Geofísica Internacional (2026) **65-3**: 2223- 2238

The Usefulness of Seismic Attribute Mapping in the Interpretation of Submarine Channel Seismic Geomorphology: A Comparative Review

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Abstract

Submarine channels are major components that transport and store sediments across the continental margins that act as confined pathways for turbidity currents, facilitating sediment transfer from the shallow to the deep ocean and forming important sand-rich deposits with high hydrocarbon reservoir potential. Sedimentary processes are crucial for sculpting submarine channel morphologies and the building blocks of their architectural elements. This could be understood by seismic geomorphology analysis, which reveals the geological and geomorphological features through seismic data. Understanding the submarine channels through their morphology and architecture will help to build detailed geometry and evolution for further application, such as reservoir prediction, hydrocarbon migration and geological carbon storage. This review evaluates the effectiveness of seismic attributes in characterizing submarine channel geomorphology. This study examines 20 peer-reviewed articles published between 2016 and 2023 that applied seismic attribute analyses for geological interpretation of submarine channels. Seismic attributes such as RMS (root-mean square), variance, instantaneous frequency, sweetness, dip, curvature, coherence, and envelope were commonly applied in the reviewed case studies. Physical attributes highlight amplitude-related variations that may reflect lithological contrasts, depending on data calibration and depositional context, while geometrical attributes delineate channel margins and planform geometries and are strongly dependent on seismic data quality. In cases where single attributes are insufficient to clearly reveal channel geomorphology, additional analyses such as co-rendering and spectral decomposition were employed to enhance interpretation. This study confirms that seismic attributes provide reliable insights into submarine channel deposits, including possible lithological contrasts, channel boundaries, channel-belt morphology, and the distribution of sediment accumulations within channel systems. However, the accuracy of interpretation depends on seismic data quality and the geological understanding of the study area. Inadequate knowledge or poor-quality seismic data can lead to misapplication of attribute parameters and potential misinterpretation.

Key words: Seismic Interpretation, Seismic Attributes, Seismic Geomorphology, Submarine channels.

Resumen

Los canales submarinos son componentes principales que transportan y almacenan sedimentos a lo largo de los márgenes continentales, actuando como vías confinadas para las corrientes de turbidez, facilitando la transferencia de sedimentos desde aguas someras hacia el océano profundo y formando depósitos importantes ricos en arena con alto potencial como reservorios de hidrocarburos. Los procesos sedimentarios son fundamentales para modelar la morfología de los canales submarinos y los elementos arquitectónicos que los componen. Esto puede comprenderse mediante el análisis de geomorfología sísmica, el cual revela características geológicas y geomorfológicas a partir de datos sísmicos. El entendimiento de los canales submarinos a través de su morfología y arquitectura permite construir geometrías detalladas y su evolución, con aplicaciones en la predicción de reservorios, la migración de hidrocarburos y el almacenamiento geológico de carbono. Esta revisión evalúa la eficacia de los atributos sísmicos en la caracterización de la geomorfología de canales submarinos. El estudio analiza 20 artículos revisados por pares publicados entre 2016 y 2023 que aplican análisis de atributos sísmicos para la interpretación geológica de canales submarinos. Los atributos sísmicos como RMS (raíz cuadrática media), varianza, frecuencia instantánea, "sweetness", inclinación (dip), curvatura, coherencia y envolvente fueron comúnmente utilizados en los casos de estudio revisados. Los atributos físicos destacan variaciones relacionadas con la amplitud que pueden reflejar contrastes litológicos, dependiendo de la calibración de los datos y del contexto deposicional, mientras que los atributos geométricos delinean los márgenes de los canales y sus geometrías en planta, y dependen fuertemente de la calidad de los datos sísmicos. En los casos donde los atributos individuales no son suficientes para revelar claramente la geomorfología de los canales, se emplearon análisis adicionales como la co-visualización (co-rendering) y la descomposición espectral para mejorar la interpretación. Este estudio confirma que los atributos sísmicos proporcionan información confiable sobre los depósitos de canales submarinos, incluyendo posibles contrastes litológicos, límites de canal, morfología de los sistemas de canal y la distribución de las acumulaciones sedimentarias dentro de estos sistemas. Sin embargo, la precisión de la interpretación depende de la calidad de los datos sísmicos y del conocimiento geológico del área de estudio. Un conocimiento insuficiente o datos sísmicos de baja calidad pueden conducir a una aplicación inadecuada de los parámetros de atributos y a posibles interpretaciones erróneas.

Palabras clave: Interpretación sísmica, atributos sísmicos, geomorfología sísmica, canales submarinos.

Received: August 4, 2025; Accepted: April 27, 2026; Published on-line: July 1, 2026. https://doi.org/10.22201/igeof.2954436xe.2026.65.3.1910

Editorial responsibility: Dr. Davide Gamboa, University of Aveiro.

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1. Introduction

Submarine channels are important morphological and sedimentary systems observed across the continental slope to the deep. They facilitate sediment transport to the deep ocean by acting as confined pathways for turbidity currents and serving as significant sand reservoirs with high hydrocarbon potential (Pickering *et al.*, 1989; Deptuck *et al.*, 2007; Mulder *et al.*, 2012; Bouchakour *et al.*, 2024 and 2025). These channels exhibit a dynamic response to variations in seafloor topography (Posamentier and Kolla, 2003; Deb *et al.*, 2012; Gamboa *et al.*, 2012; Gamboa & Alves, 2015; Bouchakour *et al.*, 2022 and 2023). Over the past decade, submarine channels have been widely studied due to the expansion of hydrocarbon exploration and the technological evolution of data quality (Mayall *et al.*, 2006, 2010; Weimer *et al.*, 2007; Di Celma *et al.*, 2010) and their relevance in assessing geohazards (Bruschi *et al.*, 2006; Thomas *et al.*, 2010; Carter *et al.*, 2014). In addition, submarine channels can archive valuable sedimentological signatures and paleoclimatic information that provide insights into the processes governing their formation (Bouma, 2001; Brenchley *et al.*, 2006; Zühlsdorff *et al.*, 2007).

In many case studies, channel features are difficult to interpret properly due to poor seismic data quality, limited seismic resolution, and pitfalls of time slice interpretation (Clark and Pickering, 1996). The use of three-dimensional seismic data for interpretation of channel geomorphology is referred to as seismic geomorphology (Posamentier *et al.*, 2023). Seismic geomorphology plays a key role in identifying and mapping the distribution of seismic facies (Posamentier and Kolla, 2003; Posamentier, 2005). Seismic characteristics are obtained from seismic data parameters and measurements such as amplitude, frequency, and attenuation, as well as combinations of seismic attributes (Sheriff, 1994; Coren *et al.*, 2001; Chopra and Marfurt, 2007a). Various reflection properties, including amplitude, dip magnitude, dip azimuth, time/depth structure, and curvature, can be analyzed to generate direct images of features relevant to deposition and structural frameworks (Posamentier, 2004). Seismic attributes are useful both quantitatively and qualitatively. Quantitative applications involve predicting physical properties such as porosity or lithology (Leiphart & Hart, 2001; Sagan & Hart, 2006), while qualitative uses focus on identifying stratigraphic and structural elements (Hart, 2008). Over the past decades, advances in seismic data visualization techniques and increased calibration through well ties have enabled seismic attributes to provide valuable insights into geological structures, lithology, and stratigraphic channels (Taner, 2001; Chopra & Marfurt, 2007a; Azevedo & Pereira, 2009). Among their applications, the most critical is the extraction of information from raw seismic data that may not be immediately apparent (Anees, 2013). Although seismic attributes are widely used by both academic and industrial communities for geological and depositional interpretations, a number of uncertainties remain when applying different attributes across varying geological settings and datasets. Therefore, improving our understanding of seismic attribute behavior and systematically testing their usefulness is essential.

This review aims to comprehensively evaluate the application of various seismic attributes in interpreting channel system deposits within a seismic geomorphology framework. By synthesizing case studies from the Taranaki Basin, Gulf of Mexico, Gulf of Thailand, Levant Basin, Offshore Nile Delta, and Kribi-Campo Basin, this review highlights the specific roles, advantages, and limitations of each attribute type in resolving channel morphology and associated depositional features. The analysis also seeks to identify the most effective attributes for enhancing the detection, visualization, and characterization of submarine channels, thereby providing guidance for future exploration and geomorphological studies.

