Over the past several decades, application of anisotropic models in seismic exploration and global seismology has become almost routine (e.g., Long and Becker 2010; Tsvankin et al. 2010). Standard velocity-analysis and imaging algorithms now operate with transversely isotropic media that often have a tilted, spatially varying symmetry axis (TTI). It has been recognized that optimal processing of many high-quality wide-azimuth offshore surveys requires building lower-symmetry orthorhombic models. Most prestack migration algorithms, including those based on the wave equation (e.g., reverse-time migration), have been extended to 3D TTI and orthorhombic media. Still robust parameter estimation for structurally complex anisotropic models remains a big challenge, which is addressed in some of the papers in this Special Issue.

Modern seismic methods increasingly operate with recorded amplitudes and waveforms, which generally are more sensitive to anisotropy than kinematic attributes, such as reflection travel times. For example, even several percent of velocity variation with angle may be sufficient to cause pronounced anomalies of geometric spreading and seismic amplitudes in general (see Chapter 2 in Tsvankin 2012). Therefore, it is extremely important to properly account for anisotropy (as well as elasticity) in full-waveform inversion (FWI), which is capable of reconstructing velocity fields with a higher spatial resolution than more traditional tomographic methods. Amplitude inversion and FWI have the potential to go beyond estimating the effective kinematic medium parameters and produce anisotropy-related attributes that give important insight into the local physical properties of the subsurface and can be used in reservoir characterization.

Introduction of the concept of elastic anisotropy and development of anisotropic processing methods in seismic exploration owe much to global seismology. Indeed, analyses of shear-wave splitting and anisotropic signatures of compressional waves in earthquake seismology have led to the discovery of large-scale anisotropy in the upper mantle and inner core of the Earth (Song and Richards 1996; Blackman, Wenk and Kendall 2002; Beghein and Trampert 2003). Some anisotropy-related approaches suggested by earthquake seismologists have been implemented and further developed in microseismic monitoring of hydraulic fracturing (see below).

The special issue opens with an invited paper by Leon Thomsen that discusses the role of seismic anisotropy in unconventional shale exploration and development with the main focus on anisotropic rock physics. Indeed, shale formations are always at least transversely isotropic and often exhibit a lower (sometimes even the most general, triclinic) symmetry due to natural fracturing and/or nonhydrostatic stresses. Monitoring of hydraulic fracturing in shale reservoirs is typically performed with microseismic borehole or surface data. It has been shown that accurate location of microseismic events and delineation of hydraulic fractures is impossible without taking anisotropy into account and building velocity models that typically include low-symmetry layers (Tsvankin and Grechka 2011; Grechka and Yaskevich 2013; Grechka and Heigl 2017).

This special issue contains 15 papers, most of which were presented at the 18th International Workshop on Seismic Anisotropy (IWSA) held in Jerusalem, Israel in November 2018. IWSA is a biennial event which unites experts from academia and industry for discussions of recent advances in anisotropy studies and of new challenges posed by this ubiquitous phenomenon of utmost importance in seismology. The first workshop was organized in Suzdal, Soviet Union, in 1982 and the next one (19IWSA) is planned in the Czech Republic in 2020. The 18IWSA, sponsored by Emerson E&P and the EAGE, featured 40 presentations authored by 50 geophysicists from 12 countries. An overview of the papers included in this special issue is provided below.

THEORY/Rock PHYSICS

Stovas, Roganov, and Roganov analyze low-frequency wave propagation in a weak-contrast layered medium with
orthorhombic symmetry. The dispersion is defined by a quadratic form with the help of a sensitivity matrix. The obtained effective anisotropy parameters are expanded up to the second-order contrasts in the elastic properties.

The only restriction on the values of the elasticity parameters is the stability condition. Within this restriction, Stanoev, Bos, and Slawinski examine the properties of the Christoffel equation for elliptic wavefronts in transversely isotropic media. They exemplify such a case for a medium resulting from the Backus averaging of isotropic constituent layers.

Ivanov studies the quantity and spatial arrangement of point singularities in orthorhombic media. He demonstrates that in typical orthorhombic models the singularities can be distributed in only three different patterns and the number and spatial arrangement of singularities is not related to the anisotropy strength. Based on these observations, he proposes a classification scheme for orthorhombic models.

Rock-physics models for unconventional reservoirs require knowledge of the anisotropic stiffness coefficients of clays. Sayers and den Boer present a method for estimating these properties given the volume fraction, aspect ratio, and the elastic properties of the clay platelets along with the effective elastic properties of the medium between the platelets.

