AUTOMATION-ASSISTED AND SIGNAL-DRIVEN RELATIVE GEOLOGICAL TIME MODEL TOWARD SEQUENCE STRATIGRAPHY AND IDENTIFICATION OF SAND FAIRWAYS IN A TURBIDITE SYSTEM: CASE STUDY, NEUQUÉN BASIN, ONSHORE ARGENTINA

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ABSTRACT

La Cuenca Neuquina posee varios sistemas petroleros probados. La depositación fue influenciada por cambios de nivel del mar. Una interpretación sísmica integral fue realizada en la Cuenca Neuquina focalizándose en el Grupo Cuyo. El trabajo ilustra cómo un modelo de tiempo geológico relativo (Relative Geological Time - RGT) guiado por la señal sísmica puede ser utilizado para mejorar la comprensión de características estratigráficas, relevando sistemas turbidíticos.
La modelización RGT se enfoca en dos pasos. En primer lugar, se calcula una cuadrícula conversión de los reflectores sísmicos en horizontes. Éstos se clasifican estratigráficamente de manera automática. El geocientista puede editarlos si es necesario. La interpolación 3D de la cuadricula convierte cada muestra de la traza sísmica en una edad geológica relativa proporcionando un modelo RGT.
Gracias al modelo pueden calcular atributos estratigráficos, extraer superficies cronoestratigráficas aún por debajo de la resolución sísmica, y realizar una transformación en el dominio de Wheeler ayudando a la delineación de superficies estratigráficas claves.
La aplicación del modelo de Embry permitió asociar el modelo teórico de referencia con dos ciclos de cambio del nivel de base, cada uno compuesto de dos cortejos sedimentarios. Las parasecuencias pueden ser submuestreadas para revelar expresiones sísmicas. La combinación Red Green Blue (RGB) de tres frecuencias discretas derivadas de una descomposición espectral resalta un sistema turbidítico compuesto de cuatro fases de crecimiento.
La visualización de un sistema turbidítico se detalló con gran resolución. Esta metodología ofrece nuevas perspectivas en la evaluación del potencial de recursos de hidrocarburos en la Cuenca Neuquina.

OBJECTIVES

There are several petroleum systems in Neuquén Basin in Argentina. Its depositional history was primarily influenced by changes in relative sea-level from the Triassic to the late Jurassic, leading to the occurrence of submarine and subaerial deposits (Brinkworth *et al.* 2018). In the study area, located in the Neuquén Embayment region, the authors performed a comprehensive seismic interpretation, focusing primarily on the Cuyo Group. The work illustrated the benefits of using a signal driven Relative Geological Time (RGT) model (Pauget *et al.* 2009) to enhance the understanding of regional scale stratigraphic features, ultimately revealing a complex turbidite system.

GEOLOGICAL CONTEXT

The Neuquén Basin has offered many high-quality case studies which integrate different aspects of basin evolution with sequence stratigraphic models. With more than four thousand meters of sedimentary infill and proven petroleum systems, the natural resources of this basin have been exploited for more than one hundred years.

The Neuquén Basin is located east of the Andes Mountains, between 32o and 40o south latitude, and its geographic distribution is triangular in shape (Fig. 1). This back-arc basin is limited by cratons, the Patagonian massif to the South and the San Rafael massif to the North, and was filled between tectonostratigraphic and accreted terranes. The structural history underwent an extension during a late Triassic rifting, a thermal subsidence over the Jurassic and early Cretaceous, a foreland basin subsidence during the middle Cretaceous, and ultimately the Cenozoic Andean compression (Howell *et al.* 2005).

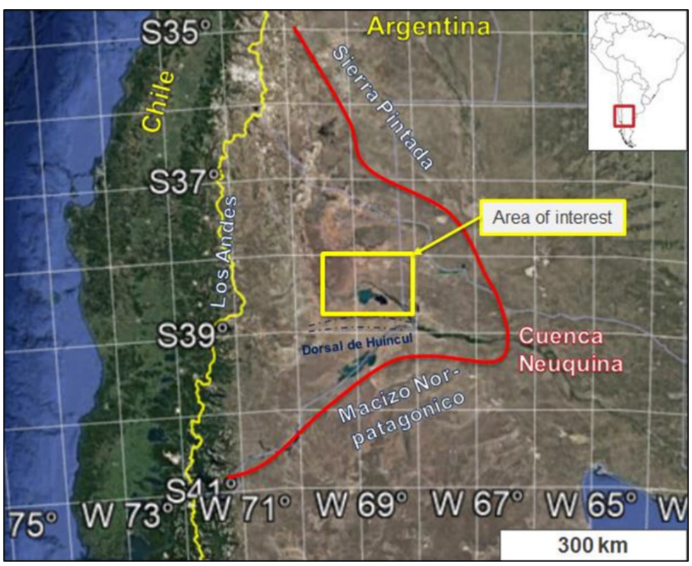

Figure 1. Location of the study area: Neuquén Embayment, onshore Argentina.

The basin can be divided into two main regions: highly deformed Neuquén Andes in the West (N-S strike foreland folds and thrust belt), and poorly deformed Neuquén Embayment in the East, where the most of hydrocarbon accumulation occurred. The majority of the subsurface sediments are from the Mesozoic Era, and numerous related outcrops illustrate the potential and quality of the main hydrocarbon bearing reservoirs.

The stratigraphic column, from Triassic to early Cretaceous, shows the strong influence of changes in relative sea level. Several cycles led to the deposition of sediments in a broad range of environmental settings, including deep-water, pelagic, carbonated, evaporitic, fluvial and aeolian (Fig. 2).

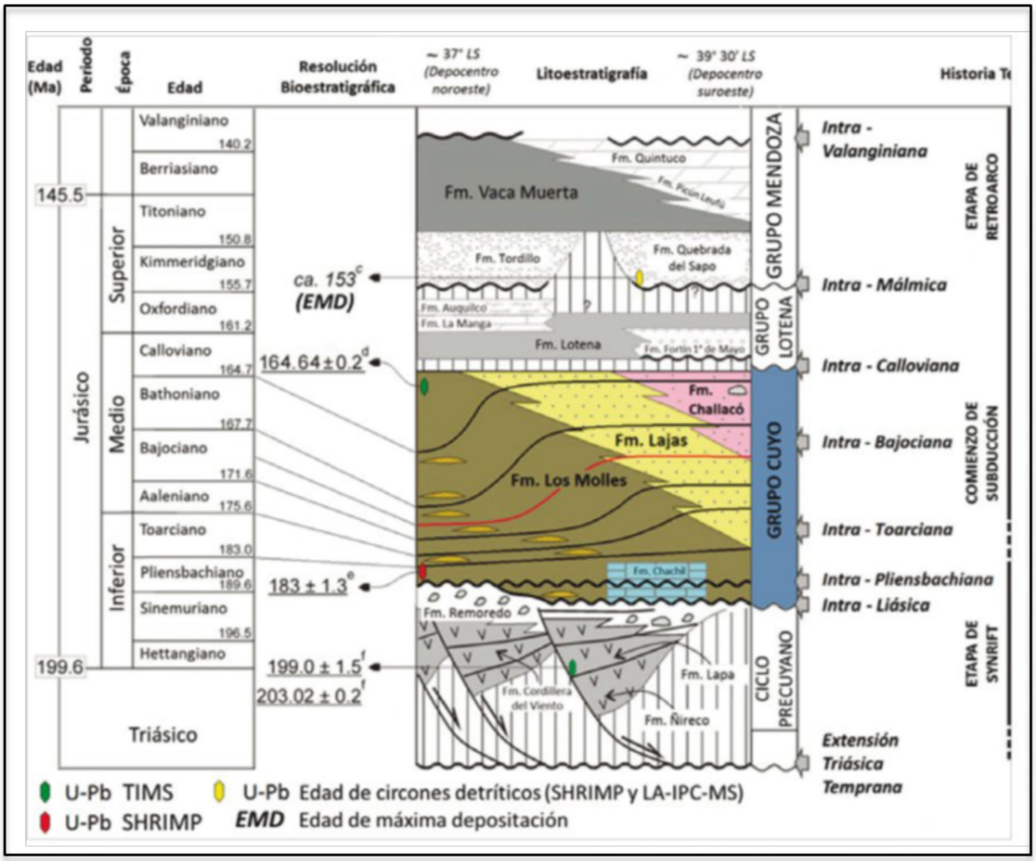

Figure 2. Stratigraphic column of Neuquén Basin, including Triassic, Jurassic and Neocomian deposits (modified after Naipauer *et al.* 2017).

SEISMIC DATA

In this current work, the focus is on a sub-zone of the Neuquén Embayment, covering an area of 700km². The post stack seismic 3D data has a vertical extension of 5 seconds TWT, a bin size / CDP spacing of 30 meters and a sampling rate of 2 milliseconds. This is a PSTM (Pre-Stack Time Migration) seismic data processed in 2016. Simple data screening facilitates the identification of the key stratigraphic groups, Cuyo and Mendoza, having average depth ranging from 2.25 to 3 seconds TWT, and from 1.6 to 1.9 seconds of TWT respectively (Fig. 3). A first pass of the RGT modelling workflow (Pauget *et al.* 2009) aims at performing a fast geological reconnaissance to define the best strategy for conducting a detailed study. A key decision, made at this stage, is to modify the seismic trace grid orientation (i.e. inlines and crosslines orientation, either ± ~45o) in order to fit the major direction of the Cuyo Group's progradational sequence, which essentially dips from SE to NW.

The Cuyo Group, which extends from Middle Lias to Late Dogger, a period of some 20 Million Years, is composed of formations that range from deep-water submarine environment to subaerial fluvial environment. The formation named Los Molles, and its corresponding turbidite deposits, are considered of the greatest importance in this study (Fig. 2).

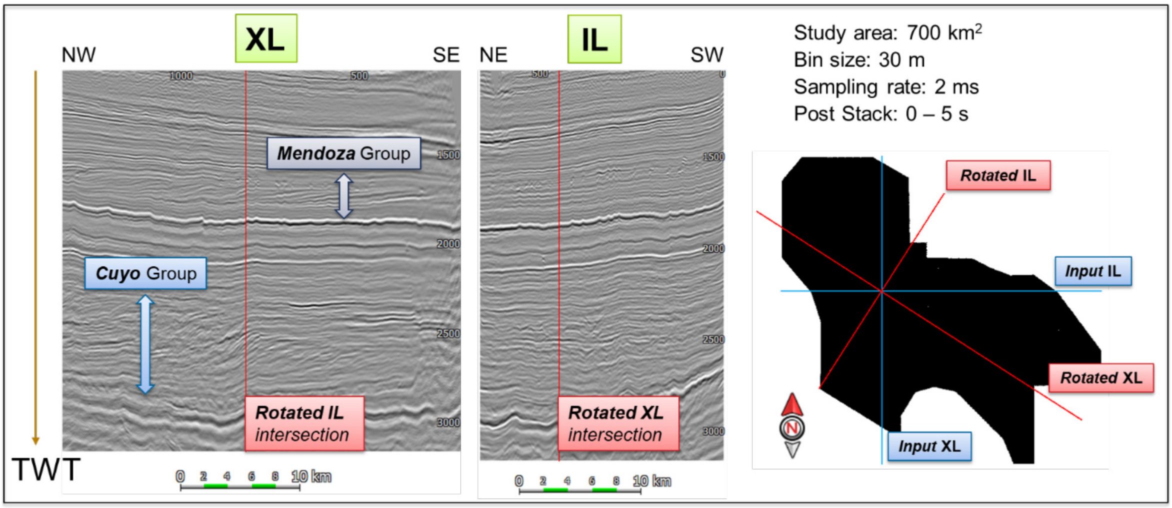

Figure 3. 3D seismic data of the study area from Neuquén Embayment.