2. Material and Methods

This review was conducted using literature sourced from the Scopus database and reputable open-access journals. The literature search applied targeted keywords, including “seismic attribute” and “submarine channel” or “seismic geomorphology”, to prioritize studies explicitly addressing seismic-based attribute analysis within a seismic geomorphology framework, while maintaining a focused and reproducible review scope. This approach does not aim to provide an exhaustive compilation of all related studies, and additional relevant literature may exist beyond the selected keyword combinations. The keyword selection was designed to prioritize specificity over completeness; consequently, studies addressing geological processes without explicit seismic attribute analysis may not be fully represented. The inclusion criteria were as follows: (1) the article was written in English, (2) it was published between 2016 and 2023, and (3) it explicitly focused on seismic attributes and their application to submarine channel interpretation. The initial search retrieved 28 articles from the Scopus database and one additional article from an open-access journal. The selection of articles have been further optimized based on filtering works focusing on submarine channel interpretation and their sedimentological context using 3D seismic data. Following this process, a total of 20 articles were selected for this review. The scope of this review focuses on the utilization of seismic attributes for interpreting submarine channel deposits within a seismic geomorphology framework. The analysis addresses three main objectives: (1) identifying the types of seismic attributes used, (2) classifying the attributes according to their purposes in submarine channel characterization,

and (3) evaluating their relative usefulness and applicability for specific geomorphological and depositional objectives.

In this review, "usefulness" is defined in relation to the interpretation objectives established in this study, rather than the original objectives of the individual case studies. It refers to the capability of a seismic attribute to identify geological features based on a set of predefined interpretation purposes established in this study, as evidenced by their application in the published literature. The usefulness of each seismic attribute was evaluated using a qualitative binary scoring approach based on six predefined interpretation purposes including lithological variation and distribution, channel boundary identification, channel orientation, channel planform geometry, channel thalweg distribution, and channel-associated deposits. Channel-associated deposits include channel-fill sediments, levee–overbank deposits, and adjacent lobe or crevasse-splay deposits, which may be expressed in seismic attribute maps through variations in amplitude, continuity, and geometric patterns. For each attribute–purpose combination, a binary score of 1 was assigned when the applicability of the attribute to a given purpose was explicitly demonstrated or could be reasonably inferred from the interpretation results and discussion presented in the literature; otherwise, a score of 0 was assigned. The usefulness score was calculated as the sum of achieved purposes divided by the total number of purposes (six) and expressed as a percentage (%). The workflow of the review process is illustrated in Figure 1.

3. Results

The selected studies in this review employed a range of seismic attributes to characterize submarine channels. These include amplitude- and frequency-related attributes (e.g., RMS, envelope, sweetness, instantaneous frequency) as well as attributes that emphasize reflector continuity and geometry (e.g., coherence, variance, dip, and curvature) (Taner, 2001; Posamentier, 2004; Chopra and Marfurt, 2006; Chopra and Marfurt, 2007a; Subrahmanyan and Rao, 2008; Posamentier *et al.*, 2022). In most studies,

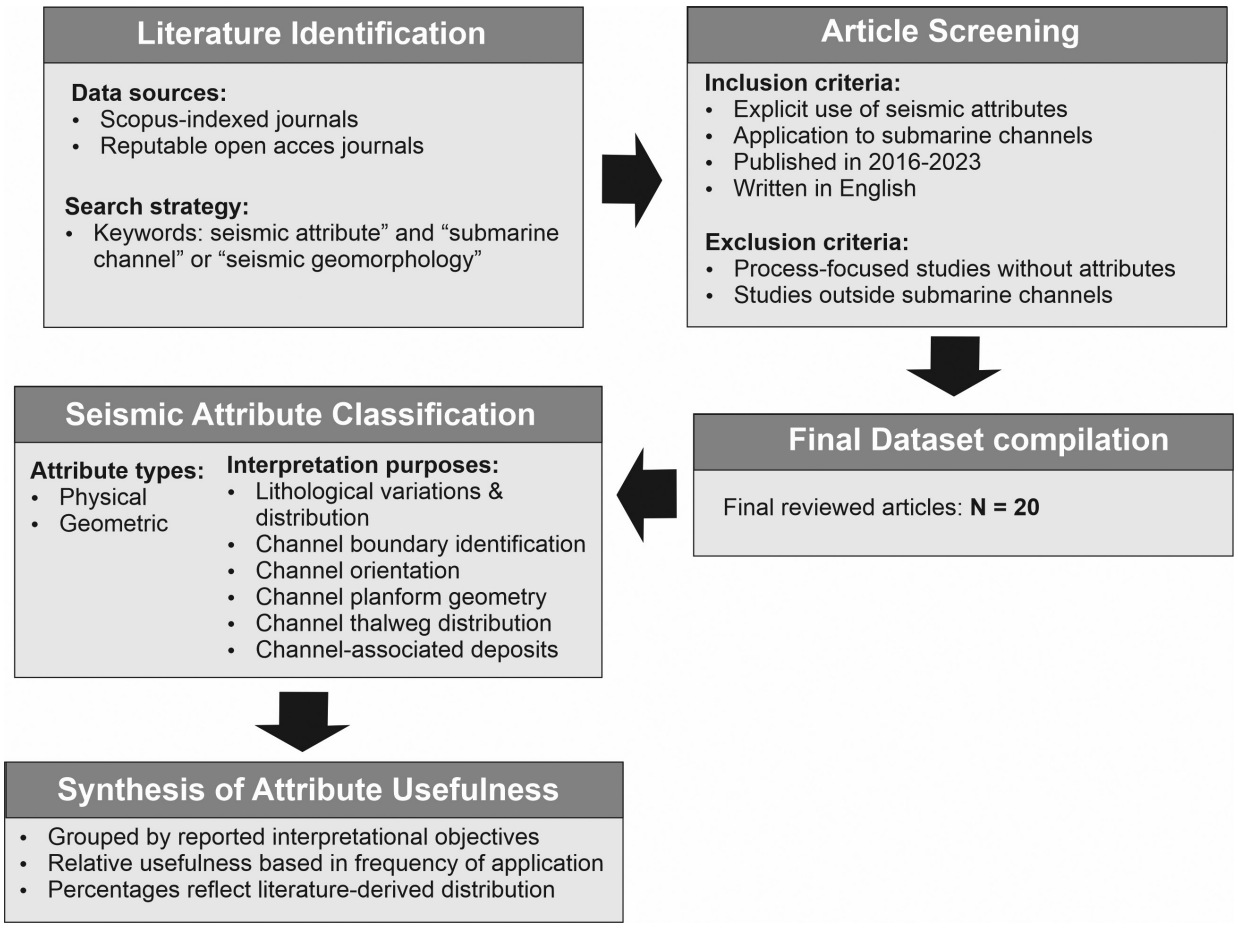

Figure 1. Integrated workflow illustrating literature identification, screening, chronological selection, classification, and synthesis of seismic attribute applications in submarine channel studies.

these attributes are not interpreted individually but are integrated to provide complementary insights into channel geomorphology, stratigraphic architecture, and associated lithological variability.

3.1. RMS Amplitude

RMS is calculated using the standard deviation, σ(t), of the seismic amplitude values, d(t), within a moving analysis window, where σ(t) quantifies the dispersion of amplitude values around their mean and thus provides a measure of reflectivity within that window (Taner, 2001; Chopra and Marfurt, 2007a; Brown, 2004; Posamentier *et al.*, 2022). The root-mean square (RMS) attribute enhances high-amplitude reflections within specific intervals or horizons, thereby aiding the delineation of channel-related depositional bodies and their planform geometries by highlighting the lateral distribution and continuity of amplitude features (Brown, 2004; Omosanya & Alves, 2013; Posamentier *et al.*, 2022). It is calculated in specific time windows around horizons where it reflects the signatures of reflection amplitudes and contrasts with background components (Posamentier *et al.*, 2022).

