VICEPRESIDENCIA DE EXPLORACIÓN

OFFSHORE COLOMBIA 2D/3D SEISMIC DATA (RE)PROCESSING & IMAGING SERVICES

SERVICE ORDER TECHNICAL SPECIFICATIONS

Jarara 3D 2020 Q-PreSDM Reprocessing, Phase 2

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1. PROJECT SUMMARY – CONTEXT & BACKGROUND

ECOPETROL VEX CAR Norte ("ECOPETROL") has requested 3D Q-PreSDM reprocessing and advanced subsurface model update services, with a selected CONTRACTOR, of the NAZ towed-streamer Jarara 2011 3D seismic dataset, starting from pre-migration gathers, and 300km approx., of 2D seismic lines, starting from field data; within the deep-water Tayrona Block, Offshore La Guajira, Colombia (figure 1.1). Therefore, ECOPETROL aims to establish, as outlined in this document, a framework of the scope of work and time schedule for this work to be performed by CONTRACTOR. The estimated turn-around time in calendar days is approximately 9 months, starting in mid-Feb 2025. In summary, the desired scope of work includes the execution of:

1. High-end "broadband" pre-migration reprocessing in time domain (at 2ms S.I.), starting from field shots for 2D seismic lines, and with strong focus on surface-related multiple elimination and bandwidth maximization at reservoir target, and AVO response enhancement, preservation and QIQC.
2. For the full data extent of the Jarara 2011 3D acquisition program; that is approximately **1833 km^2**, the reprocessing which is to be reprocessed from pre-migration gathers must be focus on surface-related multiple elimination and bandwidth maximization as well.
3. An advanced subsurface model update sequence that includes Full-waveform Inversion (FWI single parameter or multiparametric??) iterations, followed by high-resolution reflection tomography, anisotropy analysis and updates, minimizing well-seismic mis-tie errors at Orca-1, Brama-1 and the new one Orca Norte-1 wells, and multi-parameter (Vp, epsilon) tomographic velocity model building of the full-fold area of Jarara 3D 2011 **1833 km^2**.
4. Q-absorption model building based on new VSP to reduce the effect of Gas and Mud Columns, Q-tomography or LS-PSDM and subsequent TTI Q-PreSDM and TTI Q-RTM, to be tested and approved by ECP.
5. Broadband deliverables (High freq) at reservoir target level.
6. Velocity and Structural Uncertainty Analysis, for the Jarara 3D, to be confirmed.

The Jarara 2011 3D survey area covers relatively smooth bathymetry ranging from approximately 300 to 1500 m.

The Tayrona block was the first contract granted in 2004 by the National Hydrocarbons Agency (Agencia Nacional de Hidrocarburos, ANH) for exploration in the Colombian Caribbean basins. The Jarara 2011 3D field data was acquired by the CGGVeritas vessel Veritas Viking, from October to November 2011, using a single vessel, dual-array and 10-streamer acquisition configuration. Directly following acquisition, the original seismic processing (PSTM and PSDM) of the resultant Jarara 2011 3D field data was performed in the CGGVeritas Madrid Dedicated Center for Repsol from November 2011 to April 2012.

Legacy benchmark image: Based on extensive experience of ECOPETROL VEX end-users (GOF CAR asset team interpreters, GSE seismic inversion QI specialists, *etc*) with various migrated pre- and post-stack seismic products, both Kirchhoff PreSTM and PreSDM, the **2021 Kirchhoff TTI PreSDM** results of the 2021 legacy reprocessing (from field shots), carried out by SLB in Rio de Janeiro, are considered the best-to-date legacy benchmark volumes. However, this 2021 legacy reprocessing pass, starting from Jarara 2011 3D field tapes, just migrated 286.5km2 at zone of interest.

Thus, to reduce uncertainty and mitigate risk regarding the size of the structure, trap geometry, and the quality and distribution of the reservoirs, which ultimately translate into the recoverable volumes and define the feasibility of the business case, a significant step-change improvement the best-to-date seismic image quality for whole cube is necessary.

This improvement is expected to be achieved by CONTRACTOR through the requested reprocessing and imaging scope as described in this document.

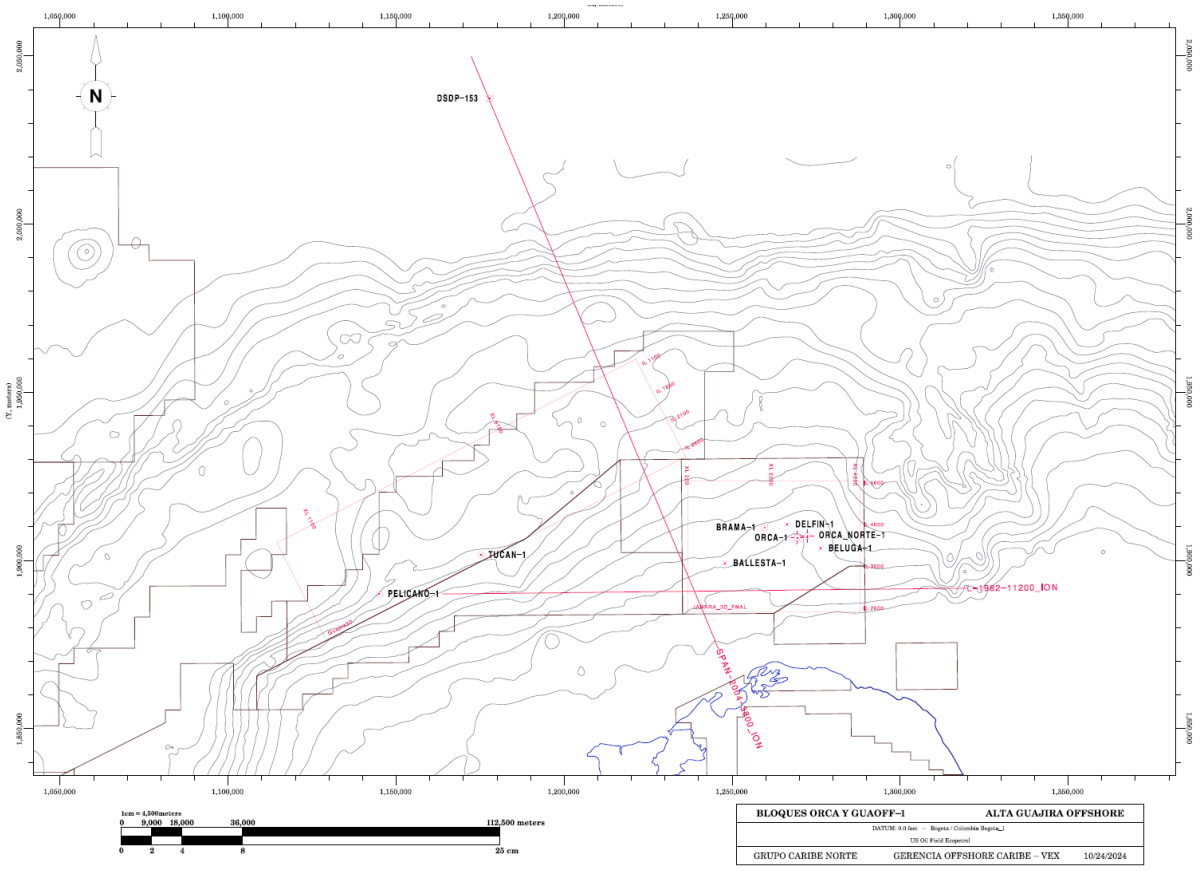


Figure 1.1. *Location map of the Jarara 2011 3D Survey polygon, 2D lines and the well locations (offshore La Guajira basin, Colombian Caribbean Sea.*

2. LOCATION

See Section 1. The NAZ towed-streamer Jarara 2011 3D seismic program, dual-source 10-cable configuration, is located within the eastern section of the deep-water Tayrona Block, Offshore La Guajira, Colombia (figure 1). This offshore area of geological interest is situated 38 km north of the north cape of Colombia/ Latin America, and about 175 north-east from the Chuchupa-Ballena-Rio Hacha production zone (nearest infrastructure). The Orca-1 discovery well (Brahma-1 well and Orca Norte 1) are located near the center of the Jarara 2011 3D survey polygon (green, figure 2.1, Full Data Extent: 1833 km2), and the Jarara Phase 1 Q-PSDM priority polygon (red, figure 2.1, FF area: 286.51 km^2) is centered on this wells coverage and includes the Orca old prospect polygon (yellow, figure 2.1, 30 km^2).

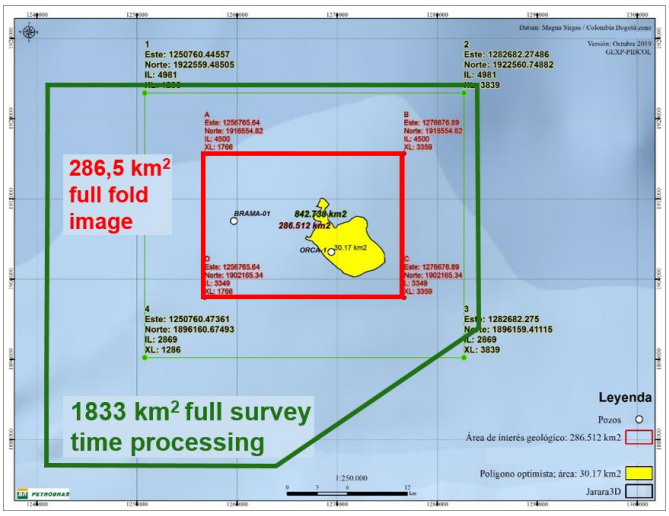


***Figure 2.1**. Location map Jarara 2011 3D Survey polygon (green) and the Jarara 3D Phase 1 Q-PSDM reprocessing and the Orca-1 discovery well and Brama-1 appraisal well locations (offshore La Guajira basin, Colombian Caribbean Sea.*

3. G&G OBJECTIVES & TARGETS

As explained in the above section this data had a Phase 1 reprocessing part where the scope of work was the appraisal and development of the Orca discovery, within the red polygonal area of interest of figure 2.1: primarily consisting of Oligocene turbiditic sandstones with secondary (Marlstone, Siamana Formation) target carbonates, limestones and immediately following markers.

From this reprocessing phase 1 ECP got the following products, figure 3.1.:

- Preprocessing: 1833Km2
- Final QPSDM (3m, 12.5x12.5): 286.5Km2
- Final RTM (3m, 12.5x12.5): 286.5Km2
- FWI to Band 4-12Hz 1500Km2
- Final QPSDM TTI vel model: 1500Km2
- Final Anisotropic fields: 1500Km2

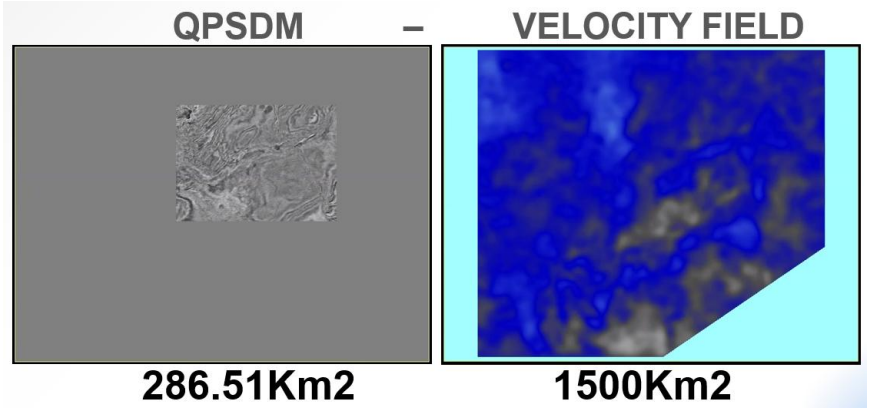


***Figure 3.1.** Extension of QPSDM and velocity field of Jarara 3D Phase 1 Q-PSDM reprocessing.*

Where the main objectives were achieved, some of them are:

- Application of statistical de-bubble.
- Directional (angular) source de-signature including dephasing (zero-phase conversion).
- Adaptive source-receiver de-ghosting.
- Focus on low-frequency content through de-ghosting and SNR enhancement at low frequencies, not merely high-frequency enhancement, mitigating risks of “ringing”, and side-lobe effects.
- Phase-only Q-compensation prior to final migration production.
- Q-Tomography and Q-PSDM (Kirchhoff and RTM).
- Reduction of migration artefacts.
- Minimization of Processing artefacts at near/far offsets.
- Eliminate residual (swell) noise at near offsets.
- Reduction of the residual multiple contamination, at near-mid offsets getting suitable CDP gathers for depth imaging.

However, after Orca Norte 1 well, the objective zones change regarding phase 1 reprocessing project, where the main zone of interest was Oligocene, in phase 2, ECP is interested in almost the whole section, Miocene, Oligocene and Eocene, and better definition of the basement as well, figure 2.3.