RGT MODELLING METHODOLOGY

The signal-driven RGT modelling approach consists of a two-step workflow (Pauget *et al.* 2009). First, a discrete stratigraphic framework, called 'Model-Grid', is computed to convert all the seismic reflectors into horizons. Those seismic consistent horizons are stratigraphically sorted, enabling the geoscientist to individually edit and refine as needed. A 3D interpolation of this discrete sequence stratigraphic framework is then performed to transform each seismic sample into a value of 'Relative Geological Time - RGT', resulting in a continuous model of RGT (Fig. 4). The RGT model is then used to interrogate the seismic volume and attribute volumes to generate a series of advanced structural and stratigraphic attributes, from which sub-seismic sample stratal slicing can be performed. The RGT model can additionally be comprehensively flattened to build a real time Wheeler diagram and subsequent sequence stratigraphic models.

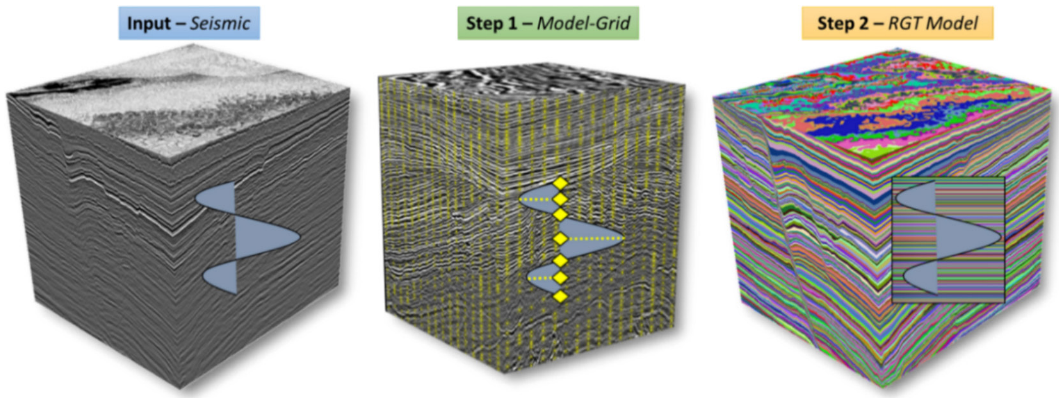

Figure 4. Concept of signal-driven RGT modelling workflow (Pauget *et al.* 2009). Data from HCA2000A seismic survey, courtesy of Australian Government.

The Model-Grid is settable thanks to parameters controlling its vertical and spatial resolutions, the horizon patches geometry (described as 'spatial sampling'), and the patches correlation threshold used for the final comprehensive horizon propagation (Fig. 5).

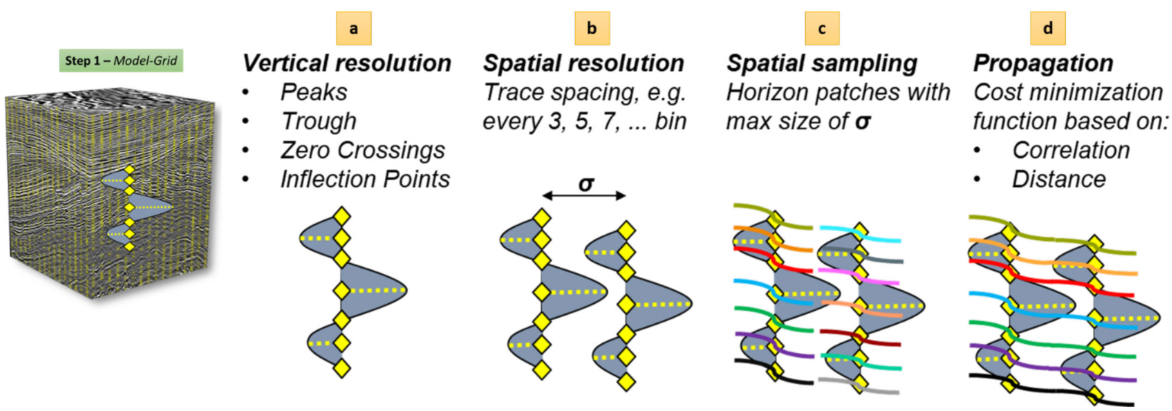

Figure 5. Discrete stratigraphic framework 'Model-Grid' parameters (Pauget *et al.* 2009). Data from HCA2000A seismic survey, courtesy of Australian Government.

For this study, the seismic data is conditioned with a 7-voxel window size (210 meters spatially, 14 milliseconds vertically) Gaussian smoothing to improve the signal continuity and enhance the horizon tracking performance. Model-Grid nodes are built from seismic peak, trough, zero crossing up and zero crossing down amplitudes, and with a spatial resolution of 3 bin (90 meters). The spatial resolution controls a first comprehensive iteration of 3x3 traces correlation (threshold of 30 %) to build polarity consistent patches from nodes. A second comprehensive iteration of patches correlation (threshold of 30 %) builds stratigraphically sorted, polarity consistent seismic horizons in a deterministic way: a cost minimization function tests all framework configurations then keeps the one with the more patches connections.

Computer-aided tools and RGT preview options are used to automatically detect potential wrong correlations within the Model-Grid before correcting them. A structurally and stratigraphically consistent RGT model is finally computed and eventually blended with seismic amplitudes and wiggles (Fig. 6).

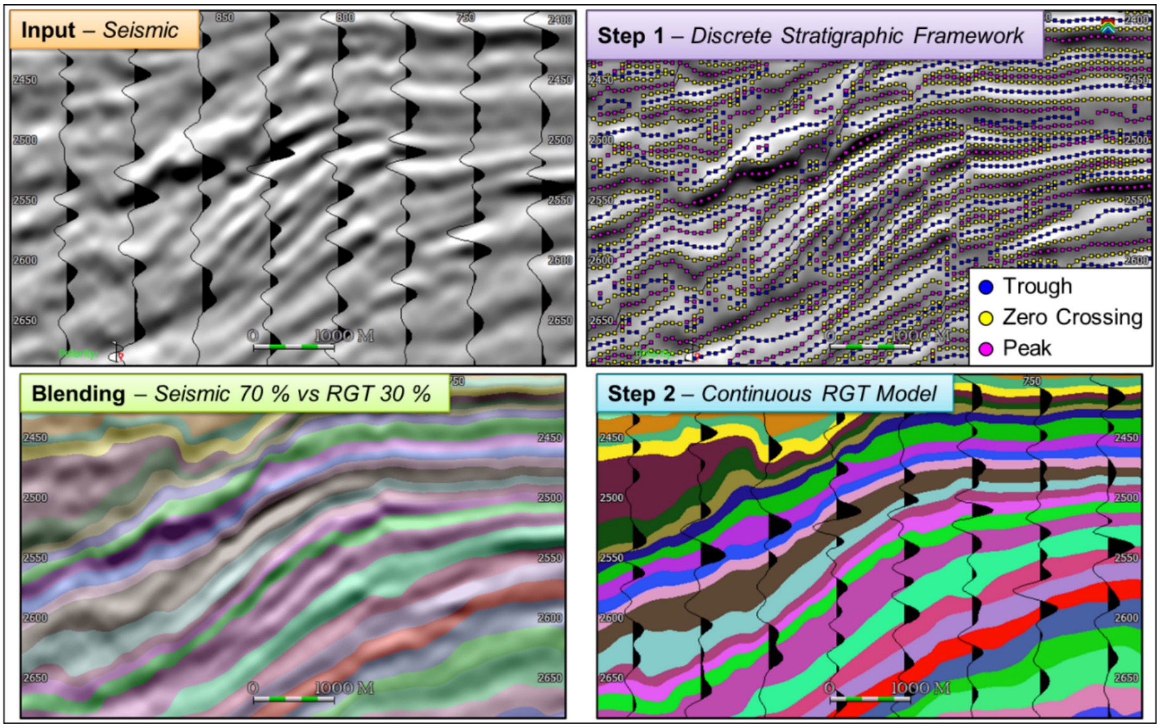

Figure 6. Application of the RGT modelling workflow to the Neuquén Embayment seismic data.

CUYO GROUP'S 3D SEQUENCE STRATIGRAPHIC MODEL

One unique derivative of the RGT Model is the Thinning attribute that corresponds to the vertical derivative of the geo-times (Fig. 7). It emphasizes zones of strata convergence (red color) and divergence (blue color) within a settable sample-based vertical window. It enables to understand stacking patterns (progradation, degradation, aggradation, retrogradation), geometrical relationships (unconformities, stratigraphic terminations), sedimentary dynamics (deposition, erosion, non-deposition) and relative extrema of accommodation space.

Thinning attribute analysis can be combined with a real-time two-way seismic voxel transformation, enabling the geoscientist to visualise and interpret in both the structural and Wheeler domains (Fig. 8). As the RGT model consistently fits the seismic data geometry (structurally and stratigraphically), the RGT-driven Wheeler transform highlights the same hiatuses for both the RGT and seismic reflections (Fig. 8). Maxima of Thinning zones can be

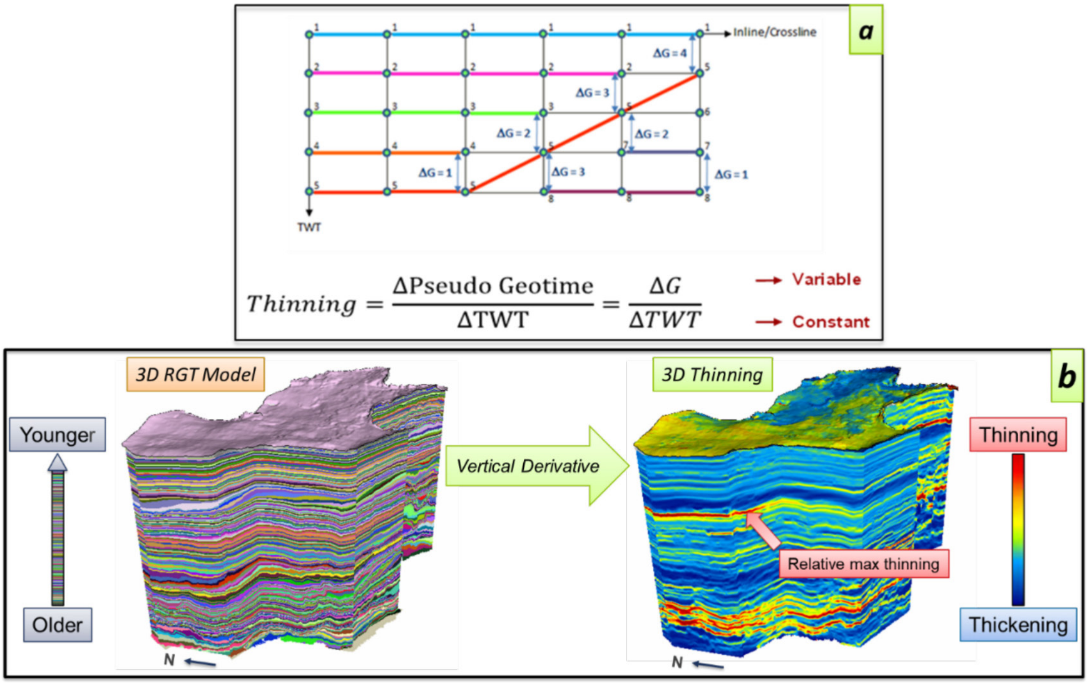

Figure 7. Real time computation of RGT vertical derivative, delivering the Thinning attribute. a: Formula; b: result with a vertical window size of 7 samples (14 ms).

correlated to gaps in the rock record (Hiatus, Fig. 8). Thinning attribute and Wheeler transform emphasize the characterization of stacking patterns and stratigraphic terminations, and therefore ease the accurate delineation of isochronous surfaces, which can be achieved at a sub-seismic sample precision.