Figure 2a illustrates strong RMS attribute contrast within channel deposits. The channel is expressed by relatively higher RMS amplitudes, suggesting a lithological contrast with the surrounding lower-amplitude deposits, such as overbank or levee deposits. These are commonly associated with coarser- and finer-grained lithologies, which should be confirmed by well data calibration. The asymmetric distribution of high RMS amplitudes outside the channel margin further suggests preferential sediment accumulation related to channel-adjacent depositional processes, which may include overbank sedimentation and/or flow-stripping-related splay-like deposits. The sinuous channel system is highlighted by elevated RMS amplitudes along the channel thalweg and inner

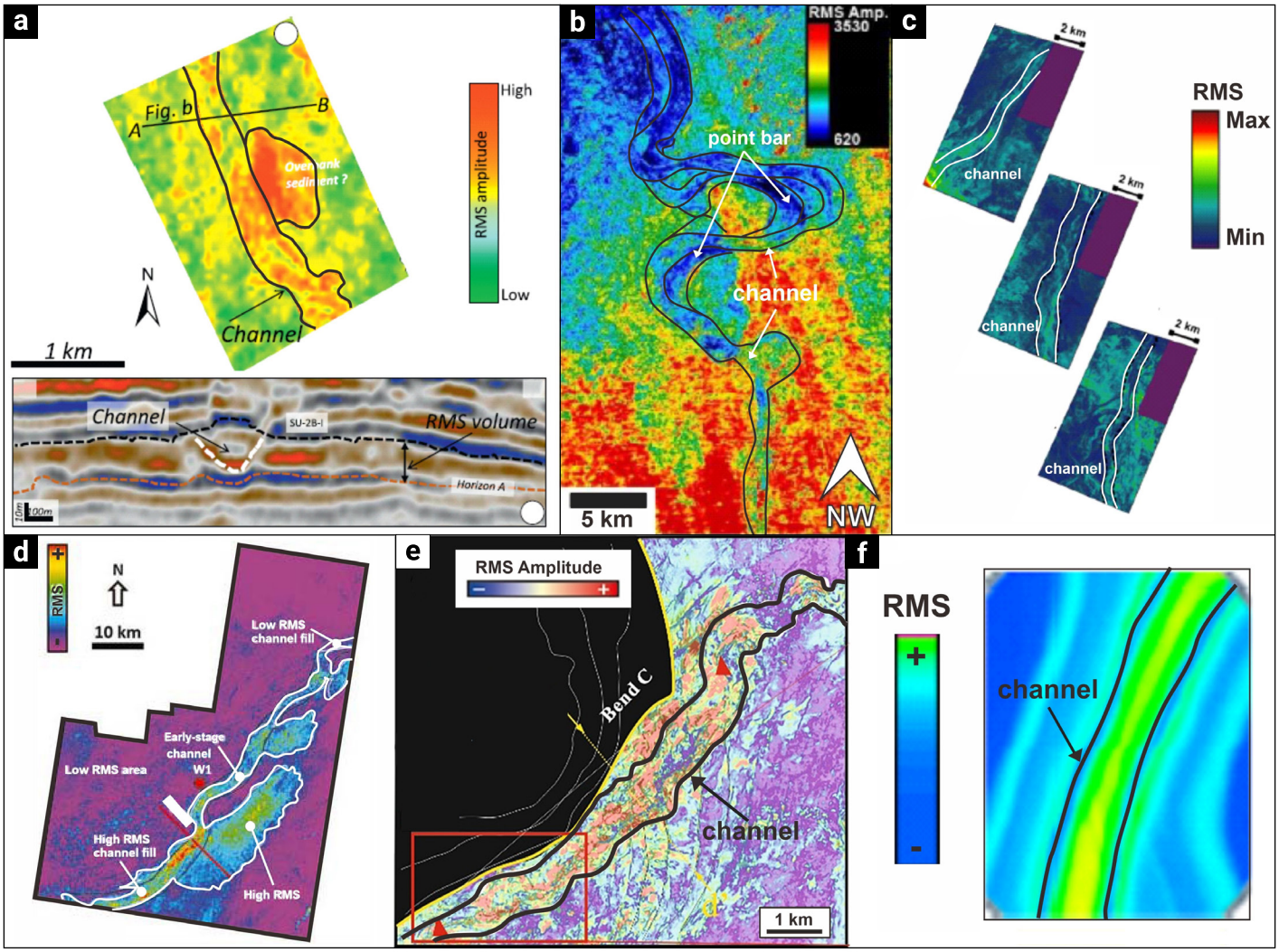

Figure 2. Submarine channel geometries highlighted by the RMS amplitude attribute, modified and compiled from previous studies: (a) Levant Basin (Niyazi *et al.*, 2018); (b) Taranaki Basin (Naewboonien, 2019); (c) Canterbury Basin (Harishidayat and Raja, 2022); (d) Kribi-Campo Basin (Gouott *et al.*, 2023); (e) Niger Delta (Bouchakour *et al.*, 2023); (f) Offshore New Zealand (La Marca *et al.*, 2023).

bends (Figure 2b). The high amplitude contrast suggests a different lithological composition between the channel body and overbank deposits, potentially reflecting sand-rich channel fills surrounded by fine-grained slope or overbank sediments. Localized amplitude enhancement at channel bends is interpreted to reflect variations in seismic response associated with changes in flow behavior along the curved channel pathway. Figure 2c illustrates relatively high RMS amplitudes confined within the channel margins, indicating a contrast in seismic response with the surrounding lower-amplitude channel-edge and overbank areas. The integration with dip-angle attributes further assists in delineating channel edges and internal stratigraphic boundaries associated with erosional surfaces. Figure 2d highlights along-channel variations in RMS amplitude that reflect temporal changes in channel infill. The channels are characterized by relatively high RMS amplitudes interpreted as sand-rich channel fills or possible sediment splays. Figure 2e shows a pattern of relatively high RMS amplitude values that can be interpreted as zones of preferential sand accumulation within the channel body. In contrast, Figure 2f shows a pronounced RMS amplitude contrast that clearly delineates channel boundaries, reflecting a sensitivity analysis performed at a smaller scale on individual channel elements within a channel complex (La Marca *et al.*, 2023), where channel geometry and attribute responses can be resolved more distinctly. Overall, these examples demonstrate that RMS amplitude is effective for lithological variation, channel boundary identification, channel trend delineation, and the interpretation of depositional elements within submarine channel deposits.

3.2. Envelope Amplitude

Envelope, also referred to as instantaneous amplitude, represents reflection strength independent of phase and highlights contrasts in acoustic impedance (Posamentier *et al.*, 2022). Essentially, this attribute primarily captures variations in acoustic impedance, that may reflect subsurface reflectivity associated with lithological contrasts, internal stratigraphic heterogeneity, and variations in bed thickness (Subrahmanyan and Rao, 2008). The envelope is effective for emphasizing discontinuities, seismic facies variations, faults, depositional changes, tuning effects, sequence boundaries, and areas of hydrocarbon accumulation such as bright spots. As an amplitude-based attribute, envelope extractions reflect differences in density and velocity, facilitating high contrast in values corresponding to lithological changes and clearer delineation of the channel bodies. Figure 3a shows the envelope attribute extracted along the mapped horizon, exhibiting relatively low envelope values within portions of the channel body. It may reflect reduced reflection strength and locally disrupted seismic continuity within a defined amplitude range. Such areas are interpreted to represent segments of the channel characterized by lower-amplitude seismic facies expression, associated with channel-related features such as channel margins and slump scars. In contrast, Figures 3b and 3c display envelope attributes extracted within a defined time window relative to the mapped horizon. These maps exhibit relatively high envelope values within the channel body, which are interpreted as sand-prone channel fills characterized by strong reflectivity. This interpretation is supported by calibration with well-log data, and the enhanced reflectivity facilitates the delineation of channel boundaries. The envelope also provides the amplitude context for other instantaneous attributes, particularly instantaneous frequency, which may become unstable in low-amplitude or noisy zones.