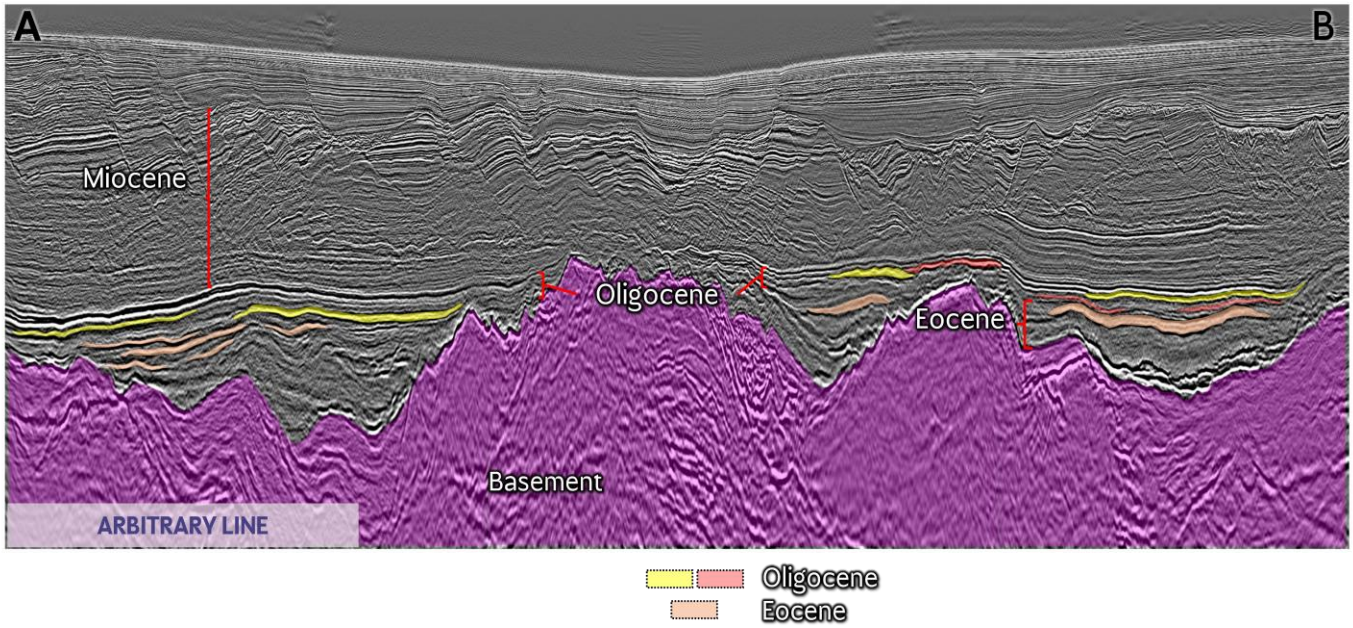


***Figure 3.2**. Arbitrary-line stack section example of QKPreSDM enhanced stack volume, emphasizes the stratigraphic opportunities (geological target).*

Additional of the difference zones of interest, the QPSDM phase 1 still has things to improve: as the diapirism effect in the Orca´s high, bad fault definition, low signal to noise ratio and the low continuity of the reflections above the Oligocene, reduce or improve these things in the Jarara 3D reprocessing phase 2, is essential.
These effects are in the following figures 3.3, 3.4, 3.5 and 3.6.

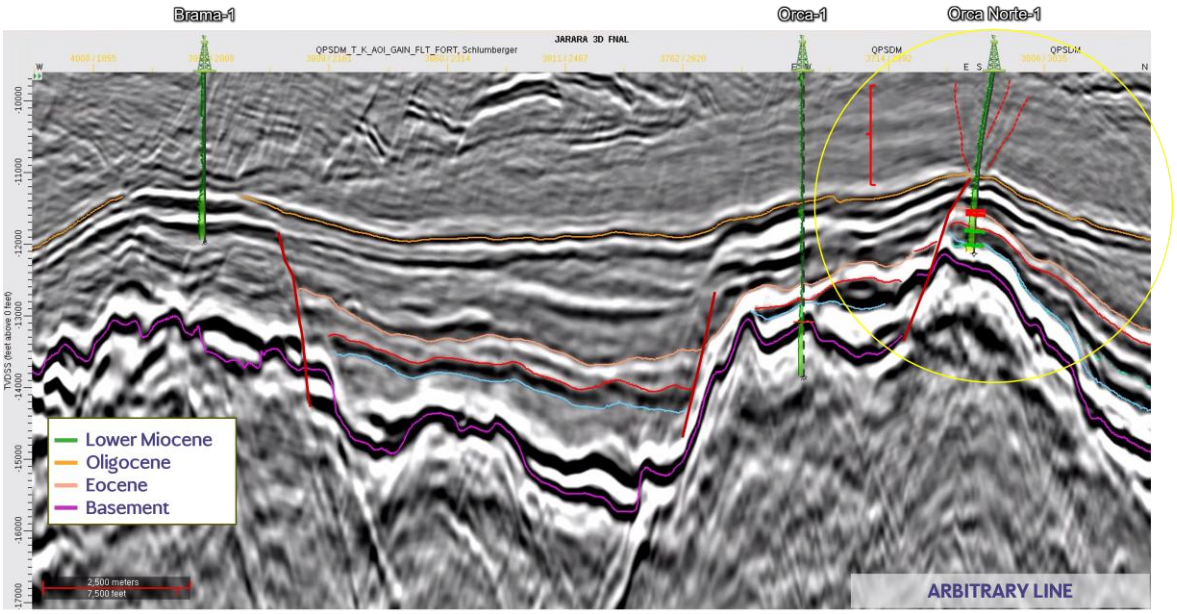


***Figure 3.3**. Arbitrary-line stack section example of QKPreSDM enhanced stack volume, emphasizes (in the yellow circle) the diapirism effect in the definition of Orca´s hight, and bad continuity of the reflections above the Oligocene.*

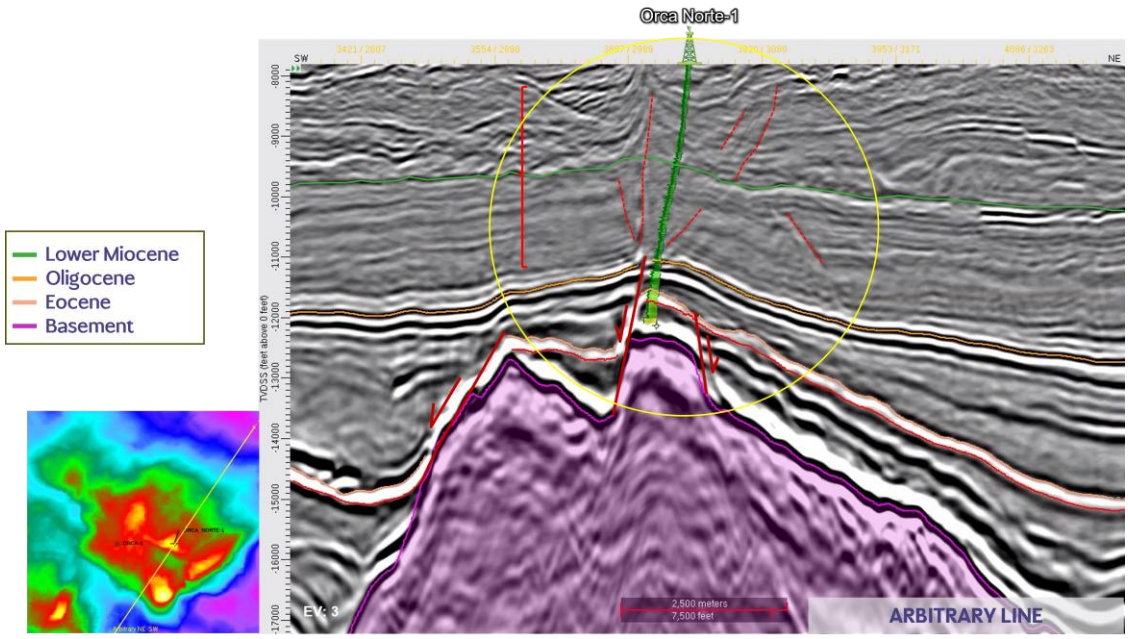


***Figure 3.4**. Arbitrary-line stack section example of QKPreSDM enhanced stack volume, emphasizes (in the yellow circle) bad fault definition or noise?.*

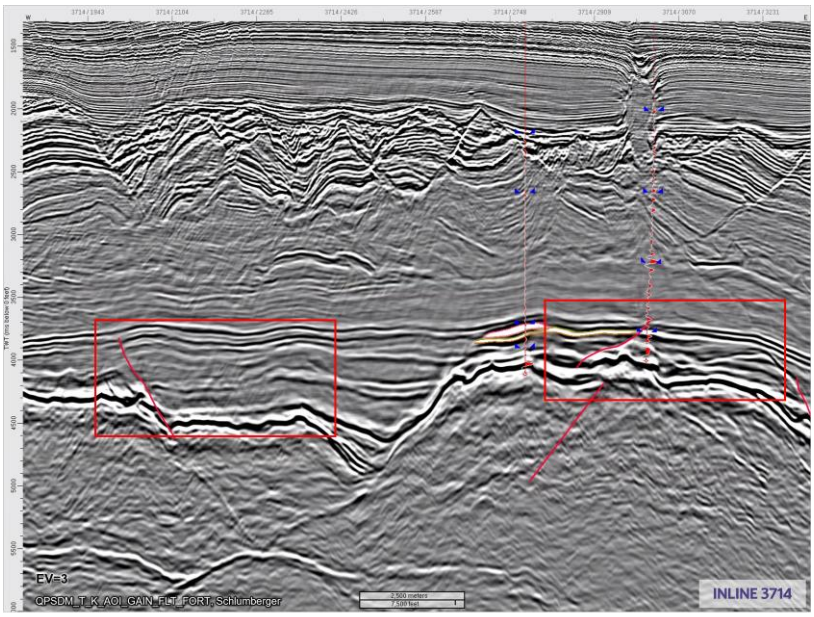


***Figure 3.5**. Iline 3714 stack section example of QKPreSDM enhanced stack volume, emphasizes (in the red zones) Oligocene and Eocene low resolution.*

About FWI & TOMOGRAPHIC VMB SEQUENCE (DEPTH IMAGING), the main goal is to enhance the TTI anisotropic velocity model that ECP already has~~ve~~ from Phase 1, to reduce the mistie with Orca Norte -1, because is a well after reprocessing phase 1, and reduce any stack image distortion, pre-stack non-hyperbolic RMO, "false structure" related to laterally mid-to-long wavelength velocity errors (i.e. "push-up" and "push-down"), and improve the TTI anisotropic velocity field comparison with well velocity log from Orca Norte 1. Figure 3.6.

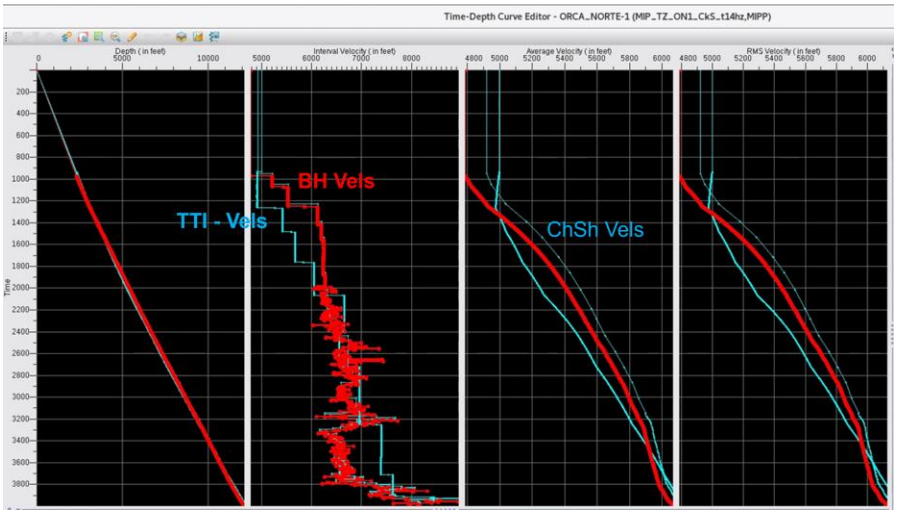


***Figure 3.6**. Velocit~~y~~ies comparison: TTI anisotropic velocity model – Orca Norte- 1 well velocity log~~.~~.*

4. SCOPE OF WORK

In order to allow the awarded offshore Colombian 2D/3D SP&I Framework Contracts, which cover this individual Service order (SO), to cover the maximum range of offshore seismic processing and imaging activities and services required by ECOPETROL, and to be able to respond in a flexible and timely fashion to ECOPETROL´s offshore seismic processing, imaging and all associated G&G and business needs, the general scope of work under this framework contract was designed to be as wide as possible. The scope and requirements for all these offshore Colombian 2D and/or 3D Seismic Processing and Imaging (SP&I) services are clearly defined and described in the technical specifications of the Framework Contract covering this Service Order, and are divided into *well-defined* and *industry-standard* activity groups:

1. **2D Pre-migration processing** in time domain, incl. front-end processing
2. **2D VTI-TTI Tomography iteration** (Vp update, incl. Tomo TTI PreSDM), SINGLE ITER.
3. **Final 2D VTI-TTI Kirchhoff PreSDM**, incl. all post-processing (5), in depth/ time domain
4. **2D post-migration processing & AVO preconditioning** (as stand-alone service)
5. 3**D VTI-TTI Tomography iteration** (Vp update, incl. Tomo TTI PreSDM), SINGLE ITER.
6. **Final 3D VTI-TTI Kirchhoff PreSDM**, incl. all post-processing (5), in depth/ time domain
7. **3D post-migration processing & AVO preconditioning** (as stand-alone service)
8. **3D Q-Tomo, including final 3D VTI-TTI Q-KPSDM**, incl. all post-processing (5), in depth/ time domain
9. **3D Q-RTM (max 60Hz)**, correlation stack output only (no gathers), incl. RTM post-stack processing

See the technical specifications of the awarded and signed Colombian offshore 2D/3D SP&I Framework Contract for more (detailed) information regarding the scope of work and bounding scope definition of these “basic” activity groups 1-5 and “key” technologies 7-13. For this specific Service Order, the following activity groups (1-5), key technologies (7-13), and specific advanced (denoted *Adv.*) technologies are required by the requesting ECOPETROL (VEX) offshore asset team, geological or geophysical operations group of end-users, and other stakeholders of ECOPETROL (and her partners), as per table 5.1 for 2D lines and table 5.2 for Jarara 3D:

No.	Requested Activity Groups		Workload
1	Pre-migration processing in time domain, including up-front processing		300 km
2	2D VTI-TTI Tomography iteration (Vp update, incl. Tomo TTI PreSDM), SINGLE ITER	5 iter.	300 km
3	Final 2D VTI-TTI Kirchhoff PreSDM, incl. all post-processing (5), in depth/ time domain		300 km
4	2D post-migration processing & AVO preconditioning (as stand-alone service)		300 km

***Table 5.1**. Base Scope of Work (2D), and the respective and workload (km) for each of these activities/ technologies.*

No.	Requested Activity Groups		Workload
1	**3**D VTI-TTI Tomography iteration (Vp update, incl. Tomo TTI PreSDM), SINGLE ITER	2 iter.	1833 km²
2	Final 3D VTI-TTI Kirchhoff PreSDM, incl. all post-processing (5), in depth/ time domain		1833 km²
3	3D Q-Tomo (1 or 2 passes), including final TTI Q-KPSDM, incl. post-processing		1833 km²
4	Final TTI Q-RTM (max 60Hz), correlation stack product(s) incl. post-processing		1833 km²
Adv	**Seismic, Velocity, and Structural Uncertainty Analysis**	**TBC**	1833 km²
Adv	Least-squares (LS) TTI 3D KPreSDM, either Q or “standard”	Test	Target line

***Table 5.2**. Base Scope of Work (3D), and the respective and workload (km2) for each of these activities/ technologies*

CONTRACTOR should note that, at the time of formalizing these technical specifications and planning of the scope or work of the respective service order of Colombian offshore 2D/3D SP&I activities, the budget to cover the costs associated with optional scope is NOT approved by ECOPETROL.

