

Multi-scale fault and fracture networks of the UK's Mississippian carbonate platforms: implications for extracting geothermal energy

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ABSTRACT

Unlocking the low enthalpy geothermal potential of the UK through heat extraction from Mississippian carbonate platforms (MCP) could support the transition to net-zero carbon emissions by providing a sustainable heat source. However, MCPs remain underexplored compared to analogous formations in Belgium and the Netherlands, largely due to limited understanding of fracture-controlled fluid flow in these low-porosity carbonate systems. This study evaluates the structural and hydraulic characteristics of MCPs through a multi-scale fault and fracture connectivity analysis across regional, local, and outcrop scales in North Wales, adjacent to the Menai Straits Fault System. Using regional fault map and seismic reflection data, drone photogrammetry, outcrop description, and bed scale fracture mapping, we assess fracture geometry, intensity, orientation, and connectivity. Fracture stability was evaluated through slip tendency (Ts) and dilation tendency (Td) analyses under varying stress scenarios, and permeability tensors were derived to characterize flow orientation. Results demonstrate a strong scale-dependency in fracture connectivity. Connectivity coefficients (CL) increase from 0.64 at regional scale to 3.03 at bed scale, while CB (Connection per branch) values rise from 0.71 to 1.58, indicating that smaller-scale datasets capture more complex and transmissive networks. Reactivation analysis shows that fractures subparallel to present-day stress, SHmax (170°) exhibit high dilation tendencies (Td > 0.8), favouring open fluid pathways. Cross-cutting relationships provide field evidence for stress rotation, with implications for multi-phase fracture development and enhanced connectivity near the Menai Straits Fault System. These findings suggest that stress field evolution and structural inheritance significantly influence fracture permeability architecture. The integration of outcrop and subsurface data improves characterization of sub-seismic fracture networks, offering valuable guidance for geothermal drilling strategies and reservoir development in underutilized carbonate platforms.

1. Introduction

Geothermal energy represents a stable, clean and sustainable source of heat that holds the potential to significantly reduce carbon emissions and mitigate climate change impacts. In the UK, where low- to medium-enthalpy geothermal systems are promising targets for low enthalpy heat provision, the utilization of geothermal resources could provide an essential contribution to the UK's energy transition (Jones et al., 2023). Among these resources, Lower (or early) Carboniferous Limestones, referred to here as Mississippian Carbonate Platforms (MCPs) have emerged as a focal point for geothermal exploration. These strata host active hydrothermal systems in Central and Southern UK, characterized

by thermal springs in locations such as Bath, Bristol, the Taff Valley (South Wales), and the Peak District (England) (Abesser et al., 2005; Downing and Gray, 1986; Gallois, 2007; Pharaoh et al., 2021). Fig. 1, Nevertheless, despite significant advances in geothermal resource development in other regions, such as Belgium and the Netherlands (Kombrink et al., 2010; Reijmer et al., 2017; van Hulten, 2012), Mississippian strata in the UK remain underexplored as a geothermal resource (Jones, 2023; Brown, 2023).

The matrix permeability of Mississippian limestone is typically poor and is predominantly controlled by faults, fractures, and bedding planes, with additional influences from karstification and dolomitization (Bear, 1993; Brown, 2023). Understanding these structural controls is critical

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to accurate geothermal resource assessment, particularly the deliverability of warm water. The permeability of fractures will be dependent on the orientation of open fractures with respect to in situ stress, which will control fluid flow through mechanisms such as slip tendency and dilation tendency (Rizzo et al., 2024).

One primary challenge in characterizing fault-fracture networks is the significant variation in data type and resolution at different scales. The characterization of fracture networks at small (bed-scale), outcrop (drone scale), local (using geological maps), and large (using subsurface 3D seismic) scales, often yields disparate data due to the complexity and heterogeneity of the networks involved (Loza Espejel et al., 2020). This variability complicates the integration of data from multiple sources, as fracture relationships and distributions can differ significantly depending on the scale of observation. For example, while outcrop studies provide detailed, localized insights, they may not capture broader trends that are observable at larger scales, potentially leading to misinterpretations of subsurface conditions (Prabhakaran et al., 2021; Rizzo et al., 2020). Another challenge is the subjective bias that can influence the collection and interpretation of fracture data (Andrews et al., 2019; Peacock et al., 2019). This introduces uncertainty during the characterization process, especially when transitioning from outcrop-scale observations to larger-scale models, where interpretations of fracture connectivity and density may vary with the observer's perspective and methodology.

At the reservoir or regional scale, using 3D subsurface seismic data presents its own set of challenges. The resolution and bin spacing of seismic data, typically ranging from 25 to 50 m, often precludes the

detection of faults with throws smaller than 10 to 30 m (Lohr, 2004; Maerten et al., 2006; Needham et al., 1996). Faults, fractures, and joints smaller than seismic resolution, referred to as sub-seismic, can only be identified using 1D borehole data (e.g., wireline logs, cores, well log images), which may lead to underestimations of fracture volumes (Maerten et al., 2006). This is particularly challenging in studies of carbonate platforms, where characterizing patterns and structures using seismic data is difficult (Burgess et al., 2013; Pomar, 2001). Therefore, outcrop analogues are crucial to evaluating small- and intermediate-scale fracture parameters that seismic and borehole data cannot quantify (Eberli et al., 2005; Gutmanis et al., 2018). Field analogues provide essential guidance in developing conceptual models of fault-fracture networks and offer spatial and statistical data to understand property distributions (Sanderson, 2016; Strijker et al., 2012).

To bridge this gap, it is essential to integrate outcrop data with core and reservoir-scale observations, providing a more comprehensive understanding of fracture network properties across multiple scales (Healy and Hicks, 2022). This study aims to address the connectivity of faults and fractures within the Mississippian-aged North Wales Platform, by integrating multi-scale datasets to evaluate its geothermal energy potential. Specifically, the research focuses on:

- Characterizing the fault-fracture network and its patterns across multiple scales.
- Developing a detailed interpretation of fault-fracture connectivity and stability from regional to bed scales.

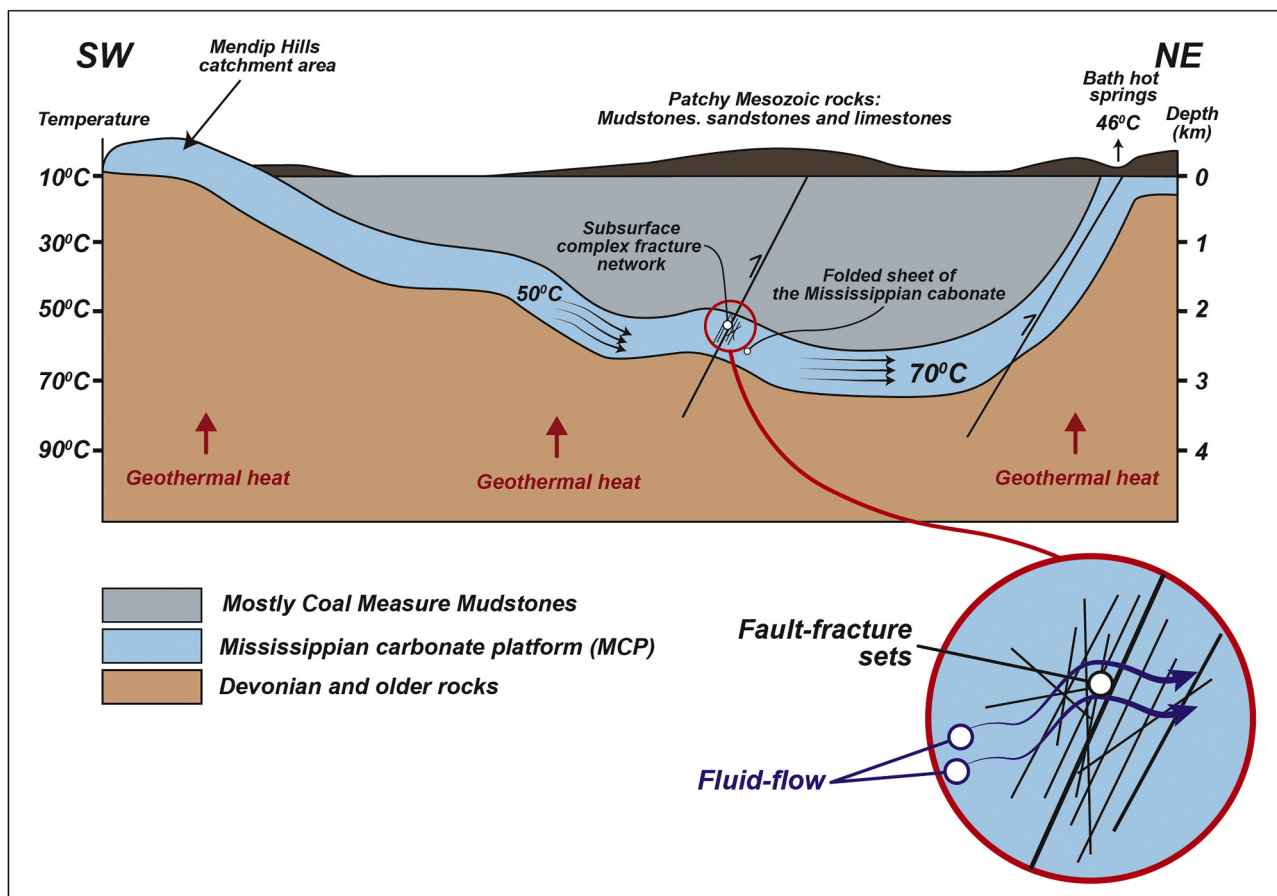


Fig. 1. Conceptual cross-section of the Mississippian carbonate platform geothermal system in southwest England, illustrating subsurface fluid flow dynamics from the Mendip Hills catchment to the Bath hot springs. The section highlights the structural and thermal framework, with fault and fracture networks within the folded Mississippian carbonate platform acting as key conduits for deep geothermal fluid circulation. Enhanced flow pathways are controlled by fracture connectivity and structural complexity, facilitating upward heat transfer. Inset shows a magnified view of fault-fracture intersections enabling focused fluid migration. Modified from Downing and Gray (1986) and Gallois (2007).

