

Fault network of a buried rift-related structural high: insights from multiscale 3D seismic analysis

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ABSTRACT

Rift-related structural highs are widespread features of passive margins and foreland basins, where they exert first-order control on structural compartmentalization, stratigraphic architecture, and fluid migration. Despite their importance, the fault network architecture and damage distribution of buried highs are rarely constrained at the seismic scale because most examples are either deeply buried or strongly overprinted by later deformation. Once mainly investigated for hydrocarbons, structural highs are increasingly considered potential sites for CO₂ storage and geothermal exploitation. Here we analyze the Gaggiano High, a buried Mesozoic structural high in the Western Po Plain (Italy), where limited Miocene inversion preserved the original extensional framework. We apply a multiscale 3D seismic workflow that integrates manual fault interpretation, throw-length scaling analysis, and curvature-derived lineament extraction. This approach allows us to characterize both seismic-scale faults and sub-seismic damage patterns. The fault system is dominated by N–S striking, east-dipping normal faults, complemented by NW–SE and subordinate E–W structures. Throw-length relationships show slopes between 1.1 and 1.4, with systematically higher throw-to-length ratios in deeper intervals, indicating mature and long-lived faults. Sub-seismic lineament analysis reveals a spatial anti-correlation between displacement and lineament intensity. Low-throw fault segments, linkage zones, and intersections coincide with lineament intensity peaks, consistent with distributed strain accommodation. These results demonstrate that inherited faults remained mechanically relevant throughout the tectonic evolution of the Gaggiano High, controlling the distribution of both seismic-scale displacement and sub-seismic damage. Our study highlights the value of multiscale seismic analysis for reconstructing fault–fracture architecture and for predicting strain localization and potential fluid-flow pathways in buried structural highs.

1. Introduction

Rift-related structural highs are prominent features of many passive continental margins and foreland basins worldwide, including the Alpine–Apennine domain (e.g., Bertotti et al., 1993; Schönborn, 1992), the Pyrenees–Cantabrian system (e.g., Lescoutre and Manatschal, 2020), the North Atlantic Margin (Shannon et al., 1995), the North Sea (e.g., Pegrum and Spencer, 1990), and the Porcupine Basin (Saqab et al., 2021). These highs are the product of extensional faulting, but their original geometry is commonly modified during subsequent compressional phases. As a result, most preserved examples are either buried (e.g., Santantonio et al., 2013) or overprinted by later deformation (e.g., Cardello and Doglioni, 2015; Schönborn, 1992), which hampers the

reconstruction of their original architecture. Nevertheless, structural highs play a fundamental role in controlling deformation style, stratigraphic architecture, subsurface compartmentalization, and fluid-flow pathways during the long-term evolution of foreland domains (e.g., Bertello et al., 2010; Butler et al., 2006; Spencer and Larsen, 1990; Livani et al., 2018; Tavani et al., 2021; Zappaterra, 1994). Traditionally investigated as prime targets for hydrocarbon exploration (e.g., Bertello et al., 2010; Zappaterra, 1994), structural highs are now increasingly considered in the context of the energy transition, particularly as potential sites for CO₂ storage and geothermal exploitation (e.g., Mulrooney et al., 2020; Soldo et al., 2020).

For this reason, the characterization of fault networks affecting rift-related structural highs is essential. Fault architecture and associated

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damage zones influence the partitioning of strain between localized slip and distributed deformation, thereby controlling subsurface permeability, fluid circulation, diagenetic processes, and mechanical anisotropy (e.g., Childs et al., 1995; Kim and Sanderson, 2005; Peacock and Sanderson, 1991; Trippetta et al., 2017). Seismic attributes such as coherency, variance, and curvature allow the identification of discontinuities below classical seismic resolution and provide quantitative proxies for damage distribution (Neves et al., 2004; Chopra and Marfurt, 2007; Iacopini and Butler, 2011; Gao, 2013; Alaei and Torabi, 2017; Boersma et al., 2020). In recent years, data-driven methods have also been applied to fracture identification and prediction in tight carbonate reservoirs (e.g., Dong et al., 2022). The characterization of the fault and fracture network in structural highs is particularly valuable where subsequent tectonic overprints have been limited, allowing the extensional framework to be preserved. The Gaggiano High, buried below the Western Po Plain (Italy), represents such a case: Oligocene–Miocene inversion was mild, and the structure retains key elements of its original rift-related architecture (Fantoni et al., 2004; Turrini et al., 2016, 2018). This makes it an excellent natural laboratory to analyze the relationship between fault geometry, displacement, and sub-seismic damage in a buried structural high.

Rift-related structural highs have been extensively investigated in terms of their tectono-stratigraphic evolution, structural inheritance, and inversion history (e.g., Bertotti et al., 1993; Fantoni et al., 2004; Santantonio et al., 2013; Turrini et al., 2016). However, the detailed geometry and scaling behaviour of the fault network bounding these structures have received comparatively less attention. This study addresses this gap by analysing the fault network that borders a well-preserved buried structural high through a multiscale seismic approach. We combine seismic-scale fault interpretation and throw-length scaling with curvature-derived lineament extraction at sub-seismic scale to investigate how strain is partitioned between localized displacement and distributed damage across stratigraphic intervals.

This was done to provide a multiscale characterization of fault architecture and sub-seismic damage in a buried rift-related structural high, with implications for structural inheritance, strain localization, and subsurface fluid-flow prediction.

2. Geological setting

The Gaggiano structure is located in the Western Po Plain (Fig. 1A). This area was originally part of the passive continental margin of Adria, developed during the Mesozoic rifting associated with the breakup of Pangea (e.g., Bertotti et al., 1993; Castellarin et al., 1992; Winterer and Bosellini, 1981). Subsequently, the interaction between the Eurasian plate and the Adria microplate led to the formation of the Alpine and Apenninic orogenic belts diachronously, starting in the Cretaceous and the Eocene–Oligocene, respectively (e.g., Carminati and Doglioni, 2012; Dercourt et al., 1986). The Neogene Po Plain foreland basin simultaneously acts as the foredeep of the Northern Apennines and the foreland of the Southern Alps (the retro-belt of the Alps) (Carminati et al., 1997; Handy et al., 2010; Turrini et al., 2014, Fig. 1A). The Apennines slab retreat generated the main accommodation space of the Po Plain basin with subsidence rates exceeding 1 mm/yr during the Plio-Pleistocene (Cuffaro et al., 2010). This double-verging system generated a complex tectonic setting, where Mesozoic extensional structures are variably reactivated or preserved beneath a thick Cenozoic–Quaternary cover ((Cassano, 1986) Doglioni, 1993; Doglioni and Prosser, 1997; Fantoni and Franciosi, 2010; Mariotti and Doglioni, 2000; Pieri and Groppi, 1981; Turrini et al., 2014). The Gaggiano High represents one of these preserved Mesozoic structural highs buried in the Po Plain.

2.1. Rift- and drift-related tectonics

During the Mesozoic, the Western Po Plain was part of the passive

continental margin of Adria (Bertotti et al., 1993; Castellarin et al., 1992; Winterer and Bosellini, 1981). Rift-related successions unconformably overlie the Hercynian basement and include Permian to Triassic continental to shallow-marine deposits locally intercalated with Triassic volcanic and volcanoclastic deposits, Upper Triassic platform carbonates, and Jurassic–Cretaceous pelagic carbonates (Bertotti et al., 1993; Cassano, 1986; Schumacher et al., 1997). The stratigraphy was segmented by ~ N–S striking extensional faults that shaped the Lombardy Basin, with intervening intra-basinal highs and lows (Bertotti et al., 1993; Bosellini, 1973; Fantoni and Franciosi, 2010). Syn-rift activity started at least in the Middle Triassic (Fantoni and Franciosi, 2010; Schumacher et al., 1997), peaked in the Late Triassic–Early Jurassic (Bertotti et al., 1993; Bosellini, 1973; Schumacher et al., 1997), and was followed by post-rift subsidence with consequent deposition of a thick Jurassic–Cretaceous succession (Carminati et al., 2010; Fantoni and Franciosi, 2010; Fantoni and Scotti, 2003). The ~ N–S striking extensional structures define the architecture of the Gaggiano High.

2.2. Contractional tectonics

Subsequent convergence produced only limited inversion of the extensional fault network bounding the Gaggiano High. While Late Cretaceous to Miocene compression strongly reactivated neighbouring structures as for example the Lacchiarella structure (Fantoni et al., 2004; Turrini et al., 2016, Fig. 1B), the Gaggiano High experienced comparatively mild deformation, mostly expressed as gentle tilting and modest displacement along inherited N–S faults. In contrast to the Gaggiano High, the adjacent Lacchiarella structure represents a former Mesozoic depocenter that underwent significant positive inversion during Neogene compression (Fantoni et al., 2004; Turrini et al., 2016). There, seismic profiles show a thickened stratigraphic succession preserved in the hanging wall of a steep W-verging thrust, indicating a partial reactivation of a pre-existing extensional basin. This inversion resulted in the structural uplift of the former basin fill and highlights the contrasting tectonic evolution between the Lacchiarella basin and the weakly reactivated Gaggiano High.