CONTRACTOR, and the ECOPETROL (VEX PGF) technical QC lead/ interventor of said Service Order shall provide, to the relevant/ key decision makers of the requesting ECOPETROL stakeholders of the Service Order, ample technical justification, through feasibility studies, trials, testing and optimizing of the individual optional scope items to justify the impact on costs/ budget and timeframe, and in order to obtain formal budget approval for the individual optional activities. Once formally approved by ECOPETROL (and her partners), the respective optional scope activities or technologies/ solutions are to be added to the scope of the Service Order as a contractual amendment ("OTROSI"), with clear cost and time implications (GANTT chart baseline re-definition), deliverable listing and workload/ scope, as relevant to the scope amendment.

These tables 5.1 and 5.2 describe the base and optional scope of work, in general and broad terms and activity groups, and as composite multi-stage and multi-iteration processing and imaging sequences within this service order. Within some of these activity groups, sequences and branches (i.e. Activity group 1: pre-migration processing in time domain), some individual "advanced" and/ or "key" marine seismic data processing technologies are to be deployed in the course, and as the focus, of the planned project:

- **2D Broadband processing solutions** at 2ms. Optimizing vertical resolution by enhancing/ maximizing and flattening-whitening the frequency bandwidth on both low- and high-frequency ends, through meticulously optimized, advanced and adaptive source and receiver de-ghosting, statistical/ deterministic de-bubble and (directional) source de-signature to zero-phase.
- **SRME**, with high-end LS Adaptive Subtraction of SRME model gathers from input, using multi-frequency split, (curvature-domain) SRME multiple model subtraction (targeting diffracted/ complex FS multiples), and simultaneous LSAS where applicable.
- **Residual Pre-migration Multiple Attenuation**: High-resolution Parabolic Radon (mild), and RNA on pre-migration (post-regularization) CMP-gather randomization of near-offset traces across the CMP offsets, ~~in order to~~to attenuate/ eliminate residual multiple across near, mid and far offsets prior to migration.
- **Relative Amplitude Preserving and Recovering (RAPR) reprocessing** (*i.e.* "AVO-friendly") from field data to final PreSDM deliverables. Protection of near-offset primary amplitudes during the full pre-migration processing sequence. Radon-base (or equivalent) near-offset "reconstruction" or extrapolation to zero offset (CoS array location) is either to be executed, for all processes involving Tau-P or other transforms or in general for all pre- and post-migration processing steps.
- **AVO/ QI QC** at key production stages during pre-migration time-domain 2D processing to ensure (Quality Assurance, QA rather than QC) that the time-domain, pre-migration reprocessing sequence, the AVO friendly and RAPR, in particular the full multiple attenuation sequence, are performed optimally. The minimum standard specifications of AVO/ QI QC (or QA) are to be specified by ECOPETROL at project start-up (Section 8.2), in addition to CONTRACTOR`s in-house AVO QC procedures and products.

Note: In all ECOPETROL projects under the Offshore Colombia 2D/3D SP&I Framework Contract, a small trial, *i.e.* a few selected in-lines and/or cross-lines, (at no additional cost to ECOPETROL, and "within reason") shall be conducted to assess the added value of one or more of the following "advanced" PreSDM algorithms, regardless of the basic sequence and advanced technologies to be applied in production:

- Least-squares (LS) Kirchhoff PreSDM
- RTM max 40-50-60Hz.
- RTM VIP gather output, assessment of added value of RTM gather products.
- Combined LS-Q Kirchhoff PreSDM

Upon evaluation of the said trial, when this trial is deemed successful in proving sufficient/ quantifiable value added to the final PSDM image at target level(s), a separate service order may be created as a "spin-off" reprocessing and/or

imaging project to include the advanced PreSDM option in the scope of work/ deliverables, to be executed by the CONTRACTOR executing the trial.

5. INPUT DATASETS

5.1. SUMMARY

Item	Input data	Format	Requirements
	Branch 1: Time-domain pre-migration (re)processing:		
1.1a	Seismic field data, raw shot gathers, without geometry applied	SEG-D	Hard requirement for project start-up
1.1b	Seismic field data, raw shot gathers, with geometry applied, *i.e.* legacy Navigation-Seismic merged field shots	SEG-Y	Hard requirement for project start-up
1.2.	Navigation, geometry and/or survey data, as asci text files	UKOOA P1/90 ascii text files	Hard requirement for project start-up
1.3.	Observer`s Logs/ Reports, Observer`s (and Surveyor`s) Notes, *e.g.* per 2D line.	PDF, DOC, XLS *or equivalent*	Hard requirement for project start-up
1.4.	Seismic acquisition report(s), for all 2D/3D seismic vintages involved in the (multi-survey) project or service order	PDF, DOC *or equivalent*	Auxiliary document
1.5.	All available original and legacy (re)processing reports	PDF, DOC *or equivalent*	Auxiliary document
1.6.	Key horizons in time, *e.g.* from legacy PSTM/ PSDM stack volumes, *e.g.* for windowing and QC purposes, conversion to depth horizons. In particular accurate WB map in time or depth, preferably with horizon amplitude extracted, and curvature.	ASCII	Auxiliary files, time saver, test line selection and QC
1.7.	All available (non-sensitive) polygons of areas of interest: Leads, prospects, discoveries, prospective areas, areas of high structural complexity, etc. Subject to acceptance by asset to share this information.	Shape files	Support for QC, test line selection, supports decision-making
1.8.	All geological background information on the AOI, stratigraphic column, etc…	Various	Auxiliary document

	Branch 2: FWI, Tomography VMB, Q-KPreSDM, Q-RTM		
2.1	Final (legacy) pre-migration gathers without gain, mute, nor NMO applied, with all statics (in headers). Datum, phase and phase-only Q-compensation information in EBCID	SEG-Y	Time-saver, Tomo FT sequence may not be needed.
2.2.	Seismic imaging support files (Legacy final PSTM/ PSDM migration and stack velocities, PSTM/ PSDM stack volumes), any 3D volumes	SEG-Y, text files	Benchmarking/ QC, IVMB Time-saver
2.3.	Original and legacy depth imaging reports	PDF, DOC *or equivalent*	Auxiliary document
2.4.	Well logs and well V_P data (P-sonic, dt or V_P, check shots, *etc*), for Brahma-1, Orca-1 and orca Norte 1.	LAS or tables	Well-seismic mis-tie analysis, for VTI delta depth trend

2.5.	Geological background information on the AOI, horizons in time/ depth, stratigraphy, rock physics, geology maps, etc…	Various	N/A

Table 5.1. *Summary of required input datasets, reports, supporting information, meta-data etc.*

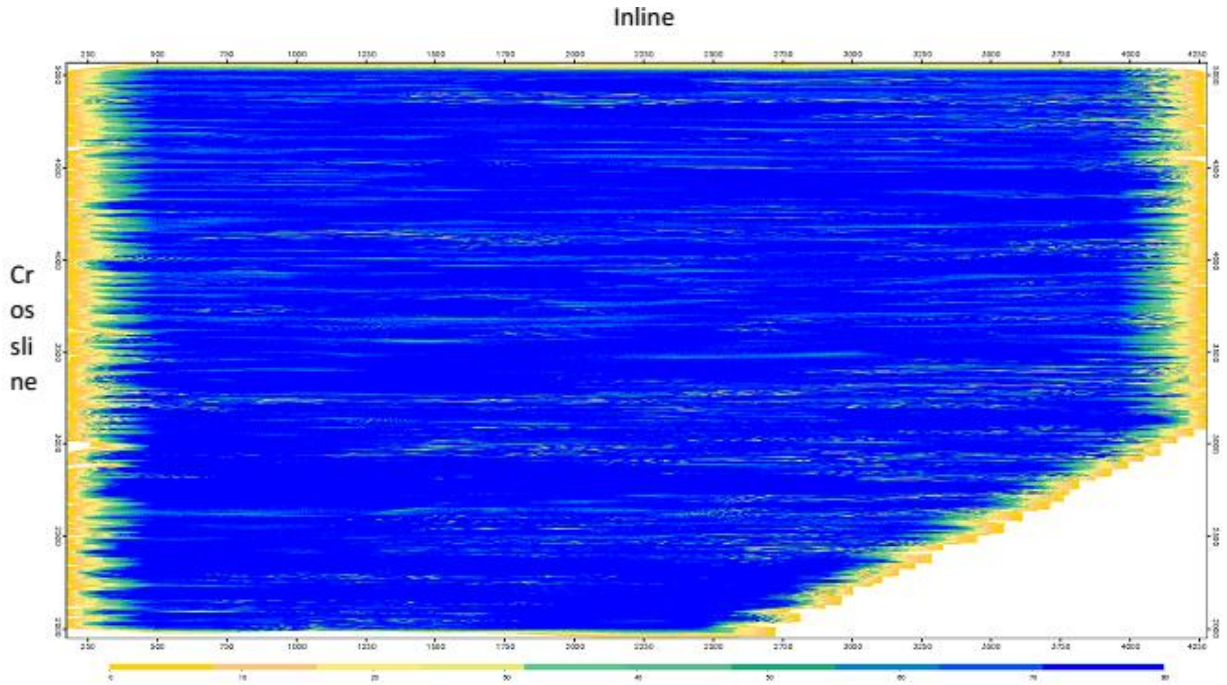


Figure 5.2. *Inline-Crossline fold of coverage map of Jarara 2011 3D acquisition. Nominal fold of the acquisition is equal to 80.*

5.2. ACQUISITION PARAMETERS

The fold of coverage map (figure 5.2.) shows that the raw Jarara 3D field data, with geometry assigned to relevant trace headers, do not present any considerable acquisition gaps and is consistent with expected nominal coverage of 80 fold. The key acquisition parameters of the Jarara 2011 3D program, for all source, streamer and recording parameters, are summarized in tables 5.2.1 and 5.2.2. The sail line/ sequence listings, observer's logs, and acquisition/ field operations report for the Jarara 2011 narrow-azimuth, 10-streamer, dual source, 3D marine seismic survey is to be provided by ECOPETROL as separate auxiliary files and appendices to this technical specification document.

And the same information as well for the 2d seismic lines.

Project Area	
Full fold (FF) area	1500 km2
Full extent (non-FF) area	1833 km2
Program area name	TAYRONA BLOCK
Nominal bin size	6.25m x 25m
Water depths range	200/ 300m to 1500m

Data acquisition contractor	CGGVeritas
Acquisition period	October 2011 to November 2011
Vessel name	Veritas Viking
Number of sail lines	103
Sequences number	003 to 106
Source Parameters	
Source type	Bolt Long Life Airguns (1500LL & 1900LLX)
Air pressure	2000 psi +/-100 psi
Total volume per source	1 x 4450 in3
Number of sources	2
Source separation	50 m
Sub-array separation	8.0 m
Source length x width	16.0m long
Shot interval	50 m (25m flip-flop)
Source depth	10 m
Bar meter output (0-128 Hz) p-p	109.6 Bar-m (10m depth)
Peak/ Bubble ratio (0-128 Hz)	13.1 (10m depth)
Source controller timing accuracy	± 0.25 ms
Source timing tolerance	± 1.5 ms of aimed firing time
Streamer Parameters	
Streamer type	Sercel Sentinel Solid Streamer
Number of streamers	10
Streamer depth	10 m
Channels per streamer	10 x 648
Streamer separation	100 m
Active streamer length	8100 m
Type of hydrophones	Sercel flexible hydrophones
Group interval	12.5 m
Group length	12.5 m
Hydrophone group sensitivity	19.7 microvolts per microbar @ 20°C
Inline offset (CoS to near trace)	160 m

***Table 5.2.1**. Summary of key acquisition parameters: Program, Source and Streamer configurations and parameters.*

Recording Parameters	
Instrument type	Sercel Seal
Recording format	SEG-D 8058 rev. 1, tr. seq., blocked 128kb
Record length	9000 ms
Sample rate	2 ms
Recording filter: Lo-cut	Digital low-cut : out
Recording filter: Hi-cut	200 Hz @ 370 dB/Oct
Recording media	IBM 3590E compatible
SOD recording delay	-50 ms

***Table 5.2.2**. Summary of key acquisition parameters: Recording parameters.*

5.3. Coordinate Reference System and Grid

Survey Spheroid Parameters	
Spheroid datum	Magna Sirgas
Ellipsoid	GRS80
Semi major	6378137.000
Semi minor	6356752.314
Inverse flattening	298.2572221

Map Projection Parameters	
Projection type	Transverse Mercator (Gauss Kruger)
Projection	Colombia
Zone	Magna Colombia Bogota
Scale factor on central meridian	1
Latitude of origin	04° 35' 46.321"N
Longitude of central meridian	74° 4' 39.028"W
False northing	1000000.00 N
False easting	1000000.00 E
Survey units	International meter

***Table 5.3.1**. Summary of Spheroid and Map projection parameters defining the coordinate reference system (CRS) of Jarara 2011 3D acquisition and all PSDM deliverables to date.*

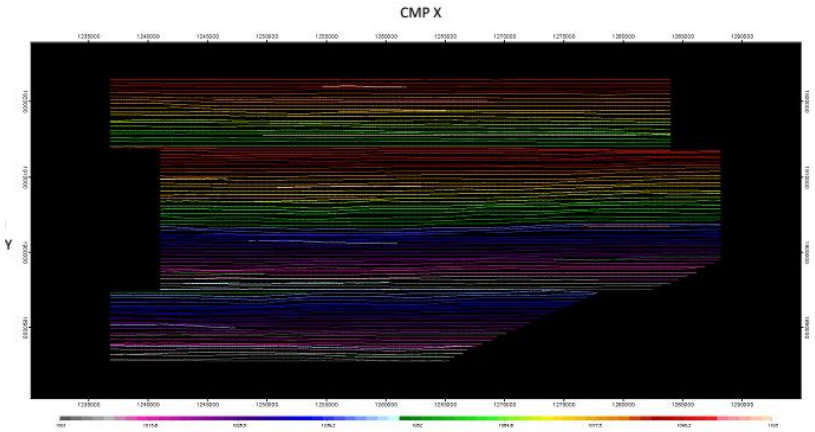


***Figure 5.3.1**. Shot point map (sequence number color-coded) of Jarara 2011 3D acquisition, using the Magna Sirgas Bogota CRS (Petrobras, 2016).*

6. OPERATIONAL REQUIREMENTS

Seismic depth-domain (re-)processing, both pre- and post-migration, model building, isotropic and/or anisotropic manual and automatic velocity analysis, tomographic model updates and PreSDM migrations of provided input datasets is to be performed in a seismic processing and imaging center at the CONTRACTOR´s designated processing/ imaging center. This designated processing/ imaging center should be capable of providing adequate computational and human resources to execute, within the given contractual timeframe, all the required seismic data processing and imaging services, as defined by the technical specifications of this Service Order.