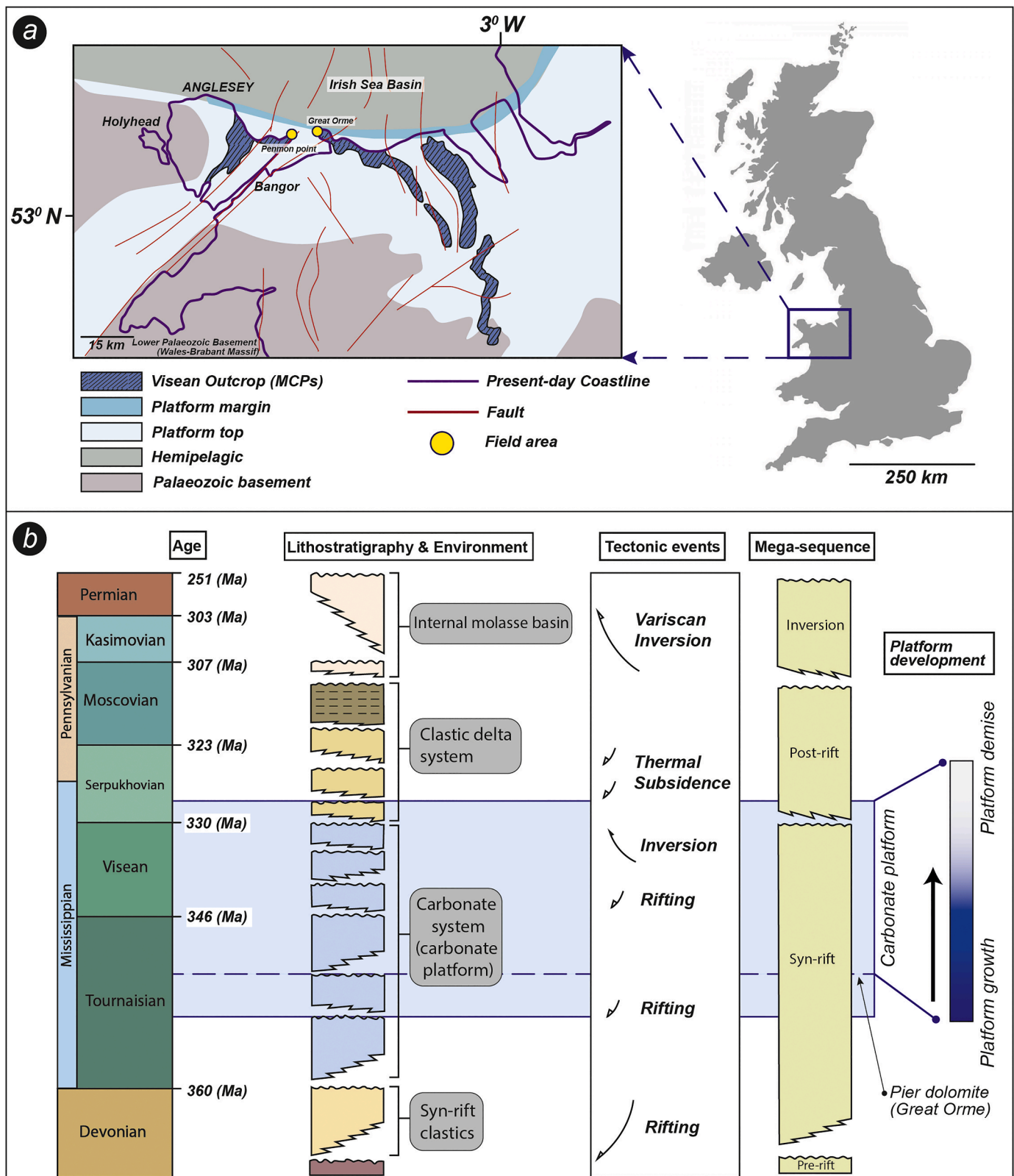


Fig. 2. (a) Geological map of the North Wales Platform and adjacent areas within the Irish Sea Basin, showing the distribution of Mississippian carbonate platform (MCP) facies and key structural elements, including platform margins, topographic highs, hemipelagic zones, and the underlying Paleozoic basement. Mapped faults and modern coastlines provide spatial and tectonic context. The outlined field area guides the focus of subsequent analysis. Modified from [Manifold et al. \(2021\)](#); [Fraser and Gawthorpe \(2003\)](#). (b) Chronostratigraphic framework of the basin, summarizing lithostratigraphy, depositional environments, major tectonic events, and megasequence development from the Devonian to the Permian. The framework highlights the Mississippian carbonate platform evolution, driven by syn-rift siliciclastics, subsequent carbonate deposition, and overlying clastic progradation. Key tectonic phases, rifting, inversion, and thermal subsidence govern platform architecture and eventual demise. Modified from [Fraser and Gawthorpe \(2003\)](#).

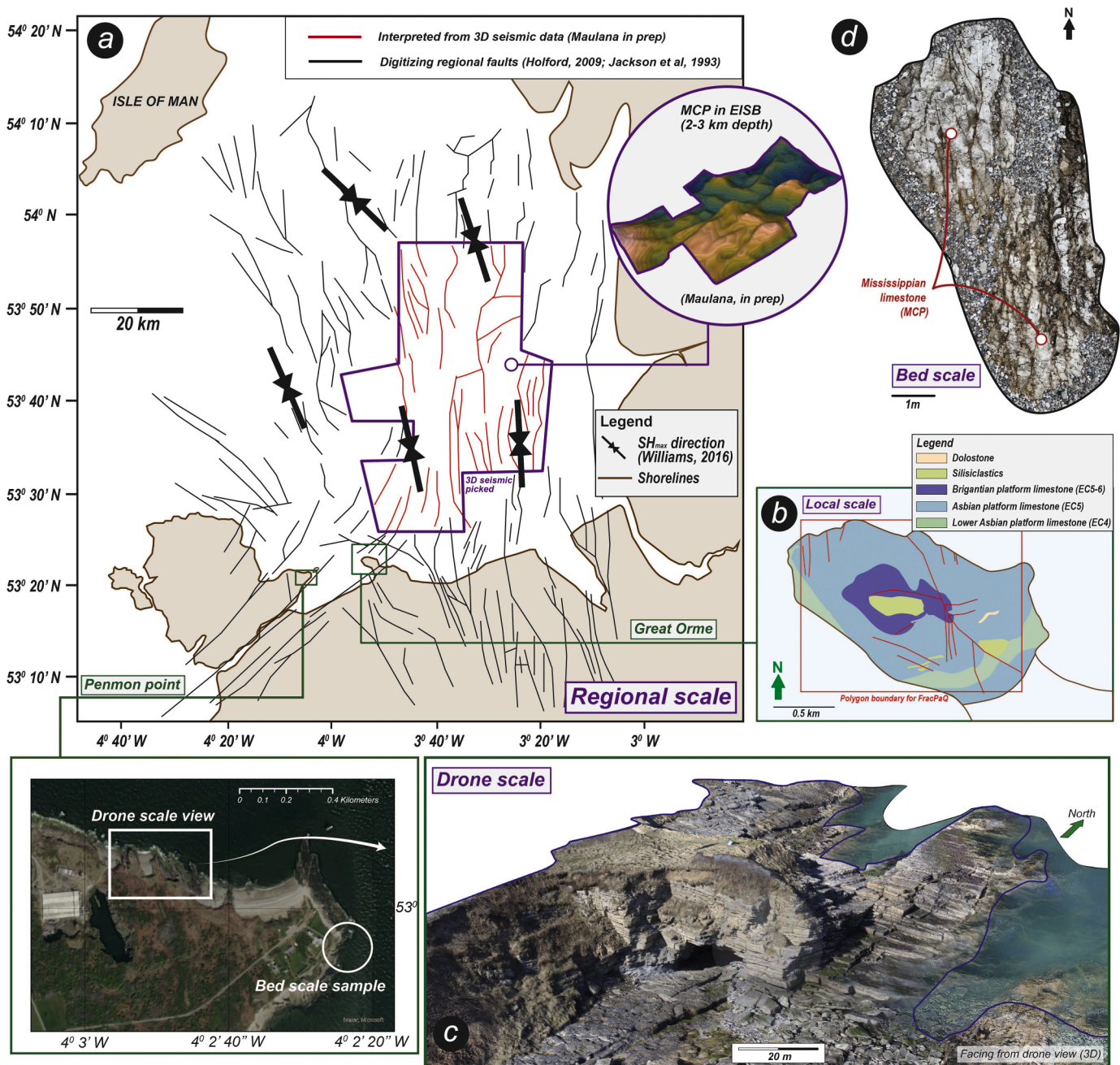


Fig. 3. Multiscale overview of structural datasets and field observations used to characterize fault-fracture systems within the Mississippian carbonate platform (MCP). (a) Regional-scale map of the East Irish Sea Basin (EISB), integrating fault datasets from 3D seismic interpretations (red lines; Aditama, in prep.) and previously published Paleozoic fault maps (black lines; Jackson and Mulholland, 1993; Holford et al., 2009). Maximum horizontal stress (SH_{max}) orientations (140° – 170°) are from Williams (2016). Inset shows 3D perspective of MCP topography at ~ 2 – 3 km depth. (b) Local-scale geological map of the Great Orme outcrop (1:10,000 scale), highlighting detailed stratigraphy and fault traces within the Mississippian platform carbonates. (c) Drone-scale structural mapping from Penmon Point, Anglesey, covering ~ 200 m of coastal exposure for fracture analysis using drone-based photogrammetry. (d) Bed-scale image of the Mississippian limestone outcrop from the Menai Strait Fault Zone, illustrating decimeter- to meter-scale fault-fracture networks within the MCP. This integrated multiscale approach underpins the structural framework and fluid-flow analysis presented in this study.

(c) Estimating the permeability tensor under current tectonic stress conditions.

Accurately characterizing fracture properties such as frequency, orientation, and connectivity are essential for building robust subsurface fluid flow models (Gambao et al., 2019; Moeck, 2014). These models will not only optimize geothermal energy extraction but also contribute to broader applications, such as predicting contaminant transport in

carbonate rocks (Palladino et al., 2020; Pruess and Narasimhan, 1982).

2. Geological setting

2.1. Mississippian carbonate platforms of the UK

In the UK, the Mississippian (Lower Carboniferous) period was characterised by the deposition of thick carbonate platforms on the

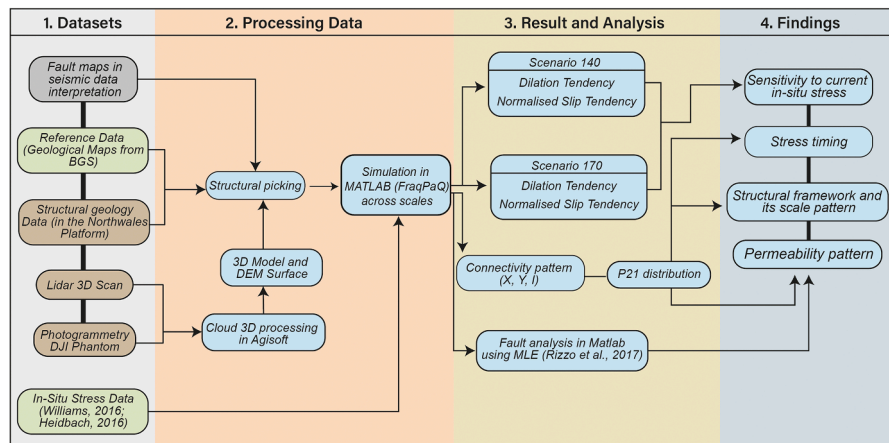


Fig. 4. Workflow of this study, showing the integration of multi-scale datasets, 3D modelling, and simulations to assess fault and fracture behaviour.

footwalls of normal faults during back-arc basin extension (Fraser and Gawthorpe, 2003). These so-called Mississippian carbonate platforms (MCPs) grew during the Tournaisian to late Visian (359–323 Ma) and are notably present in two distinct provinces, north and south of the Wales-Anglo-Brabant Massif (WABM) (Somerville, 2008). During this era, the UK was positioned at equatorial latitudes, providing optimal conditions for carbonate sedimentation within the warm, shallow shelf areas surrounding the WABM, extending from Ireland in the west to The Netherlands and Belgium in the east (Pharaoh et al., 2018; Smit et al., 2018). The carbonates were initially deposited on ramps but evolved into steep-sided platforms with remobilised carbonate sediments and clastic sediments deposited within intervening hanging wall basins (Fraser and Gawthorpe, 2003; Manifold et al., 2020).

In the central and southern UK, carbonate deposition in the Mississippian occurred within clear, shallow water that was only affected by minor periodic influx of clastic sediment from river systems on the margins of the WABM (Waters, 2011; Manifold et al., 2021). In the northern provinces of the UK, the growth of Mississippian carbonate platforms was more strongly influenced by the progradation of fluvio-deltaic systems sourced from the Southern Uplands and North-west Highlands (Barrett, 1988; Kombrink et al., 2010; Waters, 2009, 2011; Howell et al., 2022). In areas such as Northumberland, in northern England, and the Midland Valley of Scotland, most Mississippian strata are characterized by interbedding of shelf carbonates and deltaic siliciclastic sediments (so-called Yoredale facies; Booth et al., 2020; Davies, 2008; Tucker, 2003). Thickness estimates range from 250 to 3500 m based on surface exposures and well data in the Southern North Sea Basin (SNSB) and the Irish Sea Basin (EISB), and central onshore Britain (Doornenbal et al., 2019; Jones et al., 2023; Pharaoh et al., 2018). This thickness variation likely reflects both differences in carbonate platform growth and variability in the extent of deep erosion beneath the Variscan unconformity (Aditama et al., 2025; Pharaoh et al., 2021).