Flexural subsidence in the Western Po Plain promoted the accumulation of thick pelagic to hemipelagic successions, progressively burying the Mesozoic highs (Fantoni et al., 2004; Fantoni and Franciosi, 2010). Oligocene–Miocene contraction locally inverted some Mesozoic extensional structures, but did not obliterate the original rift architecture of the Gaggiano High (Fantoni et al., 2004). In addition, Paleogene extensional tectonics produced NW–SE striking normal faults (late Eocene to Oligocene), which are clearly imaged in the seismic dataset and locally control thickness variations and damage patterns. The NW–SE striking normal faults have been related to the development of volcanic edifices in the Mortara area (Fantoni et al., 1999; Fantoni and Franciosi, 2010, Fig. 1A). The limited overprint of later deformation is a key factor that allows the Gaggiano High to preserve its rift-related extensional framework while recording the influence of younger fault sets that contribute to its present-day fault architecture and damage distribution.

2.3. Stratigraphy of the Gaggiano High

Three wells, including Gaggiano–1 (Bongiorni, 1987), drilled on the crest of the Gaggiano High document a condensed stratigraphic record (Fig. 2). The succession consists of Upper Permian–Lower Triassic continental to evaporitic deposits (Lombard Verrucano, Servino, Carniola di Bovegno Fms), overlain by Middle Triassic shallow-marine and volcanoclastic successions (Perledo Varenna and Lierna Fms), and capped by Jurassic and Cretaceous pelagic limestones (Fig. 2). The succession is characterized by significant hiatus, particularly in the Upper Triassic and Lower to Upper Jurassic, reflecting the structural position of the high. From the Eocene onwards, pelagic carbonates are overlain by marls, hemipelagic mudstones, and the siliciclastic infill of the Po Plain

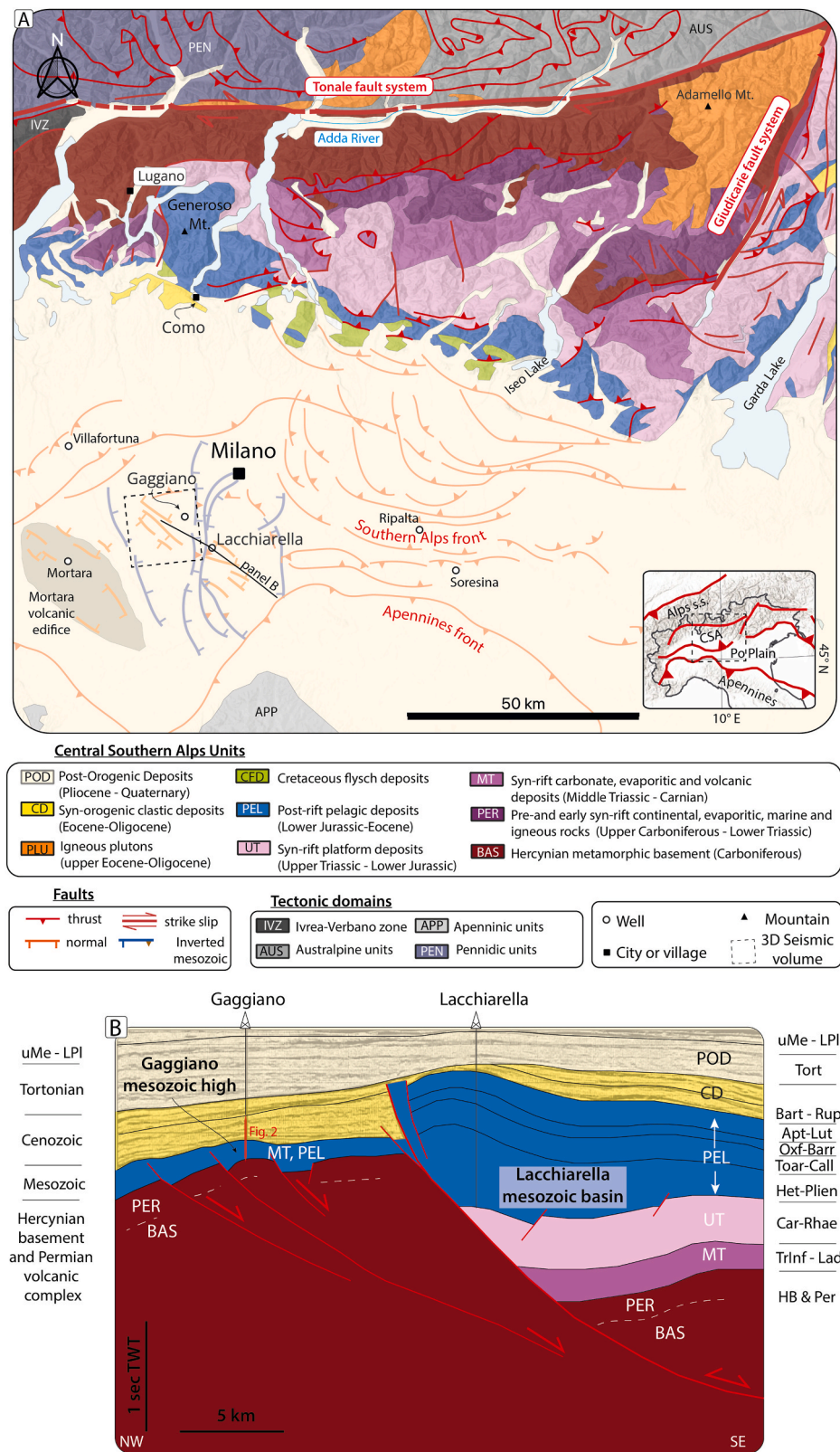


Fig. 1. Geological setting of the study area. (A) Simplified geological map of the area shown in the bottom right inset, comprising the Central Southern Alps (CSA) and Western Po Plain (modified from Bigi et al., 1989). The map highlights buried structures beneath the Neogene-Quaternary sediments of the Po Plain, hydrocarbon exploration wells (modified from Fantoni et al., 2004), and tectonic domains. The location of the 3D seismic volume is indicated. (B) Interpreted seismic section across the Gaggiano structure, highlighting the contrast between the Gaggiano Mesozoic high and the Lacchiarella Mesozoic basin, along with key stratigraphic units and fault systems.