6.1. PROJECT MANAGEMENT

A single **project manager** and (multiple) lead processor(s)/ depth imager(s) shall be allocated by CONTRACTOR to the project associated with this Service Order, as signed by ECOPETROL and CONTRACTOR. This supervising CONTRACTOR **project manager** shall be accountable for the consistency and quality of all the contractual deliverables, and for all project management aspects, including full adherence to the planned (or re-baselined) project timeline for the duration of the Service Order/ project from the kick-off meeting until formal project close-out. The CONTRACTOR`s geo-technical personnel and full processing/ imaging project team assigned to the Service Order, in particular the project manager, shall remain consistent/ unaltered as to ensure project continuity, and must all have proven ability and experience in all aspects – Testing, Production, and Quality Control (QC) – of time-domain pre- and post-migration processing steps, all algorithms of PreSTM and PreSDM migration, and tomographic depth imaging of Offshore 2D and 3D seismic data. A list of qualified and experienced CONTRACTOR manpower, with respective resumes (CV`s), planned to be allocated to the Service Order project should be provided to ECOPETROL *before start of project*.

The CONTRACTOR shall *approximately*, *i.e.* with appropriate flexibility, follow the agreed scope of work (Section 1) of the provided basic sequence pre-migration processing sequence (with requested advanced technologies), of all passes and iterations of velocity analysis, model building and tomographic/ manual updates, of the final PreSDM production, and of the post-migration processing flows. CONTRACTOR is to optimize this workflow and *all* key parameters of constituent processing stages/ modules in order to obtain best results in 2D and 3D data imaging and optimized seismic products to be delivered in a timely fashion to ECOPETROL. Any requested 2D/3D survey matching and merge plan/ sequence, as well as any (optional) advanced technologies, will be discussed and confirmed at project kick-off, after CONTRACTOR has been selected for executing a specific Service Order under the awarded Framework Contract.

Flexibility Clause:

- Minor deviations from the approved processing/ imaging sequences of the contractual scope of work, as defined by the signed Service Order (Technical Specifications) and mutually agreed upon at project start-up by CONTRACTOR and ECOPETROL, can be incorporated during the course of processing, based on data (signal and noise) requirements, and after approval by both CONTRACTOR and ECOPETROL
- These minor deviations may include, but not exclusively, differences in the order of processing steps and the inclusion and/ or exclusion of *minor and basic* processing steps (*e.g.* time-variant band-pass filters, inverse-Q filters, FK/ Tau-P filters, *etc*).
- Preliminary or informal, quality-control, or otherwise non-contractual seismic products (including velocity models, well data, interpretation, shape-files, or non-seismic datasets, meta-data, files or information), may be requested over the course of the time-domain pre-migration processing sequence, or during. These datasets, regardless of the format (SEG-Y or other), are to be requested or confirmed by ECOPETROL a week prior to intermediate or non-contractual data delivery/ transfer.

During processing, CONTRACTOR shall carry out detailed parameterization tests and optimization for each processing stage (including final PreSDM) and iterations of tomographic velocity model updating to achieve optimum processing and imaging parameters in the masterized production workflows. The results of all individual tests, and the quality of the associated test documents (e.g. MS PowerPoint™ presentation), need to be certified by an appropriate representative in the processing center of CONTRACTOR prior to sharing the test results with ECOPETROL. The production stage of each processing step will start only after the test results are finalized, and approved, and decisions on optimal parameterization and production have been made by the primary ECOPETROL project lead. Similarly, the subsequent processing (test) stage shall only commence upon completion and ECOPETROL`s formal sign-off of the Quality Control (QC) stage of the *preceding production* on the full project production dataset. On completion of all post-processing and depth imaging, as part of project closeout meeting, CONTRACTOR shall give a presentation at ECOPETROL or CONTRACTOR office, with results of final PreSTM and/or PreSDM imaging and selection of parameters.

CONTRACTOR shall provide weekly progress reports of all SP&I services to ECOPETROL. The weekly report is a “living project document” (to be meticulously updated, not just copy-pasted) and shall include, amongst other items, the test/ production status, percentage of completion of key stages and the full scope, updated summary of all decisions made to date, work schedule for the coming week, tests performed and work executed in the preceding week, as well

as an image of an updated GANTT chart. The progress report template and reporting/ communication plan shall be discussed with CONTRACTOR and approved by ECOPETROL and CONTRACTOR at project start-up.

Communication Plan:

The communication plan needs to be formalized and approved by CONTRACTOR and ECOPETROL at the project kick-off meeting. At this kick-off meeting, the primary and secondary (cover) project managers from ECOPETROL and CONTRACTOR shall be clearly communicated and formalized in the meeting minutes of the kick-off meeting. The main ECOPETROL project lead shall be the primary focal point for ALL technical and project-management related communication, both verbally (phone) and in writing (email), between CONTRACTOR and ECOPETROL. However, the secondary ECOPETROL project lead (cover) needs to be included in ALL project-related communication, both verbally (phone) and in writing (email), and needs to be present at all meetings. There are two options regarding the schedule of weekly meetings:

- Weekly project status meetings meetings, if, for alternate weeks, collaborative live data sessions can be shared remotely between ECOPETROL and CONTRACTOR locations. Teleconferences with merely status updates, i.e. without presentations or live sessions to share, can be held on alternate weeks.
- Bi-weekly meeting (every other week), for status meetings that are driven by ppt presentations

At midday (*e.g.* Bogota Time: 13:00pm), the day *before* the (bi-)weekly status meeting – if this meeting driven by ppt-pdf presentations – all presentation material to be shown during the subsequent project status meeting shall be shared with the ECOPETROL project team (all participating stakeholders), through email, ftp, or sharepoint/ teamspace site (or shared cloud location). The day *after* the status meeting, the meeting minutes are to be distributed by CONTRACTOR to the full ECOPETROL and CONTRACTOR project teams.

Beyond the weekly status report, the following project management documents are to be produced and updated, *i.e.* kept up to date, once (at start of project) on a weekly basis or for several key milestone meetings in the project:

- Technical Specifications for Service Order, including full deliverables list
- KOM presentations from requesting asset team, detailing ECOPETROL`s business needs, imaging requirements, and all *geological* targets and objectives.
- Project Risk Assessment (bi-monthly update), identifying the key data/noise challenges and operational risks (of delays). For each identified risk, a mitigation plan should be derived and implemented.
- Communication Plan, Milestone meeting schedule at CONTRACTOR location
- Weekly Status Reports
- Bi-weekly Executive Summary report.
- Delay Log with CONTRACTOR and COMPANY delays, and reasons for these delays.
- GANTT Charts, with baseline, coupled with Delay log
- Spreadsheet with a summary of all key parameterization used in production
- Delivery List and Invoicing Schedule
- More…

Strong project management by CONTRACTOR and ECOPETROL is considered paramount for the non-technical and commercial success of this project / service order.

6.2. PROJECT DELAY (LOGS)

Based on 1) the final ECOPETROL and CONTRACTOR GANTT charts, *i.e.* actual progress vs. (updated) baseline, 2) the up-to-date delay logs from CONTRACTOR, and approved by ECOPETROL, and 3) summaries of decisions made in weekly status reports, the ECOPETROL technical interventor or project lead (of requesting department) and the Contract Administrator shall assess, at project close-out, the total accumulated delay of the project/ Service Order. These accumulated projects delays are to be estimated relative to original delivery deadlines/ project end date (baseline), in work months and as a percentage of the total planned turn-around, from formal project start date to

delivery of key seismic products or formal end date of Service Order. Obviously, this total accumulated delay of the project, relative to the original project/ SO end date, is to be corrected for three (3) key delay categories associated with delays caused by ECOPETROL, rather than by CONTRACTOR:

1. **ECP-related Project "*Creep*"**, *i.e.* accumulation of incremental small delays through the course of the full project. These are ECOPETROL-induced delays in:

   - Client-decisions, of more than three (3) work days (i.e. ≤ 3 work days is not considered a client decision delay).
   - Interpretation by ECOPETROL of key (marker) horizons, beyond the time (in weeks) that was planned at project start-up for this type of in-house activities by ECOPETROL.
   - Providing CONTRACTOR with key (legacy) G&G datasets, *e.g.* wells, time and depth horizons, *etc,* thus causing delays in activities by CONTRACTOR in which they G&G datasets are essential or a prerequisite.
   - Client requests for additional and excessive testing, production QC displays, QC SEG-Y datasets *etc*
   - Production re-runs, in cases where ECOPETROL has explicitly, and in writing, approved the tested/ optimized parameters of a production master setup, and where subsequent production QC revealed the need for a change in parameters and re-run of said production stage.

   Note: Change of GANTT baseline and deadlines are not allowed in these cases, but a delay log by CONTRACTOR is highly recommended for this delay category.

2. **Additional Scope of Work**, relative to the original base plan at project start-up, in terms of an increase in input 2D/3D datasets (lines, surveys, acreage), additional processing steps, more iterations of (anisotropic) reflection tomography, and additional – previously unplanned – advanced technologies as required by the data. This covers the "ad-hoc" or "on-demand" inclusion of advanced technologies and solutions, and *basic* processing activities, *e.g.* a full "Survey or Geometry Audit" and additional iterations of (anisotropic) reflection tomography.

   Note: Change of GANTT baseline and deadlines are recommended in this delay category.
   Note: Impact on project timeline may be accompanied by an impact on project costs/ value of the Service Order, Subject to approval by ECOPETROL, as CONTRACTOR is allowed to invoice *some* of the additional basic activities and/ or additional advanced technologies (and additional datasets/ km^2).

3. **Previously Unplanned Fast-tracks** and/ or **Priority Volumes**, requested during an ongoing project/ Sevice Order by one of the requesting asset teams/ stakeholders.

   Note: Change of GANTT baseline and deadlines are required here.

Delay categories 2) and 3) are to be justified by an expected uplift in image quality, or by an early delivery of fast-track products ahead of, and due to shifting, business critical deadlines (*e.g.* drilling decision or deadline, well evaluations, inversion products or interpretation update, AHN commitments), still having value and being fit-for-purpose for the end-user in spite of the inherited compromise in quality. Before taking effect, both these delay categories 2) and 3) should ideally be accompanied by a milestone meeting with CONTRACTOR and ECOPETROL project owners and stakeholders/ end-users, and, more importantly, with "**re-baselining**", *i.e.* a re-definition of the original baseline in the GANTT chart and a shift in the projects/ delivery deadlines.
At project close-out, the ECOPETROL technical interventor/ project lead, with the Contract Administrator shall correct the total accumulated delay of the project, relative to the original Service Order end date, for any re-baselining due to ECOPETROL-associated delay categories 2) and 3). This essentially gives the total "new-baseline" accumulated delay of the project, relative to the corrected Service Order end date after re-baselining.

Subsequently, the ECOPETROL project lead and the Contract Administrator are to subtract all the ECP-related project "*creep*" (category 1) from the total "new-baseline" accumulated project delay, using the key delay log information from CONTRACTOR. The resultant total "new-baseline" accumulated project delay, corrected for ECOPETROL-associated project delays, is caused by CONTRACTOR, *i.e.* all remaining accumulated delays are not explicitly logged by CONTRACTOR nor explicitly "approved" by the ECOPETROL QC lead and not justified by technical enhancement of the datasets.

Delay Log Clause:

- If CONTRACTOR is not keeping an up-date-date delay log document or table, either as a separate document or part of weekly status report or other key project-management documents, for the full duration of the Service Order/ projects (at least for the affected activity groups), then CONTRACTOR cannot subtract all the ECP-related project "*creep*" (category 1) from the total "new-baseline" accumulated project delay.

If the percentage of this remaining "CONTRACTOR-associated" total project delay, relative to the total project turn-around (including any re-baselining), exceeds a certain value (*e.g.* 10, 20, 30%), then CONTRACTOR shall receive 3 cumulative penalty points (for each delayed project), which shall weigh CONTRACTOR down in subsequent vendor assignment process for future service orders under the Colombian Offshore 2D/3D SP&I Framework Contract. The Contract Administrator shall keep track of these accumulating penalty points for the period of three years in which the Framework Contract is effective.

Delay Penalty Clause:

- For this Service Order, the maximum "*penalty cut-off*" percentage of the "CONTRACTOR-associated" total project delay, after baseline corrections and ECOPETROL-associated project delays, relative to the total project turn-around (including any re-baselining) is: **30%**
-

6.3. GENERAL QUALITY CONTROL (QC)

ECOPETROL is to produce a database of QC display templates, QA/QC standards and minimum QC requirements for the full seismic data (re)processing and tomographic depth imaging sequences (*i.e.* Branch 1 and 2), and share this with CONTRACTOR. Beyond this QC database, Appendix B provides a summary of this database with representative QC displays of key elements of the basic marine seismic processing sequence as described in this technical specifications document. The QC displays demonstrated in this document/ QC database are intended to provide guidance to CONTRACTOR as to the style, content, and quality that ECOPETROL requires for seismic processing and/or imaging quality control (QC) displays. The examples presented are not intended to be a comprehensive representation of QC's required for any processing flow, or processing flow element; or absolutely representative of the types and rigor of QC to be provided for any processing step. The attached examples in Appendix B are representative QC displays of certain workflow elements of a marine seismic processing flow.

Key attributes of ECOPETROL QC displays:

- Slide Title is clear and descriptive
- Full processing flow with current process indicated
- Appropriate labelling is applied, *e.g.* spatial location, direction/orientation, area of interest, axes labeling, *etc.*
- Key message for the slide is communicated
- Graphical annotation is used to direct audience focus

This is not an exhaustive list of required QC displays as the exact flow for each Service Order may differ from the steps described here, albeit should be considered a minimum QC requirements guideline. There may also be additional steps, and advanced technologies, not listed that will also require the generation of other QC material. These displays represent the minimum required for the step listed if included in the processing flow, and provides guidance for the style of QC material expected for any steps not explicitly described herein.

