Volume 89 Number 3

GEOPHYSICS

This issue of GEOPHYSICS

Alison Malcolm, Editor

Case Histories

Della Justina and Smith propose two methods for estimating the uncertainty of corrected gravity data. The corrected data can be perturbed with these uncertainties multiple times, and multiple estimates of the model parameters (derived from modeling) are analyzed to estimate the uncertainty in the model parameters.

Liu et al. propose a sparse time-frequency (STF) network for computing the STF spectra, which is pretrained by using synthetic traces and STF labels, and suggest an unsupervised STF domain adaptation model to transfer to field data. The authors test the capabilities of the proposed model for seismic attenuation delineation by applying it to a 3D poststack field data volume, with encouraging results.

Anisotropy

Wang et al. propose the extended conjugate real ray-tracing method to compute the ray velocity vector and apply it to determine two specifications of slowness — traveltime gradient and inhomogeneity components — to reveal the physical meaning of the slowness vector in viscoelastic anisotropic media and make an intuitive interpretation of the phase propagation (real traveltime) and wave-energy attenuation (imaginary traveltime) wavefronts of seismic waves. The authors lay a foundation for further development of seismic ray tomography in viscoelastic anisotropic media.

Cao et al. develop an innovative approach that uses azimuthal P-wave phase velocity to calculate horizontal transverse isotropy anisotropic parameters and formulate a cost-effective 3D in situ stress estimation method using the obtained elastic parameters and fracture compliance. Field examples verify the ability and accuracy of the proposed method for predicting fracture density and anisotropic in situ stress.

Yang et al. propose an inversion method for fracture weakness based on 3C vertical seismic profiling data based on a first-order linear approximation of the traveltimes of the converted fast and slow S waves. The inversion errors are primarily influenced by the azimuth angle, with minimal influence from the receiver depth.

Borehole Geophysics

Pham et al. propose a new neural network workflow to estimate missing sonic logs by using other available well logs and seismic data as an interwell constraint. The method combines recurrent, convolutional, and dense networks to leverage log trends and seismic wavelets, with uncertainty quantification to quantify parameter and data errors.

Wang et al. establish a fast and accurate workflow for evaluating the dispersion of propagating and leaky modes in cased holes. They reveal that the velocity and amplitude of the outer Stoneley mode are sensitive to the thickness of the fluid channel.

Gao et al. describe a quantitative inversion process for high-definition electrical imaging logging in oil-based mud. This process is verified by simulation and actual logging data.

Electrical and Electromagnetic Methods

Gao et al. develop a modeling scheme for electromagnetic (EM) subdiffusion in rough media based on a dispersive conductivity. The propagation characteristics of EM fields in rough medium are analyzed by different numerical experiments.

Li et al. propose atom-profile updating (APrU) dictionary learning and nucleus sampling attention mechanism (NSAM) sparse coding and apply them to audio magnetotellurics (AMTs) data denoising. The APrU method can learn the dictionary atoms with the noise characteristics in the AMT data, and the NSAM method can select all the dictionary atoms that are similar to the noise at once, with experimental results showing that the proposed method is more effective at noise suppression than the previously proposed sparse representation methods.

Lorentzen et al. describe a near-surface continuous transient EM (TEM) survey on saline permafrost in Greenland, where the data are dominated by induced polarization (IP) effects. The authors observe unique decay shapes, demonstrate the changes of the IP-TEM inversion, observe spatial coloration that allows for a qualitative interpretation of the data, and can, based on this, present a consistent explanation of the IP-phenome in TEM related to permafrost.

Zhang et al. present an investigation of a coal mining goaf in Jinan, China, using the distributed wide-field EM method (DWFEM). The use of a third-order 2^n sequence pseudorandom signal with 39 survey frequencies for long-time data acquisition significantly enhances the understanding of the coal mine characteristics in the proposed project and highlights the DWFEM's applicability in detecting goafs in complex urban environments.

Ishizu et al. present a controlled-source EM (CSEM) configuration using towed and seafloor-based receivers to better map seafloor and embedded massive sulfides. A combined inversion of field data can map the location and shape of embedded massive sulfides identified by drilling more accurately than the inversion of individual data sets.