This study focuses on the North Wales Platform, a Mississippian-aged, land-attached system developed along the edge of the East Irish Sea Basin that is partially exposed on the Great Orme, Llandudno and at Penmon Point, Anglesey (Juerges et al., 2016; Manifold et al., 2021) (Fig. 2). The succession is partially dolomitized, forming both strata-bound bodies and halos of dolomite around faults and fractures (Juerges et al., 2016). Exposures are of Asbian and Brigantian limestone (Fig. 2), with frequent, laterally impersistent karstified surfaces with palaeosols and occasional thin, intercalated sandstones beds (Manifold et al., 2021).

2.2. Geothermal potential of Mississippian carbonate platforms

As part of a stable foreland in Europe, the UK exhibits relatively low geothermal gradients and heat flow compared to more tectonically

active regions (Busby, 2014). Although a number of studies have suggested that MCPs are located at an optimal depth for low enthalpy geothermal exploitation (Hirst et al., 2015; Jones et al., 2023; Narayan, 2018) the deliverability of warm water has not yet been established. In particular, since Mississippian strata generally have low effective porosity (<3 %) and permeability (ranging from 1 to 10 millidarcies) matrix permeability is unlikely to be sufficient to support the flux of warm water to wells (Abesser et al., 2005; Downing and Gray, 1986). Consequently, the effectiveness of the strata as a geothermal reservoir will be significantly influenced by the presence and connectivity of secondary porosity such as faulting, karstification, or dolomitization (Ingrams et al., 2020). This dynamic has been demonstrated in regions like Belgium and the Netherlands, where Mississippian strata have been appraised and developed for geothermal heat using fracture-controlled and karstic permeability (Broothaers et al., 2021; Reijmer et al., 2017).

2.3. Current in-situ stress orientations in the UK

The stress regime in the UK is significantly influenced by far-field stresses originating from the mid-Atlantic ridge push. This tectonic force results from the divergence of the North American and Eurasian plates at the mid-Atlantic ridge, where the creation of new oceanic crust generates compressional forces that propagate towards Europe (Heidbach et al., 2018). The maximum horizontal stress (σ_{Hmax}) across the UK is predominantly NW-SE, between 140° and 170° (Williams et al., 2015, 2016, 2018). This orientation is consistent with the regional compressional forces exerted by the dynamics of the mid-Atlantic ridge, playing a crucial role in understanding the prevalent strike-slip faulting observed throughout the region (Coward, 1993; Coward et al., 1989). Additionally, many of the strike-slip faults in the UK are reactivated older geological structures, and which often formed during the Caledonian Orogeny or earlier (Needham and Morgan, 1997).

3. Data and methodology

3.1. Regional, local, drone and bed scales data acquisition

For this study, regional-scale seismic data analysis was conducted using a combination of published literature and fault maps derived from seismic interpretation of the East Irish Sea Basin (EISB) (Fig. 3a; Aditama et al., 2025). Subsurface geological maps of the EISB were also sourced from Holford et al. (2009) and Jackson & Mulholland (1993). Onshore, geological maps were obtained from the British Geological Survey (BGS) geo-indexed database (accessed in February 2025). These maps depict major regional faults originating in the Paleozoic era, all exhibiting a normal displacement.

Local-scale data were derived from the BGS 1:10,000 maps covering

the Llandudno and Great Orme areas, spanning approximately 3 km² (Fig. 3b) which comprise faulted Viséan Carboniferous Limestone. Faults were manually digitized into vector lines using Adobe Illustrator and saved in SVG format for further analysis.

Field-based structural measurements were conducted during two separate field campaigns at Penmon Point and Great Orme, spanning three days in 2022 and another three days in 2025. These surveys measured fault and fracture networks within the exposed Viséan limestone at both locations. Detailed measurements of faults, fractures, and joints were collected, including their orientations and kinematic indicators such as striae, slickensides, and mineral lineations. Data were systematically recorded using the *Stereonet Mobile* application developed by Rick Allmendinger, allowing real-time visualization and preliminary structural analysis in the field. Outcrop-scale data were acquired by drone photography at Penmon Point using aerial photogrammetry (DJI Phantom 4 Pro version 2), which enabled the generation of high-resolution orthophotos and 3D models of the exposed coastal cliffs (Fig. 3c). These datasets facilitated the identification of fracture patterns along an approximately 200 m stretch of coastline, effectively bridging observations between bed-scale field data and local-scale geological mapping.

Bed-scale data were collected at Penmon Point (53°18'38.35"N, 4°2'25.45"W) by measuring fracture sets at the metre-scale (Fig. 3d). Fractures were captured using high-resolution imagery taken with an iPhone 13 Pro, combined with LiDAR data processed via the 3D Scanner app. LiDAR technology proved particularly effective for creating detailed 3D digital outcrop models, enabling precise characterization of

fractures and cavities, which significantly improves geological modelling (Liang et al., 2022). Images were taken from a height of approximately 2 m, corresponding to an average standing position. Distinctive features, such as fractures, were clearly visible in the images, showing terminations, offsets, and crossline nodes, indicating fractures and joints within the rock.

In response to the need for a visual synthesis of the applied methods, the methodological framework of this study is outlined in Fig. 4, which integrates multi-scale structural datasets, numerical modelling, and scenario-based simulations to evaluate fault and fracture behaviour under varying stress conditions. An important limitation of this study lies in the integration of datasets derived from multiple analytical methods and scales. Geological maps, drone photogrammetry, and regional seismic data differ in their resolution and coverage, which can introduce uncertainties when quantifying and linking fracture and permeability patterns across scales. These uncertainties highlight the need to interpret the results in relative rather than absolute terms and to consider the outcomes as scale-dependent representations of structural connectivity and permeability.

3.2. Fault-fracture connectivity pattern

To comprehensively define the fault-fracture network patterns at various scales, FracPaQ software was employed (Healy et al., 2017). FracPaQ allows quantitative analysis of fracture geometry and topology based on digitised fracture trace maps. In this study, we quantified fracture length distributions, orientations, intensity (P21), and

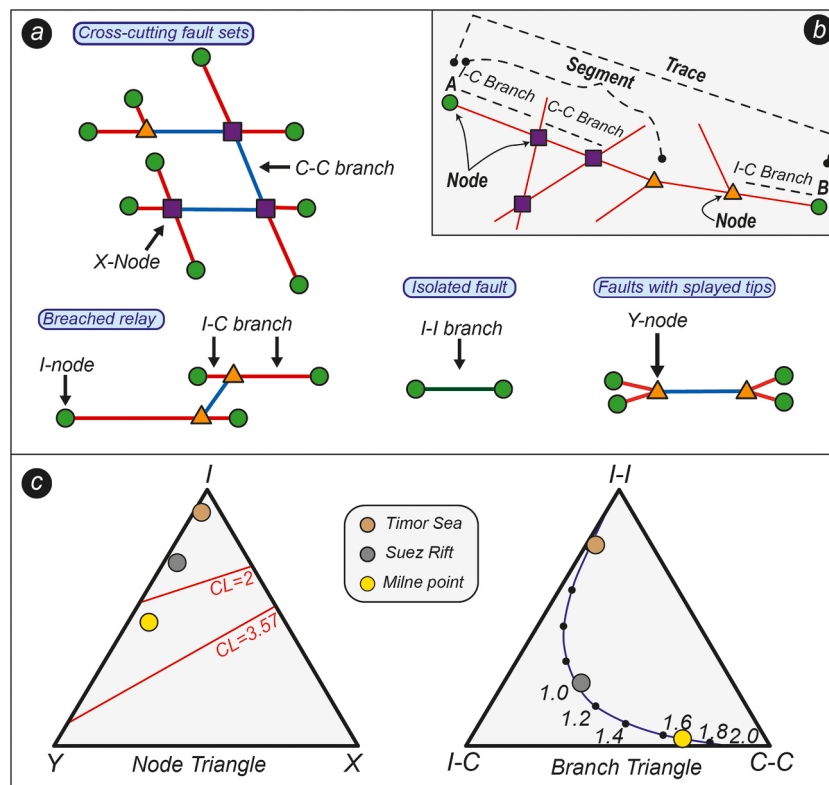


Fig. 5. Conceptual framework of fracture network topology, illustrating fault connectivity evolution and classification. (a) Schematic diagram of fault network configurations showing various node and branch types, representing the progression from isolated faults to complex cross-cutting fault systems. Node types include I-nodes (isolated; green circles), Y-nodes (splayed tips; orange triangles), and X-nodes (cross-cutting intersections; purple squares). Branch types include I-I (isolated faults), I-C (intersection to connection), and C—C (connection to connection) (modified from Duffy, 2017). (b) Illustration of fracture network sampling, highlighting trace A–B and the segmentation of faults into discrete branches and nodes. Segments represent portions of fault traces, while traces refer to the full mapped extent of a fracture (modified from Sanderson, 2015). (c) Node and branch triangle plots summarizing the topology of fault networks from physical analogue models (Based on Manzocchi, 2002). Plotted data from the Timor Sea, Suez Rift, and Milne Point fields provide comparative insight into natural fracture connectivity (after Morley and Nixon, 2016). CL = connectivity length.

Table 1

Nomenclature and definitions of metrics used for fault-fracture network analysis (Duffy et al., 2017; Sanderson et al., 2019; Sanderson and Nixon, 2015, 2018). The table describes key parameters, their formulas, and their significance in analyzing fault-fracture relationships and structural characteristics.

Metric	Description	Formula	Notes
I	Number of I-Nodes	Derived directly from network observations	Represents the total number of I-type nodes (nodes with two connections).
X	Number of X-Nodes	Derived directly from network observations	Represents the total number of X-type nodes (nodes with four connections).
Y	Number of Y-Nodes	Derived directly from network observations	Represents the total number of Y-type nodes (nodes with three connections).
NL	Number of Lines	$NL = (NI + NY)/2$	Represents the total number of fracture lines in the network.
NB	Number of Branches	$NB = (NI + 3NY + 4NX)/2$	Indicates the total number of branches connecting nodes.
I-I	a branch connecting two isolated nodes	$I-I = I(I-1)/2 \cdot NB$	Represents the proportion of branches that connect two isolated nodes. High values may indicate a fragmented or poorly connected network.
I-C	a branch connecting an isolated node and a connected node	$I-C = I(3Y + 4X)/2 \cdot NB$	Represents the proportion of branches that connect an isolated node to a connected node (Y or X type). It reflects intermediate connectivity within the fracture network.
C-C	a branch connecting two connected nodes	$C-C = (3Y + 4X)(3Y + 4X - 1)/2 \cdot NB$	Represents the proportion of branches connecting two connected nodes (Y or X). High values indicate a well-connected or clustered network, often associated with damage zones or mature fracture systems.
CL	Connections per Line	$CL = 2(NX + NY)/NL$	Measures the average number of connections per unit length of fractures.
CB	Connections per Branch	$CB = (3NY + 4NX)/NB$	Assesses the average number of connections per fracture branch.
NB/NL	Branches per Line Ratio	$NB/NL = (PI + 3PY + 4PX)/(PI + PY)$	Provides the average number of branches per line, offering insight into the network's complexity.
P21	Fracture Intensity	$I = P21 = B21 = P20 <L>$	Total fracture length per unit area, indicating fracture density.

connectivity (X, Y, I indices). These metrics are critical because fracture intensity and connectivity strongly influence fluid flow pathways in fractured reservoirs. The estimated permeability is therefore based on the premise that connected and clustered fracture networks provide more efficient fluid pathways than sparsely connected ones. Permeability values were not measured directly; rather, they were estimated from fracture network characteristics using established geometric scaling relationships and connectivity models using a crack tensor approach. We note that these results represent relative indicators of flow potential rather than absolute permeability values, as the approach is

based on 2D datasets and assumes consistent aperture scaling (Healy et al., 2017).

