Paradigm®

White Paper

GeoDepth 3D Tomography:

Enhancing Subsurface Velocity Model Determination

Overview

GeoDepth® Seismic Tomography is a state-of-the-art velocity model updating system designed to enhance the accuracy and resolution of different types of background velocity models that include both velocity heterogeneity and anisotropy. The GeoDepth Tomography system can efficiently handle large-scale models using different types of input data with the ability to impose different types of geological constraints.

GeoDepth Tomography supports both grid-based and model-based methods that can be used according to the problem to be solved. For large-scale models and especially those with high-resolution update grids, where the size of the tomography matrix can be too large to be handled even by the largest super-computers, a new approach is required. GeoDepth 3D grid-based tomography has have been shown to overcome these inherent limitations by reducing the memory and disk space required through more intense computation.

The Subsurface Velocity Model

The subsurface velocity model is defined as a set of layers, where the velocity at each layer can vary in both lateral and vertical directions. Transverse Isotropy (TI) Anisotropy effects (the change of velocity with direction) can also be assigned to some layers, defined as, for example, Vertical TI (VTI) and Tilted TI (TTI). In these layers the axial velocity is slower than the velocity in the perpendicular direction. Horizontal TI (HTI) model representation, accounting for vertical fractures, is considered a specific case of TTI.

The background starting velocity model is assumed to be smooth, enabling the implementation of ray tracing. TTI anisotropic models require reliable information about the orientation of the subsurface local reflectors: Subsurface dip, azimuth and continuity. GeoDepth supports different tools to automatically compute, smooth and condition these structural attributes.

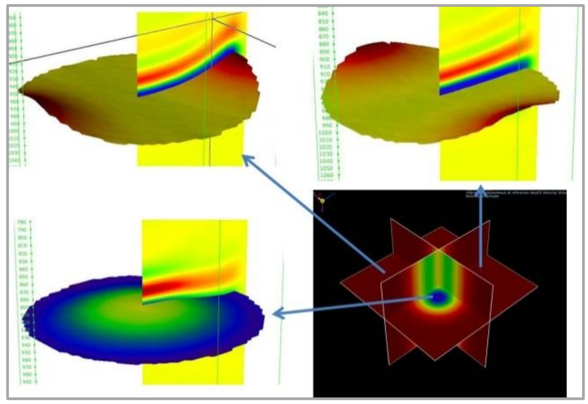
The Tomographic Approach

Tomography is based on solving a large set of linear equations that relate the desired (unknown) subsurface velocity model update parameters, with input data containing traveltime errors along different types of rays traveling across the model. Tomography is formulated as a geologically constrained inversion by using a priori information about the subsurface model, such as the depth of well markers and spatial variation characteristics of the velocity field within the different geological layers.

Using tomography, it is possible to simultaneously update all anisotropic velocity components, such as the axial velocity V_p, δ and ε Thomsen parameters. Different variances can be set to each of the material parameters at each layer, which makes the tomography extremely versatile and allows full control over the resulting updated model. For example, sea water velocity can be fixed (zero variance), the velocity variation within salt diapirs, basalt layers or hard carbonate rocks can be forced to be uniform, and velocity updates within sedimentary layers can have lateral and vertical variations, allowing local anomalies.

Input Data for Traveltime Errors

GeoDepth reflection tomography is designed to handle reflection seismic data, where traveltime errors along the rays (the required input for tomography) are measured from residual moveouts (RMO) automatically picked along common image gathers (CIGs) generated by different types of seismic depth migrations.



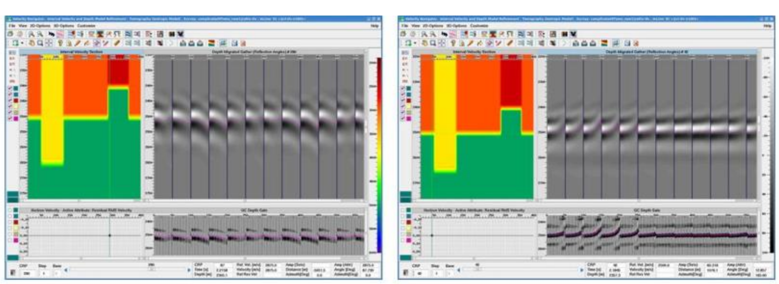
3D, full-azimuth EarthStudy 360 gathers used for high-resolution velocity updates

Reflection tomography supports surface offset domain (computed by Kirchhoff migrations) and subsurface angle domain (computed by Local Angle Domain Imaging solutions CRAM/ EarthStudy 360) CIGs. Depending on the input seismic data and the type of CIGs, the RMO can contain single, multi and even full azimuth distributions. Obviously, the richer the information about the traveltime errors along the reflected rays (e.g., from all opening angles and all azimuths) the higher the accuracy, resolution and certainty of the updated model.