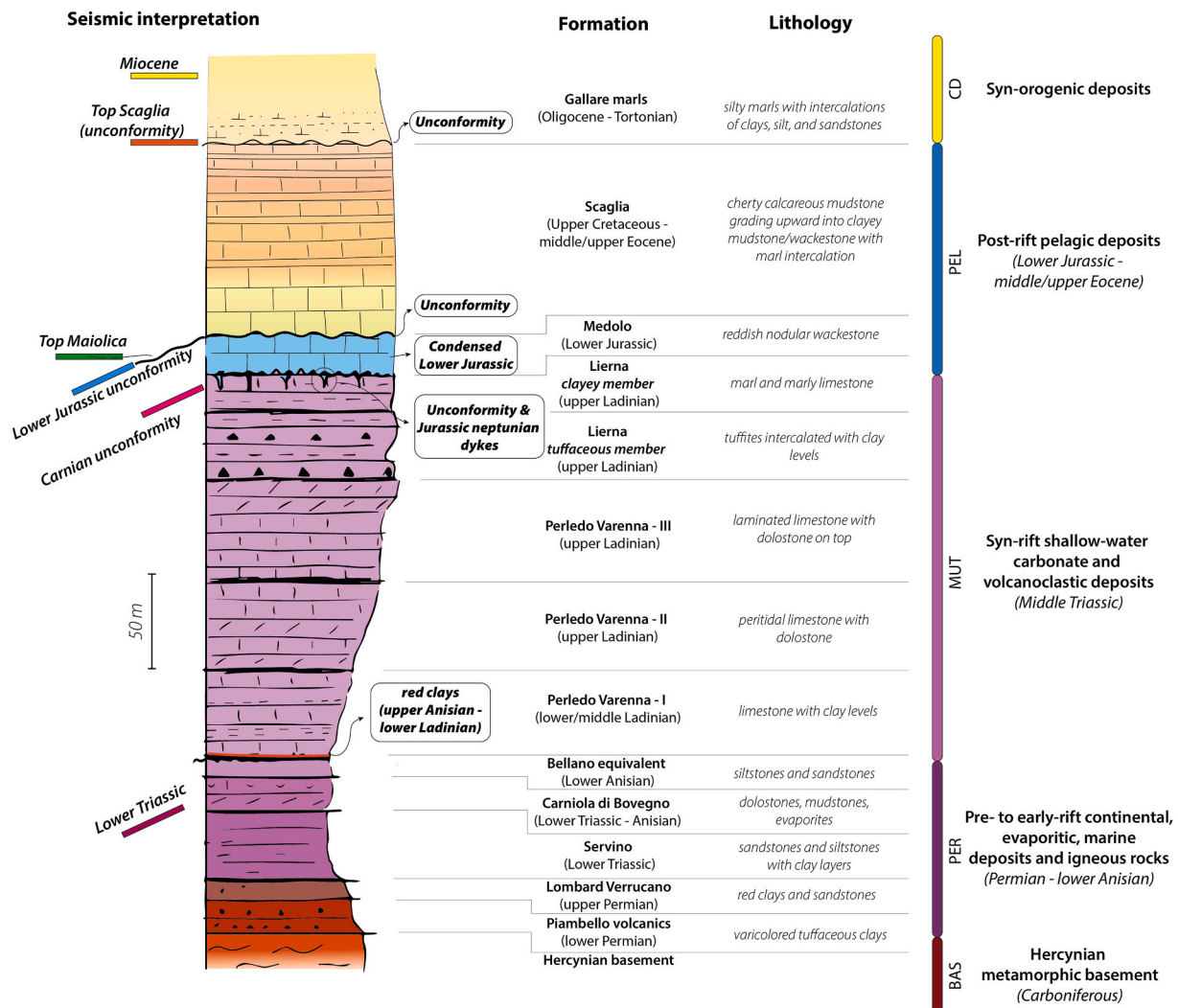


Fig. 2. Simplified stratigraphic column of the upper Permian - Miocene interval from the Gaggiano-1 well (see location in Fig. 1). Key stratigraphic horizons interpreted from the 3D seismic volume are indicated on the left. Abbreviations for stratigraphic units (e.g., BAS, PER, MUT) are the same as in Fig. 1A. Modified from Bongiorno (1987) and Cairo and Ronchi (1995).

(Bongiorno, 1987; Fantoni et al., 2004). This stratigraphy, combined with limited Neogene reactivation, results in a structural configuration where inherited normal faults remain clearly visible in seismic data across multiple stratigraphic intervals.

3. Data and methods

3D seismic interpretation was performed on a seismic volume covering a 14 km × 13 km map area in the Gaggiano region (see location in Fig. 1A). The Gaggiano seismic volume was acquired by Agip (currently Eni) in the late 1980s and consists of 578 inlines trending approximately N-S and 419 crosslines trending approximately E-W (Agip, 1987). The TWT-to-depth conversion was performed using a 3D velocity model developed by Eni, based on well calibration and time-migrated seismic data. The model was implemented and applied in Petrel as part of the structural interpretation workflow.

Seismic interpretation was carried out using Petrel software by picking six key horizons, which, from bottom to top, correspond to the following stratigraphic intervals: Lower Triassic, Carnian Unconformity, Lower Jurassic Unconformity, Top Maiolica, Top Scaglia, Miocene (Figs. 2 and 3). These horizons were selected based on different criteria: Carnian Unconformity, Lower Jurassic Unconformity, and Top Scaglia horizons correspond to unconformities or major discontinuities, while

Lower Triassic, Top Maiolica, and Miocene horizons were chosen for their high seismic reflectivity, making them easily identifiable in the seismic volume. Horizon interpretation was performed every 10 inlines (300 m) and every 10 crosslines (250 m). All seismic horizons, except for Top Maiolica, were tied to well data by correlating their intercepts with the three wells drilled along the crest of the Gaggiano High. The wells are all located in the most elevated portion of the structure, aligned approximately along a N-S trend, with the northernmost and southernmost wells spaced about 1.5 km apart in map view.

In our multiscale workflow, we explicitly distinguish between two structural scales: (i) major faults, manually interpreted in the seismic volume, which represent mappable faults with throw resolvable at seismic scale, and (ii) sub-seismic lineaments, automatically extracted from curvature attributes, which act as proxies for damage (i.e., fractures and small-scale faults) below seismic resolution.

3.1. Major fault analysis

A total of 86 major faults were digitized during seismic interpretation. To analyze the fault network affecting the Gaggiano structure, all faults and horizons were used as inputs to build a structural model using the specific functionality available in Petrel (Fig. 3). The structural model allowed for the extraction of fault orientations, fault throw values

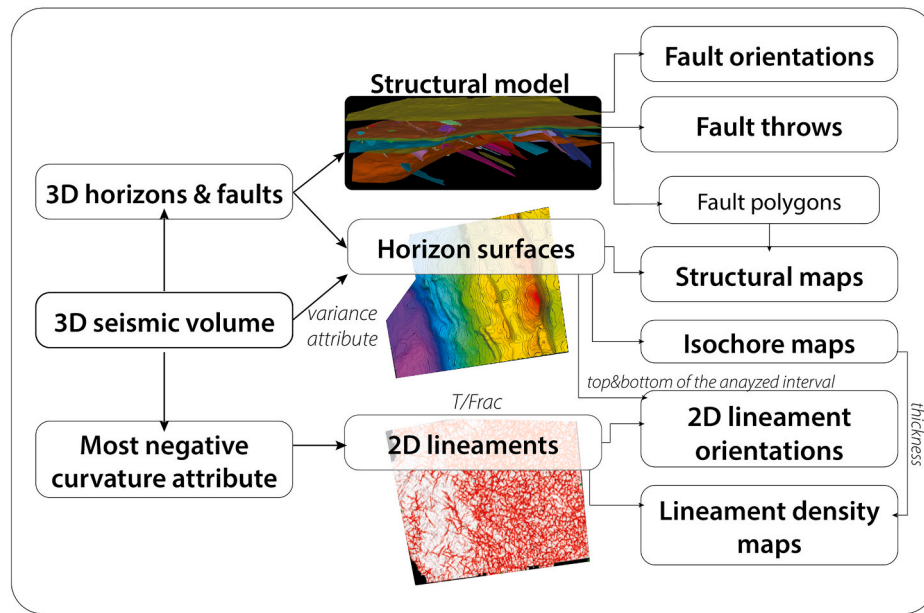


Fig. 3. Data and methods workflow. Schematic representation of the workflow adopted in this study, illustrating the extraction of structural features from the 3D seismic volume, the generation of horizon and fault surfaces, and the derivation of 2D lineaments from seismic curvature attribute.

for each horizon across the fault network, and fault polygons (i.e., the portion of a fault bounded by the hanging wall and footwall cutoffs). Additionally, throw vs. distance maps (Barnett et al., 1987; Walsh and Watterson, 1988) were generated to better visualize the spatial variation of throw along the faults.

To investigate the spatial and temporal evolution of the fault network, structural maps were generated for different seismic horizons. The interpreted horizons were first converted into 3D surfaces (grids), providing a detailed representation of the geometry of each stratigraphic level. These surfaces were then combined with the fault polygons from the structural model to generate structural maps (Fig. 3), which depict the fault network affecting each horizon. The structural maps were color-coded based on depth and integrated with variance attribute maps (Fig. 3), which enhance the visualization of structural discontinuities, including faults and fracture corridors that were not manually interpreted (e.g., Weert et al., 2025). Variance attributes are widely used to highlight lateral discontinuities in seismic reflectors and to improve fault imaging, particularly in structurally complex settings. From these surfaces, isochore maps were also constructed for selected stratigraphic intervals (Fig. 3). These maps were used to qualitatively assess thickness variations potentially controlled by fault activity.

To quantify fault growth parameters, fault length and maximum throw were calculated for each fault segment defined by its hanging wall and footwall cutoffs, as extracted from the 3D structural model. Fault length was measured in map view, while maximum throw was calculated for each stratigraphic horizon by sampling the throw distribution along fault surfaces. For each fault, we computed the ratio T/L between maximum throw (T) and fault length (L) (e.g., Kim and Sanderson, 2005; Lathrop et al., 2022; Walsh and Watterson, 1988). The resulting dataset was analysed separately for five seismic horizons (Lower Triassic, Carnian Unconformity, Lower Jurassic Unconformity, Top Maiolica, and Top Scaglia), and linear regressions were fitted in log-log space to explore scaling relationships between T and L . Regression parameters (slope, intercept, R^2) were extracted along with 95% confidence intervals and standard errors.