Clinoform delineation and sequence stratigraphic model building can be performed at different scales of stratigraphic units: large scale depositional sequences and systems tracts, small-scale parasequences, and eventually clinothem stratal slicing (see next section). In this study with shelf / slope / basin setting, a Transgressive-Regressive sequence model from Embry (2009) is used to recognize and characterize the boundaries of a material-based depositional sequence. Each boundary is thus defined as a landward-basinward combination of Subaerial Unconformity, Unconformable Shoreline Ravinement, Slope Onlap Surface and Maximum Regressive Surface (SU/SR-U/SOS/MRS). The occurrence of a Maximum Flooding Surface (MFS) with low diachroneity allows the sequence to be subdivided into two material-based systems tracts: a Transgressive Systems Tract (TST) and a Regressive Systems Tract (RST). TST are interpreted on the criterion of a rate of sediment deposition slower than the rate of base-level rise; whereas RST are interpreted on the criterion of a rate of sediment deposition faster than the base-level rise, and eventually in a base-level fall configuration.

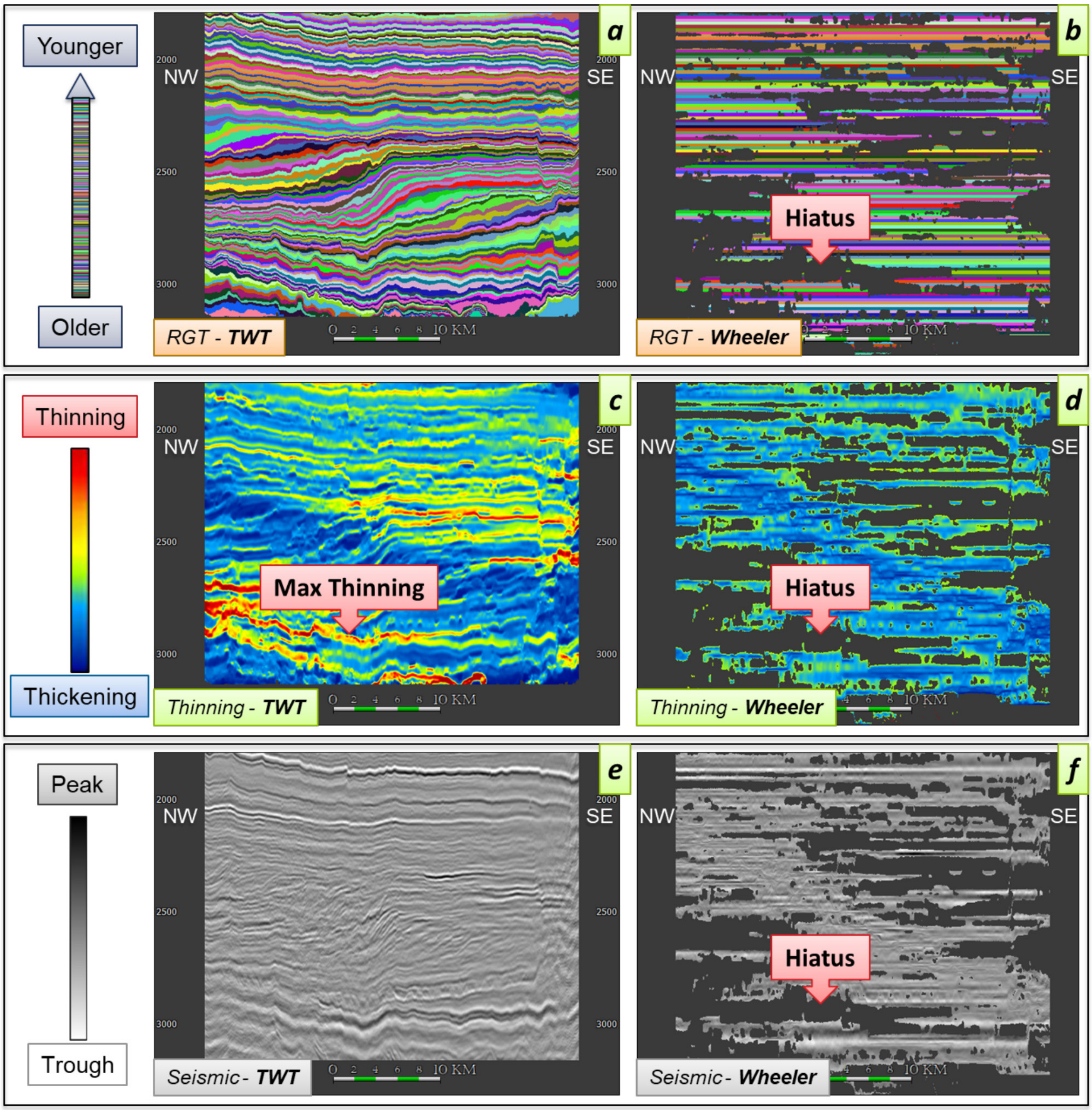

Figure 8. Comparison between RGT model, Thinning attribute and seismic amplitudes in structural and Wheeler domains.

Two cycles of base level variations are identified with a northwestward shift of location of deposition from the base of the first RST to the top of the second one. The stacking pattern of each RST shows an early increasing progradation/aggradation (P/A) ratio and a late decreasing P/A ratio (Fig. 9).

The first TST is interpreted as a thin carbonate platform from Pliensbachian stage (Chachil Formation). It is overlain by a first RST that is composed of four parasequences, which typically represent smaller scale base-level fall-rise cycles and eventually a reduction in sediment supply over a base-level rise period. Those changes in the rate of generation of accommodation space and

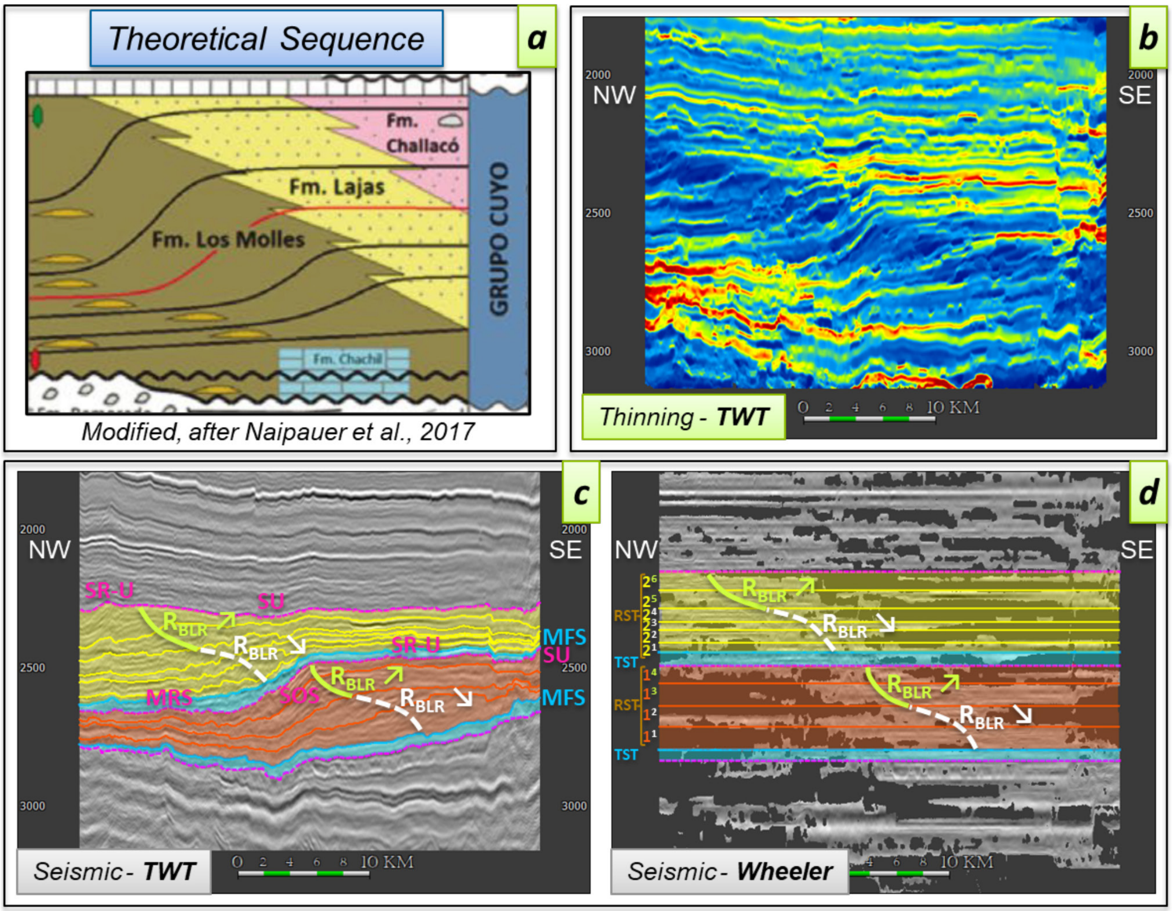

Figure 9. Final Sequence Stratigraphic model of the Cuyo Group. a: Theoretical sequence of Cuyo Group. b: Thinning attribute c & d: 3D sequence stratigraphic model based on Embry's model (2009), composed of two cycles of sea level variations, and displayed in Structural domain (c) and Wheeler domain (d). TST = Transgressive Systems Tract (blue); RST = Regressive Systems Tract with parasequences from 1^1 to 1^4 (orange) and from 2^1 to 2^6 (yellow); SU = Subaerial Unconformity; SR-U = Unconformable Shoreline Ravinement; SOS = Slope Onlap Surface; MRS = Maximum Regressive Surface; MFS = Maximum Flooding Surface; R_{BLR} ↘ = speed of initial base level rise rate decreases (dashed white line); R_{BLR} ↗ = speed of initial base level rise rate increases (solid light green line).

associated sedimentation are labelled from 11 to 14. Parasequences 11 and 12 show an increasing P/A ratio whereas 1^3 and 1^4 show a decreasing P/A ratio.