3.3. Instantaneous Frequency

Instantaneous frequency is computed as the time derivative of the instantaneous phase (Taner *et al.* 1979; Barnes 1991). The analytic signal also yields instantaneous amplitude (envelope), which is used to provide amplitude context for frequency interpretation. Subrahmanyam and Rao (2008) suggested that the instantaneous frequency attribute might reflect seismic-scale layer thickness and provide lithological insights. In some cases, it could be used to identify the thin-bed tuning effects and zones of abnormal seismic attenuation, where high-frequency energy is preferentially lost due to intrinsic absorption or scattering effects (Chopra and Marfurt, 2007a). Intrinsic absorption refers to energy loss caused by inelastic attenuation related to lithology, pore fluids, and rock properties, whereas scattering effects are triggered by small-scale heterogeneities such as thin interbedded sand–mud layers, erosional surfaces, or internal channel-fill complexity that redistribute seismic energy. Frequency-based seismic attributes are sensitive to seismic noise, and their application in stratigraphic and reservoir analysis remains limited in the industry. However, some studies have demonstrated their potential utility as part of an integrated attribute approach for identifying hydrocarbon-related indicators (Brown, 2011). As a physical attribute, the instantaneous frequency attribute has been shown to enhance the submarine channel features, including lithology prediction, depositional elements, and vertical layer thickness.

Figure 4a displays a channel pathway that is expressed by systematic variations in instantaneous frequency values relative to the surrounding background. The channel body is associated with contrasting frequency magnitudes, forming a continuous, sinuous pattern, while adjacent areas exhibit more uniform and laterally continuous frequency values. Figure 4b highlights that relatively lower instantaneous frequency values occur within

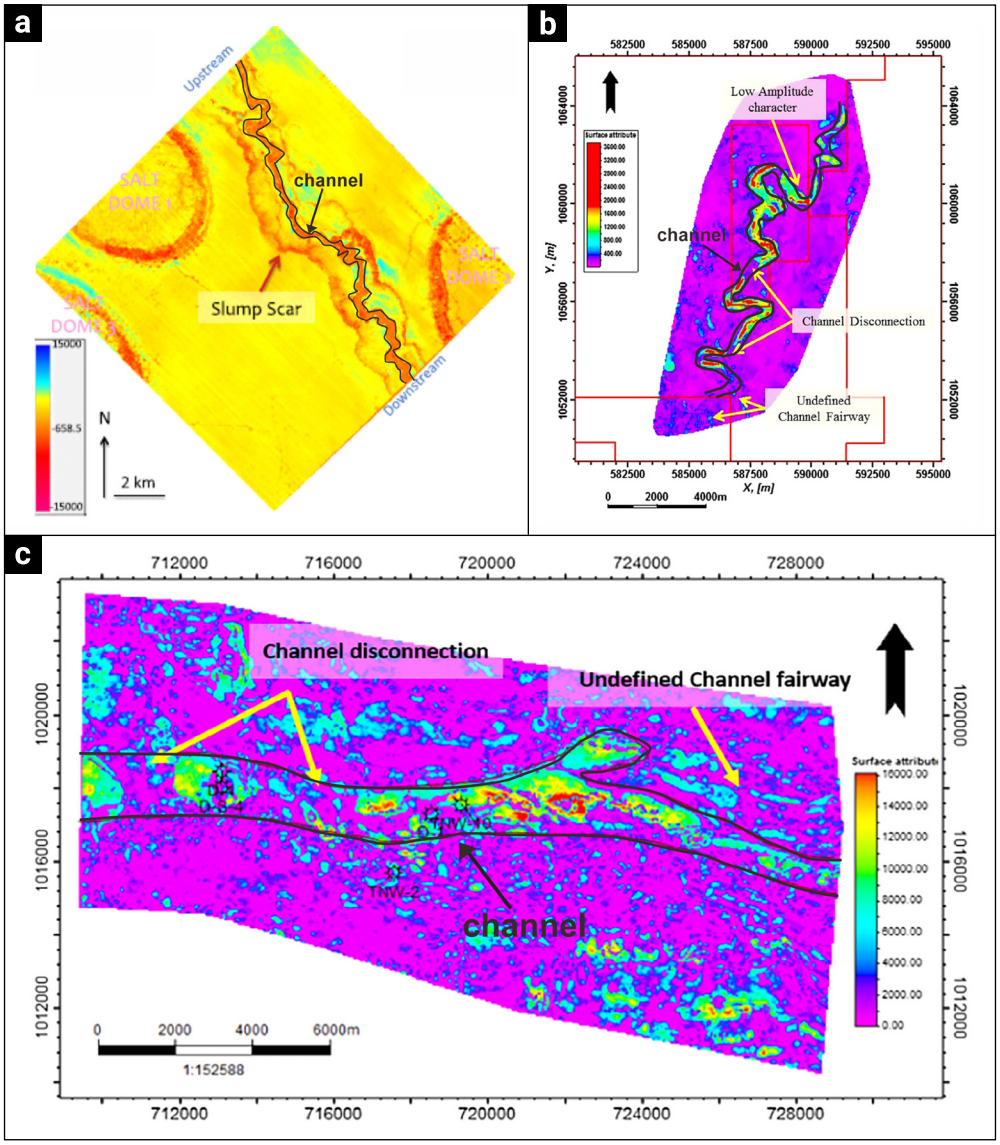

Figure 3. Submarine channel geometries highlighted by the envelope amplitude attribute modified and compiled from previous studies: (a) Gulf of Mexico (Carter *et al.*, 2016); (b) Nile Delta (Othman *et al.*, 2016); (c) Nile Delta (Othman *et al.*, 2018).

the channel body and display pronounced spatial variability. The instantaneous frequency attribute enhances internal variability within the channel body, which may be associated with thin-bedded successions and internal heterogeneities linked to lateral channel migration and stacking patterns, rather than primary channel boundaries. The channel margins are more clearly delineated by sharp contrasts between higher and lower instantaneous frequency values, indicating that frequency magnitude variations enhance the visibility of channel geometry (Figure 4c). In vertical section, the channel interval is characterized by higher and laterally variable frequency values compared to the surrounding background strata which display lower and more uniform responses, with localized low-frequency anomalies potentially indicating attenuation or stratigraphic complexity within the channel fill (Figure 4d).

3.4. Sweetness

Sweetness is a composite seismic attribute designed to emphasize high-amplitude, low-frequency responses commonly associated with thick, clean reservoir-prone intervals. It is computed by dividing the instantaneous amplitude (or amplitude envelope) by the square root of the instantaneous frequency (Radovich and Oliveros, 1998). This attribute could be used for sand-shale ratio prediction. However, it is not particularly useful when the contrast in acoustic impedance between these lithologies is low