IP of clay-rich materials may be influenced by their pyrite content. **Revil et al.** study the complex conductivity spectra of illite pyrite mixtures quantitatively and analyze it with a simple petrophysical model able to reproduce the experimental data.

Gravity and Magnetic Exploration Methods

Cai et al. propose a joint inversion framework using an adaptive unstructured tetrahedral mesh for potential field data, incorporating Gramian constraints for model coupling and adaptive mesh refinement during inversion. This approach is validated with synthetic models and applied to potential field data in Ontario, Canada, for mineral exploration.

Wei et al. propose an efficient method for quantifying the uncertainty of 3D geometries using transdimensional Monte Carlo sampling. A sparse geometry parameterization is developed to approximate the complex shape of a 3D body and greatly reduce the number of model parameters to be sampled.

Magnetic Resonance Methods

Morozov et al. describe the gradient-based surface nuclear magnetic resonance (SNMR) method that represents an effective means for improved signal colocalization in the shallow subsurface. The use of gradients significantly enhances detection and resolution of shallow groundwater as compared to conventional SNMR methods.

Multiphysics and Joint Inversion

Crepaldi et al. propose a seismic and CSEM joint inversion to estimate the inner properties of a reservoir with an oil-water contact at the limit of seismic resolution and use a linearized Gaussian approach to analytically solve the marginalization integrals. A theoretical balance assembles two equivalent prior distributions in the same likelihood for facies conditioned to data.

Near-surface and Urban Geophysics

Niu et al. propose a novel framework for nondestructive multichannel analysis of surface waves in site investigations, combining multimode dispersion spectrum matching with the finite-element method for accurate subsurface profiling. This method automates Rayleigh-wave identification and mode assignment, uses the Wasserstein distance for spectrum evaluation, and demonstrates effectiveness through synthetic data and field tests, offering high-resolution subsurface V_S profiling.

Reservoir Geophysics

FaultSSL is a novel semisupervised learning framework that guides the 3D semisupervised learning process using few labeled 2D sparse profiles, while also incorporating a large volume of unlabeled field data into training. **Dou et al.** propose two proxy tasks, namely panning consistency and patching consistency, which greatly enhance the network's performance in regions where conventional synthetic data methods have limited generalization capabilities.

Rock Physics

Birnstengel et al. use borehole seismic data to carry out a time-lapse study over a period of 12 months on a controlled CH_4 injection test at a depth of 17.5 m. By monitoring the change in water saturation in the sediments and observing the process of saturation change, the authors show that crosshole seismic data are able to verify the rock-physics relationships at the field scale and additionally quantify the relative water content changes in the subsurface.

Vosoughi et al. investigate the effects of thawing on partially saturated permafrost samples using simultaneous measurements of electrical resistivity, ultrasonic data, and time-lapse X-ray computed tomography. The results reveal significant transitions in electrical and elastic properties due to alterations in the pore network, emphasizing the importance of understanding different types of ice in cryogenic porous media for accurate electroelastic investigations of permafrost.

Wang et al. develop an integrated model for the frequency-dependent SV wave, considering fracture-background wave-induced fluid flow and fracture elastic scattering. Various parameters influencing the wave dispersion and attenuation are investigated and the model is verified with existing model and experimental data.

Wang et al. develop an integrated model for the frequency-dependent stiffness matrix for fractured reservoirs, considering multiple scale attenuation mechanisms. Their model provides a basis for integrating the measured data at different scales and frequencies.

Biyoghe et al. model the coupled electromechanical process of wave propagation from the piezoelectric transducer to the receiver in a laboratory triaxial cell, with the aim of clearly identifying the arrival time of the S wave. The numerical algorithms are validated against 1D simulations and against an exact solution constructed with the method of characteristics.

Due to limited spatial resolution, conventional laboratory methods cannot adequately describe the elastic properties of rock formations exhibiting a high degree of heterogeneity, thereby masking differences between stiff and compliant layers. **Olszowska et al.** build upon their previous work and apply laboratory angle-dependent ultrasonic reflection coefficient measurements to achieve detailed 2D descriptions of the elastic properties of complex rock samples; this method yields high-resolution descriptions of P- and S-wave velocities, as well as bulk density, across the surface of rock samples.