Adamus defines a new anisotropy parameter (ϕ) for a transversely isotropic (TI) medium obtained using Backus averaging of parallel isotropic layers and shows that ϕ is sensitive to variations of the Lamé coefficient λ among the layers. Based on Gassmann’s theory, these variations are treated as indicative of possible changes in fluid content. It is suggested that the relationship between ϕ and the Thomsen parameter γ depends on specific fluctuations of the parameter λ. This approach might be useful for fluid detection in equivalent TI media.

INVERSION AND IMAGING

Jarillo Michel and Tsvankin present a 3D waveform-inversion methodology for microseismic borehole data recorded in transversely isotropic media with a vertical symmetry axis (VTI). Multicomponent elastic wavefields are simulated using a pseudospectral technique and the inversion gradient is efficiently computed with the adjoint-state method. Synthetic examples and inversion of microseismic field data from an unconventional shale play confirm the ability of the algorithm to reconstruct heterogeneous VTI velocity models, if the source parameters are known with sufficient accuracy.

Bai and Tsvankin extend the methodology of source-independent waveform inversion to attenuation estimation in heterogeneous VTI media. The objective function, designed to suppress the influence of unknown source signature on the inversion results, operates with two additional data sets computed using convolutions with reference traces from the observed and modeled data. The robustness of the algorithm in the presence of realistic errors in the source wavelet is demonstrated on the wavefield transmitted through a medium with a Gaussian anomaly in one of the attenuation parameters and on surface reflection data from a benchmark transversely isotropic model generated by Hess.

Li et al. develop an image-domain tomographic (IDT) algorithm for tilted transversely isotropic (TTI) media which is based on an integral wave-equation operator, with extended images computed by preconditioned least-squares reverse-time migration (LSRTM). For models with the symmetry axis orthogonal to the reflectors, energy focusing in extended common-image gathers can be used to update all three pertinent parameters – the zero-dip normal-moveout velocity, Thomsen parameter δ, and anellipticity coefficient η. Application of IDT combined with image-guided interpolation to a modified anticline segment of the BP 2007 model shows that the algorithm can estimate the long-wavelength components of the TTI parameters starting from a highly inaccurate (elliptic and laterally invariant) velocity field.

Zhang, Zhang, and Li propose a modified equation for the PP-wave reflection coefficient that enables amplitude inversion for VTI media. The new approximation is highly accurate and depends on just three subsurface parameters: the impedance, the shear modulus proportional to an anellipticity parameter, and the approximate P-wave horizontal velocity. The developed inversion method is useful in shale-gas exploration because the estimated parameters may provide a robust characterization of gas-bearing shales.

Gofer and Bachrach present a workflow that combines first-break analysis with Rayleigh-wave inversion for azimuthally anisotropic media to estimate the elastic parameters in the symmetry planes of orthorhombic models. The inversion results are then used to obtain the equivalent vertically fractured transversely isotropic medium. The workflow is tested on a synthetic data set and on field data from a controlled experiment.

MODELING AND EARTHQUAKE SEISMOLOGY

Acoustic attenuative transversely isotropic models can be used to describe the velocity and attenuation anisotropy of P-waves.
in thin-bedded geologic structures. Hao, Waheed, and Alkhaliifah investigate approximate analytic solutions of the acoustic eikonal equation for a homogeneous attenuative VTI medium. They employ two similar parameterizations, utilize perturbation theory and Shanks transform to derive analytic solutions, and present numerical examples designed to find the most accurate approximation. Their approach can be extended to heterogeneous attenuative VTI models.

Gaiser simulates S-wave radiation from vertical sources to study illumination of converted SP-wave reflections in isotropic and anisotropic media. Contrary to previous claims, illumination is shown to be limited to near-vertical directions where P-waves are homogeneous. It is demonstrated that SP-wave radiation amplitudes in VTI models are confined to a narrower opening angle than in isotropic media. Using an orthorhombic fracture model, it is shown that fast S1-waves polarized parallel to fractures can have broader azimuthal illumination than slow S2-waves polarized perpendicular to fractures. Also, SP-wave reflection stacks exhibit azimuthal S-wave splitting signatures that should make processing more challenging.

Gao et al. analyse shear-wave splitting in local seismic data acquired by a temporary linear seismic array and use the results to characterise crustal seismic anisotropy in the Sanjiang lateral collision zone in the SE margin of the Tibetan Plateau. Both the polarization of the fast S-wave and the time delay of the slow S-wave exhibit variations influenced by stress, faults or deep tectonics. The same factors also produce complicated orientations of the fast S-wave polarizations at several stations. This work shows that the anisotropy parameters obtained from split S-waves can provide useful information for studying metallogeny.

Bianchi and Bokelmann describe a seismological experiment that explores the direct correspondence between in situ rock texture and seismic anisotropy. Application of the receiver-function technique to passively recorded data makes it possible to depth-locate anisotropic layers which correspond to the depths and thicknesses of highly foliated metamorphic rocks found in core logs.

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