Two scenarios were simulated based on two principal stress orientations (Williams et al., 2015, 2018); *Scenario 1* assumed a principal stress orientation (θ) of 170° , and *Scenario 2* used 140° . The simulation parameters were defined with a maximum horizontal stress (Sh_{max}) of 90 MPa (25.23 MPa/km) and a minimum horizontal stress (Sh_{min}) of 60 MPa (14.4 MPa/km), constrained by borehole breakout observations and regional stress data (Zoback, 2007; Williams et al., 2018). This depth corresponds to the present-day subsurface depth of the Mississippian stratigraphic interval and is consistent with the conditions required for geothermal water production at temperatures of around 80°C , based on a typical geothermal gradient (Jones et al., 2023).

The faults and fractures were manually digitized from datasets spanning regional to outcrop scales. Although this process is time-consuming, manual tracing using Adobe Illustrator ensured clear differentiation between actual fractures and artifacts, which might be incorporated using automated methods (Rizzo et al., 2018). Fracture density, quantified as the number of fractures per unit area (in m^2), was analyzed using the circular scan window method (Mauldon et al., 2001). This approach, integrated within FracPaQ, involves superimposing a circle of a specific diameter on the fracture network and counting the fractures that terminate within the circle's boundary (Rohrbaugh et al., 2002; Zeeb et al., 2013).

In this study, the Maximum Likelihood Estimation (MLE) methods played a crucial role in the accurate interpretation and statistical analysis of fracture data. Specifically, MLE was instrumental in refining the estimation of distribution parameters for the observed fracture sizes, enhancing both the precision and reliability of our results (Rizzo et al., 2015, 2017). To accommodate inherent variability, and ensure robustness in our estimations, we implemented a 5 % lower cutoff and a 10 % upper cutoff in our calculations. This approach, particularly when applied to log-normal distributions, proved more effective than alternative methods, allowing for a more accurate representation of the underlying fracture characteristics (Rizzo et al., 2017).

Fracture network connectivity was also evaluated as it plays a vital role in determining the ability of these networks to support fluid flow (Manzocchi, 2002). The orientations and interactions of fractures and faults significantly affects permeability and the connectivity of subsurface fluid pathways (Pisani et al., 2022). Connectivity metrics were derived through topological measurements of fracture intersections, categorized into I, Y, and X nodes (Manzocchi, 2002). "I" nodes signify isolated ends of fractures, "Y" nodes indicate branching, splays, or abutments, and "X" nodes represent cross-cutting intersections (Fig. 5a). A "branch" is defined as a segment of a fracture that either connects to or terminates at a node (Sanderson and Nixon, 2015, 2018). Networks with higher connectivity appear closer to the Y–X axis of the ternary diagram, while lower connectivity networks are positioned near the I apex (Fig. 5a) (Sanderson et al., 2019; Sanderson and Nixon, 2018).

To further understand the nature of fault-fracture connectivity, we incorporated a conceptual framework of fault network topology (Fig. 5b–c). Fig. 5b illustrates various types of nodes and branches that define fault connectivity architecture, ranging from isolated to fully connected systems. Branches are categorized based on their end-node connectivity: *I-I* (isolated to isolated), *I-C* (isolated to connected), and *C-C* (connected to connected) (Duffy et al., 2017; Sanderson and Nixon, 2015). This classification provides a systematic approach to evaluate the structural maturity and potential fluid pathways of fracture networks.

Fig. 5c presents node and branch triangle plots that quantify the proportions of node and branch types within a mapped fault trace network, offering a graphical means to assess structural connectivity and fault evolution (Morley and Nixon, 2016; Sanderson, 2016). The connectivity length (CL), which represents the average length between connected nodes, is plotted to differentiate network maturity and degree of segmentation. Applying this framework to our study supports a more rigorous interpretation of how fault connectivity controls fluid flow.

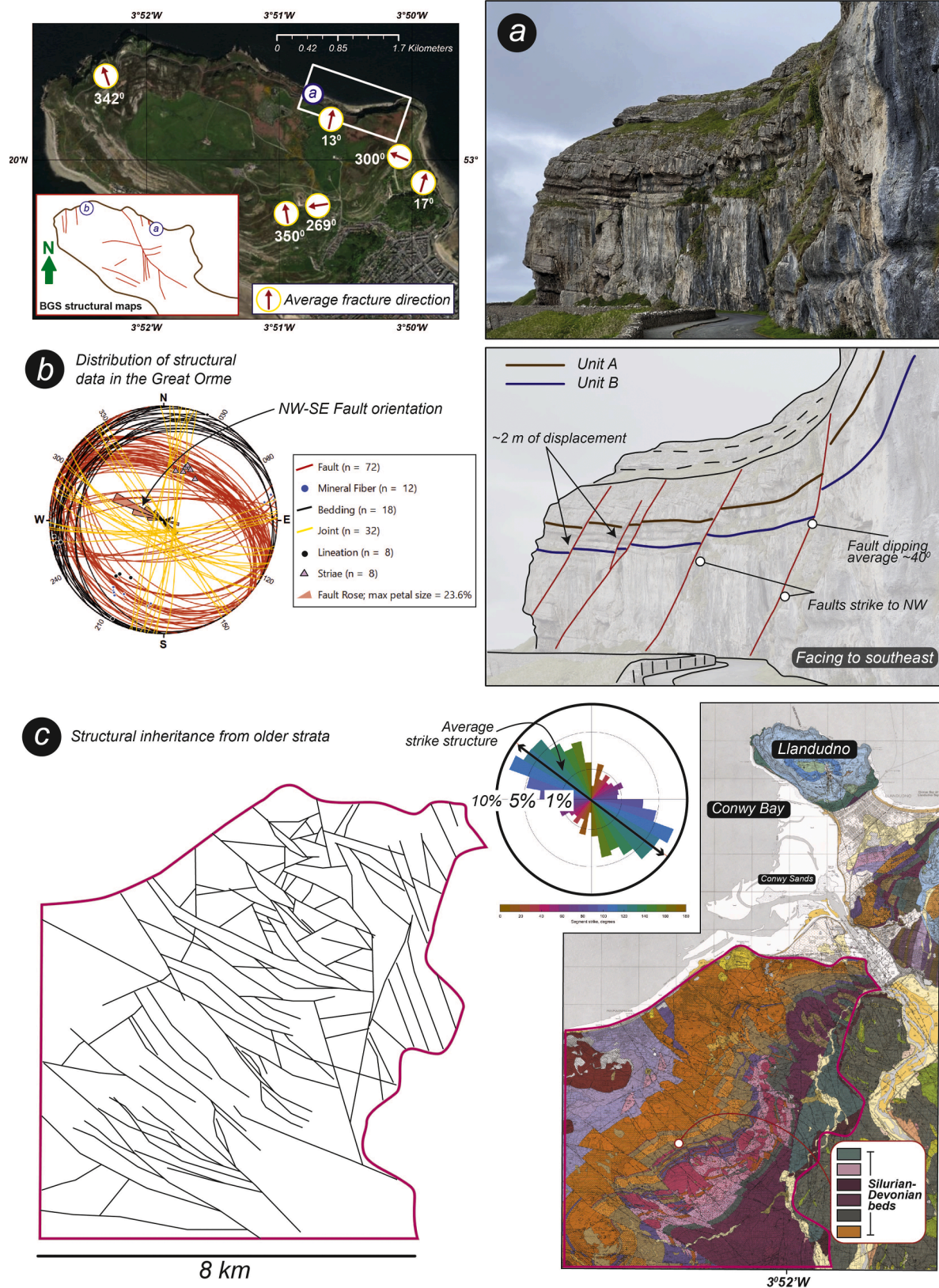


Fig. 6. Structural field observations and fracture orientation analysis from the Mississippian Carbonate Platform (MCP) at the Great Orme, North Wales. Top-left: Map showing average fracture orientations across the Orme, derived from drone photogrammetry and ArcGIS structural mapping. (a) Eastern exposure of the [Stewart et al. \(1997\)](#) Great Orme showing near-vertical, N-S to NE-SW-oriented fractures and oblique-slip faults (~2 m displacement) crosscutting bedding planes in MCP units A and B. (b) Schmidt stereonet plots of structural data from the Great Orme, indicating a dominant NW-SE fault orientation. (c) Regional analysis ~5 km south of the Orme, where older Silurian and Devonian strata are exposed, showing similar NW-SE fracture orientations. This supports the role of structural inheritance from pre-Carboniferous units in controlling deformation within the overlying Mississippian carbonate platform.