Yang et al. develop a digital pore-fracture model with varied pore structures and apply dynamic stress-strain simulations to study squirt flow-induced wave dispersion and attenuation. Their numerical findings reveal that, apart from commonly considered factors like crack density and crack aspect ratio, pore structure parameters such as pore size, crack orientation, crack length, crack width, and fluids distribution exert notable influences on wave dispersion and attenuation characteristics.

Seismic Data Acquisition

Marine towed-streamer blended data are usually challenging to deblend because of the low dimensionality of the data. **Chen et al.** revisit two notable and practical methods to improve the deblending performance of marine towed-streamer blended data, i.e., extending the 2D deblending of towed-streamer data to 3D deblending, which considers the shot domain as a sparsity-constrained domain, and incorporating traditional deblending and Popcorn reconstruction.

Revelo-Obando and Blacquière propose a novel algorithm for target-oriented seismic acquisition design, which aims to improve image quality at one or multiple target zones by optimizing a receiver density function through a deterministic iterative scheme. The algorithm exploits the advantages of full-wavefield migration and uses multiples for imaging.

Seismic Inversion

Huang et al. propose a high-resolution and reliable seismic basis pursuit inversion based on the exact Zoeppritz equation. Furthermore, they propose the ℓ_{1-2} norm as a constraint, where a regularized function is minimized with the alternating direction method of multipliers algorithm.

Gong et al. unravel the mechanism of elastic reverse time migration (RTM) using synthetic and field towed-streamer seismic data. Their paper is a first attempt to use the acoustic-elastic coupled equation-based elastic wave imaging only using towed-steamer seismic data.

Li et al. propose a joint adaptive multiparameter waveform inversion method that incorporates matched filter theory and attenuation compensation into the inversion process, which can invert for velocity and Q simultaneously. Compared with classic full-waveform inversion (FWI) methods, the proposed joint inversion method is able to cope with challenges related to attenuation-induced gradient energy loss and cycle skipping, which can lead to a superior result.

Gholami introduces an extended Gauss-Newton method that bridges the standard reduced FWI with extended FWI formulations involving model and source extensions. This novel algorithm not only increases inversion robustness but also preserves computational efficiency.

Li et al. propose an enhanced U-Net model for FWI. The authors demonstrate the effectiveness of the suggested improvements and evaluate the model's performance using the Marmousi model and field data.

Fu presents a method for the simultaneous amplitude-variation-with-offset or angle inversion of anisotropic parameters for the transversely isotropic media with vertical axis of symmetry (VTI media). The authors introduce a new PP-wave reflection coefficient approximation for VTI; compared with Rüger's equation, the authors' equation decreases the trade-off between the parameters and reduces the ill posedness of the inverse problem.

Mendes et al. propose techniques to optimize a simulated annealing method to find the starting velocity model for FWI to avoid its local minimum limitation.

Cai et al. extract depth-variant wavelets from the depth-wavenumber spectrum, which is obtained by an orthogonal matching pursuit spectral decomposition algorithm based on the depth-domain Morlet wavelet. The extracted wavelets are applied to depth-domain acoustic impedance inversion by basis pursuit.

Luo et al. propose an adaptive structure-based FWI method. This method can produce a high-resolution inversion result by mitigating artifacts caused by crosstalk and data noise.

Aghazade et al. present a robust and efficient algorithm for elastic FWI that addresses the challenges of accurate subsurface property estimation. The algorithm uses the alternating direction method of multipliers with reconstructed wavefields to minimize the misfit between observed and predicted seismic data while satisfying elastic wave equation constraints and physical model constraints.

Seismic Migration

Abolhassani and Verschuur propose a computationally efficient preconditioned least-squares wave-equation migration (PLS-WEM) algorithm for estimating high-resolution accurate seismic images. By leveraging a one-way wavefield extrapolation technique in the depth-frequency domain, PLS-WEM decomposes the massive approximate Hessian operator for the entire domain into smaller operators relevant to each depth level in the domain, reducing the number of model parameters each time the approximate Hessian and its reciprocal are calculated.