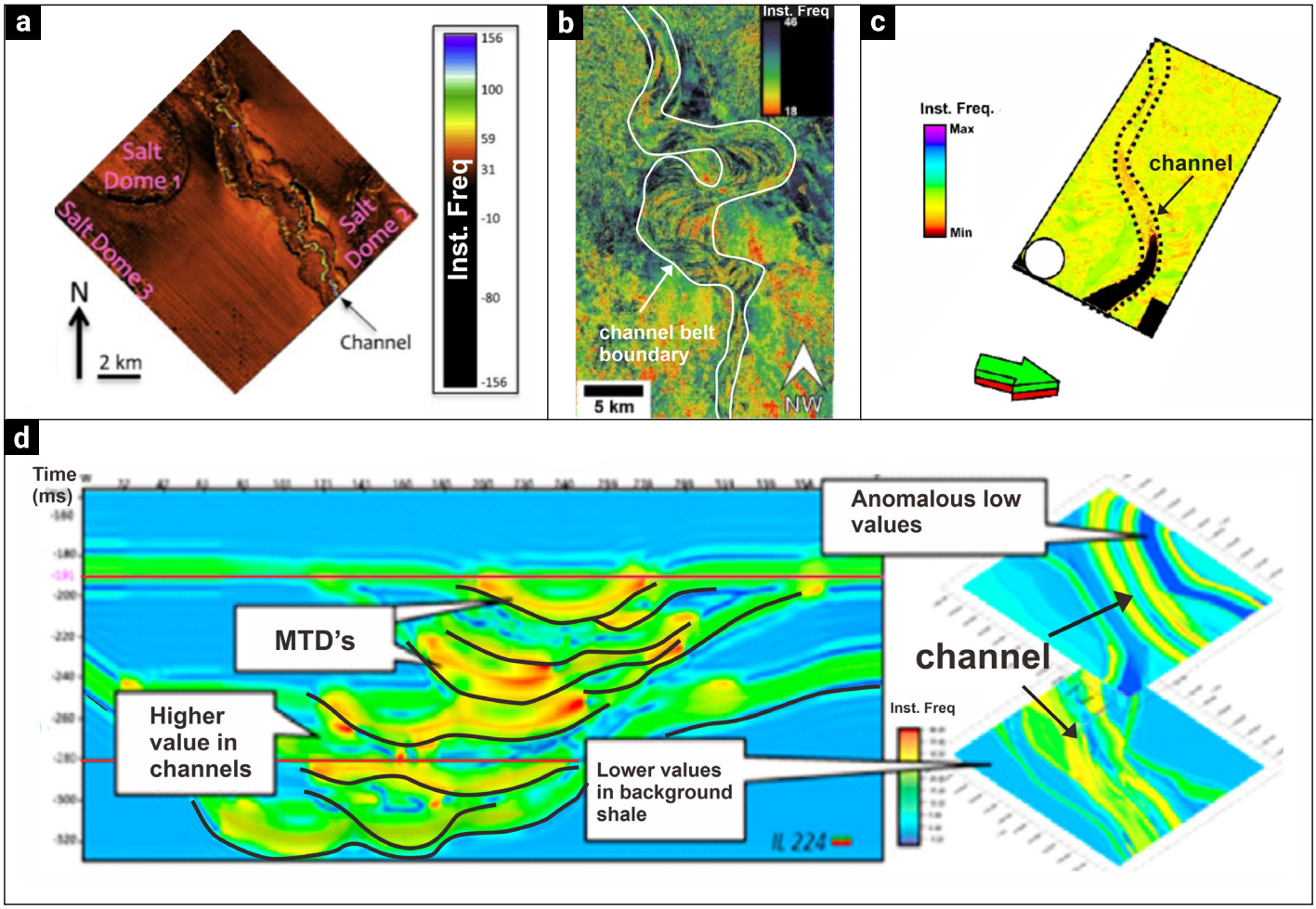

Figure 4. Submarine channel geometries highlighted by the instantaneous frequency attribute modified and compiled from previous studies: (a) Gulf of Mexico (Carter *et al.*, 2016); (b) Taranaki Basin (Naewboonien, 2019); (c) Canterbury Basin (Harishidayat and Raja, 2022); (d) Offshore New Zealand (La Marca *et al.*, 2023).

(Hart, 2008). Theoretically, identifying the sand and shale composition that forms some trend or channel features is a means to illustrate the channel features more easily. On the other hand, several authors combine the sweetness attribute with geometrical attributes (coherence) to identify submarine channels in more detail (Li *et al.*, 2017). The sweetness attribute becomes more effective for indicating potential pay zones when integrated with other seismic attributes, such as RMS amplitude, frequency, and phase, as demonstrated by Azeem *et al.* (2016) in the Sawan gas field, Pakistan. Figure 5a shows a plan-view sweetness attribute map in which the submarine channel body is characterized by relatively low to moderate sweetness values, consistent with a heterogeneous seismic response commonly associated with internally complex channel fills. In contrast, relatively higher sweetness values outside the channel zone correspond to a more uniform seismic character which may be associated with a more homogeneous lithological composition.

In Figure 5b, the alignment between the interpreted channel margins (dashed lines) and the sweetness contrast demonstrates that sweetness is a robust attribute for channel boundary delineation, particularly in areas where amplitude alone may be ambiguous due to noise or tuning effects. Figure 5c highlights internal variations in sweetness within the channel belt, suggesting heterogeneity within the channel fill, potentially related to changes in grain size, layer thickness, or stacking patterns of channel elements. Figure 5d illustrates a sweetness attribute extracted along a time-slice horizon intersecting the submarine channel and integrated with well data, seismic inversion, and AVO analysis. Relatively high-sweetness anomalies along the channel axis are interpreted as sand-prone channel fills, supported by the association of strong amplitudes and reduced frequencies. In contrast, low-sweetness regions away from the channel axis are interpreted as shale-dominated background deposits.

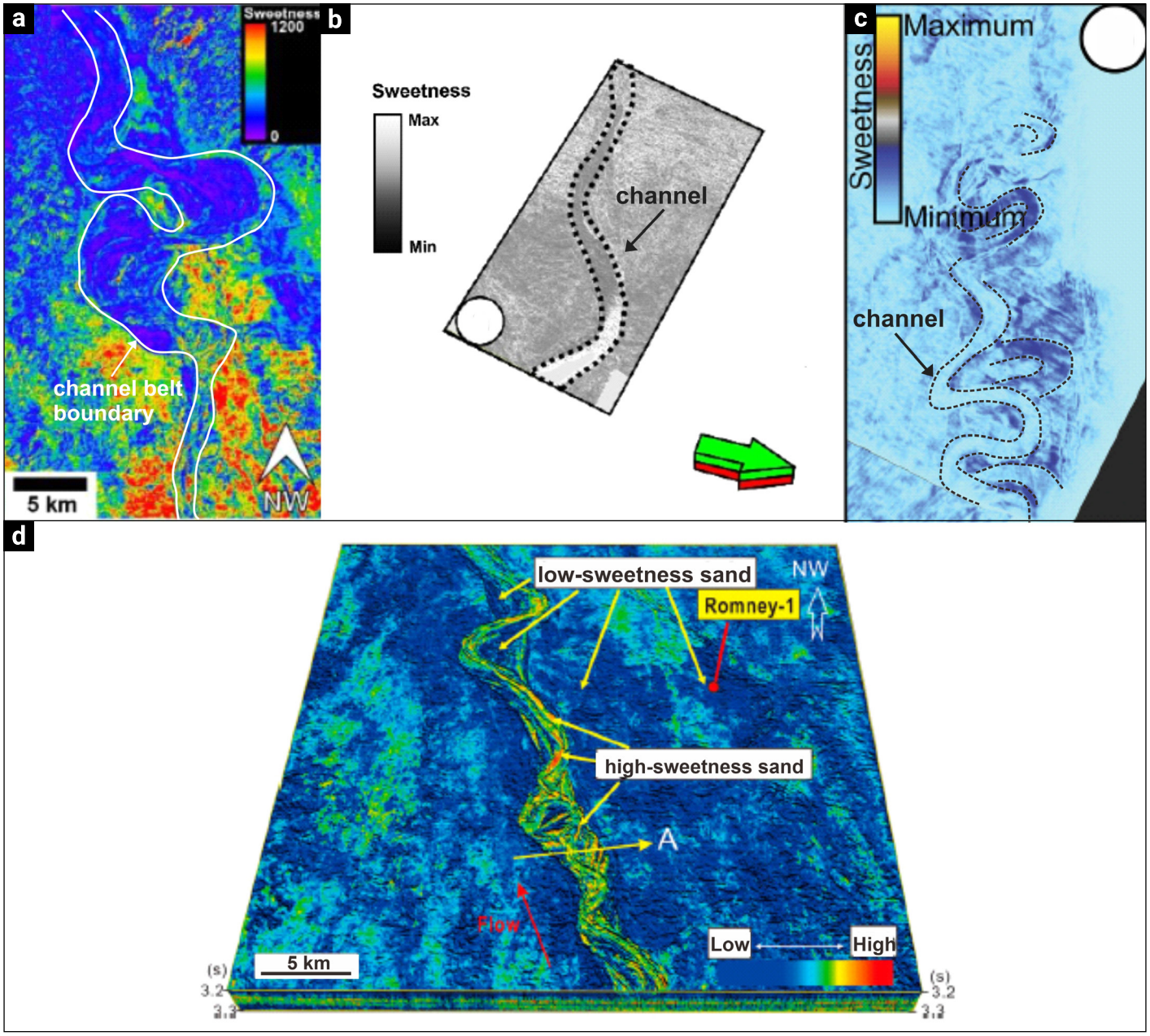

Figure 5. Submarine channel geometries highlighted by the sweetness attribute modified and compiled from previous studies: (a) Taranaki Basin (Naewboonien, 2019); (b) Canterbury Basin (Harishidayat and Raja, 2022); (c) Taranaki Basin (Larsen *et al.*, 2023); (d) Taranaki Basin (Li *et al.*, 2017).