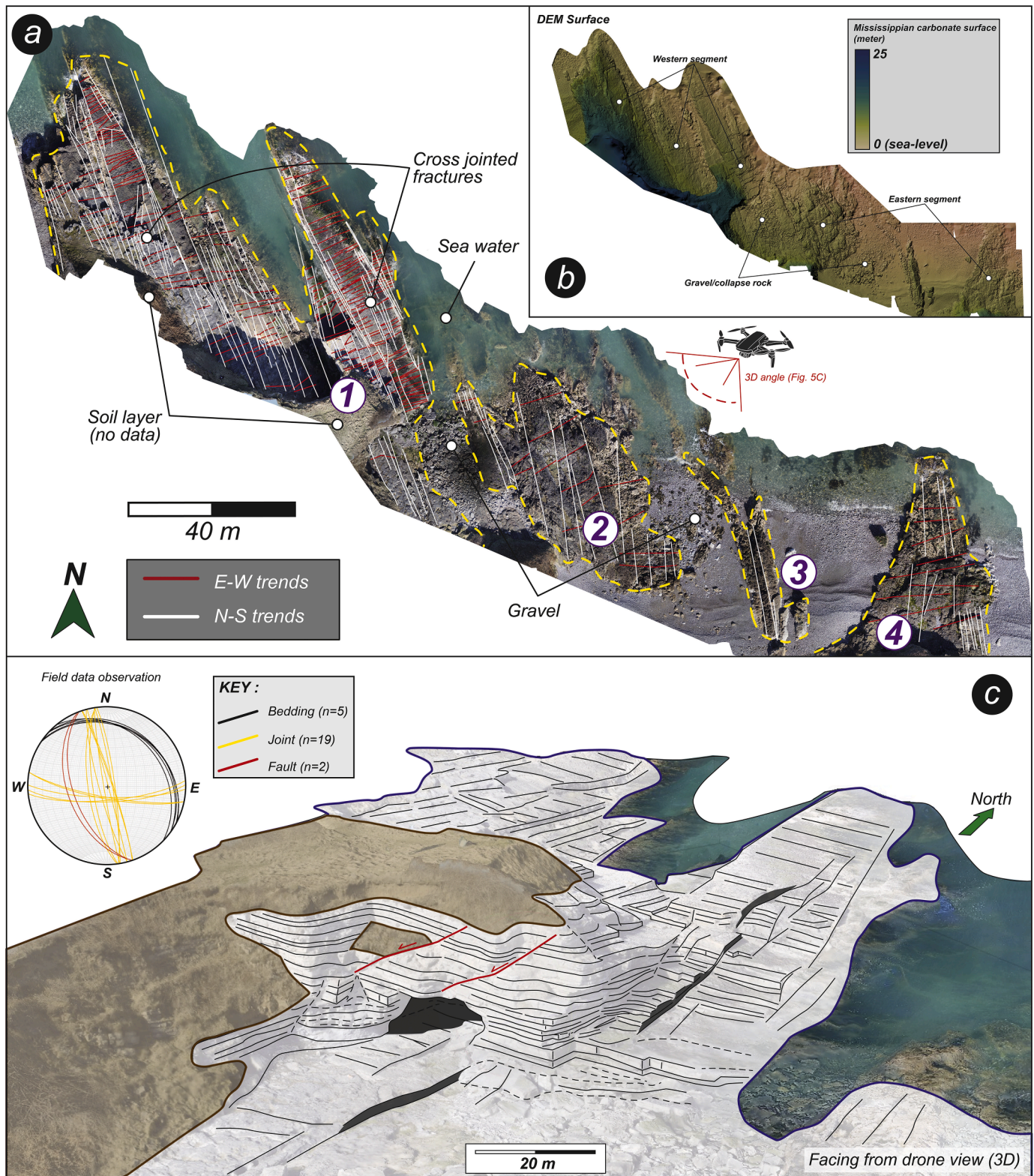


Fig. 7. Drone-based 3D photogrammetry and structural analysis of the western Penmon Point outcrop, Anglesey. (a) Orthophoto mosaic derived from drone imagery covering ~200 m of coastal exposure. Fracture sets exhibit dominant N–S and E–W trends. The outcrop is subdivided into four segments (1–4, left to right) based on data availability; remaining areas are obscured by sand, gravel, and tidal water coverage. (b) Digital Elevation Model (DEM) from drone data, with elevation values ranging from 0 to 25 m. Darker tones represent higher topography, aiding in the correlation and extraction of fracture traces and lineations. (c) Integrated 3D model and field observations reveal both fractures and small-scale faults with N–S orientations (~338°) and minor displacements (<1 m). Bedding surfaces dip gently (~25°) towards the northeast.

Table 2

Summary of fault and fracture segment characteristics across four spatial scales: regional, local, drone, and bed scale. Parameters include the number of traces and segments, dominant and secondary segment orientations, and statistical descriptors of segment length distributions derived from log-normal analysis. The log-normal mean (μ) and standard deviation (σ) quantify the central tendency and spread of segment lengths, highlighting scale-dependent variability. Segment orientations transition from consistent N–S trends at regional scale to more scattered orientations at finer scales, while segment lengths decrease markedly from kilometers to sub-meter scales. These trends reflect increasing structural complexity and resolution of deformation features at smaller spatial scales.

Structural feature	Regional scale	Local scale	Drone scale	Bed scale
Number of Traces	158	18	460	765
Number of Segments	401	37	744	1405
Dominant segment fault/fracture direction	N-S (160°–180°)	N-S (160°–180°)	N-S (azimuth: ~1650 to ~1700)	N-S (azimuth: ~50 to ~100)
Secondary segment fault/fracture direction	NE-SW	E-W	E-W (azimuth: ~60° to 70°)	E-W
Log-Normal Mean (μ)	9.1632 (km-scale faults)	5.8827 (sub-km faults)	1.691 (sub-km faults)	–1.7118 (sub-meter fractures)
Log-Normal Std Dev (σ)	0.5108 (moderate spread)	0.348 (narrow spread)	0.72 (moderate spread)	0.49826 (moderate spread)
Segment lengths range	0.5–10 km	100–650 m	1–100 m	0.01–1 m

Similarly, the branch connectivity triangle (CB) highlights node types that are pivotal in maintaining overall network connectivity, potentially serving as critical conduits for fluid migration. Table 1 details the nomenclature and metrics used in this classification.

3.3. Fault-fracture stability and permeability estimation

Fault slip is a crucial process governed by variations in stress and fluid pressure, which can result from both natural phenomena and human interventions (Kim, 2013). Gaining a comprehensive understanding of the mechanisms driving fault slip is vital for evaluating the stability of geological formations, especially in applications like geological storage and energy extraction (Cappa et al., 2018). Slip tendency (T_s) is a valuable initial indicator of fault stability as it quantifies the relative likelihood of fault reactivation under the prevailing stress field (Morris et al., 1996). Dilation tendency (T_d) measures the potential for fractures to act as pathways for fluid flow, making it a crucial parameter for understanding subsurface fluid dynamics (Ferrill et al., 2020). Fracture susceptibility (S_f) refers to the sensitivity of fractures to fluid pressure changes that can reduce effective stress and lead to failure and further enhances the understanding of fault and fracture mechanics (Moeck et al., 2009). In this context, P21 represents the total trace length of fractures per unit area and serves as a complementary metric that quantifies the spatial extent of fracturing (Sanderson and Nixon, 2015). Higher P21 values signify more extensive fracture networks, which are directly associated with increased permeability due to enhanced connectivity between fractures (Ferrill et al., 2020; Peacock et al., 2018). The integration of T_d , T_s , and P21 provides a multidimensional assessment of fault and fracture stability (Vadacca et al., 2021). For instance, a high P21 value combined with elevated dilation tendency (T_d) suggests that the fracture network is both extensive and conducive to fluid flow, potentially influencing reservoir behaviour and fault reactivation risk

(Ferrill et al., 2020). Conversely, low T_d and T_s values may indicate stable conditions, even in regions where the P21 indicates significant fracturing (Morris et al., 1996).

A widely used analytical approach for estimating the permeability of faulted and fractured rock masses involves combining the cubic law with the crack-tensor formulation (Oda, 1985; Suzuki et al., 1998). The crack tensor integrates details about fracture dimensions (length and aperture), orientation, and spatial density and is calculated in FracPaQ using 2D fracture maps. Another method for estimating permeability (Sævik and Nixon, 2017), is based on a simpler formulation that utilizes the relative proportions of I, Y, and X nodes. This method provides an upper bound estimation of permeability, assuming all fractures are fully connected.

4. Result

4.1. Field observations

Mississippian (Visean) carbonate outcrops on the North Wales Platform were studied on the Great Orme, Llandudno, and at Penmon Point, Anglesey, and occurring on either side of the Menai Straits Fault. Both outcrops represent the closest onshore exposure of Mississippian carbonate strata that extend into the East Irish Sea Basin (EISB). On the Great Orme, systematic field sampling and structural measurements were conducted from the eastern section (Fig. 6a) progressing westward. A total of 72 faults, 32 joint fractures, 8 striae (lineations), and 12 sets of mineral fibres were recorded (Fig. 6b). Faults exhibit a dominant strike direction between 291° and 300°. In the eastern section, faults with displacement up to approximately 2 m were clearly observed in outcrop (Fig. 6a). These structures, however, are not prominent on the 1:10,000-scale BGS geological maps. Conversely, in the western section, the displacement on mapped faults is less clear since the faults at outcrop are commonly expressed as collapse-related brecciated zones.

Bedding throughout the area is characterized by shallow NW-dipping beds (~10°–15°). Joint and fracture distributions are heterogeneous, with most being cross-jointed fractures that form complex geometries at smaller scales. Prominent N–S and E–W oriented fractures are observed across the Great Orme. Specifically, N–S fractures range from 342° in the western sector to 170° in the NE sector (Fig. 6). Striated fault surfaces ($n = 8$) yield lineations with plunge values of 47.1° to 53.8°, with trend directions between 014.3° and 038.4°. These moderately to steeply plunging lineations are consistent with oblique-slip kinematics, indicating a combination of dip-slip and strike-slip motion components (Tikoff and Teyssier, 1994). Such kinematic patterns are commonly associated with transpressional or transtensional tectonic regimes (Fossen, 2016).

In addition to field observations and measurements, we mapped structural features within older strata associated with the North Wales Platform, approximately 5 km south of Great Orme (Fig. 6c). Faults were digitized from regional geological maps at a 1:10,000 scale (Fig. 6c), and analyzed using FracPaQ in MATLAB. The analysis identified 116 fault traces, with a dominant NW–SE orientation (Fig. 6c), consistent with field-based measurements in the Llandudno area (Fig. 6b).

Approximately 11 km west of Great Orme, a well-exposed outcrop of Visean limestone occurs at Penmon Point, Anglesey (Figs. 3c; 7a). A high-resolution drone-based photogrammetric survey was conducted across ~200 m of the coastal cliff to document surface morphology and fracture geometries which are well exposed (Fig. 6a). The resulting orthophoto mosaic and 3D digital elevation model (DEM) captures a well-developed fracture framework, comprising dominantly N–S and E–W trending sets (Fig. 7b). These form numerous cross-jointed configurations, producing a complex fracture mesh. The outcrop is subdivided into four structural domains (1–4), primarily based on differences in lithological cover and fracture intensity. Domains 1 and 4, located at the eastern and western margins of the cliff, are partially obscured by soil and gravel, but Domains 2 and 3 feature well-exposed

