Processes and procedures used in GT processing services for challenging geology, e.g. foothill areas, overthrust zones, salt structures, subsurface anomalies in overburden, rocks with azimuthal anisotropy

GT seismic data processing technology is ready to perform the state-of-the-art, complete workflow of seismic data processing and imaging in time and depth domains. Converted waves can be also processed. Land or marine seismic. Available approximations include isotropy, VTI or HTI anisotropy, pre-stack time or depth migration with comprehensive model building in the second case, including tomography. For unconventional prospection, the world-leading full-azimuth imaging package is offered: Earth Study 360 from Paradigm. It offers top-quality results for conventional prospection as well.

GT processing philosophy is to upgrade continuously commercially available software, and tailor it to challenges of specific projects. Client can suggest to complement existing software solutions with modules having potential to meet expectations better. In particular small software modules, without excessive graphics and interactivity can be added in several days with no extra cost to Client. Just GT software is upgraded. Reliable and efficient world-class commercial software is offered, but the key determinant of technology is broad group of the in-house developments collected with a view of meeting any challenge, but with focus on land seismic.

Any particular methodology is being established through comprehensive procedure of testing, in cooperation with client.

Selected modules and solutions are brought closer hereunder.

1. Statics solutions: GLI refraction, tomostatics techniques and solutions, GT developments

i) **Refraction static correction** – consists of two-stage picking first breaks: automatic plus detailed manual edits, next, interactive building of initial model, and direct or tomographic inversion for final model, then computing static corrections. Hampson-Russell GLI package is dedicated to that work.

ii) **IRSC** - GT proprietary interactive software to assist solution in case of special near-surface complexity. That is interpretive software, especially useful in cases of large statics when cycle skips occur and automatic tools fail.

iii) **Seismic Studio** package (from Fusion Geo) ensures ability to work with very large surveys.

iv) **Tomostatics technique** is available from Hampson-Russell GLI package, Landmark's SeisSpace, and Seismic Studio package from Fusion Geo. This technique is usually applied when vertical velocity gradient is present in the near-surface layers. Any static solution is interactively verified and edited in ProMAX database in order to be consistent with comprehensive QC procedures. Long-wavelength static component is controlled with auxiliary use of stacking velocity model, and procedure of calibration to the uphole hard measurements.

v) **2D Multiline Mistie Analysis and Correction -** GT proprietary package supports 2D projects to check and correct a real consistency of the solution. This step, performed at two or three steps of processing sequence, includes review and correction of stacking velocities, if necessary.

A choice between particular packages is based on test processing routinely performed to establish processing sequence and procedures.

Any refraction static solution is calibrated to the uphole measurements, if available.
All the above solutions are available in routine production, and are compared to field statics, if available. Consistency with near-surface model is taken into account.

2. **Trace interpolation, and missing shot and missing receiver interpolation techniques and methodologies:**

i) **GT proprietary workflow 2D/3D,** based on available commercial modules. Works in multi-domain mode. Proven in numerous applications, including overthrust geology. Designed to preserve azimuthal information in COV domain, and to handle correctly near offsets to supplement commercial 5D interpolation.

ii) **5D 2D/3D pre-stack/post-stack trace interpolation** uses the MWNI method (Minimum Weighted Norm Inversion).

iii) **Beam-Steer Trace Interpolation** is a space-time adaptive signal analysis method for interpolating seismic wave fields from their recorded spatial sampling to a new, either finer or coarser, sampling. The process does not require you to track or specify the number of coherent events to interpolate. It is noise tolerant and works well in an under-sampled.
environment in which coherent signals are spatially aliased. *Used in GT production.*

iv) **LSS Trace Interpolation** uses the local dip of events to interpolate traces. This process can be used to make trace spacing regular and/or to create a finer trace spacing. *Used in GT production.*

v) **F-X Trace Interpolation** interpolates prestack or poststack traces for 2D datasets, or poststack data for 3D datasets.

vi) **Fourier Trace Interpolation 2D/3D** uses the Fast Fourier Transform method to interpolate seismic wavefields from spatially recorded sampling to either a finer or coarser sampling.

vii) **Radon Interpolation 2D/3D** uses the tau-p transform method to interpolate missing shots and missing receivers.

viii) **Full-azimuth** trace interpolation built in the Earth Study 360 software is designed to preserve azimuth-related attributes. However, the full-azimuth interpolation solution makes data volume to be increased by the order of magnitude sometimes.