Sun et al. present an efficient and accurate seismic wavefield decomposition and RTM method using a generative adversarial network. This approach tries to produce accurate directional wavefield decomposition results and high-quality reflectivity images without low-wavenumber artifacts.

Wu et al. present a novel method of least-squares RTM (LSRTM) for imaging seismic data with simultaneous sources. In each iteration of the migration process, a deep-residual neural network, trained with synthetic samples, is applied on the gradient of LSRTM to effectively eliminate high-wavenumber cross-talk artifacts.

Zhang et al. present a Q-compensated image-domain LSRTM approach through preconditioned point spread functions. Through several 2D and 3D experiments, the authors conclude that the proposed approach gives better image quality in terms of amplitude fidelity and spatial resolution relative to the conventional Q-compensated and acoustic image-domain LSRTM approaches.

Zhang et al. propose a variant pitch-angle winding configuration for helical fiber distributed acoustic sensing (DAS) to reconstruct original strain field records. The authors also develop an efficient 3D decoupled P-/S-wave operator in VTI media, which is combined with the reconstructed strain field from helical fiber DAS, to produce PP and PS images in elastic RTM.

Shoja et al. apply a novel integrated Marchenko target-oriented LSRTM algorithm to a marine data set from the

Norwegian Sea. The authors show that this new algorithm is capable of reducing overburden-generated artifacts as well as reducing the model and data dimensions.

Zhang et al. present a general deep-unrolling (DU) architecture to solve the ill-posed inverse problem for image-domain least-squares migration. Through experiments with synthetic and marine field data sets, it can be concluded that the DU architecture can effectively regularize the inversion process, resulting in reflectivity estimates with few artifacts and high resolution, and can produce a qualitative measure of the uncertainty associated with the least-squares migration process.

Li et al. propose an ocean-bottom dual (OBD)-sensor viscoacoustic and separated-viscoelastic coupled Q-compensated LSRTM in curvilinear coordinates. In this method, to solve the Q-compensated elastic inverse problem, the authors jointly use the recorded acoustic pressure and elastic multicomponent seismic data from the OBD observation system.

Seismic Modeling and Wave Propagation

Dal Moro and Mazanec analyze a set of active and passive seismic data from an industrial area to retrieve an unambiguous subsurface S-wave velocity profile. It is shown that multicomponent single-offset data obtained from a single 3C sensor (horizontal-to-vertical spectral ratio and Rayleigh-wave particle curves and group velocities) allow for the efficient joint analysis of four observables able to fully constrain the subsurface model while in case of phase velocity spectra Love waves can play a critical role.

Da Costa et al. study ultrasonic wave behavior in synthetic rocks with alternating sand-based and acrylic layers, with and without cracks, and find that cracked samples show distinct P- and S-wave velocities compared to uncracked samples, revealing seismic wave propagation complexities. The authors compare experimental results with theoretical models including Backus, Kennett, and a modified Backus model for cracked media by Schoenberg and Muir, revealing insights into seismic wave behavior in heterogeneous rock formations.

Wang and Chen present an improved average-derivative 27-point method (ADM) for the 3D frequency-domain elastic wave equation, which has higher accuracy than the regular ADM at almost the same computational cost. Moreover, the improved ADM is applied to the simulation of a moving point source for the first time, and its feasibility is verified with several numerical experiments.

Based on the constant Q model, **Han et al.** derive a new fractional-order velocity-dilatation-rotation viscoelastic wave equation that decouples P and S waves as well as amplitude attenuation and phase distortion effects. The proposed equation is more efficient than the conventional viscoelastic wave equation and can provide more wavefield information for subsequent multicomponent elastic wave RTM imaging.

Chai et al. evaluate an approach for modeling multisource multifrequency acoustic wavefields using a multiscale Fourier feature mapping physics-informed neural network with adaptive activations, directly solving for full wavefields instead of scattered wavefields. The authors use an existing technique and adapt it to a new architecture that they test with several activation functions; their tests show improvements for simulating multisource multifrequency wavefields.