Overall, the aim of tomography is to update the subsurface model with a velocity field that minimizes traveltime errors; in other words, to flatten events along CIGs when running the migration with the updated velocity field.

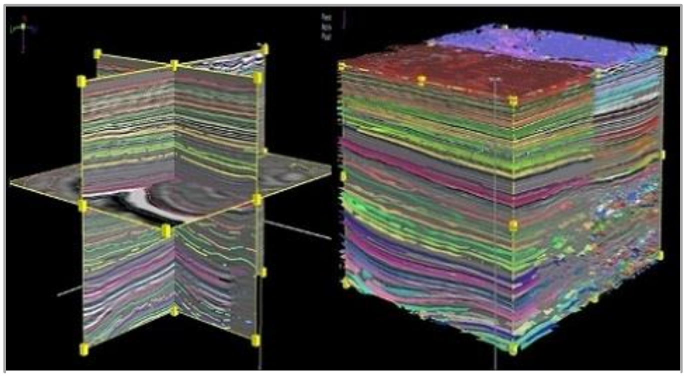
The RMO can be defined in both parametric form (up to five parameters describing the RMO second and fourth order variation along the angle/offset axis and the variability with azimuth) and non-parametric form, where the RMO values are computed and stored for each trace. The quality and reliability of the RMO data are key to the success of the tomography in converging into the “right” model.

Adding traveltime information from long offset walk-away check-shots (if available) can be extremely beneficial. The walk-away check-shot traveltimes can contribute to accurate determination of anisotropic parameters.

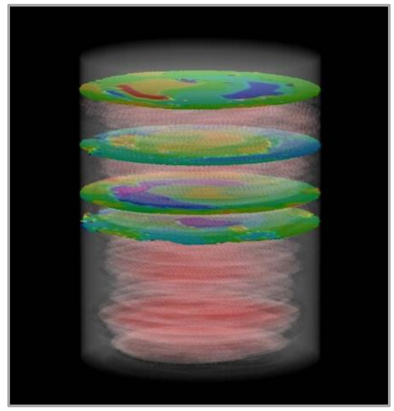


3D, full-azimuth EarthStudy 360 gathers in two different locations; each displays as multi-azimuth angle sectors, with clear azimuthal variation

The 3D Canvas window provides a comprehensive system for QC and editing the automated RMO picked data, where the RMO curves can be displayed along a massive amount of gathers, with the ability to filter out outliers according to predefined attributes.



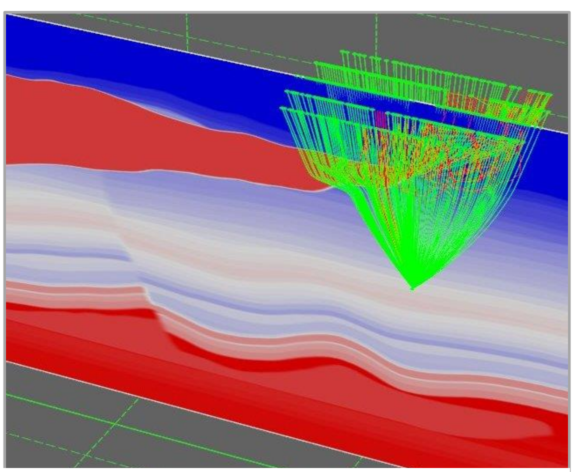
Automatic event picking in the post-migrated image domain



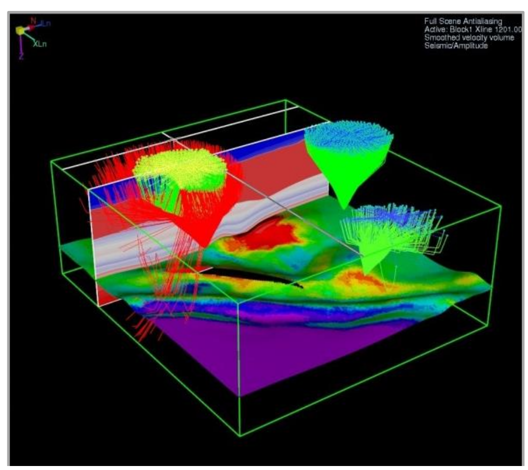
Full-azimuth RMO angle gathers, automatically computed

Ray Tracing and Construction of Tomography Equations

GeoDepth Tomography uses an efficient and accurate isotropic/anisotropic ray tracing technique that offers a satisfactory level of robustness, even when applied within complex background velocity models. Ray tracing is performed from subsurface points located along the major reflectors (horizon interfaces) and along coherent events within the layers (inter-layer horizons), which are automatically picked along the 3D subsurface image (migrated volume). Specular rays (ray pairs that obey Snell's law at the reflection surfaces) are then traced up to the surface, where each ray forms a linear relation between the velocity model perturbations in its vicinity and the known total traveltime errors. The ensemble of all rays traced from all subsurface points and for all angles/ offsets, forms the global set of tomography equations (tomography matrix) to be solved (inverted).