3. **2D Data Regularization**

i) **Shot and Receiver Regularization for 2D SRME** – *use in production when required.*
This tool performs the following tasks in order to match multiple model data with the recorded data:
- prepares input data for the 2D SRME process
- reverses regularized data to the original positions
- resets the headers to the original headers as they existed prior to the SRME process.

ii) **Trace Regularization** is a generalized 2D trace interpolator/extrapolator that can be used on prestack gathers to reposition and/or interpolate traces onto a regular offset spacing and fill in missing data.

4. **Compensation for amplitude decay with travel time**

Several options are available:

i) single g(t) function, offset-independent. Coefficients are estimated from scanning,

ii) g(t,offset,cdp) function computed from user-provided RMS velocity distribution,
iii) g(t,offset,cdp) function based on P. Newman or B. Ursin ideas.

There are options to account for array attenuation and emergence angle. No divergence compensation is applied before entering the full-azimuth imaging. Azimuth-dedicated solution is built in there.

5. Surface Consistent Residual Statics correction

Several 2D/3D algorithms are available from ProMAX/SeisSpace processing software.
Maximum Power algorithm is the best production option. It is very efficient even in case of low fold of archive data. Can be run with external model when indicated by tests.
Iterative procedure of residual statics estimation consists of two or three iteration velocity analysis – residual statics. At the beginning, stable velocity model, and low seismic frequencies are used, then through iterations, they become more detailed. Depending on test processing, velocity-statics iterations are interlaced with random and coherent noise attenuation procedures.
Solution from each iteration is interactively examined, and edited if necessary in ProMAX database. A decision about possible cumulation of solutions from consecutive iterations is based on assumption to keep horizon maps free of statics artefacts.
Alternative methods, including estimation of initial time shifts without correlation with CMP pilot trace, are available.
IRSC - in case of large statics errors, introducing cycle skips, **GT proprietary, interactive software package** IRSC is used. That can be run within ProMAX.

6. ECP-2014

Method of S/N enhancement, based on the generalized stacking idea. Designed to produce reliable, robust output. Applied pre-stack or post-stack. Proven in various geological conditions. The 2014 edition is equipped in feature preserving conflicting dips, what is crucial in areas of complicated of horizons.

7. Isotropic and anisotropic Kirchhoff migration velocity analysis

To compensate for the impact of dip and/or anisotropy on estimated velocity, Kirchhoff pre-stack time migration is routinely applied in both 2D and 3D surveys. In the time domain migrations are equipped with VTI anisotropy options.
Post-migration model updates include relevant attributes picking. Velocity and anisotropy (eta or epsilon/delta) analyses can be carried out in similar way as described above in paragraph “Stacking velocity Analysis ...”. Post-migration velocity analysis can be run in high-resolution option, using AVO-based algorithm.
3D pre-stack depth migration can correct for TTI and HTI anisotropy. Velocity analysis performed after that is fully free of structural effects. Horizon dips are picked within analysis procedure.

8. Kirchhoff pre-stack migration algorithms

Depending on specific project requirements, this is performed in ProMAX/SeisSpace, Geodepth, or in Techco software packages.

Basic approach is work from floating datum, and in common offset domain. Differences consist in methods and philosophy of initial model building and updating via residual moveouts. Particular solution is tailored to geology and requirements of project.
Migration deliverables are prestack and stacked seismic as well as model which can be multi-volume in case of anisotropy. Amplitude relations are preserved through migrations.

Techco package is limited to PreSTM at present. Is very efficient in case of complex, discontinuous reflections. Allows experienced geophysicist to uncover complex tectonics within short time.
Processing capabilities are smoothly combined with imaging software. That ensure fast model building when migrated CRP gathers need some processing before picking RMO. Migration apertures can be variant in time and space. Straight ray or curved ray options can be selected. 2D and 3D PreSTM are available in isotropic or anisotropic algorithms (eta for straight rays, and epsilon/delta for curved rays).

