the compressibility of the pore fluid. Because the seismic reflection depends on the contrast of the elastic properties in the subsurface, rock physics helps generate synthetic seismic reflections at an interface between two different rock types, such as a non-reservoir rock cap and petroleum reservoir, as well as at a fluid contact within a reservoir itself (e.g., gas/oil contact and oil/water contact).

However, in field applications, we face an inverse problem whose solution is not unique: how to interpret a seismic event, which is manifested by a reflection amplitude that stands out of the background, in terms of reservoir properties and conditions. The inherent difficulty of this problem is that the number of variables required to produce the elastic properties of porous rock is larger than the number of seismic observables. Various approaches have been developed to tackle this uncertainty; most of them based on statistical techniques that help assess the probability of the occurrence of a certain object (e.g., high-porosity sand filled with oil) at a given location in a 3D subsurface. Even when using statistical techniques, forward modeling of seismic reflections based on either well log data or theoretical rock physics is a key element of interpreting seismic data.

This book concentrates on such rock-physics-based modeling. The main idea is to create an earth model consistent with the geological understanding at the location, compute the respective elastic properties, and generate synthetic seismic traces. Rock physics enables us to systematically perturb this earth model by varying porosity, mineralogy, and pore fluid, as well as the thickness of the target and the properties of the bounding non-reservoir rock. Systematically conducted perturbational modeling leads to a catalogue of seismic reflections that can serve as a field guide to interpreting a seismic event observed in the field under the assumption that if a synthetic reflection matches the real one, the rock properties and conditions behind the real event may be the same as used to produce the matching synthetic event. Because of the flexibility of existing rock physics models, we can even bracket the interpretation of an event by finding the extreme cases outside which such an event is impossible under site-specific geologic conditions. Here we systematically explore this deterministic as well as statistics-based synthetic forward-modeling approach to generate seismic reflections of rock properties. All examples are based on seismic traces computed for a 1D earth model with the reflecting waves generated by the incidence waves traveling at a varying angle of incidence to an interface between rock types.

This book includes 7 parts, 19 chapters, and an appendix. Part I deals with the basics needed in rock-physics-based forward modeling. In Chapter 1, we introduce the concept of rock-physics-based forward modeling, discuss the non-uniqueness of this approach, revisit the concept of rock physics transforms, and give an example of a synthetic seismic catalogue.

Chapter 2 reviews theoretical and empirical rock physics models, including the velocity–porosity–mineralogy models as well as methods of fluid substitution, that is, computing the elastic properties of a sample filled with a hypothetical fluid if such properties are measured on the same sample filled with a different fluid.

Chapter 3 discusses rock physics diagnostics, a technique that uses well or laboratory data to find an appropriate theoretical model that mimics and explains these data. This process includes two basic steps: bringing all the samples to the common fluid denominator via fluid substitution and then matching the data points with the model curves.

Part II is dedicated to the principles of synthetic seismic modeling. Chapter 4 introduces quick-look rock physics modeling applets, rock-physics-based displays where the user can quickly generate a synthetic gather at an interface depending on the porosity and mineralogy of the reservoir and non-reservoir rock located above it, as well as fluid type and saturation in the reservoir. Such applets can be fairly easily coded in most programming environments.

Chapter 5 discusses the principles of building a pseudo-well relevant to local geology. Special attention is paid to depositionally consistent inputs and the resulting relations between these inputs, such as relations between clay content and porosity and clay content and irreducible water saturation. Compaction trends examined in this chapter also serve as constraints for the porosity range at a given depth.

Chapter 6 discusses the principles of statistics-based perturbations for pseudo-well generation based on existing well data, including interdependence of basic rock properties, such as porosity, clay content, and water saturation. We also describe a procedure to create pseudo-logs of porosity and other rock properties that honor the vertical trends and the vertical continuity present in the input well data. An example is also given of generating these rock properties in 3D, populating a 3D earth model with the elastic properties and generating the normal and offset reflections.

Part III discusses how to use well data and geology to arrive at earth models and respective seismic amplitude. In Chapter 7, we examine two well datasets, both from clastic sedimentary environments, one where the reservoir sand is unconsolidated and soft and the other where the sand is cemented. We systematically conduct the rock physics diagnostics, establish relevant rock physics models, create rock-physics-based modeling applets for both cases, and provide synthetic seismic gathers for various perturbations of the original well data curves.

Chapter 8 discusses vertical log shapes of lithology and porosity associated with various depositional sequences and events in clastic sediments. We construct relevant pseudo-wells and select appropriate rock physics models to translate the sedimentology-driven variables into the elastic properties. Synthetic seismic gathers generated based on such depositional scenarios can serve as a quick-look catalogue for identifying real seismic events.

Chapter 9 discusses rock physics models and laboratory data for carbonate reservoirs. We construct several pseudo-wells to analyze the effects of the pore fluid, porosity, and mineralogy of the seismic gathers as well as generate pseudo-wells and synthetic seismic traces for two concrete depositional scenarios.