The second TST is composed of maximum 3 to 4 reflectors and its recognition is mostly based on the slope onlap depositional pinch-outs. This episode of retrogradation represents a minor sediment deposition rate compared to the previous and following RST. The MFS topping the second TST is delineated where the retrogradational stacking pattern changes into a progradational stacking pattern. The second RST is composed of six parasequences, all labelled from 2^1 to 2^6. Parasequences 2^1 to 2^4 show an increasing P/A ratio whereas 2^5 and 2^6 show a decreasing P/A ratio.

In order to further characterize the transitional zone between the units where the rate of base level rise decreases (R_{BLR} ↘, dashed white line) and the units where the rate of base level rise increases (R_{BLR} ↗, solid light green line), efforts could be invested in the delineation of a Basal Surface of Forced Regression (BSFR). This abstract time-based surface separating older sediments deposited during slowing rates of base-level rise from younger sediments deposited during base-level fall (Hunt and Tucker, 1992) should subdivide each RST into two time-based systems tracts: a lower Highstand Systems Tract (HST) and an upper Lowstand Systems Tract (LST) as defined in Posamentier's and Allen's model (1999). Nevertheless, because a BSFR is hypothetical with no observable, characteristic features that would allow it to be delineated with reasonable objectivity so as to allow it to be used for correlation and bounding sequence stratigraphic units (Embry, 2009), the ambitious perspective of a base-level fall, time-based systems tract definition (interpreted as early LST with degradational stacking pattern) is not further described in this paper.

An additional reason that explains the decision to favor a pragmatic approach and a material-based depositional sequence composed of valid and practical surfaces, is the complexity of the seismic data. Two aspects may be described: firstly, the lack of exploitable seismic reflection details in the foreset and bottomset segments of the clinothems; and secondly, the high variation of clinoform scales in 3D, very likely merging to form compound clinoforms and subsequent compound parasequences depending on sediment supply and local sea-level changes. Because the Cuyo Group sequence extends over a period of some 20 Million Years (including condensed sections of TST), those compound parasequences may represent meter-scale to decameter-scale bedsets (thin 3rd to 4th order sequences, each approximately spanning less than 1 Million Year).

The stacking kinematic of Cuyo Group progradational sequence is modeled (Fig. 10, 11, 12 & 13). The isochore (vertical thickness) is computed for each TST and parasequence, revealing the location of maximum sediment deposition for every clinothem (blue-colored values of the isochore maps). From parasequence 1^1 to 2^3, the progradation has a SE-NW direction (violet-colored foreset axis) whereas parasequence 2^4 has an ESE-WNW direction lately evolving into E-W direction for parasequences 2^5 and 2^6 (brown-colored foreset axis). This 45° anticlockwise rotation of the progradation direction during deposition may highlight changes in the regional tectonic settings, leading to a multi-story, multi-source, multi-directional sedimentary supply and flow.

LOS MOLLES FORMATION'S STRATAL SLICING

Parasequences from the second RST are dynamically stratal-sliced at a sub-sample resolution to reveal subtle seismic expressions (Fig. 14). Basic and instantaneous seismic attributes like Root Mean Square and Envelope are used at an early stage to detect sweet spots lately enhanced by a spectral decomposition. A Short-time Fourier transform method is applied with a vertical window of 38 ms (Fig. 15).

The stratal slices of subsequent magnitude volumes from discrete frequencies (31Hz, 36Hz, 41Hz) are RGB-blended to emphasizes a turbidite system in the bottomsets of the second RST (yellow-coloured, Fig. 10). Based on analysis performed here, four growth phases of this turbidite system are identified, with variations in size (length, width, surface area), driving accommodated zone, and subsequent progradation direction. The four growth phases are described with several key morphological elements (Fig. 16, 17, 18 & 19).

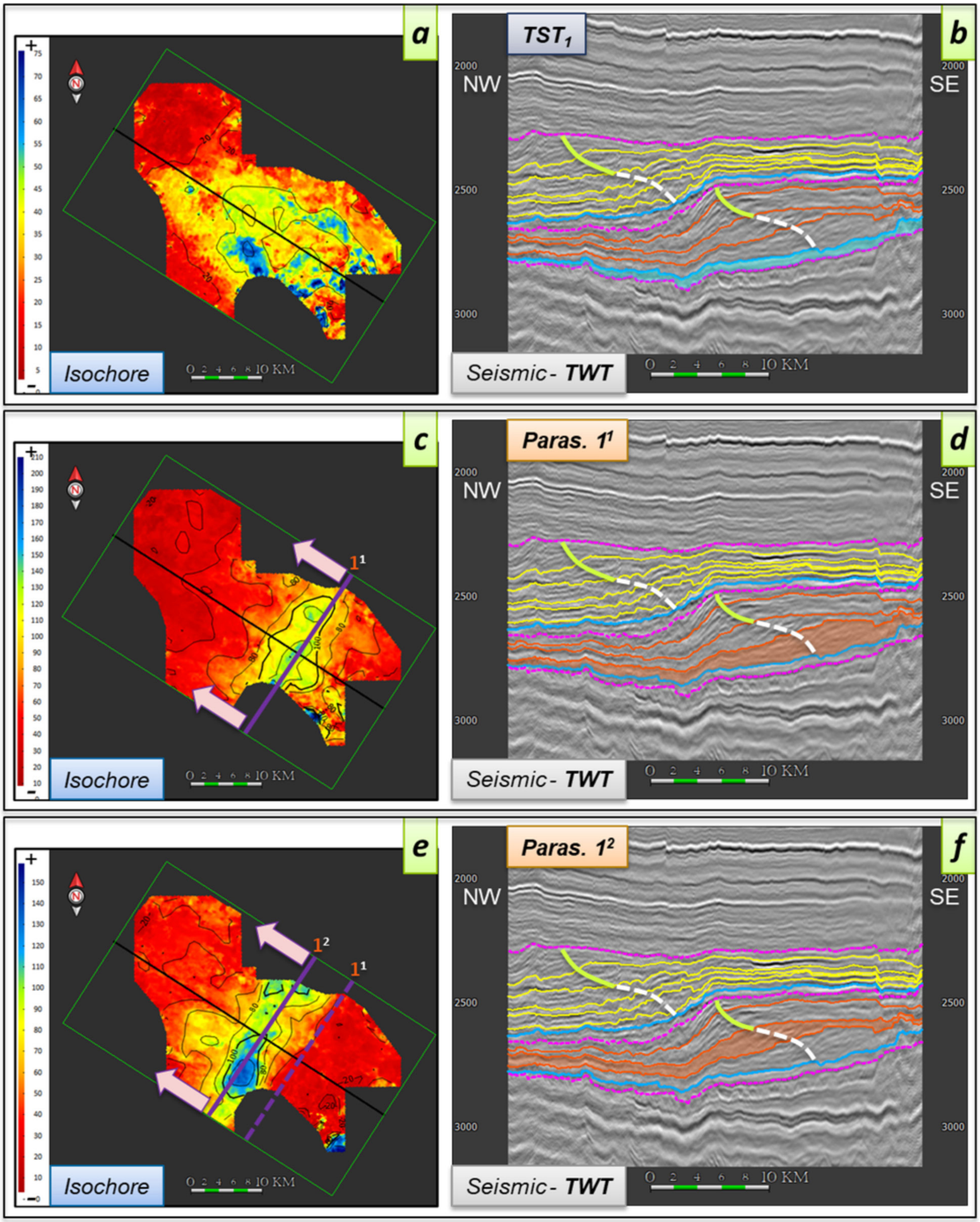

Figure 10. Stacking kinematic of Cuyo Group progradational sequence. a, c & e: Thickness map of each systems tract and subsequent subdivisions (parasequences) with axis of maximum deposition; b, d & f: Sequence Stratigraphic model in structural domain.

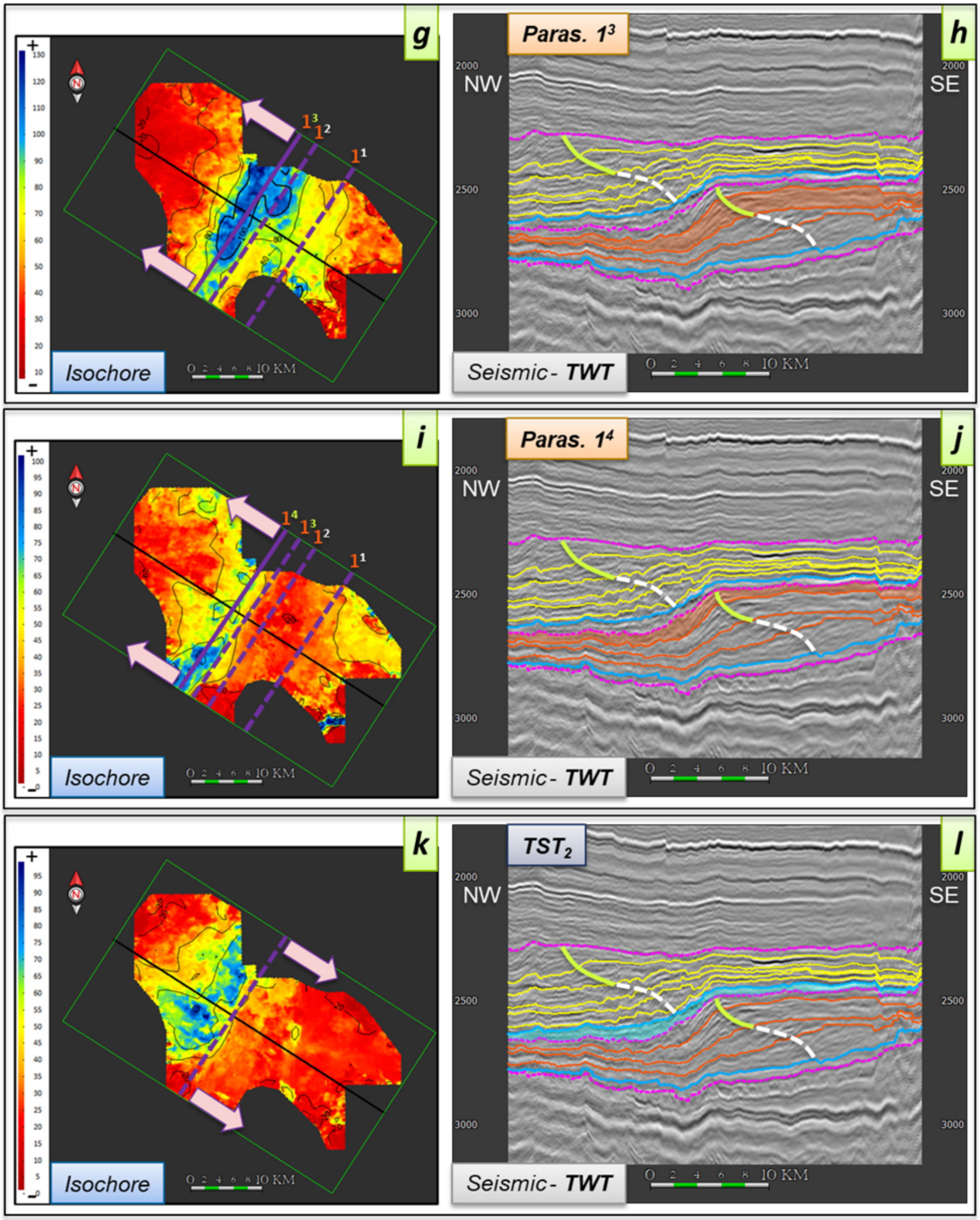

Figure 11. Stacking kinematic of Cuyo Group progradational sequence. g, i & k: Thickness map of each systems tract and subsequent subdivisions (parasequences) with axis of maximum deposition; h, j & l: Sequence Stratigraphic model in structural domain.