Two-point ray tracing (original data courtesy of Devon Energy Corporation)



Ray tracing (original data courtesy of Devon Energy Corporation)

Grid-based and Model-based Approaches

GeoDepth Tomography supports both grid-based and model-based methods that can be used according to the problem to be solved. For example, Gulf of Mexico sediments affected by long period compaction are normally parameterized by a Cartesian grid, whereas North Sea subsurface models are usually characterized by the aging of layers using a layer-based representation. The tomography workflow also supports hybrid approaches where, for example, shallow velocity anomalies can be parameterized with grids and deeper parts with geological layers. Unlike grid-based tomography, in which only the velocity parameters are updated on a predefined coarse 3D grid, model-based tomography updates both the velocity field along the geological layers and the location of subsurface horizons.

Implementation

GeoDepth Tomography is conventionally implemented in two independent stages: Constructing the tomography equations (building the tomography matrix) and solving the tomography equations (inverting the tomography matrix). The first part includes ray tracing from all subsurface points and for all angles/offsets - this is considered the most time-consuming part. The second part reads the tomography matrix and inverts it with different input parameters (constraints): Data and model variances, resolution, imposing the velocity updates to follow the background structure, and other geological constraints, avoiding recalculation of the tomography equations.

Direct 3D Grid-based Tomography

Despite the advantage of this scheme, for large-scale models and especially with high-resolution update grids, the size of the tomography matrix used in 3D grid-based tomography, which is quadratic with the number of model parameters, can be too large to be handled even by the largest super-computers. GeoDepth 3D grid-based tomography overcomes this limitation through a novel approach referred to as direct tomography. While the resulting updated subsurface velocities are identical to those of conventional 3D grid tomography, the difference is in the implementation. In 3D Direct Tomography, the tomography matrix is never generated explicitly, dramatically reducing the memory and disk space required by the application, where the inversion process (including ray tracing and the construction of the tomography equations) is performed in a single stage using an iterative process.

The main and obvious advantage of the direct tomography implementation is that it can handle large 3D updated grids (either due to the size of the survey or due to the requirements for high resolution) that could not be used before. Moreover, this type of implementation is very efficient when using clusters with massive amounts of nodes. The runtime of direct tomography is mainly related to the CPU power in globally running the ray tracing many times (for each iteration), whereas conventional 3D grid-based tomography suffers mainly from being I/O bounded, where most of the time is spent reading and manipulating the tomography matrix (many Terabytes of data).

Workflows

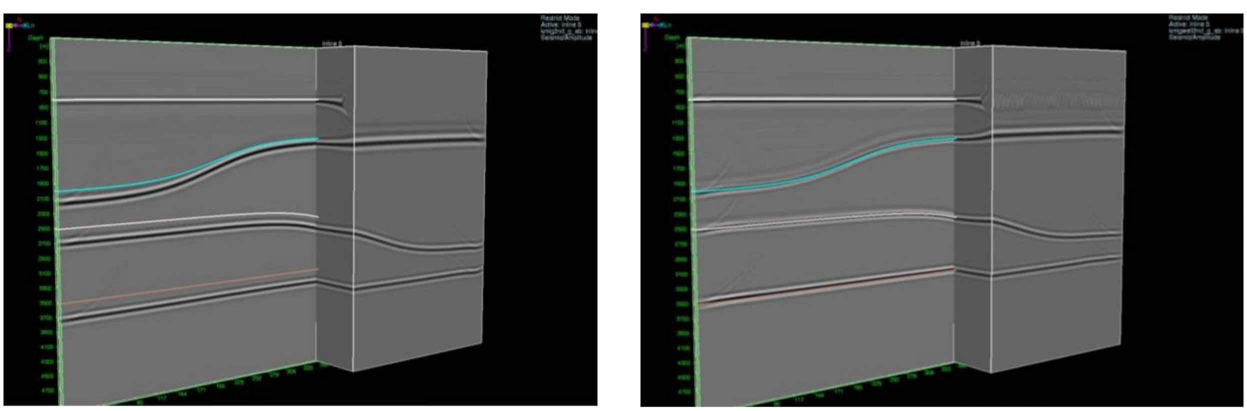
GeoDepth tomography supports different workflows, depending on the type and complexity of the subsurface geological models and the available input data. Overall, a “standard” workflow should start with a simple, long-wavelength, background velocity model that includes the main trends of the model. The tomography, after running several iterations, should bring in the small anomalies (if they exist) and the high-resolution features. It is also recommended to divide the workflow to independently update the shallow, medium and deep parts of the model, where a final iteration can be performed over the whole model.