ST1 Trace accounting
ST2 Geodetics and Navigation Merge
ST3 Water column statics
ST4 Noise attenuation
ST5 Spatial sampling (re-sampling)
Source Deconvolution
ST6 -De-bubble
ST7 -Zero phasing

ST8 -De-ghosting
ST9 -array directivity
Receiver Deconvolution
ST10 -De-ghosting
ST11 -array directivity
ST12 De-multiple
ST13 Inverse Q, spectrum shaping
ST14 Footprint Removal
ST15 COS Binning
ST16 Shot Migration Prep
ST17 Inverse Q Phase Only

Any comments, errors or general feedback on this database should be either directed to the ECOPETROL project representative, or via the end of project close-out and feedback processes (at close-out meeting).

In addition to the discrete QC templates outlined above, repeat QCs are also required. Repeat QCs are QC displays that are generated at generally pre-defined intervals during the processing project to monitor progress (improvement) and to ensure no step has introduced any undesirable or detrimental impact on the data and AVO response.

- Global AVO
- 3D Amplitude
- Spectral QC

In addition, CONTRACTOR shall list out the tomography and other processing QC schedule and procedures at key stages of imaging. Adequate facilities and procedures to carry out QC of well calibrations, tomography analysis and other parameters shall be made available to ECOPETROL.

Finally, CONTRACTOR is to adhere to various ECOPETROL QC display requirements:

- No AGC in any (QC) products, to review and QC true amplitude (variation) across the data volume spatially and vertically, throughout the project. Static QC is a potential exception to this requirement, upon ECOPETROL approval. Amplitudes on stack QC sections should be not too “hot” or “washed out” to aid ECOPETROL decision-making process, and in production are to be balanced in the pre- and post-migration sequence, in time and spatially by:
    - Simple T^{power} time gain, geometrical spreading or spherical divergence correction
    - SC Amplitude Gain/ Corrections, if required, including with production application of the long-wavelength CMP/bin scalars if associated with the near-seabed zone.
    - Absorption solutions through SC deconvolution, inverse-Q, Q-Tomography (Q-PSDM)
    - Potential application of Least-Squares PSDM to address illumination problems.

- Rather than 1inN gather QC, CONTRACTOR shall adopt a “Global” (survey-wide) Attribute Map QC, linked with “anomalous” gathers for visual inspection.

- ECOPETROL wishes to shift away from “MS Powerpoint QC” and towards Live Sessions.

7. DEFINITION OF BASIC SEQUENCE

7.1. GENERAL

As mentioned above, this section describes in more detail the technical specifications, (start-end) scope boundaries, and definitions of each of the activity groups of described in **Section 4** in these Technical Specifications of the Framework Contract. In addition to defining the scope of these individual activity groups, the following Offshore processing and tomographic depth imaging sequences specify what ECOPETROL considers to be a *basic* 2D/3D Offshore seismic Kirchhoff PreSTM/ PreSDM (re)processing and imaging sequence, *i.e.* consisting of "commodity" seismic processing and imaging technologies (at the time of writing).

Note: This basic sequence described in this section is prone to changes, and therefore does not necessarily represent the offshore 2D/3D processing and tomographic depth imaging workflows and services to be executed by CONTRACTOR under this project-specific Service Order (PSSO). In addition, the order of the individual processes is prone to change, as to CONTRACTOR`s recommendations and best practices and specific workflows and algorithms. CONTRACTOR is highly encouraged to recommend alterations to the sequence described in the following base sequence and individual workflows herein, which still need to be formally accepted and approved by ECOPETROL.

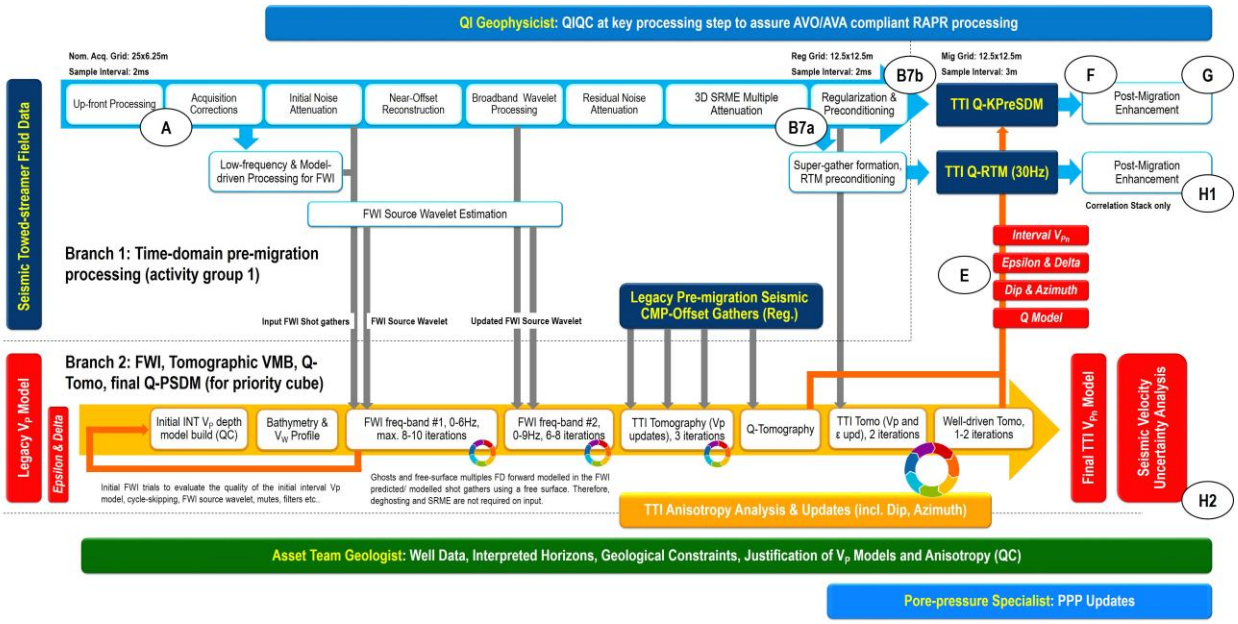


Figure 7.1 Branch 1, Time-domain Pre-migration Processing

7.2. BRANCH 1: TIME-DOMAIN PROCESSING FROM RAW FIELD DATA

This basic, "commoditized" offshore pre-migration processing sequence is to be augmented with advanced and bespoke solutions, to assure enhanced seismic image quality and value added relative to the legacy benchmark image.

- Emphasis in shallow-water Caribbean settings shall be on a) adaptive source and receiver deghosting, b) general broadband processing and bandwidth extension (both pre- and post-migration), and c) hybrid and high-end multiple attenuation techniques targeting all relevant/ observable classes of short and long-period multiples.
- Subsequently, advanced surface-to-basement velocity model building and tomographic depth imaging, for 2D shallow-water datasets, is expected to play a pivotal role in unlocking exploration potential on the Colombian Caribbean shelf.
- In deeper-water environments, Ecopetrol`s focus is on resolving remaining velocity model inaccuracies, including enhancing VTI and TTI anisotropy fields (delta, epsilon), unresolved near-seabed complexities, introducing low-Q (absorbing) anomalies and geobodies associated with free-gas, gas chimneys and gas hydrates. Here, Full-waveform Inversion (FWI), Q-Tomography and Q-PSDM shall be paramount technologies in achieving Ecopetrol`s image quality and risk reduction requirements as well as meeting its exploration and business needs.
- **Ecopetrol is committed to execute trials of Least-Squares PSDM (LS-PSDM) on various datasets to evaluate its value and impact on the bottom line.**
- **Machine learning workflows are expected to become integral component of the data processing and depth imaging sequences.**
- Focus shall be on preserving/ enhancing the signal-to-noise ratio at the low-frequency end of the amplitude spectrum, to allow for Full-waveform Inversion application in shallow and deep-water settings, to aid subsequent seismic pre-stack inversion workflows, and to obtain broad-band seismic volumes that with extended spectra on both low- and high-frequency ends (minimize side-lobes, improve "interpretability".
- Multi-domain noise attenuation – Focus on signal protection and AVO preservation (at near offsets). All domains to be investigated throughout each project: Source, Receiver, CMP, Offset
- More aggressive noise attenuation prior 4D interpolation-regularization.
- Best-of-class 4D interpolation/ regularization, with flexible and wider near-offset bins for amplitude stability at near-offsets/ angles after 4D interpolation/ regularization.
- Linear and Random Noise Attenuation (LNA/ RNA) *after* 4D interpolation/ regularization
- Relative-amplitude preserving (RAP) processing, with more attention to phase stability
- **AVO/QI Quality Control (QIQC)** at key stages

7.2.1. PHASE A: FRONT-END PROCESSING, ACQUISITION CORRECTIONS

Service Order awarded to and signed with COMPANY *– ECOPETROL to upload all required input datasets to the MS Azure Cloud Storage or by transfer of a physical storage medium (external USB hard disk).*

1. ***(A1) Load: Download navigation data –*** *UKOOA P1/90 navigation data*

   Including auxiliary Observer´s Logs/ Acquisition Reports, TSDIP profiles, Echosounder Bathymetry, and all accompanying acquisition supporting and meta-data.

2. ***(A2) Navigation QC –*** *UKOOA P1/90 and Echosounder Bathymetry QC, edits & corrections*

3. ***(A3) Load: Download seismic field data –*** *Read-in seismic SEG-D field tapes*

   At full trace length, full offset range and amplitude precision

4. ***(A4) Reformat SEG-D to CONTRACTOR in-house format***

5. ***(A5) Navigation-seismic merge/ Geometry assignment***

6. ***(A6) Geometry verification & LMO QC***

   Observer Log, SPS files and/or trace headers shall lead to the reconstruction of the entire 2D geometry in an exact and non-ambiguous way. Geodetic system shall be the same requested by ECOPETROL on final delivery. If multiple dataset are input, they shall refer to the same CRS.

- ***Official Start-of-Project*** *– Complete seismic field data and associated navigation accounted for: Includes confirmation of successful and full data transfer, load, audit, and navigation-seismic merge/ geometry assignment.*

  CONTRACTOR to produce and share with ECOPETROL a comprehensive set of source- and receiver-station statistics and QC products/ displays, including a Fold-of-Coverage (FoC) display, that confirms unambiguously and relative to expected acquisition data size and number of acquired source/ receiver stations, that the "raw" 2D field datasets are complete with complete, appropriate and correct geometry assigned.

  ECOPETROL Project Lead to communicate to Contract Administrator and Project Owner (*e.g.* Asset Team Management) this formal project start date, and the associated Service Order End Date. See figure 5.2.11 below.

- ***Kick-off Meeting (KOM)***

  It is highly recommended that the KOM should only be organized and held after the full/ complete seismic field dataset (SEG-D or equivalent) is correctly assigned with the full/ complete geometry database (from UKOOA P1/90, or equivalent), referenced to the appropriate, known, and pre-defined Coordinate Referenced System (CRS) for all 2D and 3D seismic vintages included in the project.

  In case of "missing" datasets, a clear plan is to be derived by ECOPETROL and CONTRACTOR as to how to proceed or commence with the project; a) wait for the missing filed data or essential geometry/ auxiliary files to be retrieved and included in the starting dataset, or b) proceed with the incomplete dataset as-is and allow for the missing datasets to "catch up" prior to a predefined key processing stage, for example, regularization/ interpolation.

  Note: The invoicing schedule is to be updated accordingly in order to allow for the missing data to catch up, without affecting invoicing dates or by using percentages of deliverables.

THIRD CLAUSE – PAYMENT METHOD AND PERIOD OF SERVICE ORDER EXECUTION

PAYMENT METHOD:

a)		Upon receipt to satisfaction of the totality of the contracted deliverables.
b)	X	According to invoicing schedule, based on receipt to satisfaction of pre-defined intermediate contracted deliverables.
c)		% Advance ( ) Pre paid ( ) and balance for monthly invoicing According to the approved progress

The last invoice will at least [ ] % of the value of the contract

Other [ ]

EXECUTION TIME:

Total Term	**XX Months**	Calendar Days (**x**) Labor Days ( )

From the Start Date:

DAY/MONTH/YEAR

Start:	1) Upon formal confirmation (in writing) by Contractor *and* Ecopetrol Project Lead that input field data is complete and with correct and full geometry assigned. 2) Kick-off Meeting Date, which should be *after* "Field Data/ Geometry Complete" Confirmation Date 1) 3) Date of whichever event 1-2 occurs last
End:	**XX Months** after Project Start Date

Figure 7.2.1.1 *Definitions of start and end of project, and project duration, as per the Service Order Clause 3*

7. ***(A7) Reverse Receiver Polarity Correction (RRPC)*** *– typically for legacy datasets only, if required.*

8. ***(A8) Initial field edit application****, (bad shot & channel editing, per sail line) based on field edits reported in Observer´s/ Acquisition Logs, and full-trace RMS Amplitude QC (identification, flagging, and/or editing of consistently dead, very weak, prohibitively noisy, or spike-affected receiver and source stations)*

   Automatic processes only, no manual editing at this stage beyond the application of field edits reported in Observer`s Logs. Edited source and receiver stations to be clearly reported with absolute/ unique values of edited stations and percentage with total number of stations for sources and receivers.

9. ***(A9) Initial first-break picking*** *(zeroed FBPs for prohibitively noisy traces to investigate impact of noise on FBP distribution), if requested at project start-up. Potentially useful in shallow-water "Early-Arrival" FWI projects (preceding diving-wave tomography). If required for FWI mute definitions or other puposes.*

10. ***(A10) Instrument/ system recording delay correction & bulk time shift QC***

Data Delivery A: *Geometry-assigned and edited shot gathers, at 2ms sample interval, with all relevant navigation data, xy coordinates, 2D, field edit flags, and initial first-break picks in appropriate trace headers in SEG-Y format.*

The SEG-Y EBCDIC and trace header format for Deliverable A is to be clearly defined by ECOPETROL in Appendix A of the specific Service Order.

7.2.2. PHASE B: BASIC TIME-PROCESSING SEQUENCE – PRE-MIGRATION PHASE

B1. ACQUISITION CORRECTIONS, INITIAL NOISE ATTENUATION

1. ***(B1.1) Cable motion & receiver statics correction***

2. ***(B1.2) De-bias filter**, if required by ECOPETROL*

   In shallow-water environments, this de-bias filter (or DC, ultra-low-cut 0-2Hz filter) is to be applied with a wrap-around time shift, trace-length extension and tapers, or equivalent solutions, to protect the start- and end-of-trace zones from filter edge effects.