3.2. Sub-seismic lineament analysis

We extracted sub-seismic lineaments from the 3D seismic volume by applying the T/Frac workflow (Magistroni et al., 2014), an Eni

proprietary methodology based on established principles of seismic attribute analysis. The method relies on the assumption that lineaments visible on structural seismic-attribute (e.g., coherency, curvature) slices represent the expression of medium to large-scale tectonic discontinuities below seismic resolution (Fig. 3). The workflow enhances curvature extrema on closely spaced depth slices and automatically extracts laterally continuous high-curvature trends using amplitude and geometric continuity thresholds, grouping them into linear segments for subsequent statistical analysis (Magistroni et al., 2014). This procedure implies that curvature-derived lineaments do not represent individual fractures directly, but rather the cumulative seismic expression of distributed deformation zones. These may include minor faults, fracture corridors, or flexural bending of reflectors. Their detection is influenced by seismic resolution, signal-to-noise ratio, and reflector continuity. Moreover, curvature anomalies may locally reflect stratigraphic or imaging artefacts unrelated to tectonic deformation. For these reasons, lineaments are interpreted here as geometric proxies for sub-seismic damage patterns, and their distribution is analysed in a statistical and spatial sense rather than as one-to-one representations of discrete fractures. For this study, 99,388 lineaments were extracted by analyzing the Most Negative Curvature seismic attribute on 40 m-spaced depth slices. These slices were grouped into two stratigraphic sequences: Top Scaglia–Lower Jurassic Unconformity and Lower Jurassic Unconformity–Lower Triassic. The orientation of the extracted lineaments was analysed using rose diagrams, while their spatial distribution was evaluated through maps displaying the areal lineament density (i.e., P20) and areal lineament intensity (i.e., P21) parameters (Sanderson and Nixon, 2015), computed on a $50\text{ m} \times 50\text{ m}$ grid, normalized by the vertical thickness of each interval.

To further explore the relationship between fault throw and lineament intensity, we extracted local P21 values along selected regional fault traces within a 200 m wide across-strike corridor (100 m on each side of the fault trace). In detail, we selected two faults, taken as representative of the two main orientation sets (i.e., N-S and NW-SE striking). This analysis was performed separately for the two stratigraphic intervals (Lower Triassic–Lower Jurassic Unconformity and Lower Jurassic Unconformity–Top Scaglia), and results were compared with the corresponding vertical throw measured along the same faults.

4. Results

4.1. Seismic interpretation and structural model

4.1.1. Fault geometry and structural architecture

The interpreted dataset reveals a fault system composed of 22 N-S striking ($\sim 340^\circ\text{--}010^\circ$) E-dipping faults, 15 antithetic W-dipping faults, and 49 subsidiary E-W to NW-SE striking structures (Fig. 4A). The E-dipping N-S faults are the longest (up to 8–10 km), show the highest throws (up to ~ 900 m) and define the main structural framework of the Gaggiano High, bounding the westward tilted fault blocks that extend down to the Lower Jurassic Unconformity (Fig. 4). Antithetic faults are $< 5\text{--}6$ km long and show smaller throws (less than ~ 300 m) (Fig. 4B–D). The E–W faults are minor, mostly confined between N–S structures, and characterized by throws ≤ 100 m (Fig. 4C). NW–SE faults are longer (up to 5 km), with maximum throws of ~ 180 m, and locally crosscut or branch from the N–S system (Fig. 4B–D).

The main fault, located in the eastern sector of the seismic volume, strikes N–S and dips eastward (Fig. 4B–D). It reaches a maximum throw of ~ 900 m at the Lower Triassic horizon and displacement progressively decreases upward (Fig. 4B–E). Detailed along-strike throw variations and quantitative displacement analyses are presented in section 4.1.3.

Seismic crosslines indicate dominant normal kinematics, although deeper units locally display reverse offsets (Fig. 4B–D). Small-scale contractional anticlines occur in the hanging wall of some extensional faults suggesting limited inversion or buttressing (Fig. 4B–D).

The interpreted horizons highlight stratigraphic–structural relationships. The Lower Jurassic Unconformity is tilted and truncated by the main N–S fault, whereas younger horizons (e.g., Top Maiolica) show onlap geometries against the structural high (Fig. 4B–D). In places, Top Maiolica terminates in toplap against Top Scaglia, which drapes the crest of the structure (Fig. 4B–D). The Miocene horizon dips to the SSW, recording mild Neogene tilting of the Gaggiano High (Fig. 4B–D).

4.1.2. Structural and isochore maps

Variance attribute maps delineate the main fault network and additional minor structures, not captured by manual interpretation (Fig. 5, left column). Structural maps (Fig. 5, middle column) confirm the predominance of eastward dipping $\sim$ N–S to NNW–SSE striking faults, accompanied by subordinate NW–SE and E–W structures. Isochore maps (Fig. 5, right column) reveal thickness variations that reflect the progressive tectono-stratigraphic evolution of the Gaggiano High.

The Lower Triassic–Carnian Unconformity interval exhibits marked thickness changes along N–S faults, consistent with block tilting during

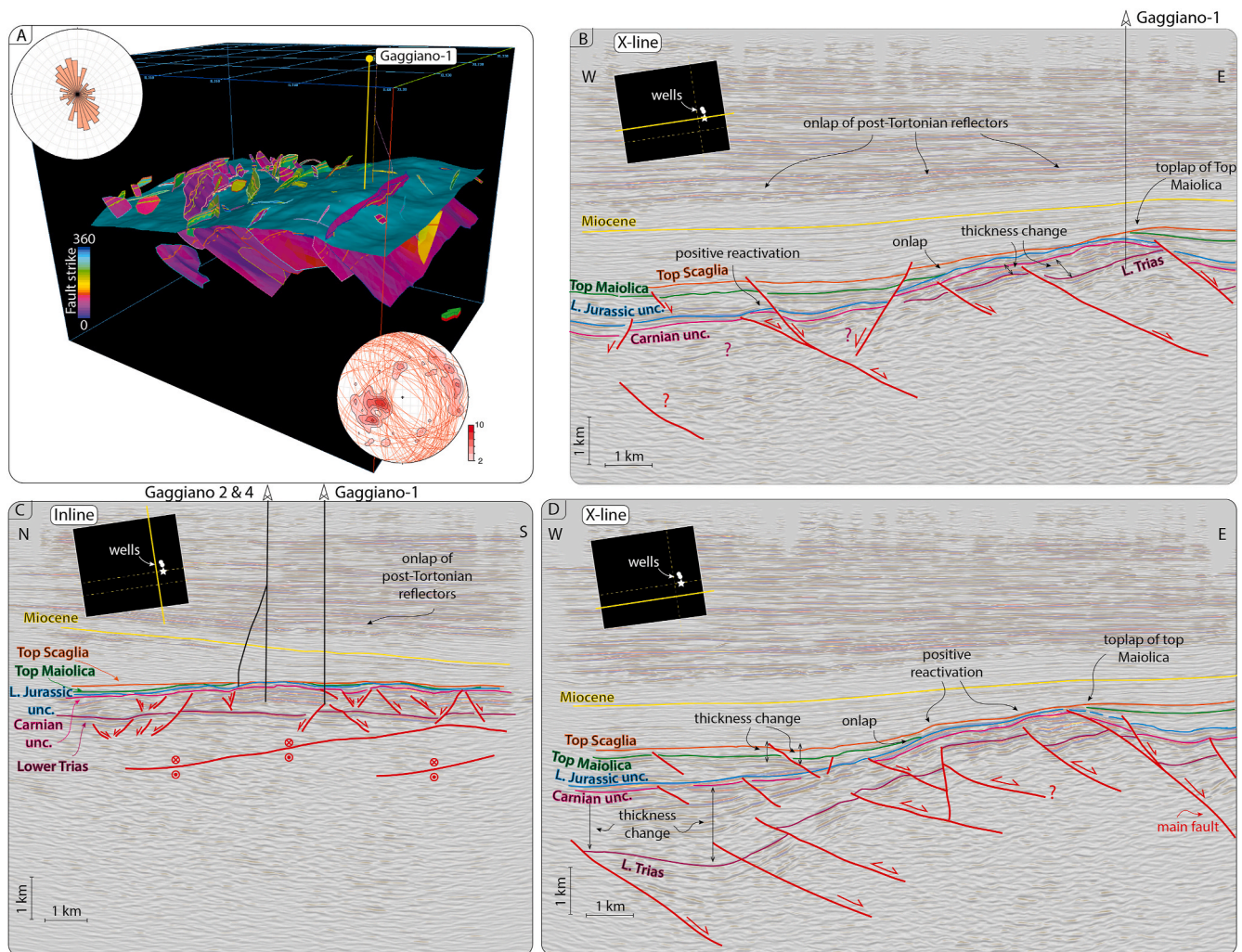


Fig. 4. Structural interpretation of the Gaggiano High. (A) 3D structural model showing the Lower Jurassic Unconformity and interpreted faults, colour-coded by strike (right-hand rule). Fault orientations are represented in the rose diagram (upper left) with 10° -wide petals and in equal-area stereonet (lower right) as a lower hemisphere projection with contour density to poles. Green arrow indicates the North direction. (B–D) Interpreted seismic profiles with main fault traces and key horizons. The insets show the approximate location of the seismic line in the 3D seismic volume. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