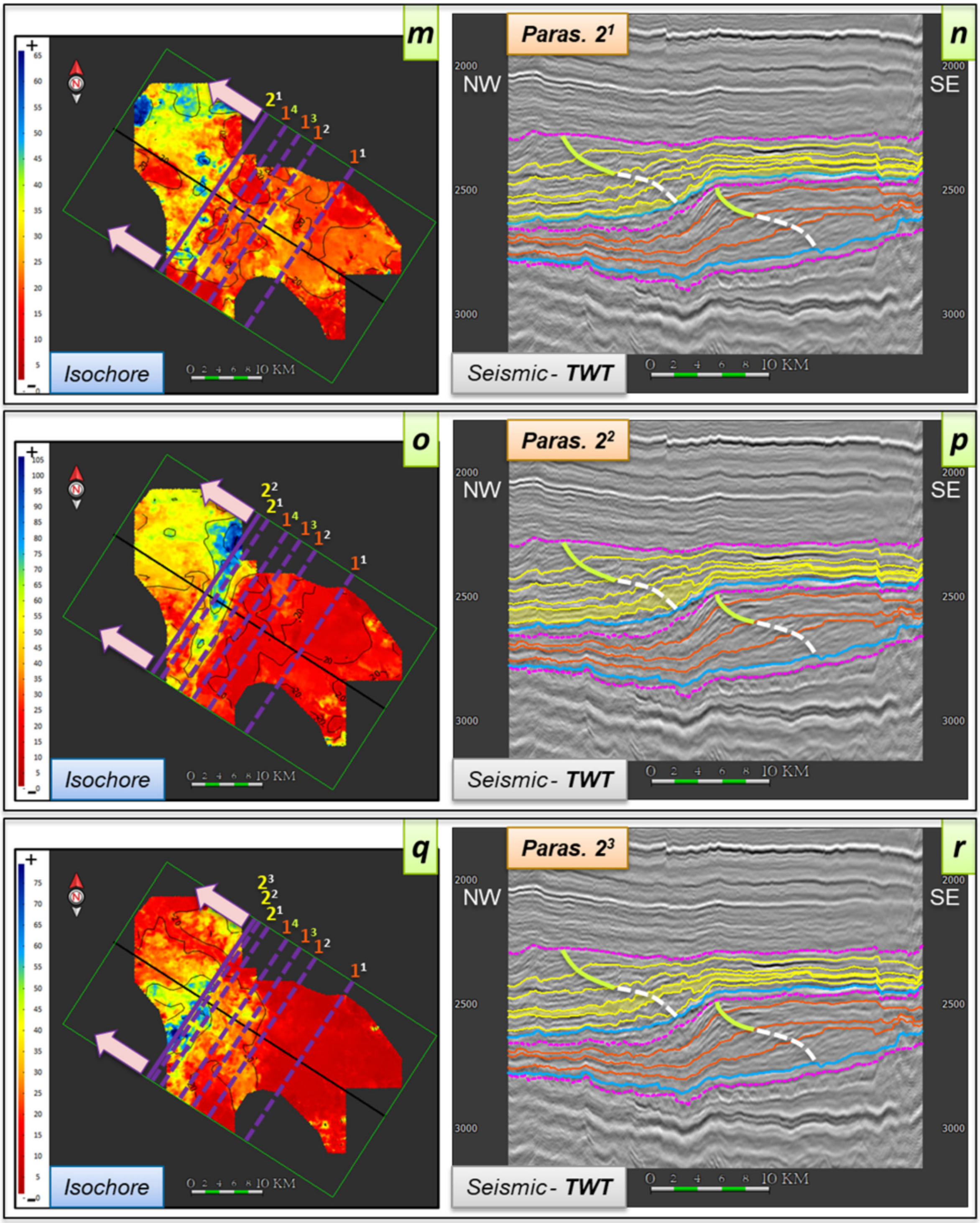

Figure 12. Stacking kinematic of Cuyo Group progradational sequence. m, o & q: Thickness map of each systems tract and subsequent subdivisions (parasequences) with axis of maximum deposition; n, p & r: Sequence Stratigraphic model in structural domain.

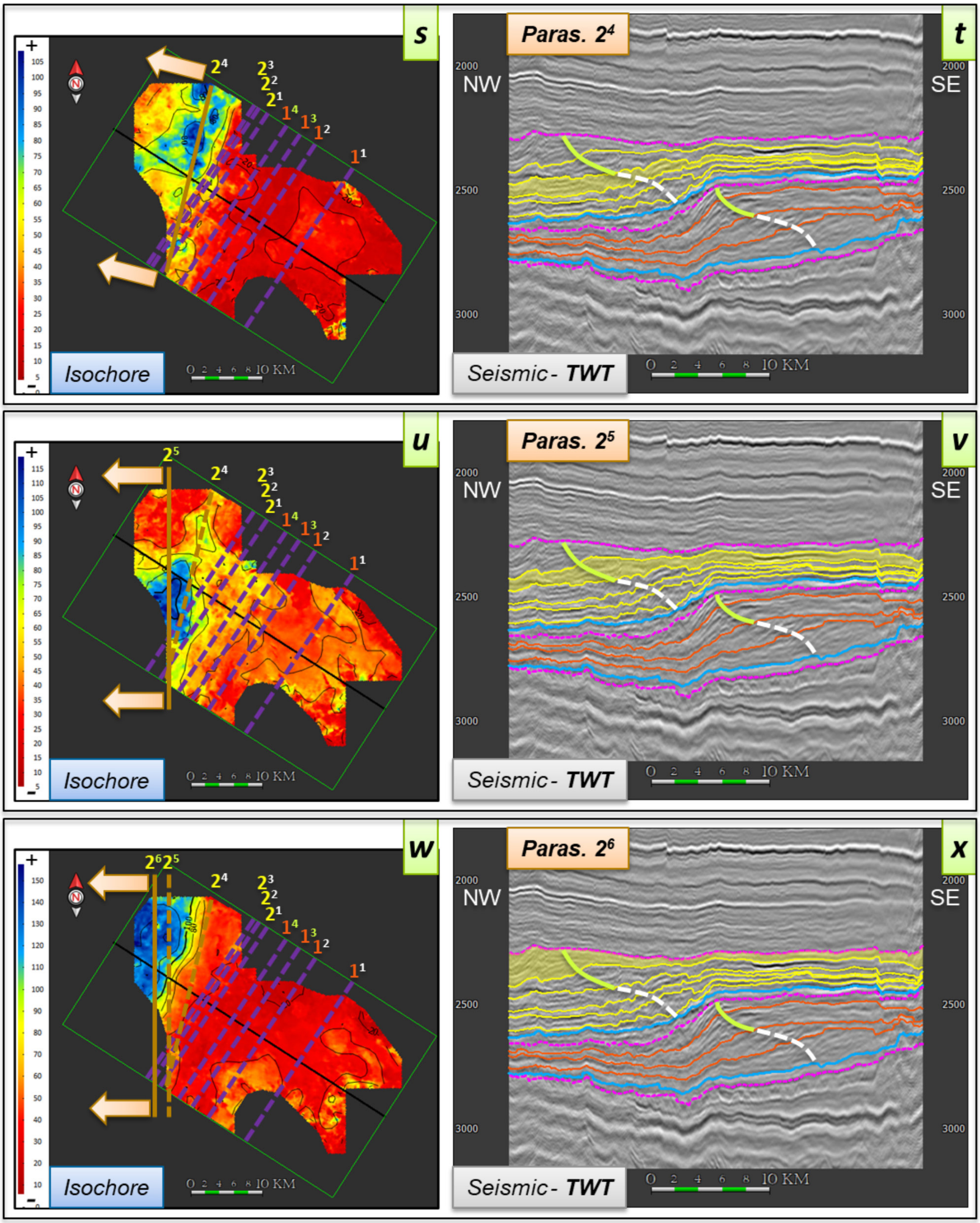

Figure 13. Stacking kinematic of Cuyo Group progradational sequence. s, u & w: Thickness map of each systems tract and subsequent subdivisions (parasequences) with axis of maximum deposition; t, v & x: Sequence Stratigraphic model in structural domain.

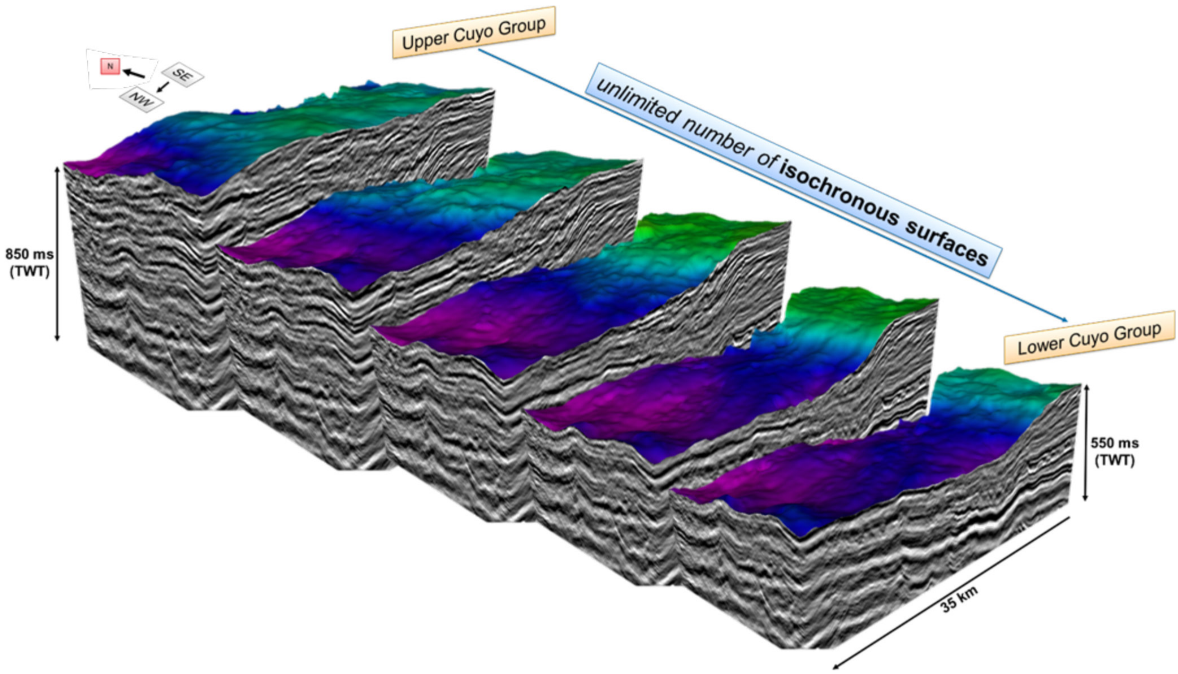

Figure 14. Concept of interactive, RGT-driven, sub-sample stratal slicing applied in the Cuyo Group sequence. Isochrones can be mapped with topography-derived (Z-value, example), seismic-derived and RGT-derived attributes.