In Chapter 10, we address the changes in seismic reflections due to hydrocarbon production (the time-lapse of 4D seismic). The two main factors that affect the elastic properties of the reservoir are the changes in the pore pressure and hydrocarbon saturation. We show how these two factors interact to contribute to discernible temporal amplitude variations or cancel each other and leave the amplitude practically unchanged.

Part IV is dedicated to practical approaches to frontier exploration. Chapter 11 describes a rock-physics-based practical workflow used in hydrocarbon exploration, including selection of a rock physics model, time-to-depth calibration, and depth compaction curves. These results are then used in synthetic seismic gather generation and hydrocarbon- and depth-driven AVO classification for potential hydrocarbon detection.

The following Chapter 12, continues the practical workflow topic and discusses methods of validation of apparent hydrocarbon indicators and assesses the probability of success in actually tapping into a hydrocarbon reservoir after drilling a wildcat well. The direct hydrocarbon indicator check list described in this chapter is placed in the appendix.

Part V deals with advanced rock physics applications. In Chapter 13 we discuss four rock physics diagnostics case studies that reveal the universality of diagenetic trends, meaning that the same theoretical model can be used at different geographical locations and depth intervals; the self-similarity in rock physics, showing that although the porosity and clay content affect the elastic moduli of the rock in separate ways, a certain combination of these two variables can uniquely define that elastic property; a study that reveals that sometimes there is a relation between porosity, stiffness of the rock, and its permeability; and stratigraphy-constrained rock physics modeling based on a dataset from a Tertiary fluvial oil field.

In Chapter 14, we explore the issue of the *S*-wave velocity and Poisson's ratio prediction using rock physics models. The problem addressed is that many effective-medium-based models predict fairly small Poisson's ratio in gas-saturated sand while the actual well data may sometimes comply with this prediction but also show a much larger Poisson's ratio. We discuss the physical reasons for such disparities and, in the end, show how discrepancies in Poisson's ratio prediction affect synthetic seismic gathers and whether such variations affect the interpretation of a seismic anomaly.

Chapter 15 presents theoretical methods for predicting attenuation from rock properties measured in the well and elaborates on the basics of attenuation theory and experimental results. Example synthetic seismic gathers are generated based on well data with and without including attenuation and are compared to each other.

Chapter 16 is dedicated to the rock physics of gas hydrates and discusses real data collected in gas hydrate wells as well as theoretical models that relate the elastic moduli in sediment with gas hydrates to the hydrate fraction in the pore space. It has been observed that the presence of hydrates often results in significant attenuation of seismic energy traveling through the sediment. This effect is theoretically explained and synthetic seismograms are generated with the attenuation taken into account.

In Part VI we discuss how rock physics operations can be applied directly to seismic amplitude and seismically derived impedance. Chapter 17 presents an example of a rock physics operation, fluid substitution, performed directly on the seismic amplitude. We show, by generating synthetic seismic reflections, that in some cases there are fairly straightforward transforms between the amplitude measured at a wet reservoir and that measured at the same reservoir but filled with gas. Such relations may hold in a range of porosity, mineralogy, and thickness variations. Synthetic modeling is followed by a field example where the original full seismic stack was obtained at a wet reservoir and then transformed into that at a hypothetical gas reservoir. The elements of rock physics analysis behind this transform are discussed in detail.

Chapter 18 shows how simple rock physics analysis can serve to delineate the fluid contact and also map porosity based on a seismic impedance inversion section from a North Sea field.

Part VII is dedicated to an evolving rock physics technique, computational rock physics. It contains one chapter, Chapter 19, where we discuss how computational (or digital) rock physics can serve as a source of controlled experimental data for designing rock physics models and trends in a range of spatial scales of measurement. We discuss the disparity between the scale of various controlled experiments and show that the transforms obtained between two rock properties, such as porosity and velocity, at one scale may be stable in a range of spatial scales.

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All three authors learned about rock physics and learned rock physics itself at the Stanford Rock Physics Laboratory founded more than three decades ago by Amos Nur. Amos has continuously encouraged advancing rock physics theoretically and experimentally, merging it with geology, and eventually making it a practical instrument in exploration and development. This book would not have happened without Amos. Neither would it have happened without Gary Mavko, one of Nur's first students and a leading rock physics scientist and practitioner, domestically and internationally. His knowledge and advice have contributed to shaping and implementing our ideas. Gary has generously provided the software for generating the synthetic seismic traces used throughout this book. His editorial comments have served to improve the manuscript. We also acknowledge our Stanford colleague Tapan Mukerji for help and support, as well as numerous colleagues in the industry for critically discussing ideas and approaches. The computational rock physics chapter has benefited from help of our colleagues at Ingrain, Inc. We thank Elizabeth Diaz for encouragement and help. We also thank Dawn Burgess for crucial editorial help. The authors thank the Society of Exploration Geophysicists for permission to repurpose material from a number of the authors' papers originally published in *Geophysics* and *The Leading Edge*.