3.5. Variance and Coherence

Variance and coherence are closely related seismic attributes that image lateral variations in seismic signals over horizons or intervals and are widely used to enhance structural and stratigraphic discontinuities (Posamentier *et al.*, 2022). They are fundamental to seismic interpretation and are commonly integrated with other attributes, such as RMS or RGB spectral decomposition, to improve the visualization of channel architectures and associated features, including mass-transport deposits (Almasgari *et al.*, 2020; Howlett *et al.*, 2022; Larsen *et al.*, 2023).. They are computed from trace-to-trace waveform similarity and statistical variability, whereby seismic traces across faults or stratigraphic discontinuities exhibit reduced similarity relative to surrounding, laterally continuous reflections (Bahorich and Farmer, 1995; Gersztenkorn and Marfurt, 1999). The primary distinction between the two attributes lies in their computational approach, where coherence relies on trace-to-trace similarity measures, whereas variance quantifies statistical dispersion within a defined analysis window. Variance quantifies local

dissimilarities in seismic signals, while coherence evaluates the degree of similarity between neighboring seismic traces (Posamentier *et al.*, 2022). Together, coherence and variance enhance the detection and visualization of seismic reflector discontinuities associated with faults and stratigraphic changes, delineating fault planes and channel margins across both horizon slices and vertical seismic sections.

These attributes are processed within a three-dimensional analysis window, this attribute quantifies trace-to-trace variability across a sample interval, enhancing lateral acoustic impedance contrasts associated with stratigraphic discontinuities such as channel belts and mass transport complex as demonstrated by Bouchakour *et al.* (2022). Higher variance values correspond to zones of increased discontinuity, for example where strong contrasts occur between the submarine channel belt axis and its bounding levees (Naewbonieen, 2019). In contrast, coherence typically exhibits low values along faults and stratigraphic boundaries, indicating geological discontinuities associated with lateral changes in seismic character (Li *et al.*, 2017). In terms of submarine channel identification, coherence provides better constraints in distinguishing the channel axis from the surrounding levee background compared to variance, as it is based on the similarity of seismic traces. Similarity-based coherence evaluates a short "mini-trace" in multiple directions, allowing systematic comparison with neighboring traces, which enhances sensitivity to subtle lateral changes in seismic character and typically results in more precise delineation of channel-related discontinuities (Posamentier *et al.*, 2022).

Previous studies demonstrate that variance and coherence attributes enhance the imaging of submarine channel architecture and are commonly used in combination with other seismic attributes to improve channel delineation (Deptuck *et al.*, 2007; Hansen *et al.*, 2017; Li *et al.*, 2017; Naewboonien, 2019; Gouott *et al.*, 2023; Larsen *et al.*, 2023; La Marca *et al.*, 2023; Silver and Bedle, 2021; Bouchakour *et al.*, 2025). Figure 6a shows that the variance attribute highlights high trace-to-trace variability along sinuous channel margins, delineating erosional boundaries and stepwise lateral channel shifting relative to the surrounding overbank deposits. Elevated variance values delineate channel edges and zones of internal architectural complexity, reflecting abrupt lateral changes in seismic character associated with channel incision and fill (Figure 6b). Figure 6c exhibits low variance values outlining the channel axis, with additional associated channel-related elements, whereas higher variance values may indicate internal variability within the channel fill. The coherence attribute exhibits pronounced low-coherence lineaments along channel margins, clearly defining channel boundaries and zones of lateral discontinuity within the submarine channel system as shown in Figure 6d and 6e. Figure 6f further demonstrates that coherence contrasts effectively image channel margins and erosional features, enabling detailed mapping of channel geometry.

3.6. Dip Attribute

The strike and dip of sedimentary layers are analogous to the magnitude and azimuth of the dip. Marfurt (2006) emphasizes that accurate estimation of reflector dip magnitude and azimuth (i.e., vector dip) constitutes the fundamental building block for geometric seismic attributes and structurally oriented filtering. Such estimates can be obtained using several approaches, including complex trace analysis, discrete vector dip scanning, and gradient structure tensor methods; reliable vector dip estimation further enables the calculation of coherent amplitude gradients along structural dip, thereby enhancing the delineation of subtle stratigraphic features such as channels expressed through lateral variations in thin-bed tuning. Compared to variance and RMS attributes, which primarily emphasize discontinuities and amplitude contrasts, dip attributes capture changes in reflector orientation, providing improved imaging of subtle structural features surrounding or crosscutting submarine channels, such as internal channel terraces. Dip magnitude represents the magnitude of the reflector's local slope, quantifying the steepness of the seismic reflector relative to the horizontal plane, with values ranging from 0 to 90. Dip azimuth defines the horizontal direction of the maximum reflector slope and corresponds to the azimuthal direction of the vector dip, typically measured clockwise from north or relative to the survey coordinate system. In terms of submarine channel characterization, dip attributes reveal increased reflector tilting along channel flanks, as well as a broad downstream gradient following the channel flow.

In recent quantitative workflows for submarine channel analysis, spatial variations in dip magnitude have been used to highlight structural gradients and localized deformation, aiding the identification of channel-bounding structural markers such as channel margins and bank failure–related features (Bouchakour *et al.*, 2025). Figure 7a exhibits systematic variations between low and high dip azimuth values that define the sinuous channel pathway, including meandering segments and shifts in channel orientation. These azimuthal contrasts emphasize channel curvature and inferred flow direction, while also revealing the influence of adjacent salt domes that locally deflect channel trajectories. The dip magnitude attribute shows higher dip angle values concentrated along the channel flanks, reflecting increased reflector tilting associated with channel incision and lateral relief, whereas lower dip magnitudes characterize the channel axis and produce a clear and continuous expression of the channel thalweg (Figure 7b).