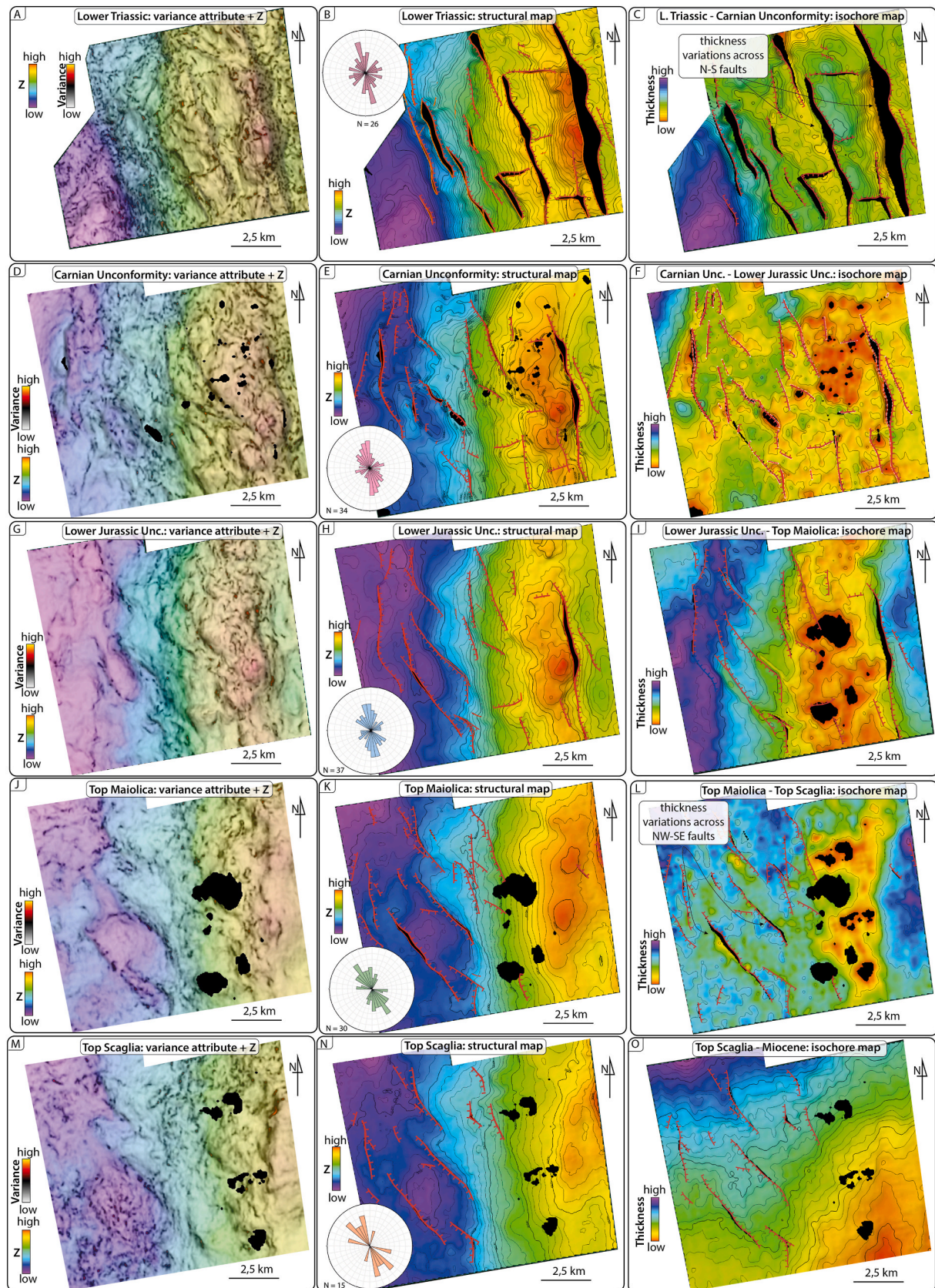


Fig. 5. Structural and isochore maps of the Gaggiano High. Left column: variance attribute maps highlighting the fault network. Middle column: structural maps with interpreted faults and equal angle rose diagrams (10°-wide petals). Right column: isochore maps for selected intervals showing thickness variations ascribed to syn-kinematic deposition. Vertical distance between contour lines is 50 m.

syn-rift deposition (Fig. 5C). The interval between the Carnian and Lower Jurassic Unconformities shows depocenters aligned with N-S faults, though with less pronounced contrasts (Fig. 5F). In the interval between the Lower Jurassic and Top Maiolica, depocenters become more localized and occur near intersections between N-S and NW-SE faults (Fig. 5I). In the interval between the Top Maiolica and Top Scaglia, thickness variations are mainly associated with NW-SE faults, suggesting syn-sedimentary tectonic activity during Scaglia deposition (Fig. 5L). Finally, Oligo-Miocene deposits show a thickening toward the N-NW, attributed to regional tilting rather than local fault control (Fig. 5O). Overall, the isochore maps document syn-tectonic growth along inherited extensional faults during the Mesozoic evolution of the structural high.

4.1.3. Throw-distance and throw-length relationships

Along-strike throw-distance profiles provide first-order constraints

on fault growth behaviour (Fig. 6A–C). The main N-S fault exhibits a bimodal throw distribution at the Lower Triassic level, with two throw maxima separated by a central low-throw segment (Fig. 6A). At the Lower Jurassic Unconformity, the throw profile becomes more uniform and nearly flat-topped, with lower maximum displacement values relative to the Lower Triassic level (Fig. 6A).

The NW-SE striking fault shows an asymmetric throw-distance profile, with maximum displacement located in its northwestern sector and decreasing values toward the southeast (Fig. 6B). The E-W striking fault displays lower overall displacement and a comparatively symmetric throw profile (Fig. 6C).

A total of 86 fault polygons were analysed to investigate the scaling relationships between maximum throw (T) and fault length (L) across different seismic horizons (Fig. 6D). The T–L plots show positive log-log correlations for all horizons, with coefficients of determination (R^2) ranging from 0.59 (Carnian Unconformity) to 0.75 (Lower Triassic).

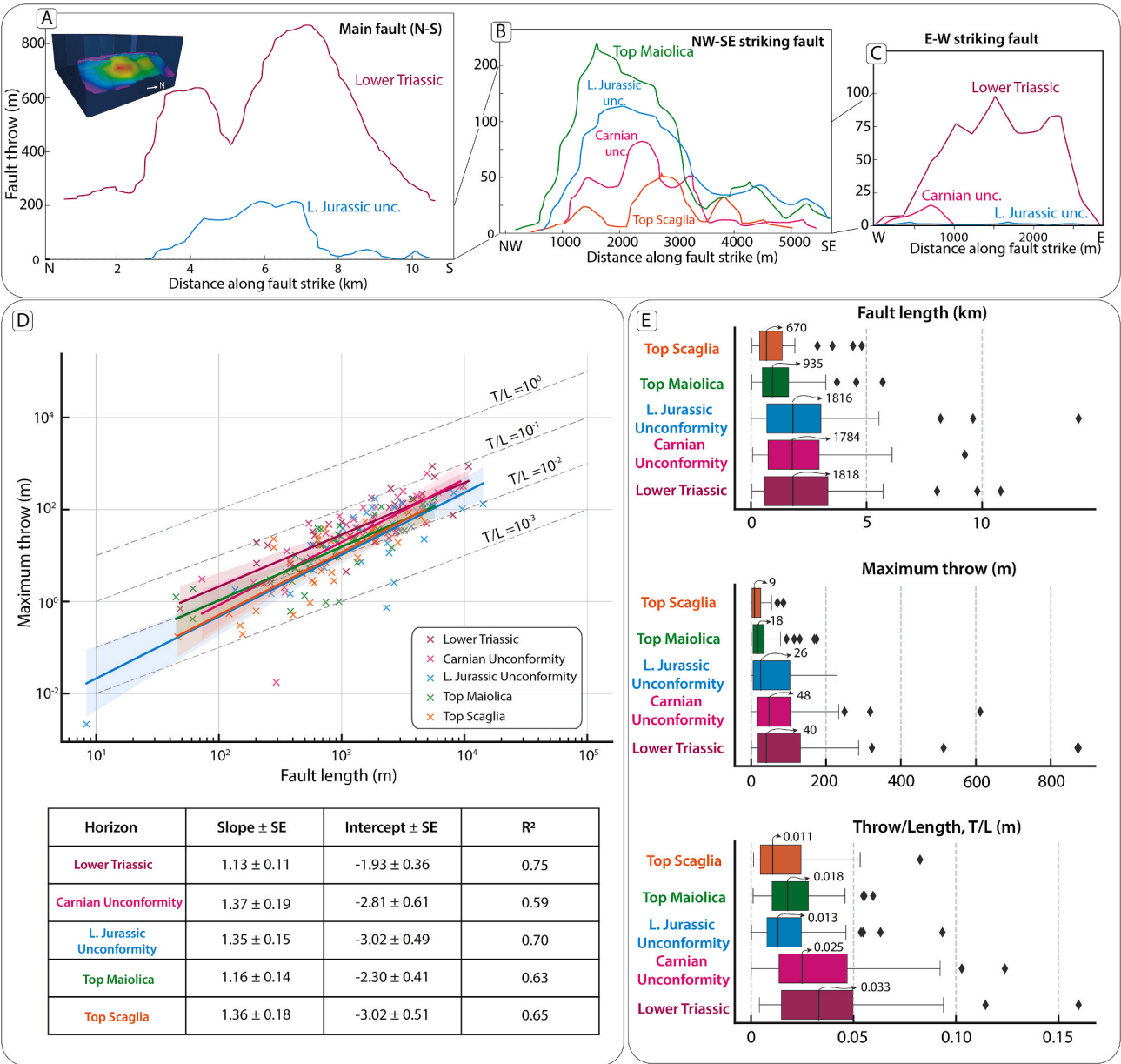


Fig. 6. Throw-length analysis. (A–C) Throw profiles along selected faults for different horizons: (A) main N-S fault (inset showing a 3D view of the throw distribution along the fault surface), (B) NW-SE fault, and (C) E-W fault. (D) Log-log plots of maximum throw vs fault length for the main horizons, with regression lines, 95% confidence intervals, and the coefficient of determination, R^2 (inset). (E) Boxplots of fault length, maximum throw, and T/L ratios across horizons, arranged stratigraphically from oldest (bottom) to youngest (top). Labels next to each box indicate the median value of the distribution.