Geodepth is selected for its comprehensive tools to build initial model, and for complete set of migration algorithms: time, depth, 2D, 3D, PreSTM, PreSDM, isotropic, anisotropic, plus appropriate tools for RMO picking and model updates.
2D and 3D tomographies are used in grid or layer oriented options depending on structure complexity, continuity of interpreted horizons, and magnitude of residual moveout.
3D isotropic PreSDM (eikonal or wavefront travel time calculation) tomography is currently basic option in production (several projects already completed). 3D VTI Kirchhoff PreSDM (wavefront travel time calculation) can be available on rental basis in case when justified by contract. Available is also full-azimuth HTI tomography – a module of the Earth Study 360 software package.
Horizon demigrations are standard in Geodepth, and Kirchhoff-related volume demigrations are available in SeisSpace.

i) **Anisotropic PreSTM workflow**

Trace interpolation and missing trace regularization is performed before pre-stack time migration.

1. Algorithms available (selected for workflow depending on specific data characteristics)

Algorithms of Kirchhoff PreSTM available in Landmark system:

- Straight ray 3D (Vrms model),
- Curved Ray 3D (Vint model),
- Wave Equation 2D (Vint model).

Algorithms of Kirchhoff PreSTM available in GeoDepth system:

- Straight ray 2D (Vrms model),
- Curve fitting 2nd order 3D (Vrms model),
- Curve fitting 4th order 3D (Vrms model, effective eta model),
- Curved rays isotropic 3D (Vint model),
- Curved ray anisotropic VTI 2D/3D (Vint, epsilon, delta) model. Anisotropy parameters (if available), and verified well data (markers, time-depth pairs, sonic logs, well trajectories and others) – should be delivered by Client.

Note: curved-ray VTI 3D with (Vint, epsilon, delta) model is not recommended option as building the Vint (interval velocity) model in time domain is not sufficiently stable in practice: there are ambiguities between Vint and epsilon. In that case PreSDM (prestack depth migration) is recommended. However, if complexity of tectonics allows for PreSTM, eta model usually is sufficient.

Algorithms of Kirchhoff PreSTM available in Techco system:

- Isotropic migration 2D / 3D (Vrms model),
- Anisotropic VTI migration 2D / 3D (Vrms, effective eta models),
- Anisotropic VTI + HTI migration 3D (Vfast, Vslow, azimuth of Vfast, effective eta models).

2. Workflow (iterative procedure)
    - Data preparation for 3D PreSTM:
      The data (CMP gathers) and RMS velocities after residual statics referenced to the floating datum:
    - After data conditioning (wavelet processing, noise elimination).
    - With inelastic gain curve only (spherical divergence compensation not applied or removed if applied earlier).
    - Initial model building from stacking velocities and interpreted results of PoSTM (interpretation of the time migrated horizons should be delivered by Client).

Note: In case of complex structure, when interpretation of the PoSTM is ambiguous, more robust method can be applied: running constant velocity panels, then interactive interpretation of horizons' pieces visible in different individual migrated panels.

- Full volume 3D PreSTM for picking of residual velocities/moveouts.
- Residual velocity/moveout analysis (vertical).
- Updating initial model with residuals.

Note: initially, isotropic migration is run, followed by updating short-offset velocity model. Next, eta-anisotropic migration is performed, followed by usually 2 updating iterations. Residual moveouts (RMO) are picked automatically with interactive editing. Iterative kernel of the procedure is highlighted in blue. Details of the updating method are established through experiments, depending on quality of data and complexity of geology.

- Final 3D PreSTM performed on full volume of the data (with tested parameters).
- Automatic residual velocity/moveout analysis.
- 3D PreSTM stacking.
- 3D post-stack processing.