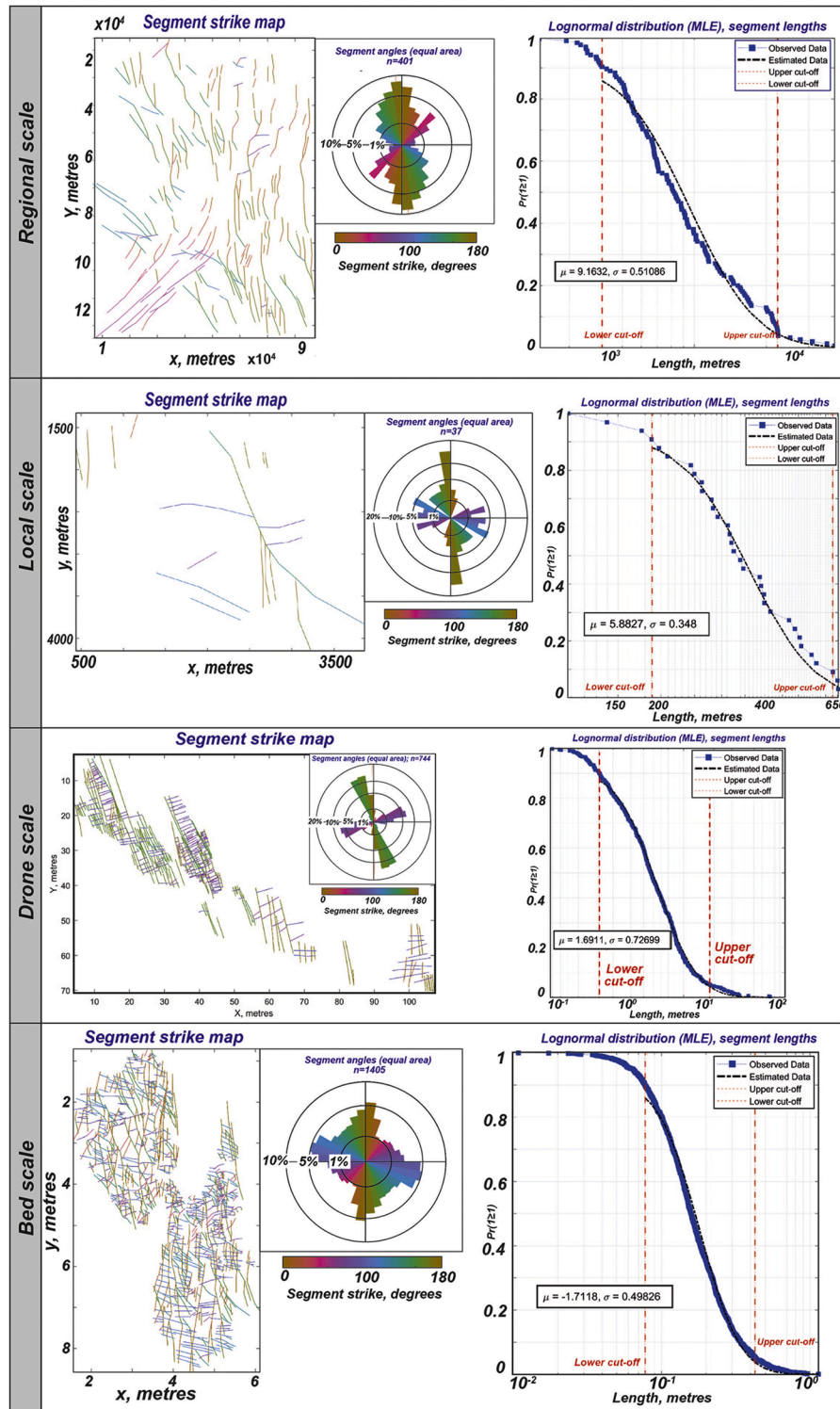


Fig. 8. Comparative analysis of fault segment orientations and length distributions across four spatial scales: regional, local, drone, and bed scale. The left panels show segment strike maps, with orientations visualized using equal-area polar histograms. The right panels present lognormal distributions of fault segment lengths, calculated using Maximum Likelihood Estimation (MLE), with 5 % lower and 10 % upper cut-off thresholds indicated by dashed red lines. At the regional scale ($n = 401$), fault orientations reveal dominant N-S to NW-SE trends, with longer segment lengths ($\mu = 9.16, \sigma = 0.51$). The local scale ($n = 37$) displays more localized structural trends with a narrower distribution of shorter segments ($\mu = 5.88, \sigma = 0.35$). Drone-scale analysis ($n = 744$) captures a higher degree of fault orientation heterogeneity and shorter segment lengths ($\mu = 1.69, \sigma = 0.73$). At the bed scale ($n = 1405$), fault segments exhibit the highest density and orientation variability, dominated by very short segments ($\mu = -1.71, \sigma = 0.50$). These results demonstrate a clear scale-dependent increase in fault network complexity from regional to outcrop level.

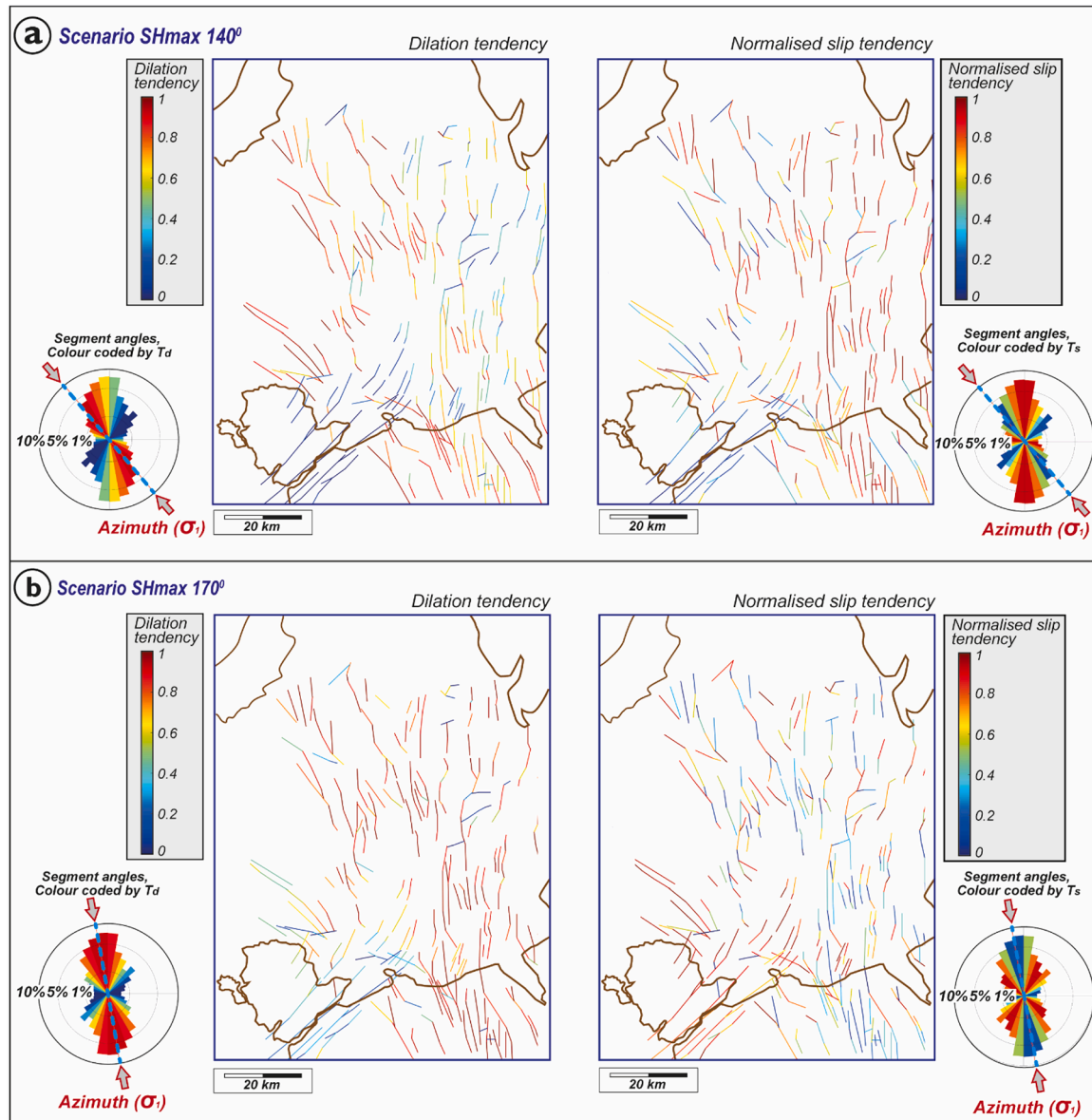


Fig. 9. Regional-scale fracture reactivation analysis in the East Irish Sea Basin (EISB) under two maximum horizontal stress (SH_{max}) orientations. (a) Scenario 1: $SH_{max} = 140^\circ$ High slip tendency values (0.7–1.0) occur mostly along N–S faults (170°–190°), which dominate the fault dataset. A few E–W faults (~80°–100°) also show elevated slip tendency. Dilation tendency is highest (0.8–1.0) along NW–SE faults (130°–150°), aligned subparallel to SH_{max} , while NE–SW fractures (~45°) show minimal dilation. (b) Scenario 2: $SH_{max} = 170^\circ$ Slip tendency decreases overall (mostly 0–0.5), with slightly higher values along NE–SW and NW–SE faults. In contrast, dilation tendency is highest (0.8–1.0) along N–S faults (150°–190°), which are most favorably oriented for tensile opening in this stress configuration.

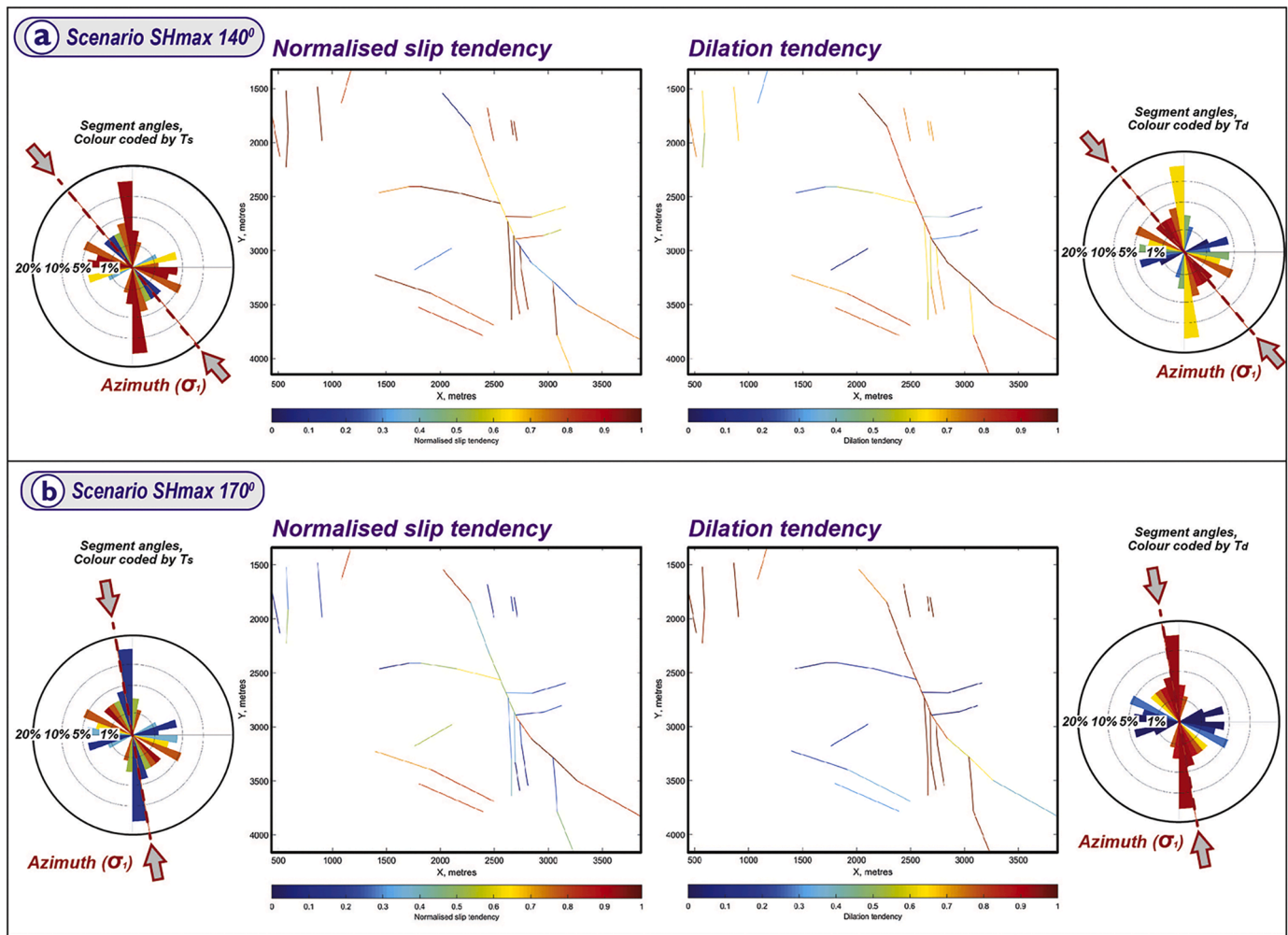


Fig. 10. Local-scale fracture reactivation analysis at the Great Orme under two maximum horizontal stress (SHmax) orientations. (a) Scenario 1: SHmax = 140°. High slip tendency values (0.8–1.0) are observed along major N–S to NW–SE faults (~500 m to 1 km in length), highlighted in red. These trends align with faults recorded in the field (see Fig. 5). In contrast, NE–SW oriented faults (~45°) show low slip tendency ($T_s < 0.2$, in blue). Dilation tendency is highest (0.8–1.0) along faults trending 150°–170°, located ~30°–40° offset from SHmax, especially along dominant N–S faults. (b) Scenario 2: SHmax = 170°. High slip tendency shifts to NW–SE faults, though these are less common. N–S faults (~170°), aligned with SHmax, generally show low slip tendency ($T_s < 0.2$). However, these same N–S faults exhibit the highest dilation tendency (0.8–1.0), while E–W faults display the lowest dilation ($T_d < 0.2$), indicating a strong stress-dependent fracture response.

carbonate beds, allowing for detailed structural mapping and analysis.