3. ***(B1.3) Low-cut filter – max. 3Hz**, if required by ECOPETROL, not advisable when FWI activities are planned.*

   In shallow-water environments, this low-cut filter is to be applied with a wrap-around time shift, trace-length extension and tapers, or equivalent solutions, to protect the start- and end-of-trace zones from filter edge effects.

4. ***(B1.4) Global Initial Attribute QC** – Linking Attribute Maps with Seismic Gathers*

5. ***(B1.5) Residual shot/ channel editing**, identified through full-trace RMS Amplitude QC*

6. ***(B1.6) Enhanced first-break picking –** Automatic first-break picking up to maximum offsets, with manual infill picking, QC, and optimization/ editing if necessary. Meticulous QC required. Potentially useful in shallow-water "Early-Arrival" FWI projects (preceding diving-wave tomography).*

7. ***(B1.7) Initial amplitude corrections***

   A. *Spherical Divergence Correction, Geometrical Spreading Correction, True Amplitude Recovery*
   B. *Weak channel scaling, dead channel edits (DO NOT decrease channel amplitudes!!)*
   C. *Weak gun-array corrections – gun drop outs, array output differences*

B2. DEGHOSTING PRECONDITIONING

Objective: The goal in this sub-sequence is to enhancing the Signal-to-Noise (S/N) ratio as far as possible before near-offset reconstruction and eventually prior to the key source and receiver deghosting stage, in particular on the near offsets. Given that the noise floor is a critical factor in any *broadband processing* approach, all efforts should be made to eliminate environment and acquisition noise before the application of processes designed to shape the frequency spectrum. This is particularly important when subsequent deghosting is applied in shot Tau-P domain, as high-level (residual) noise will be smeared across channels coming out of Tau-P domain. These initial noise attenuation steps should be applied at as fine a trace interval as possible. Special attenuation needs to be paid to low (<12hz) and ultra-low frequencies (<5 Hz) to ensure that selected filters are not damaging low frequency data that maybe very low in amplitude compared to the noise.

1. ***(B2.1) Noise analysis**: Consistently noisy channel and residual bad shot edits (mis-fires etc)*

2. ***(B2.2) Shot-domain despike** and **high-threshold anomalous amplitude suppression**, using automatic methods to attenuate spikes and noise bursts, whilst protecting the mud-roll cone.*

3. ***(B2.3) Initial swell noise attenuation** – Pass #1*
   - 2D Offset/ channel domain only, thus avoiding near-offset edge effects
   - Multiple cascaded passes as required by signal-to-noise ratio, up to 20-25Hz

- Spatial window width related to the maximum width of batches of consecutive noise channels

4. ***(B2.4) Initial linear noise attenuation***
   - Near- and far-offset cable jerks, etc. Intra-cable "chevron" noise.
   - No Tau-P, FK, FX transforms: SVD and curvelet-domain noise attenuation to be tested

5. ***(B2.5) Acquisition-configuration-related (multi-monochromatic) noise suppression***

   Should include power noise suppression (centered on 60Hz and harmonics) and/or targeted notch filter on affected channels, or equivalent techniques targeting similar narrow-band ambient noise components (vibrations of birds, etc). As a minimum, this type of channel-consistent noise should at least be analyzed.

B3. NEAR-OFFSET RECONSTRUCTION/ EXTRAPOLATION TO ZERO OFFSET

Objective: ECOPETROL is aiming to obtain the maximum range of offsets and angles with fit-for-purpose traces, i.e. of sufficient S/N ratio, for generating input data to be used in AVO/AVA, Quantitative Interpretation (QI) and pre-stack seismic inversion work. For towed-streamer marine datasets, the near offsets are typically prone to relatively high levels of acquisition-related random and coherent noise contamination due to proximity to the vessel, gun arrays and front-of-cable acquisition equipment. Stresses on this front-of-cable acquisition configuration due to swell, currents and vessel turns can also impact near-offset noise relative to mid-far offsets. In addition, the typical near-offset acquisition gap between source arrays and nearest-offset channel generally produces near-offset artefacts when applying forward and subsequent reverse FK and Tau-P/ Radon transforms in the processing sequence, despite geometry compensation solutions and pre- and post-conditioning measures. This is true in the presence of the near-offset noise contamination mentioned before.

ECOPETROL therefore requests near-offset reconstruction/ extrapolation to zero offsets, using a Radon-based method in CMP domain, to be applied early in processing sequence and re-applied before Tau-P mute linear noise attenuation and the demultiple sequence. The objective is to produce a "buffer" for any near-offset edge or windowing effects across the full time (re-) processing sequence, and to minimize Tau-P near-offset acquisition geometry (edge) effects and artefacts, at low frequencies. These extrapolated traces are to be retained throughout the sequence up to the final migration preconditioning stage and should be recreated prior to the Tau-P mute LNA and demultiple stage.

1. ***(B3.1) CMP Radon-domain near-offset extrapolation to zero offset***

2. ***(B3.2) Final pre-deghost swell noise attenuation*** *– Pass #2*

   - Shot domain only, i.e. across the original and extrapolated near offsets
   - Multiple cascaded passes as required by signal-to-noise ratio, up to 20-25Hz
   - Spatial window width related to the maximum width of batches of consecutive noise channels

3. ***(B3.3) Seismic Interference Elimination (and Adaptive Noise Attenuation)***

4. ***(B3.4) Multi-domain Residual Noise Attenuation***

   Multi-domain despike, noise attenuation, and high-threshold anomalous amplitude suppression (Receivers stations, CMPs, Offsets, Shots), using automatic methods to attenuate "randomized" spikes and noise bursts. In particular, RCVR, Offset and CMP domains should be (at least) investigated at this point in the sequence.

B4. BROADBAND WAVELET PROCESSING SEQUENCE (LOW-FREQ)

1. ***(B4.1) Intra-gather channel*** *and* ***shot infill***

2. ***(B4.2) Initial Zero-phasing: Deterministic/ Statistic source signature deconvolution***
    - Removing instrument response and source wavelet
    - Initial zero-phasing
    - Excluding deterministic debubble
3. ***(B4.3) Statistical, data-driven debubble***
4. ***(B4.4) Linear/ Coherent noise attenuation***
    - Tau-P mute or curvelet early-arrival attenuation
    - Domain-appropriate coherent noise attenuation, multiple-domain noise attenuation
5. ***(B4.5) Adaptive source*** *and* ***receiver de-ghosting***
    - Adaptive in case of uncertainties in source and receiver depth
    - Optimal source/ receiver depth estimation (QC)
6. ***(B4.6) Tidal & water-column statics correction***

B5. RESIDUAL NOISE ATTENUATION

Objective: Due to the broadband data requirements of the pre-stack seismic inversion planned on the reprocessed deliverables, ECOPETROL desires extra focus on enhancing the low-frequency signal-to-noise (S/N) ratio during the individual noise attenuation processing steps. Gather, stack and attribute display QC products should include sufficiently high-cut filtered versions to assess the preservation of low-frequency signal and the attenuation of targeted low-frequency noise components.

1. ***(B5.1) Residual noise analysis:*** *Final bad trace and shot edits (if required)*
2. ***(B5.2) Residual swell noise attenuation***
    - Multiple domains
    - Multiple passes
3. ***(B5.3) CMP Radon-domain near-offset extrapolation to zero offset***
    - Replacement of initially reconstructed traces, if requested by ECOPETROL
4. ***(B5.4) Linear/ Coherent noise attenuation***
    - Tau-P mute early-arrival attenuation
    - Domain-appropriate coherent noise attenuation, multiple-domain noise attenuation
    - If not already applied prior to deghosting

B6. PREDICTIVE MULTIPLE ATTENUATION SEQUENCE

Objective: ECOPETROL expects the latest deterministic, model-driven water-layer related multiple (WLRM) elimination techniques to be present in the shallow-water demultiple sequence below. Industry-standard SRME techniques should be adapted to the shallow-water zone(s) of the survey area by convolving input data, preconditioned up to the demultiple stage, with Green's Function propagator gathers representing (finite-difference) forward-modelled seafloor reflection data. This best-to-date shallow-water SRME technique, using wavefield extrapolation through the

water column, produces source- and receiver side peg-leg WLRM models that can be adaptively subtracted from the input data.

ECOPETROL is also interested to see capabilities of weighted "simultaneous" least-squares adaptive subtraction (SimLSAS, in offset domain) of the various multiple-model gather datasets, created with the different techniques listed below and/or in different domains. This allows for efficient assessment of the added value and enhanced multiple attenuation strength by incrementally adding more flavors of multiple model gathers to the simultaneous adaptive subtraction input. A single (final) or two passes of simultaneous adaptive subtractions of these various multiple model gathers would also mitigate the risk of primary energy attenuation and negatively affecting relative amplitude with offset relationships.

1. ***(B6.1) Deep-water 2D/3D Surface-Related Multiple Elimination (2D/3D SRME)***

- Potentially limited to deep-water zones within the survey area (>200-300m water depth)
- Global "long-window" LS adaptive matching (offset domain) to be applied on generated SRME model gathers, meticulous QC is expected for this step.
- Final subtraction from input data may be performed in a single adaptive subtraction step.

2. ***(B6.2) LS Adaptive Subtraction*** *of above 2D/3D SRME multiple model gathers*

- Shot domain preferred LSAS, or 2D offset/channel domain.
- Curvelet-domain LSAS to be tested, aggressive LSAS may be required for 2nd bounce/ order Plio-Pleistocene FS multiples and 1st bounce/ order FS Upper Miocene multiples
- LSAS in 2 or 3 separate frequency bands.

3. ***(B6.3) High-resolution parabolic Radon demultiple***

- To start after the predicted double seabed TWT (2xWBTWT), as a proxy of the onset in two-way travel time of the free-surface related multiple reverberations, which typically are the predominant (residual) high-energy, high-frequency multiples residing on the pre-migration dataset at this stage. The
- Potentially limited to areas with deep (>600m) water depth, to be tested.
- Move-out definitions of signal and multiple noise energy should be kept conservative/ mild to preserve (near-offset) primary signal, in particular primary diffractions.
-

B7. MIGRATION PRECONDITIONING/ REGULARIZATION

1. ***(B7.1) Final model-consistent processing, pre-migration footprint attenuation***

- Gun-array Amplitude Balancing (GAAB) to be applied, if not applied earlier in the sequence ECOPETROL to provide presentation and documentation regarding workflow.
- Surface-consistent deconvolution or SC amplitude correction, focus on sail line-by-line scalars
- Decomposition: Smoothed CMP (geology), unique sail line/ sequence or Seq Gun track numer (strb-port), individual shots, offset bins (long-wavelength AVO trend), unique channel number for all cables (residual short-wavelength "jitter")
- Unique Sail Line or SL Gun track scalars, and/or individual unique shot point scalars to be applied
- Overburden amplitude (absorption, illumination) effects to be investigated using CMP component (if required)

2. ***(B7.2) Linear/ Coherent noise attenuation****, if required by ECOPETROL*

- Tau-P mute or equivalent (*e.g.* curvelet) linear noise attenuation

- Domain-appropriate coherent noise attenuation, multiple-domain noise attenuation (low-frequency SNR enhancement and primary preservation)
- Alternatively, to be applied prior to the predictive multiple attenuation sequence, or after regularization/ interpolation.

3. ***(B7.3) Phase-only Q compensation*** *(see legacy Q-values)*

Data Delivery B7a: *Pre-regularization Shot gathers – no NMO, no gain, no mute applied*

The SEG-Y EBCDIC and trace header format for Deliverable B7a is to be clearly defined by ECOPETROL in Appendix A of the specific Service Order.

Split-off Point for Reverse Time Migration (RTM) preprocessing, e.g. super-gather formation and final processes, and final Q-RTM production,

Pre-migration Milestone Meeting (Decision Points):

- *Final Residual Noise QC, pre-migration, in particular at the near offsets and 2-12 degrees (near) partial angle stack vs. 12-24° (mid), 24-36° (far), 36-48° (ultra-far).* ***QIQC B7.***
- *Options for having larger bin sizes for near offsets to improve fold in reconstructed near-offset traces.*
- *Assessment of residual long-period and internal multiple contamination (at near offsets/ angles) and the negative impact on AVO compliance.*
- *Quantification of remaining absorption challenges to be addressed with high-end inverse-Q (spatially variable), Q-tomography workflows and final Q-PSDM (amplitude/ phase). Discuss and record the Q-Tomo and Q-PSDM capabilities of CONTRACTOR.*
- *Definition of the PreSDM post-migration processing sequences, both pre- and post-stack. Not defining this sequence at this stage can severely delay the project in the final delivery phase, or result in delivery errors, mistakes, reruns.*
- *Confirmation and run-through of full deliverables listing, re-obtain consensus regarding these deliverables.*
- *Final Kirchhoff PreSDM tests of key migration parameters (e.g. half- or full-aperture, anti-aliasing, maximum angle, impulse-response taper etc.). Include smoothing tests and thorough QC of the final KPreSDM Vp model.*
- *KPSDM stack benchmarking comparisons between legacy raw out-out PSDM and test PSDM stack sections, final post-regularization input gathers, with the final smooth PSDM Vp model, approved PSDM parameters.*

4. ***(B7.4) Geometry Load and 3D-4D Interpolation/ Regularization (Production)*** *onto a single "master grid" in case of multi-3D merge projects and overlapping 3D surveys*

- ECOPETROL and CONTRACTOR to review the observer`s logs and the acquisition/ field operations reports of the 3D seismic program, in particular to investigate the underlying reason for re-shoot, secondary-line, and infill sequences (R1…n, P2…n, I1…n, etc). Based on this joint investigation, the prioritization and weighting of the overlapping line segments due to reshoots, infill, and line extensions/ completions can be formalized on intput and geometry load into regularization/ interpolation production.
- Larger "flexible" bin options for near offsets or near-offset bins should also be extensively discussed between technical experts of ECOPETROL and CONTRACTOR during the preceding milestone meeting.

- Keeping 2D reconstructed near-offset channels across all streamers, *i.e.* zero-offset extrapolated traces, on input into regularization/ interpolation may help the SNR and amplitude stability for the nearest 1-3 offset bins, potentially with less regularization/ interpolation footprint in these originally poorly populated near-offset bins during acquisition. This can be beneficial to the AVO/AVA response and stability at the near offsets/ angles, respectively.
- Post-regularization footprint attenuation is to be investigated and tested at least on the nearest regularized offset volumes.