Almuteri et al. develop a finite-difference approach for modeling the full acoustic wavefield triggered by a moving source in the presence of a time-varying sea surface and use a mimetic finite-difference method to formulate the required system of first-order partial differential equations in a generalized coordinate system to account for the source motion and time-varying free surface. The authors investigate the impact of a time-varying sea surface on marine vibrator data (i.e., a moving source with a long-duration sweep) in the common-source and common-receiver domains.

Yao et al. introduce a novel first-order pseudo-Helmholtz decomposition method, assisted by the wavefront phase direction. In comparison to existing pseudo-Helmholtz decomposition methods based on eigenform analysis, the proposed method attains first-order accuracy in P-/S-wave decomposition with a comparable cost to the zero-order pseudo-Helmholtz decomposition method.

Seismic Velocities and Traveltimes

Wang et al. propose a novel multistage picking framework called multistage segmentation picking network (MSSPN) to simulate the manual picking process, where the velocity-constrained trend estimation module in MSSPN introduces a global prior and a local constraint, enhancing the accuracy of the picking range for refined picking. MSSPN not only outperforms current state-of-the-art methods on benchmark data sets but also achieves a picking accuracy of 89.74% on a data set with a low signal-to-noise ratio (S/N).

Parsimonious refraction interferometry struggles with direct and diving waves, hindering accurate seismic imaging. **Lee and Pyun** leverage deep learning (U-Net) to overcome these limitations and improve first-arrival traveltime tomography results.

Signal Processing

Hao et al. propose an airborne TEM (ATEM) noise-suppression method based on multiple single-step and multiple superposition-step implicit iterative formats with minimum curvature and study the noise suppression characteristics using Fourier spectrum analysis theory. This method effectively suppresses noise in synthetic and real ATEM data during processing.

Dong et al. use a realistic synthetic training data set and propose a novel reconstruction network, called MSG-Net, for incomplete-seismic-data recovery. The experimental results indicate that the proposed method can restore missing data and significantly improve the reconstruction accuracy.

Wang et al. propose a multicomponent adaptive prediction filter (MAPF) based on noncausal regularized nonstationary autoregressive models to implement random noise attenuation in the t-x-y domain. The authors further propose a fast MAPF combining the data pooling and coefficient reconstruction strategies to improve computational efficiency.

Xu develops a novel high-resolution method for calculating sonic slowness, addressing challenges of noise interference and damaged channels. Using super-virtual interferometry, the approach accurately extracts slowness with a 0.5 ft receiver spacing, is validated through synthetic calculations and successfully applied to IODP Brothers volcano field measurements.

Feng et al. propose a heterogeneous knowledge distillation model for low S/N DAS signal recovery. This model consists of a teacher network and a student network: the teacher network is trained using high-S/N data to extract distinct signal features; meanwhile, the student network is designed to process low-S/N data guided by the signal features that are distilled from the teacher model.

Kiraz et al. provide a CNN-based solution for attenuating free-surface multiples and ghost reflections for blended seismic data. The approach requires neither deblending nor near-offset interpolation, as opposed to the conventional approaches.

Liu et al. propose an effective method for reducing random noise via spectrum reconstruction. The method eliminates the need for data segmentation based on offset, thereby improving processing efficiency in active-source wide-angle seismic data.

Li et al. propose a new method for the estimation of Rayleigh wave group velocity spectra. This innovative approach significantly enhances the resolution of the dispersion image compared to traditional methods.

Li and Liu propose a robust orthogonal matching pursuit algorithm with Radon operators to solve the strong group sparsity problem. This approach can be used to interpolate seismic data and attenuate erratic noise simultaneously.

Kakhki et al. develop deconvolutive short-time Fourier transform (DSTFT) by estimating phase spectra and updating moduli to address residual cross-terms. The authors use DSTFT moduli as weights and apply a weighted least-squares technique to estimate a high-resolution and almost cross-term-free Wigner-Ville distribution.