Linear regressions yield slopes between 1.13 (Lower Triassic) and 1.37 (Carnian Unconformity and Top Scaglia).

Boxplots (Fig. 6E) show systematic differences in fault length, throw, and T/L ratios among horizons. The Lower Triassic and Carnian Unconformity horizons are characterised by longer faults (median ~ 1800 m), higher throws (median $T = 40\text{--}48$ m), and higher T/L ratios ($\sim 0.025\text{--}0.033$). In contrast, the Top Scaglia horizon shows shorter faults (median ~ 670 m), lower throws (~ 9 m), and the lowest T/L values (~ 0.011). The Lower Jurassic Unconformity and Top Maiolica horizons display intermediate values, with T/L medians of ~ 0.013 and ~ 0.018 , respectively.

4.2. Analysis of sub-seismic 2D lineaments

Lineament maps extracted from curvature attributes provide a proxy for sub-seismic damage and complement the seismic-scale fault interpretation (Fig. 7A and B).

In the Lower Triassic–Lower Jurassic Unconformity interval (Fig. 7A), P21 values are relatively high (range: 0 and $24 \times 10^{-4} \text{ m}^{-1}$) and nearly homogeneous, with maxima along major N–S faults and secondary peaks near NW–SE structures. In the Lower Jurassic Unconformity–Top Scaglia interval (Fig. 7B), P21 values are lower (range: $0\text{--}14 \times 10^{-4} \text{ m}^{-1}$) and more heterogeneous, with clusters concentrated along NW–SE faults. Rose diagrams confirm a predominant N–S orientation in the lower interval and a stronger NW–SE component in the upper one (Fig. 7A and B).

Integrated analysis of throw profiles and P21 values highlights a consistent spatial anti-correlation (Fig. 7C–F). Along the main N–S fault, the Lower Triassic horizon shows a bimodal throw distribution with a central low-throw segment corresponding to a local P21 maximum (Fig. 7C). At the Lower Jurassic Unconformity, throw is lower and more evenly distributed, while P21 is higher and more uniform (Fig. 7E). In addition to the spatial anti-correlation between throw and P21, secondary P21 peaks occur along the main N–S fault at locations

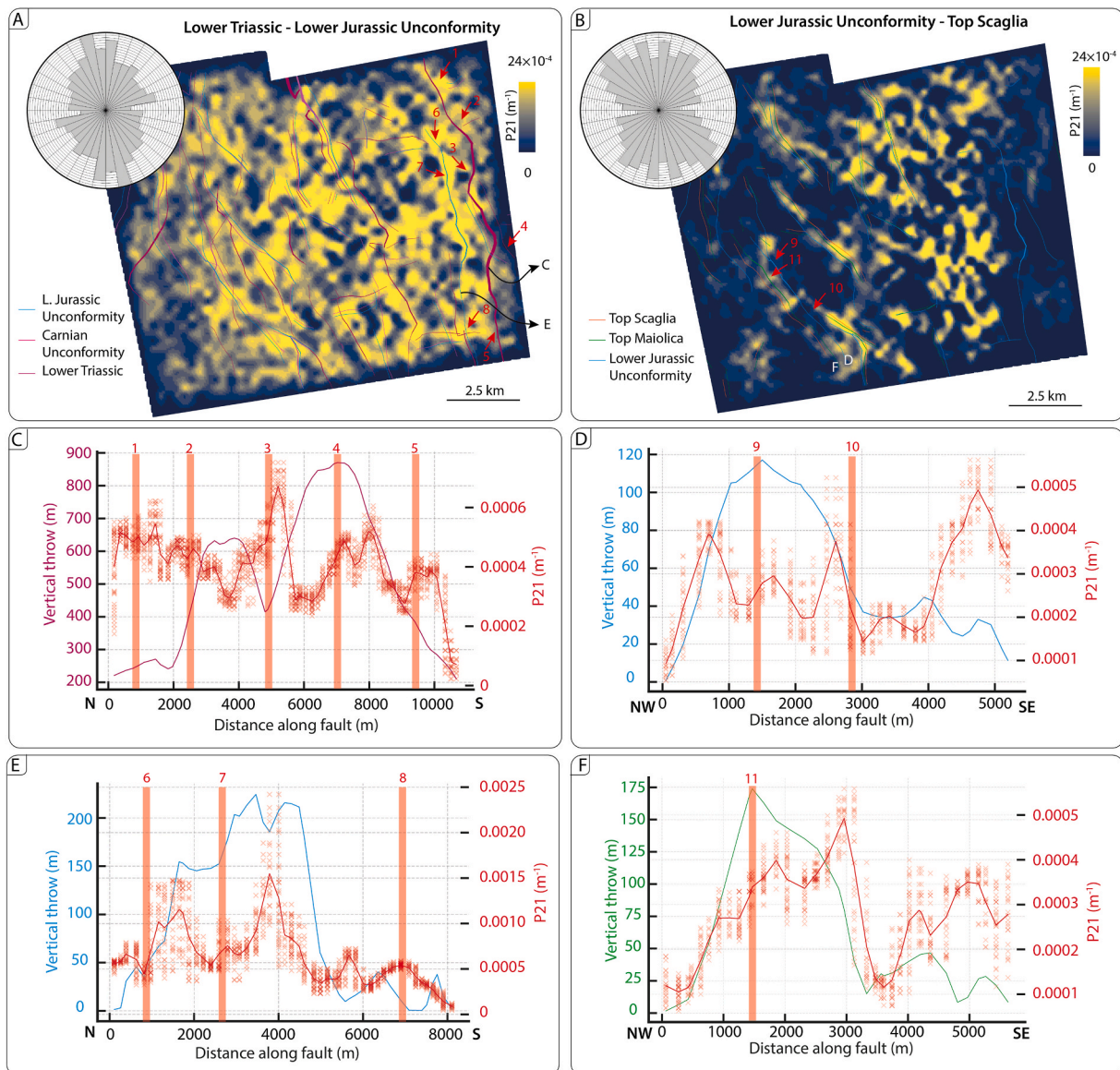


Fig. 7. Sub-seismic lineament intensity (P21) and throw profiles. (A–B) P21 maps for the Lower Triassic–Lower Jurassic Unconformity and Lower Jurassic Unconformity–Top Scaglia intervals, with fault traces (hanging wall cutoff) and rose diagrams. Fault traces are color coded based on the stratigraphic horizon and their thickness is scaled to the vertical throw. (C–F) Comparison of throw and P21 along selected N–S (C, E) and NW–SE (D, F) faults. Red lines represent the local mean of P21. Vertical red bars labelled with numbers mark the approximate positions of intersection or interaction between the analysed fault and other mapped faults (cf. panels A–B). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

corresponding to intersections with other mapped faults (Fig. 7C–E). Along the NW–SE fault, throw profiles are asymmetric, with maxima in the northwestern sector and decreasing southeastward (Fig. 7D–F). In both cases, local P21 peaks coincide with throw minima, particularly near linkage zones and tips (Fig. 7D–F).

5. Discussion

5.1. Geological evolution of the Gaggiano High

3D seismic interpretation, well data, and isochore maps reveal for the Gaggiano High a multiphase evolution, initially controlled by N–S striking extensional faults and later influenced by NW–SE structures. Unlike the adjacent Lacchiarella structure, a pre-existing Mesozoic basin strongly inverted and uplifted during Neogene contraction, the Gaggiano High experienced only mild compressional overprint, preserving key features of its original extensional architecture. Its persistence throughout the Mesozoic, coupled with contrasting syn-orogenic deformation between the high and the Lacchiarella basin, highlights the long-term control exerted by inherited extensional structures and syn-sedimentary tectonics. This limited compressional reactivation is a key reason why the Gaggiano High represents an excellent case to investigate the multiscale architecture of the fault network in a buried rift-related structural high.