5. ***(B7.5) Final Coherent and Random noise attenuation – Tau-PQ Mute, Curvelet denoise, Mild Radon** or **equivalent***

- Leveraging regular gathers in CMP and/or offset domains.
- Targeting linear noise, refracted head-waves, inter-bed multiples, P-S converted waves, near- or post-critical events and other linear interfering with hyperbolic reflections, near the basement (high impedance contrast, hard kick, critical angles at mid offset?) and at far offsets/ angles.
- Protection of near-mid offsets/angles is paramount and a prerequisite.
- Pre-migration, mild, Radon noise attenuation is an option, if not applied directly after 3D SRME.

6. ***(B7.6) Pre-migration high-frequency bandwidth extension** – preferably time-variant, if required by ECOPE~~E~~PTROL*
    - Focus on high-frequency extension/ enhancement of amplitude-frequency spectrum
    - Mild parameterization, *i.e.* dB allowance of bandwidth extension restricted to avoid "ringing" appearance of pre-migration stack sections. Attention of low-frequency content to mitigate boosting side-lobes.
    - Preferably layer-based (approximately) or time-variant.

7. ***(B7.7) Final Migration Preconditioning:** Back-off gain, Time-variant filtering, etc.*

***Data Delivery B7b:** Final ~~reguralized~~regularized pre-migration CMP-offset gathers – no NMO, no gain, no mute applied – with all amplitude gain backed off, at MSL datum*

The SEG-Y EBCDIC and trace header format for Deliverable B7b is to be clearly defined by ECOPETROL in Appendix A of the specific Service Order.

7.3 BRANCH 2: FWI, TOMOGRAPHIC VMB, Q-TOMO & FINAL Q-PRESDM

7.3.1. PHASE E: BASIC TOMOGRAPHIC DEPTH IMAGING

1. ***(E1) Initial anisotropic velocity model building** using sufficiently smooth (anisotropic) legacy tomographic KPreSDM interval V_P depth model, and/or available log data from (offset, regional) wells in the area of interest.*

Input: Legacy 2016 time-processed pre-migration input gathers

2. ***(E3) 1 iterations of anisotropic, grid-based or layer-based, non-linear tomographic update of velocity field***

The following sequence (**blue box**) indicates a full iteration of tomographic velocity-model update:

- ***TTI Kirchhoff Pre-Stack Depth Migration (100x100m tomo output grid or smaller):*** *maximum amplitude algorithm, maximum aperture, maximum angle, dip tapering, AA and other key parameters to be optimized by initial testing during the first iteration of tomography*
- ***Horizon interpretation in depth or DTD conversion/ stretching, or "map-migration"*** *(if necessary)*
- ***Dip and Azimuth field re-estimation or adjustment*** *(if necessary)*
- ***Gather preconditioning for Residual Move-out (RMO) analysis/ picking***
- ***Dense Residual Move-out (RMO) analysis*** *via automatic picking across the preconditioned and muted common-image point (CIP) migrated gathers.*
- ***Generation of differential equations***
- ***Linearized tomographic update of velocity field***

3. ***(E4) TTI Seismic Anisotropy Characterization and Updates*** *at well log location and/or quasi-VTI seismic sectors*
   The process is intended to be interactive and no testing will be produced for it. Epsilon and Delta function at analysis locations will be interpolated along the whole 2D line or 3D survey using provided interpreted layers. Where possible, delta shall be derived from available VSPs or log markers.

4. ***(E5) Seismic anisotropic velocity re-scaling, TTI properties updates from previous analysis***

5. ***(E6) Q-Tomography (1 or 2 iterations of linear Q-Tomography****, constrained or unconstrained by horizons/ intervals with expected absorption (gas pockets etc.)*

***Input*: Final time-processed migration input gathers: Deliverable B7b**

6. ***(E7) 2 iterations of TTI anisotropic, non-linear tomographic update of velocity (and epsilon) field*** *– See blue box*

Data Delivery (EV):

A. *Final anisotropic TTI Q-PreSDM Tomography **Interval velocity** model in depth, as used in the final TTI APreSDM productions (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Tomography Interval Velocity depth model in filename and SEG-Y EBCDIC header (Appendix A).*

B. *Final anisotropic TTI Q-PreSDM Tomography **Delta** model in depth, as used in the final VTI-TTI APreSDM production (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Tomography Delta depth model in filename and SEG-Y EBCDIC header (Appendix A).*

C. *Final anisotropic TTI Q-PreSDM Tomography **Epsilon** model in depth, as used in the final VTI-TTI APreSDM production (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Tomography Epsilon depth model in filename and SEG-Y EBCDIC header (Appendix A).*

D. *Final anisotropic TTI Q-PreSDM Tomography **Dip field** in depth, as used in the final TTI APreSDM production (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Tomography Dip field in filename and SEG-Y EBCDIC header (Appendix A).*

E. *Final anisotropic TTI Q-PreSDM Tomography **Azimuth field** in depth, as used in the final TTI APreSDM production (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Tomography Azimuth field in filename and SEG-Y EBCDIC header (Appendix A).*

F. *Final anisotropic TTI Q-PreSDM Q-Tomography **Q field** in depth, as used in the final TTI APreSDM production (Kirchhoff Q-PSDM and Q-RTM). Clear references to final Q-Tomography Q field in filename and SEG-Y EBCDIC header (Appendix A).*

7.3.2. PHASE F: KIRCHHOFF PRE-STACK DEPTH MIGRATION

- ***(F1) Final Anisotropic TTI Kirchhoff Pre-Stack Depth Migration** outputting offsets or CDP gathers. If required, sort back to CDP gathers.*

  A. Final (A)KPreSDM **Seismic Gather Input (B7b)**: Approved offset-binned volumes
  B. Final (A)KPreSDM **Final VTI-TTI Tomo Vp Fields (EV)**: Approved
     - Final Tome Vp field
     - Final Delta field
     - Final Epsilon field
     - Final Dip/ Azimuth fields

  C. Final (A)KPreSDM **Output Grid, Polygon, Offsets**: Approved Grid, offset-binning scheme
  D. Final (A)KPreSDM **Key Parameters**: Approved from testing:
     - Depth step, typically 3 meters
     - Half- or full-aperture length (m)
     - Type of and strength of anti-aliasing (filter)
     - Time-variant maximum angle (degree)
     - Impulse-response taper (length, type)
     - Kirchhoff PreSDM algorithm, in RAP mode

- ***(F2) Depth-to-Time (D2T) Conversion**, using a sufficiently smooth P-wave velocity model*

  To allow for post-PSDM processing in time-domain and application of filters in a geophysically correct manner.

- ***(F3) Phase rotation** from earlier well calibrations as requested and approved by the ECOPETROL AVO specialists to avoid changed the AVO response*

- ***(F4) Ultra-far Angle Mute**, to remove all normal move-out stretch effects beyond the critical angle, which is typically not used by AVO/AVA inversion (QI) follow-up work.*

  Although typically 60 or 65 degrees is sufficient, this requires testing, in overburden and at target and basement intervals, and approval after agreement with AVO-inversion specialist. Subsequent stack mute should be tighter than this ultra-wide angle mute from surface down to end-of-trace.

***Data Delivery FG (G: Gathers):** Raw VTI-TTI Anisotropic Kirchhoff PreSDM CDP gathers in depth (NMO corrected, no gain, no filters, only ultra-far angle mute), i.e. OUT-OUT as a straight output from VTI-TTI Anisotropic KPreSDM, only sorted back to CDP gathers and ultra-far-angle outer mute. (Appendix A)*

- ***(F5) Stack (angle** or **manual) mute** and **CRP stacking***

  Typically 30, 35, or 40 degrees angle mute, or hybrid outer mute with “manual” near-surface mute is preferred. Fully manual stack outer trace mute is acceptable, but this (spatially variable) mute pattern - time-offset pairs - needs to be recorded in the final report and preferably in the FG deliverable and/ or as an mute asci text file, *i.e.* requires specification in order to replicate in future benchmarking and in-house stacking of raw (re-) migrated PSDM CDP gathers.

- ***(F6) Post-stack footprint attenuation (3D only)**, TKxKy with automatic notch detection, if required and at no additional costs to Ecopetrol. Requires testing, parameters can be re-used for all enhanced (partial) stack volumes.*

- ***(F7) Time-function (exponential** or **T-power) gain** to balance the vertical amplitude distribution (post-stack) between near-surface, overburden, Tertiary, Cretaceous, reservoir target level and basement.*
- ***(F8) Time-to-Depth (T2D) Conversion**: This should be completely reversible relative to the associated D2T Conversion step (F2), i.e. data to be restored to the original depth step, trace length and without artefacts.*

***Data Delivery FS (S: Stack):** Raw VT-TTI Anisotropic Kirchhoff PreSDM stack, in depth (only simple exponential time gain, no filters), i.e. OUT-OUT as "minimally processed" output from TTI Anisotropic KPreSDM (Appendix A).*

7.3.3. PHASE G: PRESDM POST-MIGRATION PROCESSING

Input: Raw PreSDM CIP Gathers, Output from F1

- ***(G1) Residual Move-Out** & **Stacking Velocity Analysis/ Correction** – Hyperbolic PreSDM RMO gather flattening*

  High-density, high-resolution velocities are picked using an automated (semblance-based) routine while preferably following geologic horizons and structures. Ideally, this approach favors spatially continuous horizons while rejecting anomalous picks that conventional automated velocity picking routines may have generated. Radon preconditioning on input to RMO Gather flattening may be required in presence of strong residual multiple

Data Delivery GV:

- *Final "Residual" KPreSDM interval velocity model after RMO flattening, in depth, mildly smoothed and as used in creating the final TTI KPreSDM stack deliverables. Clear references to Residual PSDM Velocity field in filename and SEG-Y EBCDIC header (Appendix A)*

- ***(G2) Depth-to-Time (D2T) Conversion**, using a sufficiently smooth P-wave velocity model*

  To allow for post-PSDM processing in time-domain and application of filters in a geophysically correct manner.

- ***(G3) Phase rotation** from earlier well calibrations as requested and approved by the ECOPETROL AVO specialists to avoid changed the AVO response*
- ***(G4) Sliding- or Multi-window trim statics** or **similar residual, non-hyperbolic CRP flattening***

  To be tested. Nearest offsets may need to be excluded in case of insufficient signal-to-noise ratio (SNR) or low-amplitude levels. Maximum time-shifts no more than 8-12ms, with sufficiently long moving window length.

- ***(G5) Pre-stack Random/ Linear Noise Attenuation** (RNA/ LNA)*

If required based on SNR and subject to pre-migration Radon and RNA/ LNA applications Subsequent post-migration Radon may address any linear and random noise challenges.

- ***(G6) Possibly Cascaded: High-resolution Radon Coherent Noise Attenuation –*** *may include linear noise attenuation and typically random noise attenuation. Cascaded with more Radon or residual flattening.*
- ***(G7) Final time-variant*** *or* ***layer-based band-pass filters****, in particular below basement level.*
- ***(G8) Bandwidth extension/ spectral enhancement***

  In particular low-frequency enhancement/ spectral flattening/ whitening, with limited high-frequency enhancement to mitigate any "ringing" appearance of the enhanced data (*i.e.* side-lobe amplification). To be tested on best-to-date PSTM stack volume, applied in production on production PSTM CRP gathers.

Data Delivery GGt: *Final post-processed VTI-TTI Anisotropic Kirchhoff PreSDM CDP gathers, converted to time (NMO corrected and with residual flattening, no gain, all filters/ noise attenuation applied, with 60-65 degrees ultra-far angle mute applied as for CG), i.e. IN-IN. See Appendix A.*

Data Delivery GGd (G: Gathers): *Final post-processed VTI-TTI Anisotropic Kirchhoff PreSDM CDP gathers in depth (NMO corrected and with residual flattening, no gain, all filters/ noise attenuation applied, with 60-65 degrees ultra-far angle mute applied as for CG), i.e. IN-IN. See Appendix A.*

- ***(G9) Final (angle) mute*** *and* ***Stack***

  Including full stack and (4) partial angle stack products for AVA Inversion/ QI follow-on work. Partial stack angle ranges to be defined by ECOPETROL. Typically 30, 35, or 40 degrees angle mute for full stack, hybrid outer mute with "manual" near-surface mute preferred. Inner angle mute ramping in below reservoir level is optional.
- ***(G10) Post-stack footprint attenuation (3D only)****, TKxKy with automatic notch detection, if required and at no additional costs to Ecopetrol, on all (partial) stack products.*
- ***(G11) Post-stack Random Noise Attenuation, Structural Tensor/ Dip Filtering, Principle Component Filtering****,* ***Curvelet Domain, FXY Decon****, or equivalent*

  On all enhanced PSTM (partial angle) stack products. Mild parameterization, minimum amplitude smearing across minor fault planes and small-scale structure of interest. Requires careful testing.
- ***Final Exponential*** *or* ***Time-function Gain, Spatial Amplitude Balancing*** *(**no AGC**)*

  On full stack only, to balance the vertical amplitude distribution between near-surface, (shallow) overburden, Tertiary, Cretaceous, reservoir target level and basement structures. This step is to be clearly specified in EBCDIC and final report.