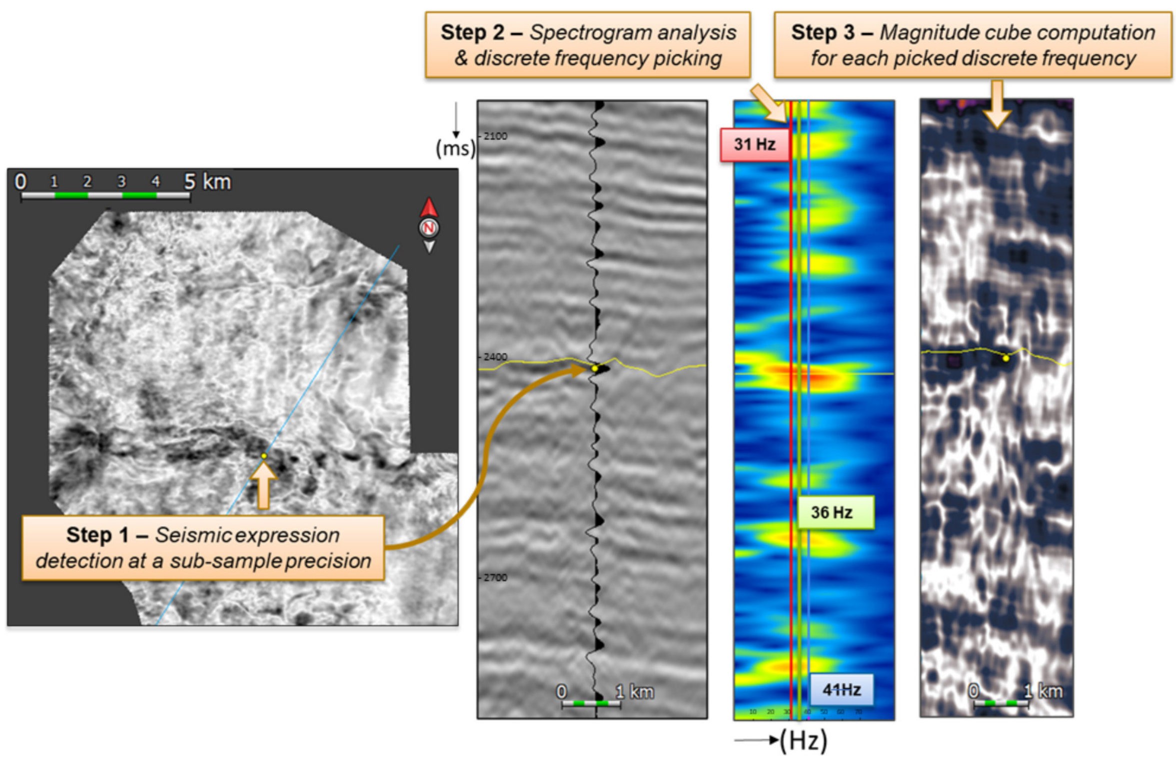

Figure 15. Spectral Decomposition guided by stratal slicing and seismic attribute mapping. Cross correlating the viewers enables to dynamically select the reference traces. A Short-time Fourier transform method is chosen with a vertical window of 38 ms. Magnitude cubes are visualizable and eventually RGB-blended in real time.

1st growth phase – Parasequence 2^2

The turbidite system is 21.4 km long, 5.6 km wide and 43.5 km² large (Fig. 16). A sinuous plan-form geometry is interpreted as a leveed channel zone (blue-colored dashed polygon). It is locally stacked with a sheet-like geometry (light green-colored dashed polygon), interpreted as High-Amplitude Reflection Packets (HARPs) and witnessing the deposition of unchannelized sandy flows in the inter-channel area after the channel bifurcation and avulsion (red-colored point). The downstream segment (i.e. deep sea fan) cannot be observed as it appears to extend beyond the limits of the available seismic survey (gold color-filled zone).

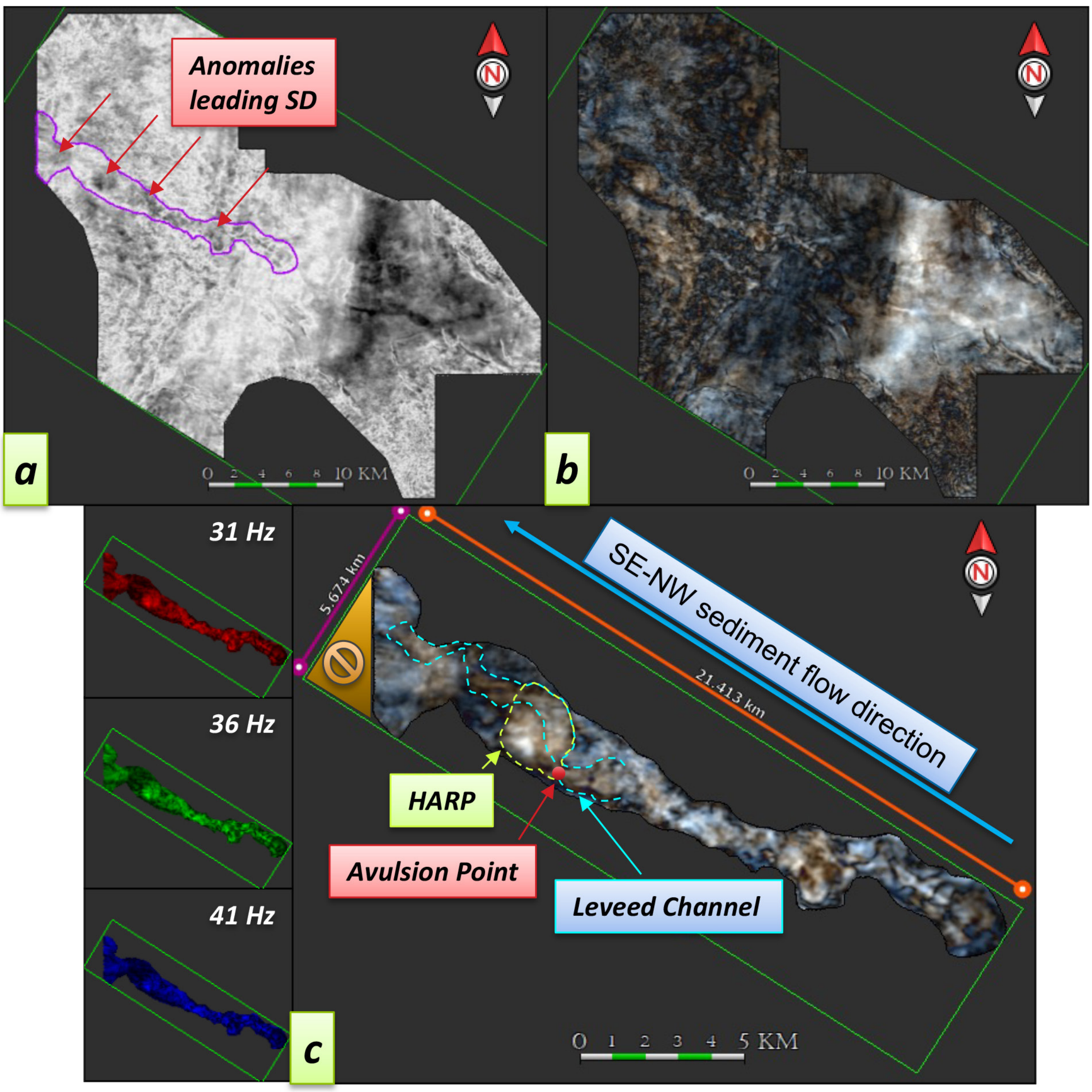

Figure 16. Strategy to emphasize the 1st growth phase of Los Molles turbidite system in parasequence 2^2. a: Stratal slice with seismic Envelope mapping; b: RGB-blend Spectral Decomposition revealing the main morphological elements; c: Contouring and description of the morphological elements.

2nd growth phase – Parasequence 2[3]

The turbidite system is 18.4 km long, 6 km wide and 44.7 km² large (Fig. 17). A hierarchy can be established between stacked events: abandoned turbidite channels (orange-colored dashed polygons) stacked with continuous leveed channels (light blue-colored dashed polygon). A canyon-mouth lobate form is well delineated (red-colored dashed polygon) and may drive further investigation for lobe complex characterization.