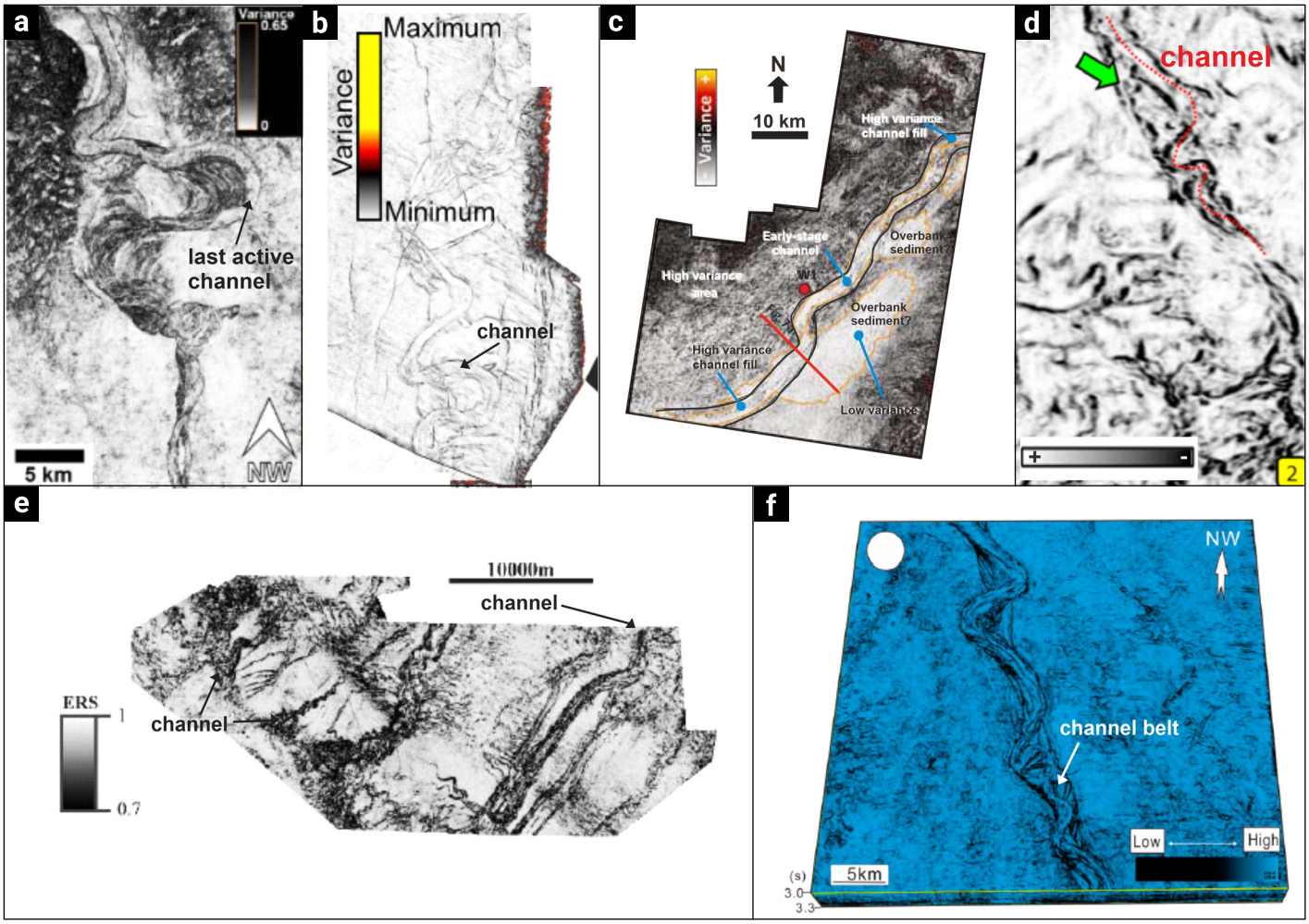

Figure 6. Examples of submarine channel identification using discontinuity-based seismic attributes, modified and compiled from previous studies: (a) variance attribute, Taranaki Basin (Naewboonien, 2019); (b) variance attribute, Taranaki Basin (Larsen *et al.*, 2023); (c) variance attribute, Karibi/Campo Basin (Gouott *et al.*, 2023); (d) coherence attribute, Offshore New Zealand (La Marca *et al.*, 2023); (e) coherence attribute (ERS is energy ratio similarity), Taranaki Basin (Silver and Bedle, 2021); (f) coherence attribute, Taranaki Basin (Li *et al.*, 2017).

3.7. Curvature

Curvature is a three-dimensional seismic attribute that represents the local second-order geometric variation of a surface, quantifying the degree to which a horizon deviates from planarity (Chopra and Marfurt, 2006; Chopra and Marfurt, 2007b). By minimizing the influence of regional dip, curvature analysis enhances subtle, small-scale surface irregularities that are commonly associated with primary depositional elements or minor structural features such as small-scale faults. However, curvature attributes are sensitive to disrupted seismic images or limited depositional continuity, where noise, reflector truncation, or poor imaging may generate spurious curvature anomalies and lead to misleading geological interpretations. This attribute enhances subtle geometric irregularities and abrupt changes in surface curvature, making it particularly effective for identifying minor structural flexures and fault-related deformation.

Curvature can be applied to surfaces or time slices and is also helpful for the stratigraphic analysis of features such as channel margins, reefs, compaction structures, and debris flows (Chopra & Marfurt, 2007b). Two main types of curvature exist: (1) maximum curvature (kmax), defined as the curvature of a circle with the smallest radius and representing the direction of the most pronounced surface bending, and (2) minimum curvature (kmin), which characterizes the curvature of a second circle oriented perpendicular to the kmax direction and corresponds to the least pronounced bending of the surface at that point (Al-Dossary and Marfurt, 2006; Chopra and Marfurt, 2007b). In seismic geomorphology, maximum curvature commonly accentuates sharp ridges and levee crests, whereas minimum curvature emphasizes channel axes and erosional troughs, making the combined analysis particularly effective for delineating channel geometry and subtle structural deformation (Chopra and Marfurt, 2006; Chopra and Marfurt, 2007b). Positive values in the

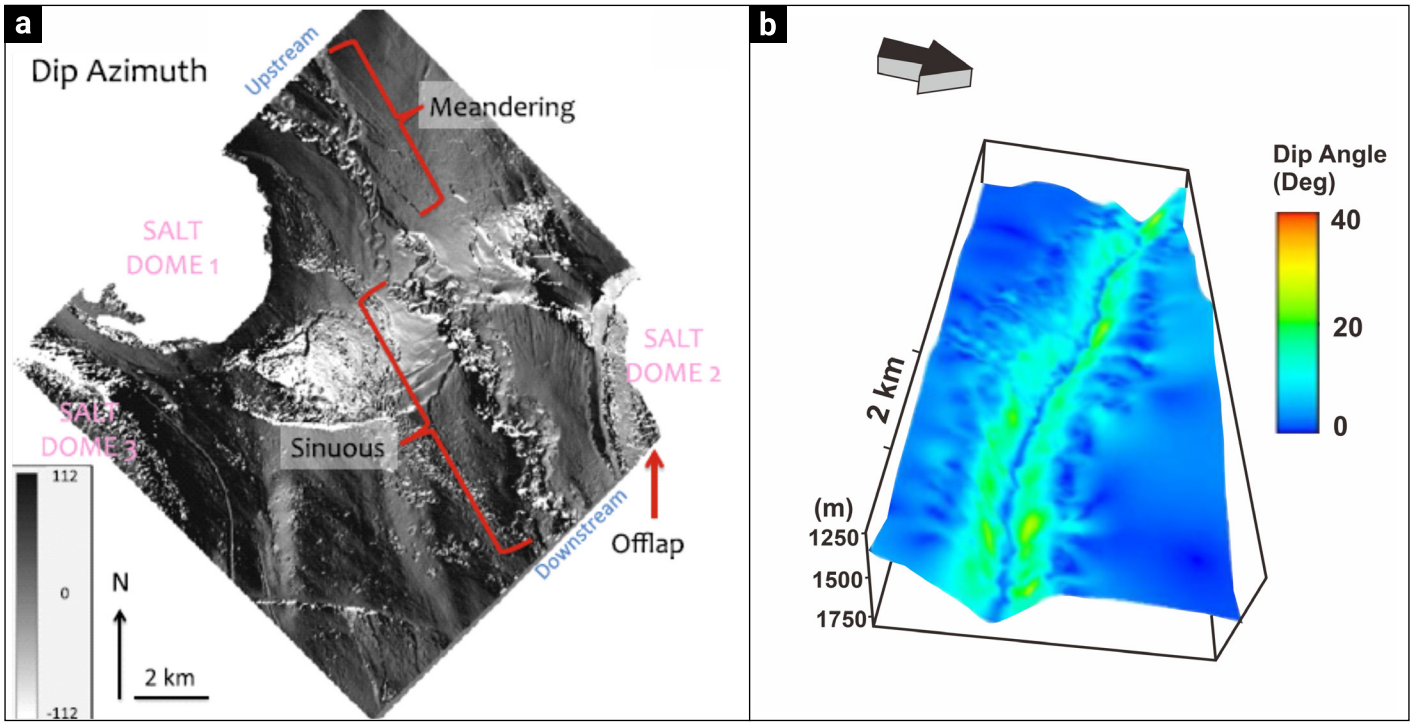

Figure 7. Dip attribute extraction for identifying submarine channels, modified and compiled from previous studies: (a) Gulf of Mexico (Carter *et al.*, 2016) and (b) Canterbury Basin (Harishidayat and Raja, 2022).

most-positive curvature (k1) highlight concave-down structures, including channel banks and levees, while negative anomalies in the most-negative curvature (k2) indicate concave-up features, such as the base of a channel (Figure 8a; Silver and Bedle, 2021). Figure 8b highlights the contrast between minimum and maximum curvature which enhances the geometric definition of the channel outline, allowing the channel pathway and boundaries to be accurately delineated.

4. Discussion

Since the 1990s, seismic attribute analysis has been increasingly applied to visualize and interpret submarine channel deposits within deep-water systems, with continued methodological development driven by advances in computerized seismic processing and interpretation technologies (Posamentier and Kolla, 2003; Chopra and Marfurt, 2007a; Mayall *et al.*, 2010; Mayall and Kneller, 2021; Bouchakour *et al.*, 2022; Bouchakour *et al.*, 2025). Many researchers have used specific attributes and have made combinations between them or have applied additional methods to enhance the visualization of channel features. For instance, spectral decomposition and RGB color blending (Partyka *et al.*, 1999; Chopra and Marfurt, 2007a; Carter *et al.*, 2016; Othman *et al.*, 2018; Almasgari *et al.*, 2020; Silver and Bedle, 2021; Bouchakour *et al.*, 2023; Kamaruzaman *et al.*, 2023). Spectral decomposition has been widely integrated with other seismic attributes to enhance the visualization of channel features by exploiting frequency-dependent seismic responses, particularly in areas with limited seismic imaging quality or subtle channel expression. This integration improves the identification of channel morphology and planform characteristics, as well as associated depositional elements in submarine channel systems. Other studies have applied co-rendering of two seismic attributes, typically integrating amplitude-based and discontinuity-based attributes, to enhance the visualization of channel features (Li *et al.*, 2017; Niyazi *et al.*, 2018; Naewboonien, 2019). Such integration provides effective visualization of channel features but generally relies on good seismic image quality and clear channel expression.

