

## Seismic modeling study of the Earth's deep crust

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### ABSTRACT

We use seismic modeling methods to validate the interpretation of deep-crust seismic exploration. An approximation of the stacked section is obtained with the nonreflecting wave equation and the exploding-reflector approach. Using this technique and ray-tracing algorithms, we obtain a geological model by comparing the synthetic section with the real stacked section. An isotropic constitutive equation is assumed in this phase. The exact synthetic stacked section is then obtained by applying the standard processing sequence to a set of synthetic common-shot profiles computed with the variable-density acoustic wave equation. We introduce elliptical  $P$ -wave anisotropy and the effects of small-scale inhomogeneities by using a von Kármán autocorrelation probability function that simulates scattering  $Q$  effects. Verification of the geological model by poststack migration constitutes an additional test. The methodology, which is suitable for areas of complex geology, is applied to a seismic line acquired in the northern Apennines as part of the Italian deep-crust exploration project, CROC. This area is particularly difficult to interpret because of the presence of a complex tectonic setting.

### INTRODUCTION

The objective of seismic numerical modeling is to predict the seismogram that a set of sensors would record, given an assumed structure of the subsurface. It is a valuable tool for seismic interpretation and an essential part of seismic inversion algorithms. It is also used to provide data for testing processing algorithms and for evaluating acquisition parameters and processing options for various targets of interests before field data acquisition (Chedevor et al., 1995).

Seismic modeling has been used for hydrocarbon exploration problems (Kang and McMechan, 1990; Fagin, 1992),

for earthquake seismology problems (Priolo, 1999), and for crustal studies (Yarnold et al., 1993; Monguile, 1998; Monguile et al., 1998). Modeling synthetic seismograms may then have different purposes. In exploration geophysics, for instance, it is important to perform a sensitivity analysis related to the detectability of a petrophysical variable, such as porosity, fluid type, or fluid saturation. In earthquake seismology the scale of the investigation can be of the order of kilometers for site-response problems (Priolo, 1999) or of the order of tens of kilometers for deep crustal studies (Poussini et al., 1995). We develop a methodology to validate the seismic response of the Earth's crust on a large-scale basis for the purpose of verifying the main geological features of the upper and lower crusts obtained during the interpretation process.

The interpretation of large-scale structures of the deep crust is mainly based on  $P$ -wave information [examples of seismic data are from the Italian CROC and the German DEDCORP deep-crust exploration projects (Finetti, 1994; Picli et al., 1998; Rabbel and Gajewski, 1995)]. The source and acquisition parameters for the CROC-03 seismic survey are given in Table 1 (Berthelli and Mazzotti (1999); see also Mazzotti et al. (2000) for alternative parameters). The survey has been interpreted by Finetti et al. (2001). Amplitude information is relatively important, but a precise determination of the interval velocities is difficult because the residual NMO of reflection events beyond 4–5 s becomes very small. Additional problems are the complex tectonic regime and rough topography with outcrops of high-velocity layers. Moreover, the data are usually of low S/N ratio, thus invalidating the use of techniques such as prestack depth migration. Therefore, we should deal with almost zero-offset  $P$ -wave data, and the model design should be based on the stacked time section: well data are scarce, and only oil exploration wells down to 4 km depth are available. The data generally show a rather scarce reflectivity and diffractions, which may reveal the presence of fault planes. On the basis of these facts, it is unrealistic to use sophisticated modeling techniques. Therefore, we do not consider mode conversion (i.e.,  $S$ -waves) and intrinsic attenuation, which, in this situation, constitute second-order effects. Anisotropic effects on the  $P$ -wave are modeled with an

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# Seismic Modeling Of The Earths Crust

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chemical state of Earth's mantle which ultimately holds the key to unlocking the secrets of the evolution of our planet. This series of topical reviews and original contributions address 4 themes. Theme 1 covers topics in geophysics including global and regional seismic tomography, electrical conductivity, and seismic imaging of mantle discontinuities and heterogeneities in the upper mantle, transition zone, and lower mantle. Theme 2 addresses geochemical views of the mantle including lithospheric evolution from analysis of mantle xenoliths, composition of the deep Earth, and the effect of water on subduction zone processes. Theme 3 discusses geodynamical perspectives on the global thermochemical structure of the deep mantle. Theme 4 covers application of mineral physics data and phase equilibrium computations to infer the regional scale thermochemical structure of the mantle.

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## **Table of Contents Seismic Modeling Of The Earths Crust**

1. Understanding the eBook Seismic Modeling Of The Earths Crust
  - The Rise of Digital Reading Seismic Modeling Of The Earths Crust
  - Advantages of eBooks Over Traditional Books
2. Identifying Seismic Modeling Of The Earths Crust
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Seismic Modeling Of The Earths Crust
  - User-Friendly Interface
4. Exploring eBook Recommendations from Seismic Modeling Of The Earths Crust
  - Personalized Recommendations
  - Seismic Modeling Of The Earths Crust User Reviews and Ratings
  - Seismic Modeling Of The Earths Crust and Bestseller Lists
5. Accessing Seismic Modeling Of The Earths Crust Free and Paid eBooks
  - Seismic Modeling Of The Earths Crust Public Domain eBooks
  - Seismic Modeling Of The Earths Crust eBook Subscription Services
  - Seismic Modeling Of The Earths Crust Budget-Friendly Options



6. Navigating Seismic Modeling Of The Earths Crust eBook Formats
  - ePub, PDF, MOBI, and More
  - Seismic Modeling Of The Earths Crust Compatibility with Devices
  - Seismic Modeling Of The Earths Crust Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Seismic Modeling Of The Earths Crust
  - Highlighting and Note-Taking Seismic Modeling Of The Earths Crust
  - Interactive Elements Seismic Modeling Of The Earths Crust
8. Staying Engaged with Seismic Modeling Of The Earths Crust
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Seismic Modeling Of The Earths Crust
9. Balancing eBooks and Physical Books Seismic Modeling Of The Earths Crust
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Seismic Modeling Of The Earths Crust
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Seismic Modeling Of The Earths Crust
  - Setting Reading Goals Seismic Modeling Of The Earths Crust
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Seismic Modeling Of The Earths Crust
  - Fact-Checking eBook Content of Seismic Modeling Of The Earths Crust
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
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