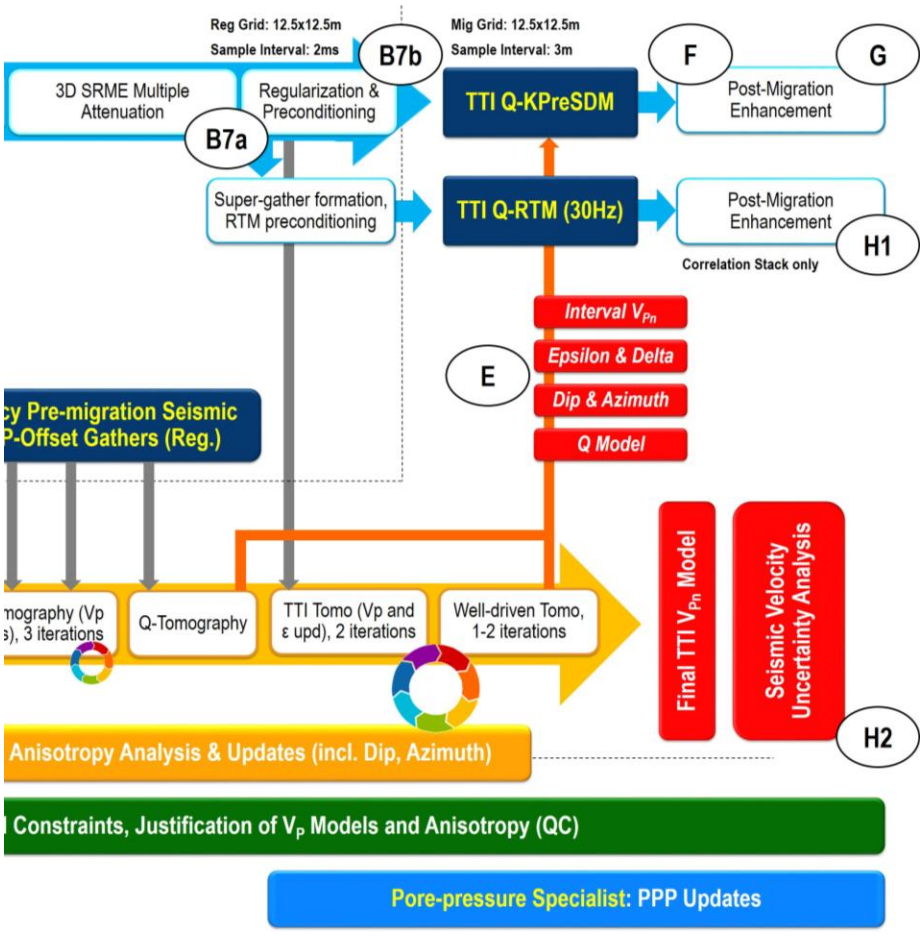
Data Delivery GSt: *Final post-processed TTI Anisotropic Kirchhoff PreSDM stack volume, converted to time (with residual flattening, time-function gain, all filters/ noise attenuation applied) i.e. IN-IN. See Appendix A.*

Time-to-Depth (T2D) Conversion

This should be completely reversible relative to the associated D2T Conversion step, *i.e.* reversed to the original depth step, trace length, *etc*. and <u>without artefacts</u>. For GSd delivery only, not to be applied on the production dataset (yet).

Data Delivery GSd (G: Gathers):

A. *Final post-processed TTI anisotropic Kirchhoff PreSDM **full stack**, in depth (with stack power optimization, final gain, all filters/ noise attenuation applied), i.e. IN-IN. See Appendix A.*
B. *Final post-processed TTI anisotropic Kirchhoff PreSDM **partial angle stack** products (4), in depth (with stack power optimization, <u>no</u> gain, all filters/ noise attenuation applied), i.e. IN-IN. See Appendix A.*



8. DELIVERABLES

8.1. BASIC SEQUENCE

For the time-domain pre-migration processing sequence, tomographic depth imaging VMB, PreSDM and post-migration processing sequences as defined in Section 8, CONTRACTOR shall deliver the following products where applicable to this SP&I Service Order.

As a standard data delivery requirement for all Service Orders covered by said Offshore Colombian 2D/3D Seismic Processing and Imaging (SP&I) Framework Contract, in particular where the SP&I activities defined in the scope of work of the respective Service Order involve a work commitment of ECOPETROL to ANH, CONTRACTOR is to produce and deliver to ECOPETROL, an additional copy of all contractual deliverables for EPIS (acting databank of ANH).

- The (SEGY rev 1) formatting, EBCDIC, binary, and trace headers (incl. bite locations) of these contractual seismic products and deliverables to EPIS/ ANH, as defined by the deliverable listing stipulated in the shall be the same as the copies for ECOPETROL, albeit on a separate set of USB drives or tapes, unless specified otherwise prior to delivery of the individual seismic products. ECOPETROL to clearly define these seismic deliverable formats for each service order.

- The copies for ANH/EPIS should be sent to ECOPETROL. Upon review, quality-control and subsequent acceptance of ANH/ EPIS deliverables by ECOPETROL, ECOPETROL is to forward/ transfer the ANH/ EPIS deliverables in an appropriate fashion to the relevant ANH/ EPIS ~~datacentre~~datacenter.

- Subject to the number of partners (of the consortium) participating in the individual offshore 2D/3D Colombian SP&I Service Order, under the Framework Contract, and the commitment to ANH, the number of copies (for each contractual delivery of the Service Order, are to be clearly defined in the Technical Specifications (deliverable listing, invoicing schedule etc) of said Service Order.

- The number of copies (i.e. to Ecopetrol, ANH/ EPIS, and N partners) does NOT affect the cost of the Service Order. In other words increasing, within reason, or decreasing the number of copies for each deliverable has no impact to the total cost/ value of the individual Service Order. Adding copies per deliverable does NOT carry additional cost for ECOPETROL or its partner(s). Note that altering the deliverables listing, after signing date of the Service Order, may have an impact on costs and timeline of a Service Order, regardless of the number of copies of (additional) seismic deliverables.

	Format	Sample Interval, Delivery Grid	Invoicing Point (% of total value)
FIELD DATA and supporting documents			
A. Front-end Processing			
A. Geometry-assigned raw shot gathers, with all relevant xy and elevation (z) coordinates, 2D grid, field edit flags, and initial FB picks in the trace headers	SEG-Y	2ms (recorded) 6.25x25m acq. grid	0%
B. Time-Processing Sequence – Pre-Migration Phase			
B7a. Pre-regularization shot gathers (no NMO, no gain, no mute applied) at MSL datum.	SEG-Y	2ms, 6.25x25m	0%
B7b. Final pre-migration CMP-Offset gathers (no NMO, no gain, no mute applied) at MSL datum	SEG-Y	2ms, 12.5x12.5m	**10% (2025~~0~~)**
E. VMB: FWI, Tomographic Depth Imaging, Q-Tomo			
EVa. Final anisotropic (TTI) Q-PreSDM Tomography ***Interval velocity*** model in depth at MSL datum, as used in the final TTI Q-PreSDM production (Kirchhoff PSDM and RTM).	SEG-Y	Same as seismic: 3m, 12.5x12.5m	**10% (2025~~0~~)**
EVb. Final TTI Q-PreSDM Tomography ***Delta*** model in depth at MSL datum, as used in the final TTI Q-PreSDM production (Kirchhoff PSDM and RTM).	SEG-Y	Same as seismic: 3m, 12.5x12.5m	
EVc. Final TTI Q-PreSDM Tomography ***Epsilon*** model in depth at MSL datum, as used in the final TTI Q-PreSDM production (Kirchhoff PSDM and RTM).	SEG-Y	Same as seismic: 3m, 12.5x12.5m	
EVd. Final TTI Q-PreSDM inline-crossline or Euclidean ***Dip*** field(s) at MSL datum, as used in the final TTI Q-PreSDM production (Kirchhoff PSDM and RTM). Clear explanation of dip conventions given in final report.	SEG-Y	Same as seismic: 3m, 12.5x12.5m	
EVe. Final Q-PreSDM ***Azimuth*** field at MSL datum, as used in the final TTI Q-PreSDM production (Kirchhoff PSDM and RTM). Clear explanation of azimuth conventions given in final report.	SEG-Y	Same as seismic: 3m, 12.5x12.5m	
F. Final TTI Q-KPreSDM			
FG. Raw (anisotropic TTI) Kirchhoff Q-PreSDM CIP gathers at MSL datum (NMO corrected, no gain, no filters, no mute), *i.e.* OUT-OUT as a straight output from TTI Q-KPreSDM production, only sorted back to CIP gathers.	SEG-Y	3m, 12.5x12.5m	**10% (2025~~0~~)**
FS. Raw (anisotropic TTI) Kirchhoff Q.PreSDM stack at MSL datum (only simple exponential amplitude gain, seabed mute, no filters), *i.e.* OUT-OUT as a straight output from (anisotropic) KPreSDM.	SEG-Y	3m, 12.5x12.5m	
G. TTI Q-KPreSDM Post-processing			
GGt. Final enhanced TTI Kirchhoff Q-PreSDM CIP gathers at MSL datum, converted to **time**, (NMO corrected and with residual flattening, final gain, all filters/ noise attenuation applied, but no inner nor outer mutes)	SEG-Y	2ms, 12.5x12.5m	**10% (Q3~~1~~ 2025~~1~~)**

GV. Final Q-PreSDM **Residual** "stacking" velocity model (INT and RMS Vp) after residual CIP RMO flattening in depth at MSL datum, mildly smoothed and as used in creating the final enhanced Q-KPreSDM stack deliverables.	SEG-Y	Same as seismic: 3m, 12.5x12.5m	
GSt. Final enhanced TTI Kirchhoff Q-PreSDM full stack, converted to **time**, at MSL datum (with stack power optimization, final gain, all filters/ noise attenuation applied)	SEG-Y	2ms, 12.5x12.5m	
GPt. Final enhanced TTI Kirchhoff Q-PreSDM partial stack products (4), converted to **time**, at final datum (with stack power optimization, final gain, all filters/ noise attenuation applied)	SEG-Y	2ms, 12.5x12.5m	
GSd. Final enhanced TTI Kirchhoff Q-PreSDM full stack, in **depth**, at final datum (with stack power optimization, final gain, all filters/ noise attenuation applied)	SEG-Y	3m, 12.5x12.5m	
GPd. Final enhanced TTI Kirchhoff Q-PreSDM partial angle stack products (4), in **depth**, at final datum (with stack power optimization, final gain, all filters/ noise attenuation applied)	SEG-Y	3m, 12.5x12.5m	
GGd. Final enhanced TTI Kirchhoff Q-PreSDM CIP gathers at final datum, in **depth**, (NMO corrected and with residual flattening, no gain, all filters/ noise attenuation applied, wide angle mute)	SEG-Y	3m, 12.5x12.5m	
Final Processing Report	Word	DVD	
(Deliver reports within one month of project completion)		Hardcopy	**10% (Q~~4~~1 2025~~4~~1)**

All shipments must be prepaid and shall be accompanied by transmittal documents providing a detailed listing of all items shipped and shall clearly identify ECOPETROL as the owner of said data. Tapes also must be labelled with complete identifying information, including the SEG-Y header map, survey name, area, country, line and shot point/CMP range(s) and the processing stage.

The Final Processing Report will include the following sections:

- ***Introduction***: Description of the multiple datasets contributing to the final product. Processing objectives. Survey location. Geodetic parameters. Survey size with map. Location of processing shop. Geological setting (from contract). Key personnel and positions.
- ***Acquisition summary***: Acquisition company and dates. Orientation. Key intervals (group interval, shot point interval, etc.). Vital statistics for source, recording instruments, navigation system.
- ***Processing summary***: Two or three page summary, enumerating the processing steps. Flow diagram, where outputs and QC steps are identified.
- ***Personnel and equipment***: Personnel involved in the project, with reference to the reporting structure. Computer hardware in place when the processing was performed.
- ***Project management***: Reporting procedures. Meeting minutes. Timelines.
- ***Testing***: Include only those tests which resulted in parameter decisions. Description of the analysis in each test, along with PowerPoint slides or images. Focus on parametric testing.
- ***Production QC***: Discussion of and images supporting each QC stage.
- Comprehensive process and parameter description: A full expanded version of the processing summary (3), where purpose and parameterization is described for each processing step.
- ***Deliverables***: Each set of deliverables described. Include spreadsheet. Tape header mapping information for each set of deliverables (Header name, byte locations, and format). Transmittals. Global data description:

client, country, survey, process, sample rate, record length, format, media type, volume number range, destination, attention to, date sent, date received, navigation datum.

- ***Field data description***: Include spreadsheet. Transmittals. Navigation editing spreadsheet. Field seismic editing spreadsheet (observer's logs).
- ***Description of technology***: Only for highlighted advanced technology. As specified by ECOPETROL

    - Appendix 1: List of lines and shot point ranges processed.
    - Appendix 2: Final Product Disposal - giving all reel numbers and including copies of transmittals.
    - Appendix 3: Personnel - giving the names and titles of all the CONTRACTOR and ECOPETROL personnel directly involved in the project.

8.2. ADVANCED TECHNOLOGIES – ADDITIONAL DELIVERABLES

H1. TTI Q-RTM – Raw and Enhanced Correlation Stack Volumes			
H1Rt. Final raw TTI Q-RTM correlation stack, converted to **time**, at MSL datum (without post-stack final gain, no filters/ noise attenuation applied)	SEG-Y	2ms, 12.5x12.5m	**25% (Q1 2021)**
H1Rd. Final raw TTI Q-RTM correlation stack, in **depth**, at MSL datum (without post-stack final gain, no filters/ noise attenuation applied)	SEG-Y	3m, 12.5x12.5m	
H1Et. Final enhanced TTI Q-RTM correlation stack, converted to **time**, at MSL datum (with all post-stack final gain, filters/ noise attenuation applied)	SEG-Y	2ms, 12.5x12.5m	
H1Ed. Final enhanced TTI Q-RTM correlation stack, in **depth**, at MSL datum (with all post-stack final gain, filters/ noise attenuation applied)	SEG-Y	3m, 12.5x12.5m	
H2. Seismic Velocity Uncertainty Analysis			
H2V. Vertical Case: "Velocity Model" (PP) Uncertainty Analysis deliverables, to be specified by CONTRACTOR, at the planned Orca appraisal well location. A range of N (500) vertical interval velocity depth profiles, i.e. equiprobable solutions at the well location, ALL capable of flattening the PSDM CIP gathers in a mini-cube around the (vertical) Orca Appraisal well trajectory. This Seismic Velocity Model uncertainty is to be translated by CONTRACTOR (with support from ECOPETROL WD &GP) to Pore-pressure Uncertainty (mud window).	Unknown, to be specified	1 well location, Planned Orca Appraisal well	**25% (Q1 2021)**
H2H. Horizontal Case: "Structural" Uncertainty Analysis deliverables, to be further and accurately specified by CONTRACTOR, of the Top Oligocene Reservoir horizon:	Various, to be specified	Top Oligocene Reservoir horizon	
P10/P50/P90 target horizons (x500)	ASCII		
Gross Rock Volume (GRV) statistical distributions			
Spill point contours (x500)	Shapefiles		
Reliability maps	ASCII		

8.3. Timeframe

GANTT Chart to be provided by CONTRACTOR, as part of the technical/ commercial bid to the vendor assignment (bid-tender) process or this Service Order, subsequently approved by ECOPETROL, and discussed/ finalized at project start-up, considering the expected timeframe requested by the asset team and the invoicing schedule detailed below in Section 12.

- Turn-around: 9 months
- Project start: February 15th 2025
- Project delivery: November 15th 2025