5.2. Multi-scale analysis of faulting

5.2.1. Scaling relationships and fault maturity

The throw-distance profiles described in Section 4.1.3 provide insights into the internal segmentation and growth behaviour of the fault system. The bimodal displacement distribution observed along the main N–S fault at the Lower Triassic level (Fig. 6A) suggests that the fault trace may have evolved through the linkage of initially distinct segments (e.g., Peacock and Sanderson, 1991; Childs et al., 1995; Fossen and Rotevatn, 2016; Nicol et al., 2020). The more uniform and flat-topped throw profile at the Lower Jurassic Unconformity (Fig. 6A) likely reflects progressive displacement redistribution along the fault trace (Kim and Sanderson, 2005; Fossen and Rotevatn, 2016; Nicol et al., 2020).

Similarly, the asymmetric throw distribution observed along the NW–SE striking fault (Fig. 6B) may indicate preferential propagation toward one tip and structural interaction with adjacent N–S structures (e.g., Peacock and Sanderson, 1991; Childs et al., 1995; Fossen and Rotevatn, 2016). In contrast, the comparatively symmetric and lower-amplitude throw profile of the E–W striking fault (Fig. 6C) suggests a more limited growth history.

The observed scaling relationships between maximum throw (T) and fault length (L) across multiple seismic horizons show positive log-log correlations with slopes ranging between 1.1 and 1.4 (Fig. 6D), consistent with values reported in literature (e.g., Kim and Sanderson, 2005; Nicol et al., 2020; Lathrop et al., 2022; Walsh and Watterson, 1988). Slopes >1 may reflect enhanced displacement localization relative to fault length. This trend could be associated with the limited lateral propagation of faults, potentially due to mechanical stratigraphy, structural inheritance, or reactivation of pre-existing discontinuities (e.g., Kim and Sanderson, 2005).

Throw-to-length ratios are systematically higher in the deeper stratigraphic intervals (Fig. 6E). The highest median values (~ 0.03) are recorded for the Lower Triassic and Carnian Unconformity, interpreted here as reflecting more mature or isolated faults developed during early extensional phases and subsequently affected by reactivation. In contrast, the Top Scaglia and Lower Jurassic Unconformity exhibit the lowest T/L ratios (~ 0.01), suggesting less developed fault segments, possibly resulting from post-rift reactivation.

These trends indicate that the deeper intervals preserve more evolved fault geometries resulting from longer propagation histories and greater displacement, whereas faults affecting shallower intervals either

represent late-stage reactivations or are mechanically inhibited from significant growth, possibly due to differences in the mechanical properties of the stratigraphic succession (e.g., Redpath et al., 2022; Shipilin et al., 2020; Tvedt et al., 2013).

5.2.2. Structural and lithologic control on lineament density

The analysis of lineament intensity (P21) across the two main stratigraphic intervals reveals distinct patterns that likely reflect both lithological and tectonic influences. The Lower Triassic–Lower Jurassic Unconformity interval displays relatively higher P21 values and a more homogeneous distribution of lineament density, with local maxima concentrated along major N–S faults and subordinate NW–SE structures (Fig. 7A). In contrast, the Lower Jurassic Unconformity–Top Scaglia interval exhibits generally lower P21 values and a more heterogeneous spatial distribution, with lineament clusters associated mainly with NW–SE faults (Fig. 7B). The spatial correspondence between curvature-derived lineament clusters and manually interpreted fault traces supports a structural origin for the extracted features, thus excluding a significant contribution of artefacts. Moreover, lineament orientations are consistent with the dominant fault sets, and intensity peaks systematically coincide with mapped faults (Fig. 7). This geometric coherence argues against a purely stratigraphic or imaging-related origin of the curvature anomalies and supports their interpretation as proxies for distributed fault-related deformation.

These differences may be interpreted in terms of both mechanical stratigraphy and tectonic history of the two intervals (Fig. 8A). The observed variations in lineament density above and below the Lower Jurassic Unconformity highlight the role of lithologic mechanical properties in controlling fracture development and preservation. The lower interval is composed predominantly of shallow-marine platform carbonates (i.e., dolostones and limestones; see Fig. 2), which might be more prone to brittle deformation and fracture preservation (e.g., La Bruna et al., 2020; Manniello et al., 2022; Menegoni et al., 2022). Conversely, the upper interval consists of pelagic carbonates, which are typically more fine-grained and mechanically layered, potentially favouring strain accommodation by more distributed or ductile mechanisms (e.g., Zuccari et al., 2021). Additionally, the reduced seismic expression of damage in this interval may result from weaker curvature signal contrasts.

From a tectonic perspective, the Lower Triassic–Lower Jurassic Unconformity interval is older and records the deformation starting from Mesozoic rifting, with distributed extensional deformation and pervasive fracturing. The upper interval, by contrast, mostly records the imprint of Paleogene extension along NW–SE striking faults and Oligo-Miocene contraction, which may have produced more localized faulting or less brittle deformation (Fig. 8A).

5.2.3. Fault throw vs. sub-seismic damage

A more direct link between fault throw and sub-seismic damage is illustrated by the comparison between vertical throw and lineament intensity (P21) along selected fault segments (Fig. 7C–F). Along the main N–S fault, throw profiles for the Lower Triassic horizon show a bimodal distribution, with two maxima separated by a central low-throw segment, which coincides with a local peak in lineament intensity (Fig. 7C). This spatial anti-correlation suggests that the fault likely evolved by linkage between originally distinct segments, with the central relay zone accommodating strain through more diffuse fracturing rather than localized slip (Fig. 8B). This interpretation is consistent with previous studies that associate damage and displacement distribution with segment linkage, fault bends, and branching processes (e.g., Childs et al., 1995; Crider and Pollard, 1998; Peacock and Sanderson, 1991; Alaei and Torabi, 2017; Mercuri et al., 2020).

The vertical throw at the Lower Jurassic Unconformity (Fig. 7E) is lower and more evenly distributed along the same fault, whereas lineament intensity is generally higher and more uniformly spread. The weaker anti-correlation between throw and P21 at this level may reflect