Table 1 highlights a synthesis of the reviewed literature, illustrating how different seismic attributes contribute to the identification of submarine channel deposits across various interpretation purposes, as reflected by their respective usefulness scores. The review qualitatively compares the effectiveness of seismic attributes in identifying channel features based on the usefulness score.

The usefulness scores highlight clear contrasts between amplitude-based, frequency-related, and geometric attributes in terms of their versatility and functional scope. Amplitude-related attributes, particularly RMS amplitude, exhibit the highest usefulness score (100%), indicating that they have been reported to support all predefined interpretation purposes. This reflects

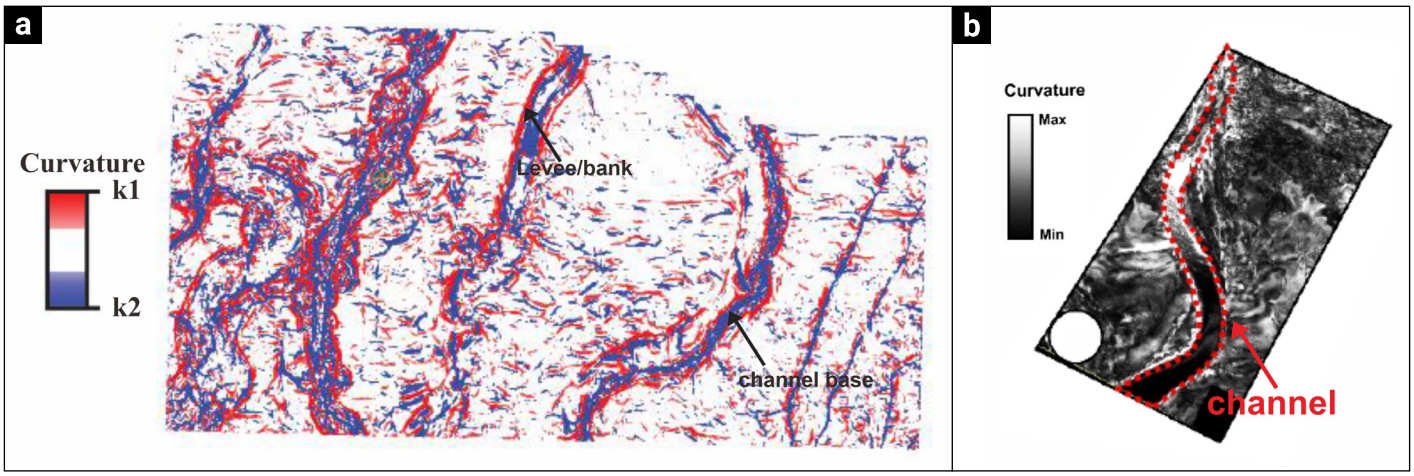

Figure 8. Curvature attribute extraction for identifying submarine channels, modified and compiled from previous studies: (a) Taranaki Basin (Silver and Bedle, 2021) and (b) Canterbury Basin (Harishidayat and Raja, 2022).

the well-established sensitivity of RMS amplitude to changes in lithology and impedance contrasts, which are fundamental to identifying channel boundaries, internal geometries, and associated depositional elements (Posamentier and Kolla, 2003; Chopra and Marfurt, 2007a; Bernhardt *et al.*, 2012; Posamentier *et al.*, 2022). The high applicability of RMS amplitude across studies underscores its role as a first-order attribute in submarine channel analysis, particularly in settings where sand–mud contrasts and stratigraphic variability are pronounced. Envelope amplitude and sweetness attributes also show high usefulness scores (83.3%), suggesting broad applicability, though dependent on geological and data quality context. This pattern indicates that amplitude-derived attributes are highly effective for outlining channel architecture and depositional elements but may be less consistently applied to more detailed geomorphological elements, depending on data resolution and depositional complexity. Although instantaneous frequency can assist in identifying lithological variations and channel-associated deposits, its application to channel trend delineation and thalweg interpretation remains inconsistent, indicating strong context dependence. This variability likely reflects the sensitivity of frequency attributes to tuning effects, attenuation, and noise, which can complicate their application in laterally heterogeneous channel systems. The high usefulness score of variance, coherence, and curvatures (83.3%) highlights their robustness in capturing lateral discontinuities and channel margins, whereas the lower score of dip attributes (66.7%) reflects their limited application in lithological prediction and channel-associated deposit identification.

These results highlight that geometrical attributes are most effective when integrated with physical attributes, underscoring the value of multi-attribute approaches in submarine channel interpretation (Chopra and Marfurt, 2006; Chopra and Marfurt, 2007a; Chopra and Marfurt, 2007b). Overall, physical attributes provide lithological context, whereas geometrical attributes define structural and morphological characteristics. Combining both types enhances overall interpretation, and the usefulness score provides guidance on selecting the most suitable attributes for specific geomorphological tasks. Attributes with lower usefulness scores should therefore not be interpreted as having inferior performance; rather, they reflect a relative scarcity of documented applications linking these attributes to specific interpretation purposes in the existing literature, highlighting opportunities for further methodological exploration.

5. Conclusion

This study investigated the usefulness of seismic attributes to visualize the morphologies of submarine channel systems and associated deposits within several areas, including Taranaki Basin, Gulf of Mexico, Gulf of Thailand, Levant Basin, Offshore Nile Delta, offshore Niger Delta, and Kribi-Campo Basin. The method used a qualitative review of 20 articles, which applied different techniques and attributes to their analysis. Generally, two types of seismic attributes were used according to Taner's (2001) classification: physical attributes and geometrical attributes. Physical attributes include RMS amplitude, sweetness, envelope, and instantaneous frequency, whereas, geometrical attributes are variance, coherence, dip attribute, and curvature.

Physical attributes, particularly amplitude-based measures such as RMS amplitude, exhibit the broadest reported applicability across lithological, architectural, and depositional elements, highlighting their strong depositional usefulness in characterizing submarine channels and associated deposits. In contrast, geo-

Table 1. The summary of seismic attribute application by interpretation purposes and their usefulness score.

No	Name of Attribute	Type of Attribute (Taner, 2001)	Interpretation purposes	Binary score	Usefullness score (%)
1	RMS Amplitude	Physical	Lithological variations and distribution	1	100
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	1	
			Channel-associated deposits	1	
2	Envelope Amplitude	Physical	Lithological variations and distribution	1	83.3
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	0	
			Channel-associated deposits	1	
3	Instantaneous Frequency	Physical	Lithological variations and distribution	1	66.7
			Channel boundary identification	1	
			Channel orientation	0	
			Channel planform geometry	1	
			Channel thalweg distribution	0	
			Channel-associated deposits	1	
4	Sweetness	Physical	Lithological variations and distribution	1	83.3
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	0	
			Channel-associated deposits	1	
5	Variance & Coherence	Geometrical	Lithological variations and distribution	0	83.3
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	1	
			Channel-associated deposits	1	
6	Dip attribute	Geometrical	Lithological variations and distribution	0	66.7
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	1	
			Channel-associated deposits	0	
7	Curvature	Geometrical	Lithological variations and distribution	0	83.3
			Channel boundary identification	1	
			Channel orientation	1	
			Channel planform geometry	1	
			Channel thalweg distribution	1	
			Channel-associated deposits	1	

metrical attributes primarily enhance the delineation of channel boundaries, trends, and planform geometries, demonstrating pronounced morphological usefulness by capturing lateral discontinuities and channel-scale geometry rather than detailed lithological variations.

These results underscore that robust interpretation of submarine channel systems requires a purpose-driven integration of physical and geometrical attributes rather than reliance on any single attribute type. The direct application of individual seismic attributes may not always be sufficient and often requires complementary analyses such as attribute co-rendering, parameter tuning, and spectral decomposition. Overall, any interpretation method depends on seismic data quality and geological conditions. Therefore, strong geological understanding is essential in seismic interpretation and the use of the seismic attributes.

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