Anisotropy velocity model determination requires access to some well data (well markers or check-shots) in order to define the axial velocity V_p and the small offset (near axial direction) δ Thomsen parameter values. Long offset RMOs are needed to define the far offset (near horizontal) ε Thomsen parameter values. Users can choose to either first invert for V_p and δ (see paragraph below) and then to invert for ε (and V_p and δ) or (recommended workflow) to start with V_p and ε using far offset (wide opening angle) RMO data and then to continue finding δ (and V_p and ε). Note that the tomography uses the anellipticity parameter $\eta = \varepsilon - \delta$, instead of ε explicitly.

In cases where the input seismic data contains surface offset azimuthal information such as 3D land data or wide (rich) marine azimuth data, the EarthStudy 360 Imager can provide extremely useful continuous full-azimuth angle gathers that can be used to better define the different subsurface anisotropic model parameters. The full-azimuth angle domain RMO extracted along these gathers, and the amplitude inversion applied to them (AVAZ) can be further used to detect velocity directivity and geomechanical properties. These may point to the existence of stress/fracture systems, and to help estimate their orientation and intensity. Such information is critical in the exploration and production of unconventional plays, such as shale gas, shale oil and heavy oil.

Time-Preserving Tomography Using Well Markers

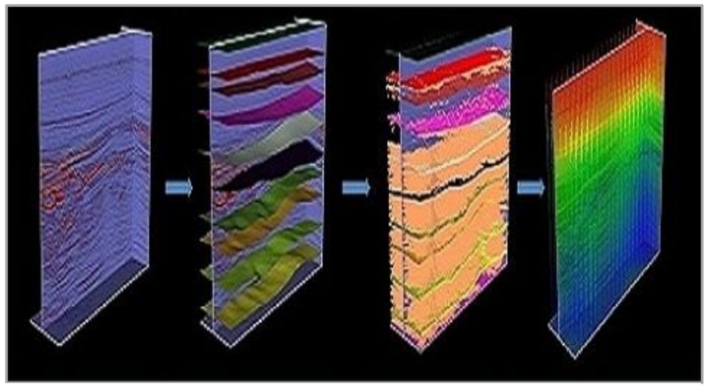
GeoDepth Tomography can also be used to simulate different model scenarios while preserving the total traveltime (traveltime errors or RMO values along the rays are zero). In this case, image gathers should be flat for each simulated model. An example of this type of tomography implementation is when the input consists of only depth mistie maps computed from sparse selected well markers. This mode is very attractive when converting isotropic models to anisotropic models, in particular, when inverting for the δ Thomsen parameter (especially in the case of TTI model representation.



Isotropic velocity model obtained using tomography (left), where image gathers are flat, but the depth horizons are wrong due to VTI anisotropy (true horizons are indicated by the colored lines). In the image on the right, using the well marker tie tomography, the depth reflectors follow the true horizons, while preserving the flatness of the gathers.

The GeoDepth Tomography System

Velocity model determination workflows, especially when using tomography approaches, comprise several key stages. Each stage needs to be analyzed and optimized, enabling the fast and reliable QC that will ensure a convergence process. The Paradigm software suite provides the most technologically advanced components required for successfully completing the different types of tomography workflows:



Imaging of various attributes, e.g. RMO, dip and azimuth, illumination, main and interlayer horizons, uniquely stored in a Pencil database

- A novel 3D geomodeling solution (SKUA®) to build and update geologically plausible subsurface structure models
- A comprehensive anisotropic ray tracing system (EarthStudy Illuminator)
- Efficient and accurate pre-stack depth migrations for generating the subsurface image and the offset/angle domain CIGs (GeoDepth Kirchhoff migration and CRAM/EarthStudy 360 Imager)
- An optimized processing system for automatic event picking in both post-stack and pre-stack domains
- A comprehensive visualization and interpretation system (3D Canvas) to analyze, QC and edit the picked events

Due to its specially designed infrastructure and unique, iterative approach, GeoDepth Tomography uses the Paradigm Parallel Framework (PPF), its high performance computing (HPC) system, in order to solve the tomography equations using clusters with many nodes. It is the combination and integration of all these components that makes GeoDepth tomography the leading system for velocity model determination.