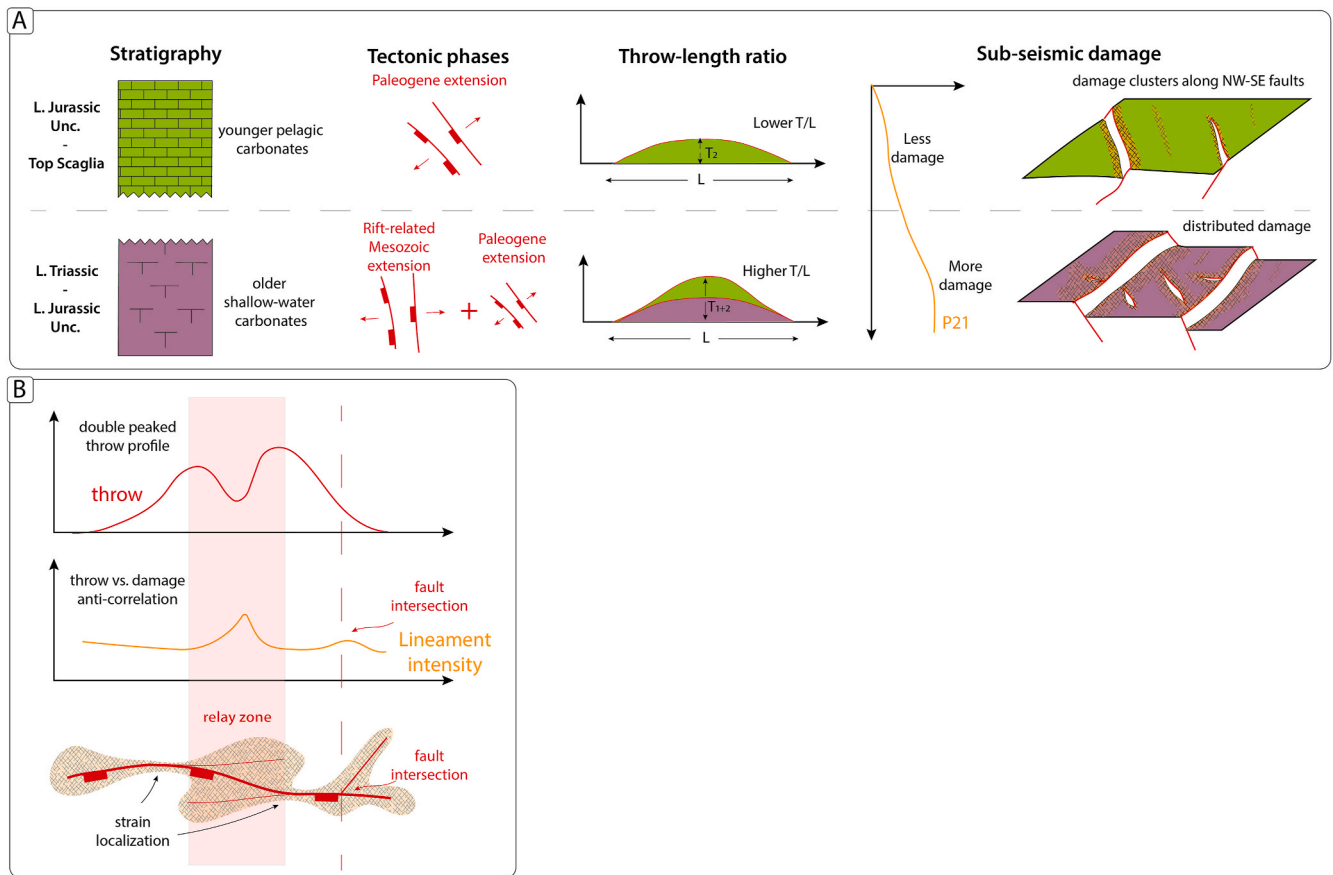


Fig. 8. Conceptual synthesis of factors controlling fault architecture and sub-seismic damage distribution at different scales in the Gaggiano High. (A) Comparison between the two main stratigraphic intervals. The Lower Triassic–Lower Jurassic Unconformity interval is characterized by higher throw-length (T/L) ratios and relatively high and homogeneous sub-seismic lineament intensity (P21), reflecting more mature and variably oriented fault geometries. In contrast, the Lower Jurassic Unconformity–Top Scaglia interval displays lower T/L ratios and overall lower P21 values, with damage preferentially clustered along NW–SE faults. (B) Conceptual model of along-strike variations in fault displacement and sub-seismic damage. Throw profiles reflect segment linkage, whereas damage intensity (P21) tends to increase in low-throw segments, relay zones, and fault intersections, and decrease where strain is more strongly localized.

incomplete strain localization in the overlying units, rheological contrasts between stratigraphic intervals, or the upward propagation of faulting. Additional P21 peaks are observed near intersections with secondary faults (e.g., labels 2–5 and 8), suggesting that fault interaction enhances damage through local stress perturbations and strain concentration (e.g., Curewitz and Karson, 1997; Peacock et al., 2017). Such structurally complex areas are also likely to represent preferential pathways for fluid circulation (e.g., Person et al., 2012). Toward the southern edge of the seismic volume, P21 values decrease, possibly due to edge effects and reduced imaging quality near seismic volume boundaries.

A similar pattern is observed along the NW–SE striking fault (Fig. 7D–F). Throw profiles show asymmetric distributions, with maxima located in the northwestern portion of the trace and decreasing toward the southeast. In both cases, zones of low throw tend to correspond to local maxima in lineament intensity, especially in the central and eastern segments. These observations reinforce the interpretation that low-throw segments, relay zones, and fault tips are prone to enhanced off-fault deformation, possibly reflecting segment maturity and progressive strain localization during fault growth (Fig. 8B).

Overall, these results highlight a consistent mechanical behaviour: segments with higher throw tend to localize strain more efficiently, whereas zones of lower displacement—whether related to linkage, tip effects, or fault interaction—are associated with more distributed damage (Fig. 8B). Seismic scale studies have documented non-linear relationships between fault displacement and damage zone width (e.g., Schueller et al., 2013; Alaei and Torabi, 2017), with significant

scatter attributed to lithological controls and structural complexity. In particular, Alaei and Torabi (2017) showed that subsidiary faulting, fault bends, and segment linkage strongly influence the geometry and width of fault damage zones and modulate displacement-damage scaling. While these previous works primarily quantify damage zone width, the present analysis focuses on deformation intensity (P21) derived from sub-seismic lineaments. It is important to note that the P21 values were extracted within a fixed 200 m-wide corridor centred on the manually interpreted fault trace (see Methods). Therefore, the present analysis does not directly constrain the full width of the damage zone. Variations in lineament intensity may reflect either changes in the degree of internal fracturing within a damage zone of constant width, and/or local variations in damage zone thickness that are not fully captured by the adopted extraction window. Consequently, the observed spatial patterns should be interpreted as relative indicators of distributed deformation intensity rather than direct measurements of damage zone width.

The observed spatial anti-correlation between throw and P21 suggests that distributed deformation may peak in linkage zones and low-throw segments, reflecting incomplete strain localization at the segment scale (Fig. 8b). This interpretation is consistent with broader fault-zone models that emphasize the hierarchical organization of fault cores and damage zones and the progressive localization of strain during fault growth (e.g., Savage and Brodsky, 2011; Torabi et al., 2019).

5.2.4. Implications

The analysis of the Gaggiano High provides insights into how

inherited normal faults influence fault architecture and fault damage in a buried rift-related setting.

- (i) **Fault maturity and inheritance.** Deeper stratigraphic intervals preserve mature faults with higher T/L ratios, confirming that extensional inheritance controls the long-term mechanical behaviour of structural highs.
- (ii) **Multiscale seismic approach.** Integrating fault throw analysis with sub-seismic lineament mapping allows bridging the gap between seismic and sub-seismic scales, providing new insights into the distribution of damage in the subsurface. The spatial anti-correlation between throw and sub-seismic lineament intensity confirms that linkage zones and low-throw segments are preferentially associated with distributed damage, suggesting that throw gradients can be used as a proxy to predict damage concentrations in buried settings. The multi-scale approach can be applied to other settings, with implications for georesources and, in particular, for the modelling of fluid flow in the subsurface.
- (iii) **Permeability anisotropy and fluid-flow implications.** The observed spatial distribution of lineament intensity has direct implications for subsurface permeability. Zones characterized by elevated lineament intensity -particularly at fault linkage areas and fault intersections-define volumes of enhanced deformation and fracture connectivity, which may favour fluid circulation (Sibson, 1996; Ferrill and Morris, 2001; Cox, 2005; Fossen and Rotevatn, 2016). In contrast, high-throw fault segments, where displacement is strongly localized, may concentrate strain within the fault core of narrower fault zones, potentially reducing across-fault permeability while maintaining preferential flow along the associated damage zones (Caine et al., 1996; Faulkner et al., 2010). The presence of two dominant structural trends (N-S and NW-SE) suggests that deformation is not isotropic within the structural high. Such structural anisotropy may result in directionally controlled fracture connectivity, potentially leading to preferential fluid-flow pathways in the subsurface.

Beyond the specific case of the Gaggiano High, the results presented here have broader implications for buried rift-related structural highs preserved within foreland basins. The documented segment-scale variability in distributed deformation suggests that fault growth dynamics and structural inheritance exert a first-order control on damage distribution. More generally, the integration of seismic-resolvable fault analysis with curvature-derived damage proxies provides a transferable framework to investigate multiscale fault architecture in structurally complex subsurface settings, enhancing the predictive value of seismic interpretation for georesource assessment and fluid-flow modelling.

6. Conclusions

The Gaggiano High preserves the geometry of a buried Mesozoic structural high where limited Neogene inversion allowed the original extensional framework to be retained. Our multiscale seismic analysis highlights the following points:

Fault system architecture – The high is bounded by N-S striking, east-dipping normal faults complemented by NW-SE and subordinate E-W faults. These structures define westward-tilted fault blocks that remained mechanically active throughout tectonic evolution, being partly inverted as compressive faults during the Alpine-Appenninic compression in their foreland.

Scaling behaviour – Fault length-throw relationships show positive log-log correlations with slopes between 1.1 and 1.4. Throw-to-length ratios are systematically higher in deeper stratigraphic intervals, indicating more mature and long-lived faults, and decrease upward, reflecting late reactivation or mechanically inhibited growth.

Sub-seismic damage – Lineament analysis reveals that low-throw fault segments, linkage zones, and fault intersections are consistently

associated with higher lineament intensities. This spatial anti-correlation between displacement and lineament intensity reflects strain partitioning between localized slip and distributed damage.

Lithological control on damage – Lithology exerts a primary control in the mechanical behavior, with shallow-water carbonates favoring pervasive brittle deformation and pelagic carbonates promoting a more localized and ductile deformation.

Implications – The results underscore the long-term mechanical relevance of inherited faults in buried highs and demonstrate the value of integrating seismic-scale fault analysis with sub-seismic lineament mapping to assess strain localization and damage distribution. The proposed multiscale approach provides a transferable framework for predicting fault-related damage and potential fluid-flow pathways in structurally complex subsurface settings, with direct implications for hydrocarbon exploration, geothermal systems, and CO₂ storage applications.

In summary, the Gaggiano High illustrates how inherited extensional structures continue to control fault scaling behaviour and damage distribution in foreland basins, providing a rare subsurface example of fault-fracture architecture in a buried rift-related structural high that is directly relevant for subsurface characterization and georesource assessment.

CRedit authorship contribution statement

M. Mercuri: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **L. Spaggiari:** Methodology, Project administration, Resources, Supervision, Writing – review & editing. **A.P. Amodio:** Methodology, Resources. **S. Bigi:** Validation, Writing – review & editing. **A. Corrao:** Methodology, Resources. **C. Doglioni:** Validation, Writing – review & editing. **F. Trippetta:** Validation, Writing – review & editing. **E. Carminati:** Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marger.2026.207844>.

Data availability

The data used in this study are confidential.

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