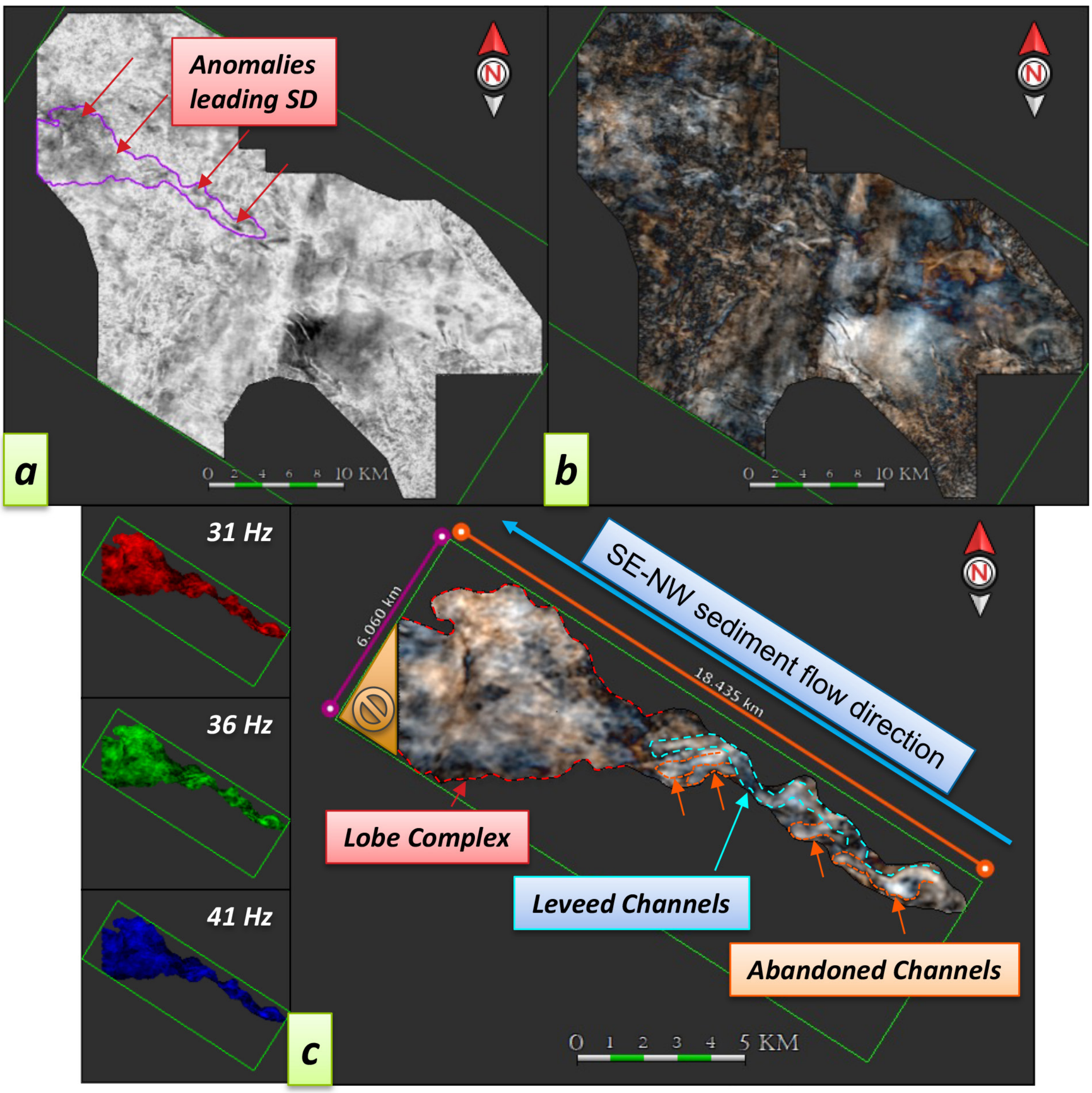

Figure 17. Strategy to emphasize the 2nd growth phase of Los Molles turbidite system in parasequence 2³. a: Stratal slice with seismic Envelope mapping; b: RGB-blend Spectral Decomposition revealing the main morphological elements; c: Contouring and description of the morphological elements.

3rd growth phase – Parasequence 2[4]

The turbidite system is 19.4 km long, 3.7 km wide and 26.3 km² large (Fig. 18). It appears to be translated southwestward. This could be the consequence of the aggradation that previously fills the canyon and channels of 1st and 2nd growth phase, combined with a maximum of subsidence rate that is transferred southwestward, making the early canyon no longer active. Standard geomorphological elements are revealed and delineated: leveed channel zone (blue-colored dashed polygon), stacked with HARPs (light green-colored dashed polygon). The avulsion point is eventually located (red-colored). The downstream segment (i.e. deep sea fan) is noisy and cannot be fully delineated as it appears to extend beyond the limits of the available seismic survey (gold color-filled zone).

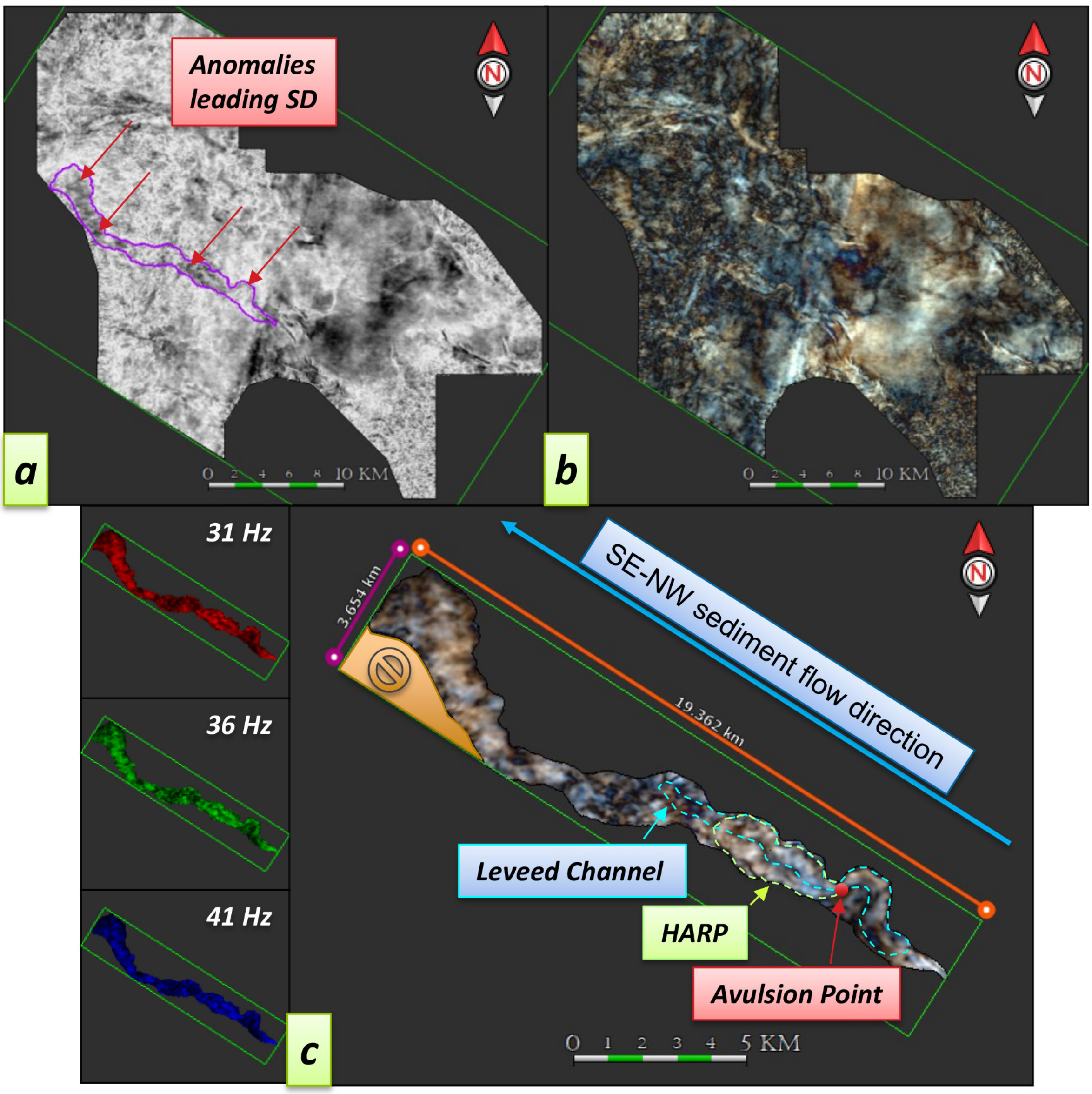

Figure 18. Strategy to emphasize the 3rd growth phase of Los Molles turbidite system in parasequence 2[4]. a: Stratal slice with seismic Envelope mapping; b: RGB-blend Spectral Decomposition revealing the main morphological elements; c: Contouring and description of the morphological elements.

4th growth phase – Parasequence 2[5]

The turbidite system is 16.7 km long, 3.6 km wide and 34.5 km² large (Fig. 19). It is translated northward, and shows a 45° anticlockwise re-orientation with a new E-W direction (previously explained in section 4). The upstream segment appears to extend beyond the limits of the available seismic survey, leading to no modelling of both the shelf and eventually the topset of the clinothem that may embed the canyon. No image could thus be exploited to analize the sediment supply path. The clinoform foreset zone shows the canyon with channels (blue-colored dashed polygon) followed by unclear seismic expressions (purple-colored dashed polygon) that could embed distributary channels. A fan geometry is ultimately encompassed (red-colored dashed

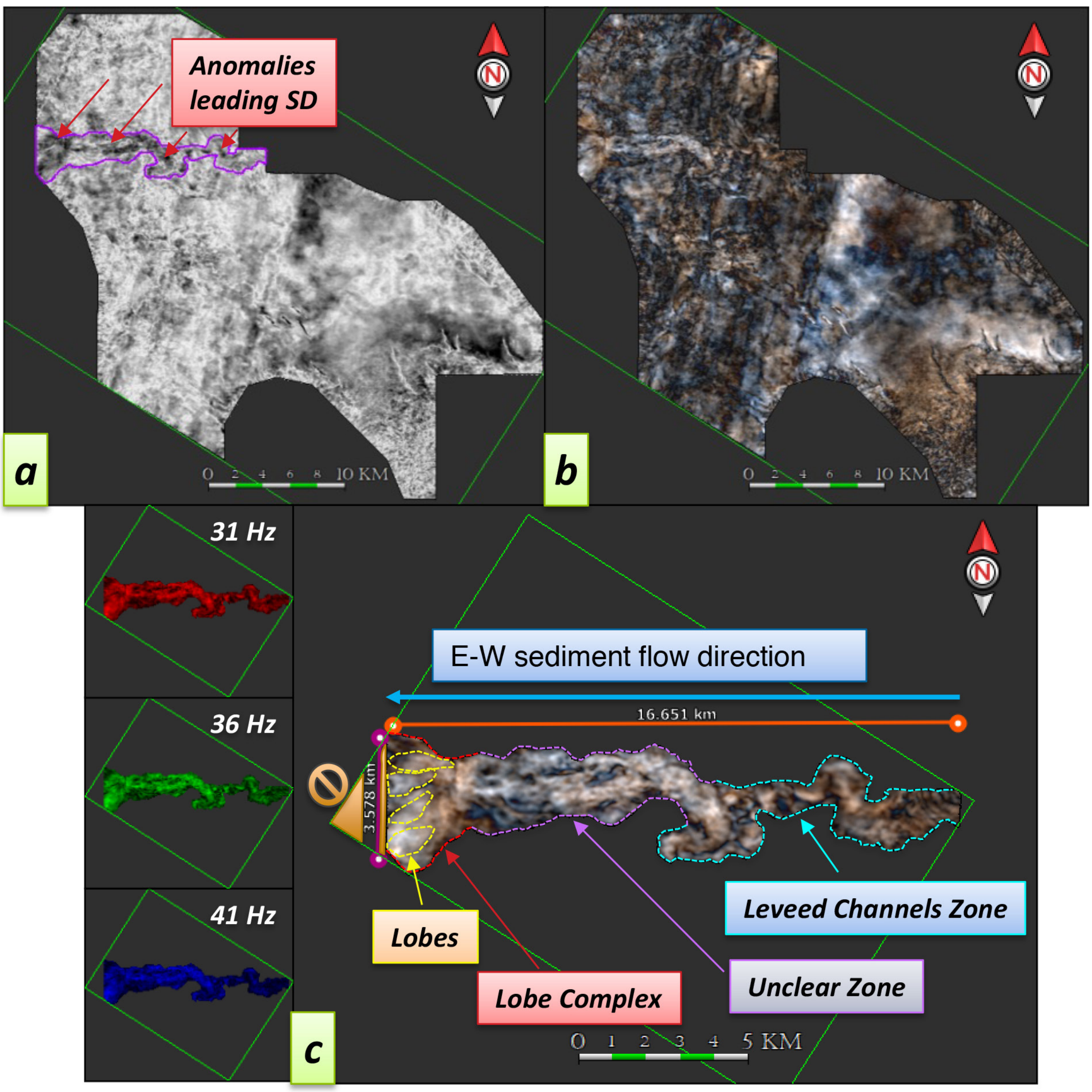

Figure 19. Strategy to emphasize the 4th growth phase of Los Molles turbidite system in parasequence 2[5]. a: Stratal slice with seismic Envelope mapping; b: RGB-blend Spectral Decomposition revealing the main morphological elements; c: Contouring and description of the morphological elements

polygon) and interpreted as lobe complex with emphasized individual lobes (yellow-colored dashed polygon).