Fracture mapping indicates a heterogeneous spatial distribution, with elevated fracture density concentrated in topographically higher zones, as shown by darker tonal variations on the digital elevation model (DEM) (Fig. 7b). Bedding planes dip gently toward the northeast at approximately 25°, as illustrated by black lines on the stereonets, consistent with the regional Mississippian carbonate platform geometry. Fractures (joints) within the exposure exhibit dominant N–S orientations (~358°), along with subordinate E–W trends (~270°), forming a bimodal pattern (Fig. 7c). At this scale, normal faults are also present, typically forming parallel arrays with displacements of approximately 1 m and generally dipping toward the west.

4.2. Fault-fracture pattern quantification

A summary of multi-scale fault and fracture quantification is presented in Table 2.

4.2.1. Regional scale

At the regional scale, fault length data from the East Irish Sea Basin and adjacent locations were analyzed using a log-normal distribution with Maximum Likelihood Estimation (MLE) and a 5 % lower cut-off and

10 % upper cut-off. The analysis, based on 127 fault traces and 394 segments, yielded a mean logarithm of fault lengths (μ) of 8.2645 and a standard deviation (σ) of 0.47119 (Fig. 8). The faults predominantly range from kilometres to tens of kilometres in length, representing the largest structures observed in this study. Most of the fault segments strike in a north-south direction, with dominant orientations between 160° and 180° (Average 170°). The moderate spread in fault lengths reflects variability across the dataset, suggesting a diverse population of fault sizes that capture both primary large-scale faults and smaller secondary structures.

4.2.2. Local scale

At the local scale, fault data from the Great Orme that were manually digitized from the geological maps (10 K scale) included 18 fault traces and 37 segments. The log-normal distribution fit produced a mean logarithm (μ) of 5.8827 and a standard deviation (σ) of 0.348, reflecting shorter fault lengths compared to the regional scale, ranging between 262 m and 650 m (Fig. 8). The fault segments predominantly strike north-south (160°–180°), but east-west striking, medium-scale faults were also observed. The narrower spread in fault lengths compared to the regional scale indicates a more uniform fault population at this scale.

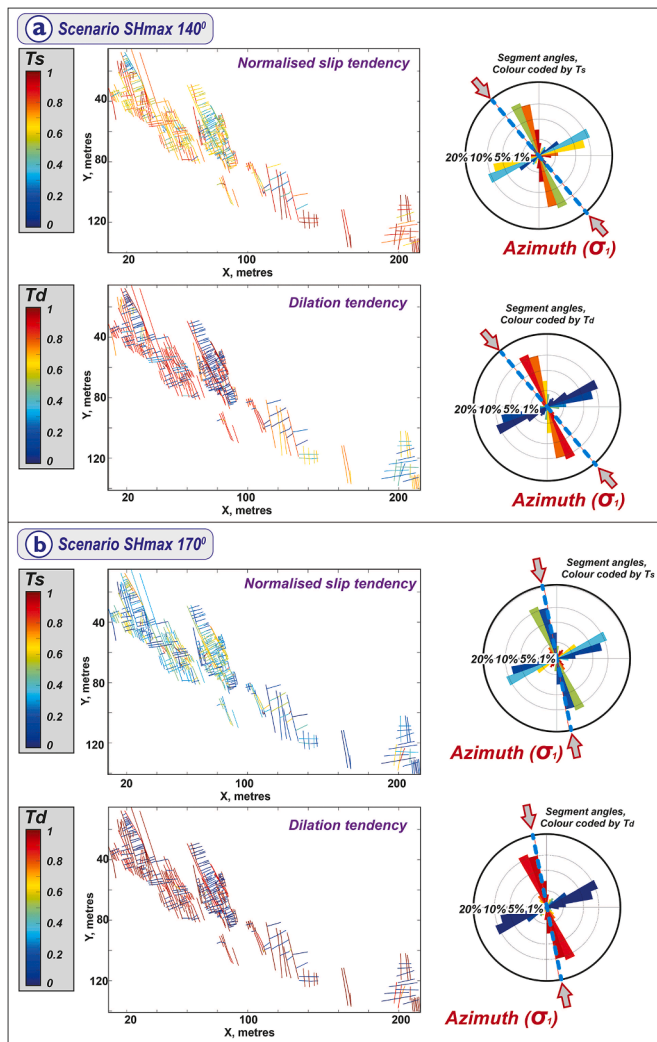


Fig. 11. Fracture reactivation analysis at drone scale using structural data from Penmon Point (see Fig. 3c and Fig. 6), under two maximum horizontal stress (SHmax) orientations. (a) Scenario 1: SHmax = 140° High slip tendency ($T_s \approx 1.0$) is concentrated along N–S fractures (170°–180°), shown in red. NE–SW fractures (~050°–060°) show low slip tendency ($T_s < 0.2$), shown in blue. Maximum dilation tendency ($T_d = 0.8$ –1.0) occurs along NW–SE fractures (165°–170°), aligned with SHmax. (b) Scenario 2: SHmax = 170° Slip tendency is generally low across the area ($T_s = 0$ –0.5), but dilation remains high along N–S fractures (~160°–170°). E–W fractures show the lowest dilation response. The results highlight how fracture orientation relative to SHmax controls reactivation potential.

4.2.3. Outcrop scale

At the outcrop scale, fracture data acquired from high-resolution photogrammetric mapping at Penmon Point comprise 460 fault traces and 714 segments. The log-normal distribution, using Maximum Likelihood Estimation (MLE), produced a mean logarithm (μ) of 1.6911 and a standard deviation (σ) of 0.72699, reflecting fault lengths that typically range from 10 to 100 m (Fig. 8). The dominant fracture orientations are oriented north–south and east–west, forming an orthogonal bimodal pattern consistent with conjugate fracture systems. A high frequency of segments striking between ~165° to ~170° and ~60° to 70° marks a shift from the simple north–south trends observed at regional and local scales.

4.2.4. Bed scale

At the bed scale, fracture data from Penmon Point, Anglesey

comprised 765 fracture traces and 1405 segments. The log-normal distribution yielded a mean logarithm (μ) of -1.7118 and a standard deviation (σ) of 0.49826 , capturing sub-meter to meter-scale fractures (Fig. 8). The fault segments predominantly strike north south but exhibit a slight clockwise rotation of approximately 10°, shifting the dominant orientation from an average strike of 170° at the regional and local scales to around 10° (Fig. 8). Additionally, fractures with an east–west distribution were identified at this scale,

4.3. Fault-fracture stability analysis

4.3.1. Regional scale (EISB)

4.3.1.1. Azimuth of SHmax = 140°. Scenario 1 applies a maximum horizontal stress (SHmax) oriented at 140°. Under this configuration, the highest normalized slip tendency values (0.7 to 1.0) are predominantly associated with north–south (N–S) striking faults, particularly in the 170°–190° range (Fig. 9a). A smaller number of east–west (E–W) striking faults (80°–100°) also display high slip tendencies. However, these represent a minor portion of the dataset, as approximately 90 % of the mapped faults are dominantly N–S in orientation. These high-slip areas are visually expressed in red tones on the map, indicating zones of elevated reactivation potential under this stress scenario. The dilation tendency in this scenario reaches its maximum (0.8–1.0) within fractures-oriented northwest–southeast (NW–SE), typically trending between 130° and 150°. These orientations lie subparallel to the SHmax, promoting tensile opening (Fig. 9a). In contrast, fractures-oriented northeast–southwest (NE–SW) (~45° azimuth) exhibit the lowest dilation tendencies, attributed to their nearly perpendicular alignment to the stress axis.

4.3.1.2. Azimuth of SHmax = 170°. Scenario 2 assumes an SHmax orientation of 170°, which is broadly aligned with the dominant regional structural grain. Approximately 90 % of the regional fault population exhibits N–S trends, and this structural alignment significantly governs the mechanical response under this stress condition (Fig. 9b). Under Scenario 2, the normalized slip tendency is generally low across the study area, with most values ranging between 0 and 0.5. This is visually represented by green to blue tones on the slip tendency map. Only a small subset of faults, primarily those trending NE–SW and NW–SE, display higher slip tendencies, indicating localized reactivation potential. In contrast, the dilation tendency is highest along N–S striking faults, particularly those oriented between 150° and 190°, which dominate the fracture dataset at this scale. These faults exhibit dilation tendency values between 0.8 and 1.0, making them the most favourable structures for tensile opening in this scenario (Fig. 9b).

4.3.2. Local scale (Great Orme)

4.3.2.1. Azimuth of SHmax = 140°. In Scenario 1, with SHmax oriented at 140°, normalized slip tendency values range between 0.8 and 1.0, observed along major N–S to NW–SE oriented faults (Fig. 10a). These faults, with lengths of approximately 500 m to 1 km, are highlighted in red on the map, indicating relatively high slip tendency values under the applied stress condition. This corresponds to faults also observed in the field dataset (Fig. 6), where NW–SE fault orientations were recorded. In contrast, NE–SW oriented faults (~45° azimuth) display minimal slip tendency, shown in blue on the map. The dilation tendency in this scenario is concentrated within faults oriented approximately 30°–40° offset from SHmax, particularly in those trending 150°–170° (Fig. 10a). These regions are highlighted in red tones, especially along the dominant N–S faults. The maximum slip tendency is observed along faults trending approximately 180°.