When doing anisotropic workflow additional analyses and updates of eta, HTI anisotropy (GT proprietary software), or epsilon and delta are necessary.

ii) 3D/2D Pre-stack Depth Migration algorithms available from GT

Algorithms of 2D PreSDM (each of them is isotropic with anisotropy option):

- **Kirchhoff** – one-way ray tracing from free surface to target. VTI anisotropy,
- **CRAM** – one-way ray tracing from target to free surface. VTI anisotropy,
- **RTM** – two-way ray tracing. VTI or HTI anisotropy option,
- **Earth Study 360** – large, complete system of the full-azimuth model building (including full-azimuth anisotropy) and imaging. Migration based on CRAM (Common Reflection Angle Migration) algorithm. Working in natural geologist domain: depth , incidence angle, azimuth angle. Input data should be corrected for short wavelength statics, wavelet imperfections, noise, and LVL-related amplitude variations. The rest is corrected inside Earth Study 360. It is the most advanced available correction for overburden impact, providing interval

attributes of the multi-parameter model. Migrated data (CRP gathers) are free of NMO stretch effect, so long offset information is well preserved along with azimuthal information. Perfect data for both, unconventional and conventional prospection.

iii) Model building:

Algorithms of residual velocity picking:

- Interactive picking based on vertical semblances,
- Interactive picking based on horizon semblances,
- Automatic picking based on AVO attributes.

Algorithms of global tomography:

- Grid based,
- Horizon based
- Full-azimuth.

iv) Workflow (iterative procedure) of model building – based on Kirchhoff migration:

- Initial model building: from time Vrms, through Image Ray Migration to depth Vint*(interpretation of the time migrated horizons – on PreSTM results - should be delivered by Client)*
- PreSDM (on target lines for interactive picking of residual velocities /moveouts or full volume for automatic)
- Picking of full/parts of horizons *(in depth domain – Client participation)*
- Residual velocity/moveout analysis (horizon-based along picked horizons)
- Updating initial model with global tomography (grid/horizon based)
- Final PreSDM performed on full volume of the data (with test-derived parameters).

9. RTM – 3D/2D prestack depth migration

Designed to handle cases of complex structure (especially near-vertical interfaces), when Kirchhoff algorithm is insufficient. The method is capable to invert prism waves or duplex waves appearing when seismic waves are two or more times bounced before coming back to receiver, so offers also some potential of multiple attenuation, provided velocity model contains velocity interfaces and/or velocity gradients being generators of such phenomena.

10. IWS – Interactive Wavelet Shaping

Apart of routine wavelet processing methods applied during processing seismic data, an attempt to increase vertical resolution is offered. Assumption of GT methodology is to obtain narrower wavelet to increase vertical resolution of seismic data while avoiding artifacts generated by various other methods. A couple of methods is available to do that:

- wavelet transform,
- complex spectral transform,
- spectral inversion.

Software modules from SeisSpace (Landmark) and Hampson-Russell are applied to perform the frequency band widening. Selected modules from GT proprietary development are applied for QC. Wavelet is estimated with homomorfic analysis technique.
The input data is usually standard processed stack (PreSTM or PoSTM), but the procedure can be applied prestack, to upgrade effectiveness of such operations as seismic inversion or AVO analysis.
Effectiveness of widening amplitude spectrum depends on parameters of acquired seismic, and, in case of land survey, on precision of estimated statics. When width of spectrum becomes wider than 4 octaves, dispersion of seismic waves has to be accounted for as it is, for example, in Q compensation. IWS technology can do that.
Amplitude relations are sensitive to BE parameters, thus it is always checked: the BE result against the input data, reference well-derived data (synthetic seismograms or VSP corridor stacks, compatibility of result with geologic concept. QC procedure provide indication how to limit high-frequency end of spectrum. Especially VSP data, as featuring higher resolution than surface seismic, are important reference for seismic data transformed to higher resolution.

Papers making reference to the GT band extension methodology:

1. *Chopra et al., 2003, High-frequency restoration of surface seismic data, The Leading Edge, Aug. 2003.*
2. *Smith et al., 2008, Extending seismic bandwidth using the continuous wavelet transform, First Break, June 2008.*
3. *Jedrzejowska-Tyczkowska et al., 2012, Wanted and unwanted effects of surface seismic data resolution improvements, First Break, Sept. 2012.*
4. *Ulrych, 1971, Application of homomorphic deconvolution to seismology., Geophysics, 36(4), 650-660.*
5. *Tribolet, 1979, Seismic applications of homomorphic signal processing., Prentice-Hall, Engelwood Cliffs.*