PROGRADING SYSTEM AND ASSOCIATED TURBIDITE DEPOSITS: SYNTHESIS

The cross correlation of Cuyo Group's sequence stratigraphic model and Los Molles Formation's stratal slicing unlocks the description and analysis of the turbidite system kinematics (Fig. 20 & 21). The stratigraphic model has a vertical extension of 400-500 ms TWT, with clinoform height of 50-150 ms TWT. The turbidite system is remarkably short (20 km), narrow (3-5 km), small (25-45 km^2) and its stacked phases of growth have a limited vertical extension (200 ms TWT).

Based on their scale, geometry, and general depositional setting, clinothems can be classified as shelf-edge scale type, supposed to be contained entirely within the continental shelf, where an intervening slope separates the topset of normal shelf from the bottomset of deeper shelf (Patruno and Helland-Hansen, 2018). The hectometric scale of the clinoforms height is consistent with the occurrence of turbidite deposits, while mass transport deposits may explain local chaotic seismic expressions of the system. The development of deep sea fans on the shelf rather than in a basin plain could be explained by the small scale of the Neuquén Basin in comparison with examples from literature used to establish reference models.

CONCLUSION

This study has been conducted by combining a proven automated comprehensive method for seismic interpretation (Pauget *et al.* 2009) with concepts of sequence stratigraphy and deep-water sedimentology. It reveals an unprecedented level of visualization detail from seismic images previously unavailable when using conventional interpretation methods. The method is successfully applied to a small scale turbidite system, ranging from 25 to 45 km^2 in surface area, depending on the stratigraphic level being investigated. Such a methodology offers the ability to draw new perspectives and insights in the evaluation legacy data and further demonstrate the potential prospectivity within the hydrocarbon resource rich Neuquén Basin. Further work can take advantage of the integration of additional data from well logs, cores and outcrops which can be incorporated into the workflow presented in this study.

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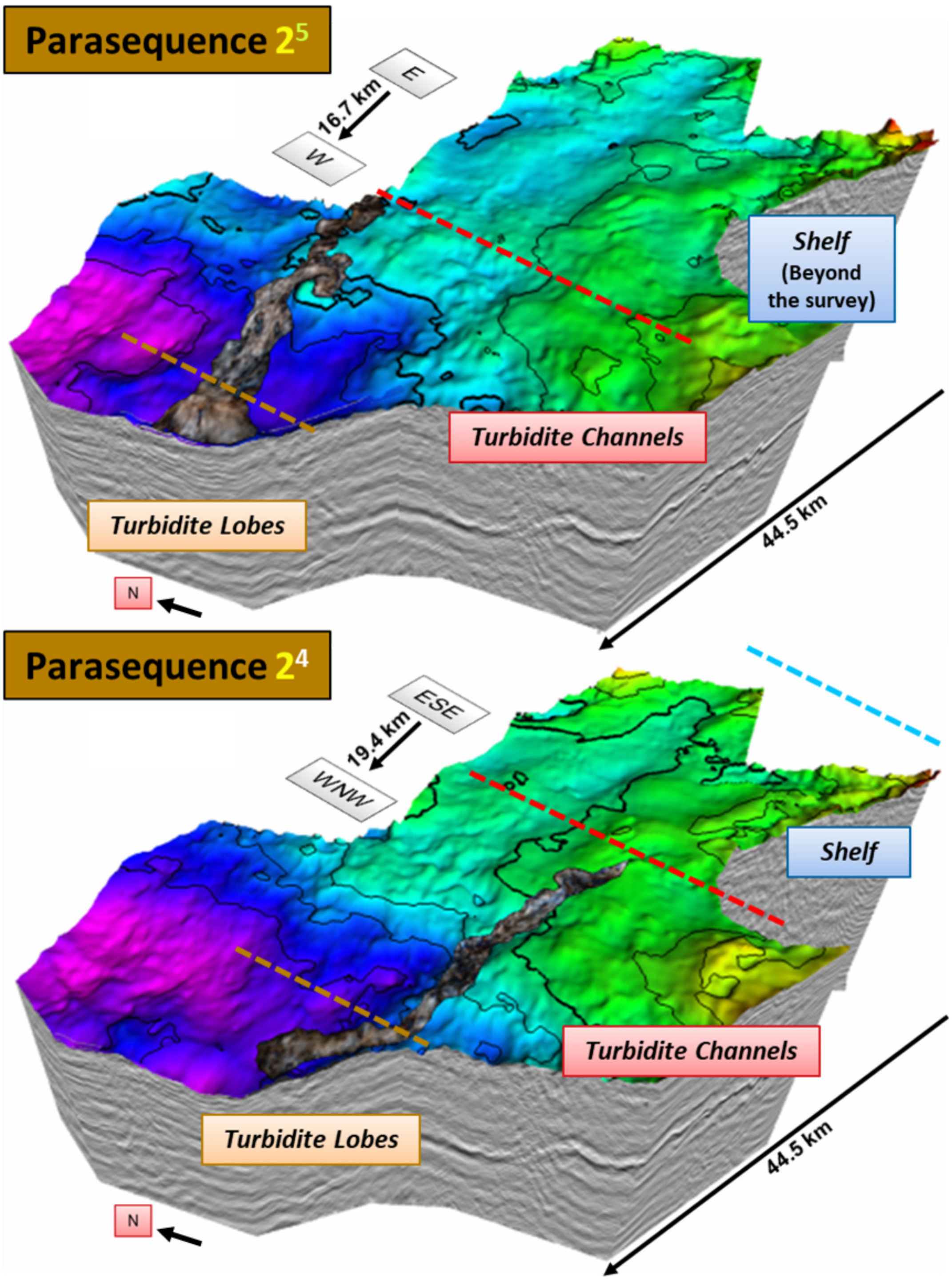

Figure 20. Kinematic of the two last growth phases of the identified turbidite system, all from the second Regressive Systems Tract of the stratigraphic model. Key depositional trend surfaces are mapped with topography (i.e. Z-value) and overlayed with RGB-blended magnitude signatures (31Hz, 36Hz, 41Hz) for parasequences 24 to 25. Key segments (canyon and channel-dominated zone, then lobe-dominated zone) are highlighted.

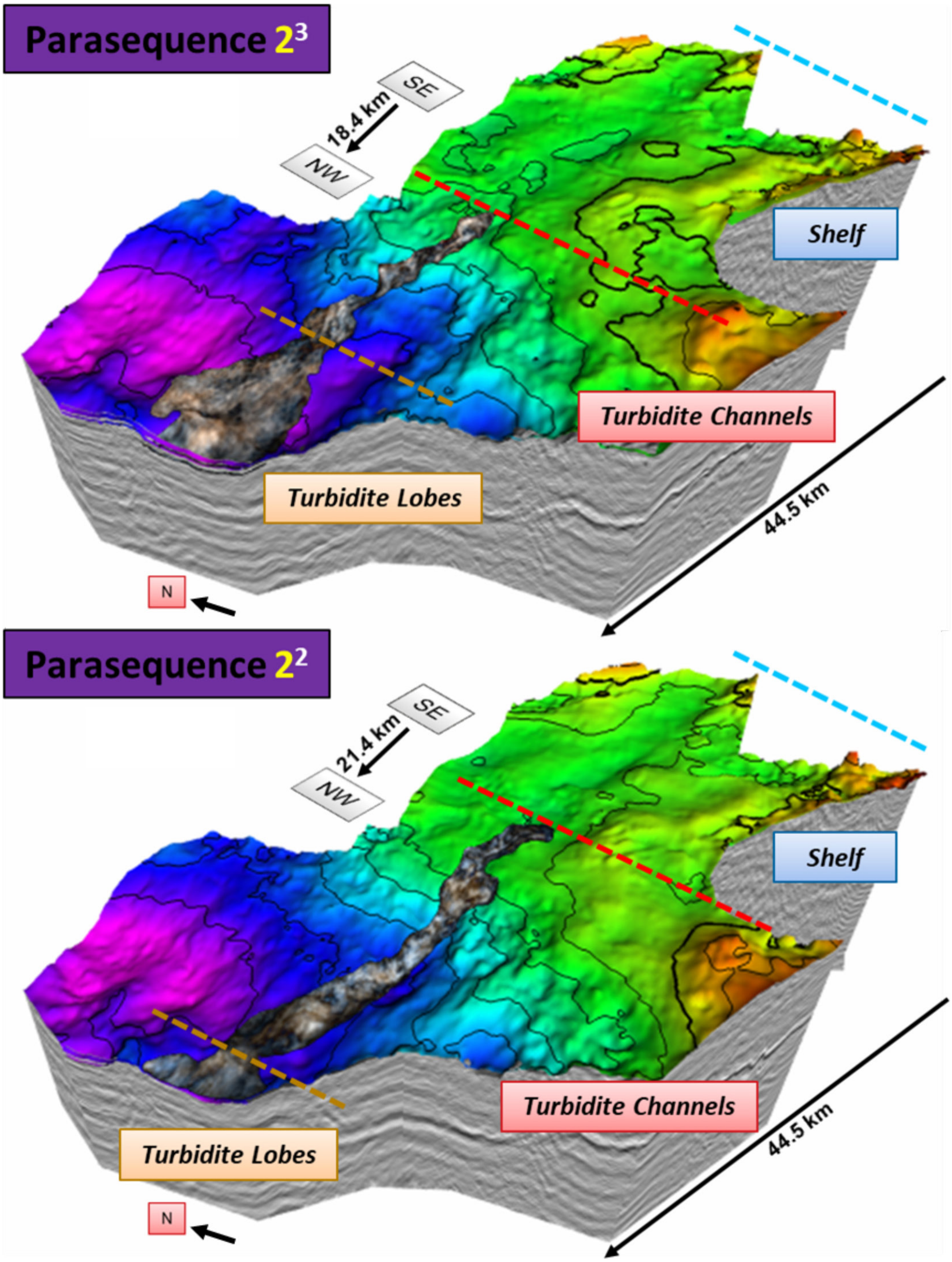

Figure 21. Kinematic of the two first growth phases of the identified turbidite system, all from the second Regressive Systems Tract of the stratigraphic model. Key depositional trend surfaces are mapped with topography (i.e. Z-value) and overlayed with RGB-blended magnitude signatures (31Hz, 36Hz, 41Hz) for parasequences 22 to 23. Key segments (canyon and channel-dominated zone, then lobe-dominated zone) are highlighted.

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