4.3.2.2. Azimuth of SHmax = 170°. In Scenario 2, with SHmax oriented

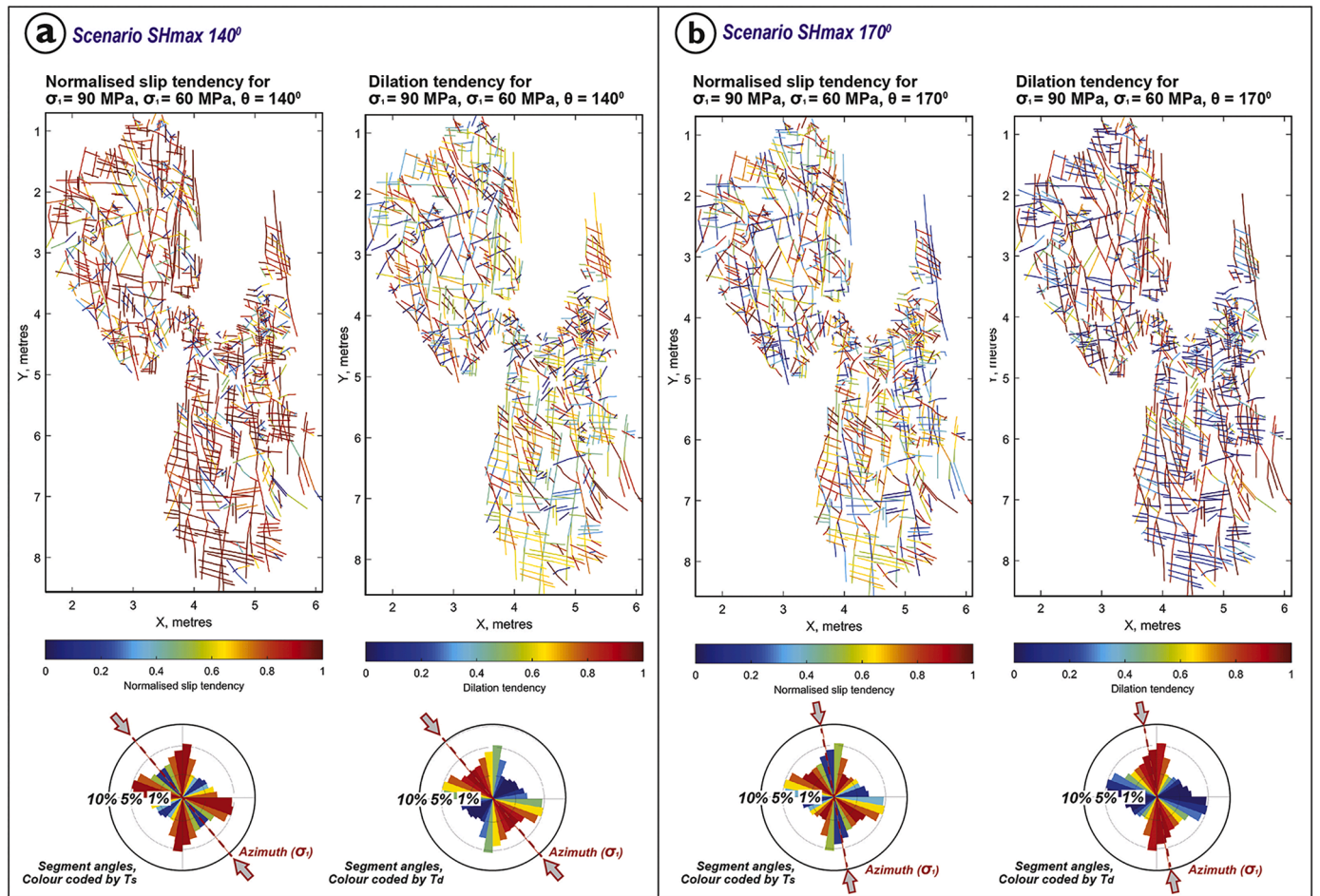


Fig. 12. Bed-scale fracture reactivation analysis under two maximum horizontal stress (SHmax) orientations at Penmon Point. (a) Scenario 1: SHmax = 140°. Fractures show high density and are primarily oriented N–S (170°–190°) and E–W (90°–100°), both exhibiting high normalized slip tendency values (Ts = 0.5–1.0), represented in red and comprising ~80 % of the dataset. NW–SE and NE–SW oriented fractures show lower slip tendency (Ts < 0.4). Dilation tendency is more variable, with maximum values (Td = 0.8–1.0) observed along NW–SE trending fractures (130°–150°), accounting for ~30 % of the total fracture population. (b) Scenario 2: SHmax = 170°. Slip tendency is more evenly distributed across orientations, with highest values (Ts = 0.5–1.0) recorded along NW–SE and NE–SW fractures (~30 % of the dataset). Dilation tendency peaks along N–S fractures (160°–180°), aligned with SHmax, while E–W fractures display low dilation (Td < 0.2).

Table 3
Summary of fault–fracture connectivity parameters across four spatial scales: regional, local, drone, and outcrop. Metrics include the number of nodes (Nx), branches (Ny), isolated nodes (Ni), links (NL), and connected branches (NB), as well as derived indices such as branch-to-link ratio (NB/NL), clustering coefficient (CL), and betweenness centrality (CB). P21 values reflect the spatial intensity of mapped fault segments. Results show limited connectivity at the regional and local scales, with low CL and CB values and high proportions of isolated nodes. In contrast, drone and bed scales demonstrate a substantial increase in network complexity, connectivity, and spatial intensity, with markedly higher CL, CB, and NB/NL values.

Sampling scale	Node Numbers			Branch proportions			NL	NB	NB/NL	Line connection (CL)	Degree of connectivity (CB)
	I	Y	X	II	IC	CC					
Regional scale	223	28	12	51 %	31 %	18 %	125.5	177.5	1.41	0.64	0.74
Local scale	27	5	0	53 %	31 %	16 %	16	21	1.31	0.63	0.71
Drone scale	719	238	309	9 %	25 %	66 %	478.5	1334.5	2.79	2.29	1.46
Bed scale	1216	412	821	5 %	20 %	75 %	814	2868	3.52	3.03	1.58

at 170°, high normalized slip tendencies (0.8 to 1.0) are noted primarily along NW–SE oriented faults, although these occur less frequently within the study area (Fig. 10b). Faults aligned with the SHmax direction, particularly those at ~170° azimuth, generally show low slip tendency values, ranging from 0 to 0.2. In this scenario, N–S aligned faults, especially those between 160° and 180°, display the highest dilation tendencies, ranging from 0.8 to 1.0 (Fig. 10b). In contrast, E–W oriented faults show lower dilation tendencies, typically between 0 and 0.2, as shown in blue on the dilation map.

4.3.3. Drone scale

4.3.3.1. Azimuth of SHmax = 140°. In Scenario 1, slip and dilation tendency analyses were performed on the Penmon Point fracture dataset (Figs. 3c, 7), assuming a maximum horizontal stress (SHmax) oriented at 140°. The normalized slip tendency results show a distinct concentration along north–south striking fractures (170°–180°), with values approaching 1.0, indicating high relative slip potential (Fig. 11). These areas are highlighted in red on Fig. 11, corresponding to the dominant fracture orientation. In contrast, fractures striking perpendicular to

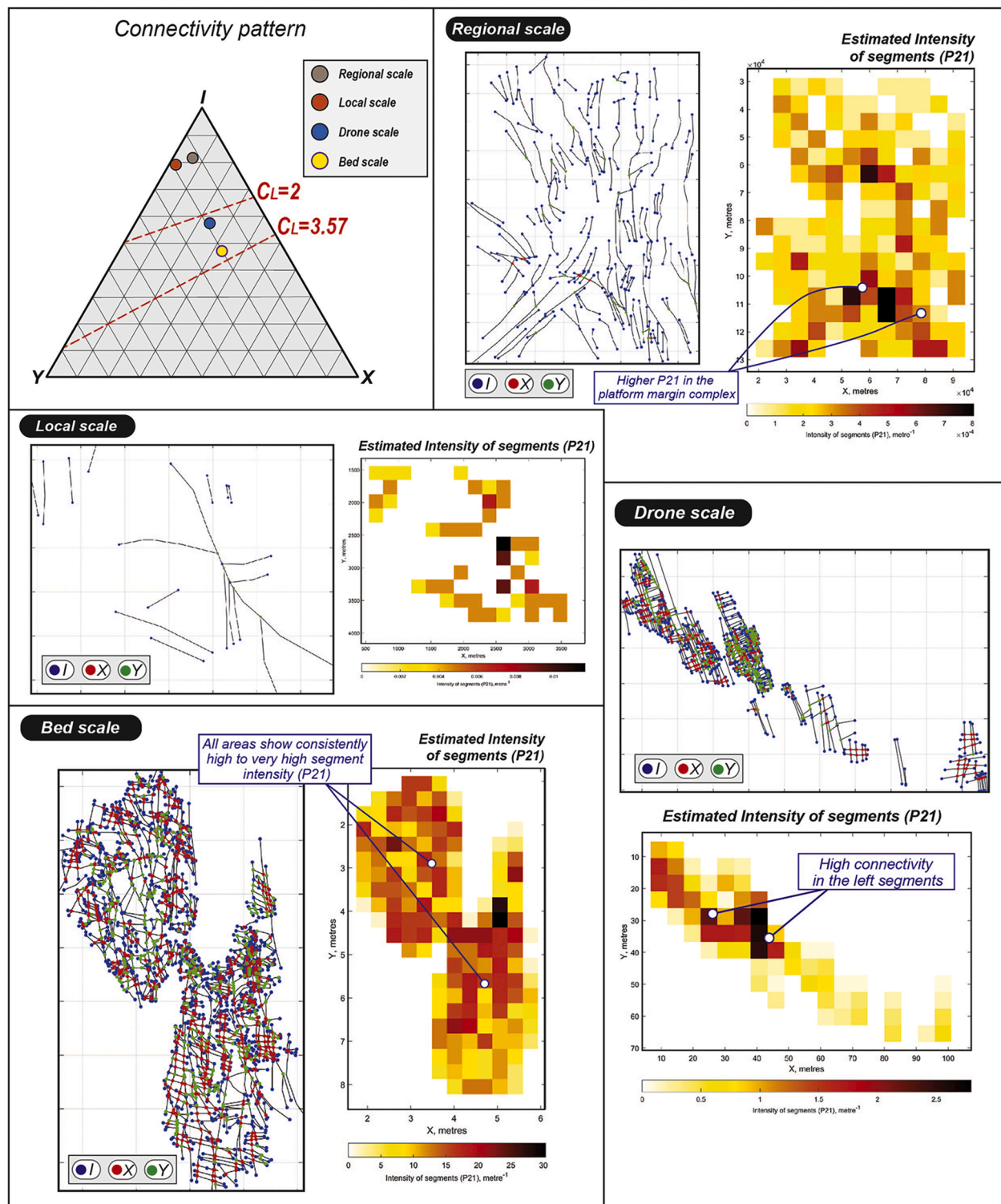


Fig. 13. Multiscale analysis of fault–fracture network connectivity and segment intensity (P21) across regional, local, drone, and bed scales. Left panels illustrate node and branch topology for each scale, highlighting the presence of intersection nodes (X), splayed nodes (Y), and isolated terminations (I). Right panels show P21 heatmaps, indicating the spatial distribution of fault segment intensity. At the regional and local scales, networks display limited connectivity, with sparse node distribution and localized P21 values, particularly along major mapped faults. In contrast, the drone and bed scales reveal significantly enhanced connectivity, characterized by increased node and branch density and higher P21 values across broader areas. These results reflect a progressive increase in fault–fracture complexity and connectivity with improved spatial resolution and observational scale.

SHmax, particularly in the northeast–southwest (NE–SW) orientation ($\sim 045^{\circ}$ – 060°), exhibit very low slip tendency values (≤ 0.2), represented by cooler blue tones on Fig. 11. Dilation tendency analysis for this

stress orientation shows the highest values (0.8–1.0) concentrated along fractures striking between 165° and 170° , closely aligned with the SHmax direction. These high dilation zones are also visible as red-

Table 4

Permeability tensor results calculated from FracPaQ at multiple spatial scales. The table includes estimates of maximum permeability (K_1), minimum permeability (K_2), anisotropy ratio (K_1/K_2), and dominant orientation of maximum permeability for each scale. All permeability values are in square metres (m^2).

Scale	$K_1 (m^2)$	$K_2 (m^2)$	K_1/K_2 ratio
Regional	5.0×10^{-12}	1.5×10^{-12}	~ 3.3
Local	1.6×10^{-11}	5.0×10^{-12}	~ 3.2
Drone	2.2×10^{-10}	6.8×10^{-11}	~ 3.2
Bed	2.2×10^{-9}	6.5×10^{-10}	~ 3.4

highlighted features on Fig. 11. In contrast, NE–SW trending fractures ($\sim 050^\circ$ – 060°) show minimal dilation tendency due to their oblique to perpendicular orientation relative to the imposed stress field.

4.3.3.2. Azimuth of $SH_{max} = 170^\circ$. In Scenario 2, with SH_{max} reoriented to 170° , the overall slip tendency (T_s) values across the dataset are notably reduced. Most fault segments, regardless of whether they strike N–S or E–W, exhibit low slip tendency values, predominantly ranging between 0 and 0.5 (Fig. 11). There is a widespread distribution of low T_s values, with no significant concentration in any particular orientation. However, dilation tendency results under this stress regime display a different pattern. Fault segments striking close to the SH_{max} orientation (160° – 170°) exhibit maximum dilation tendency values (0.8–1.0), shown in red on Fig. 11. In contrast, E–W striking segments present markedly lower dilation tendencies, indicating limited potential for opening under this stress orientation.

4.3.4. Bed scale

4.3.4.1. Azimuth of $SH_{max} = 140^\circ$. At the bed scale in Scenario 1, where the maximum horizontal stress (SH_{max}) is oriented at 140° , the fracture network reveals a higher density of fault–fracture relationships compared to the regional, local, and drone scales. The dataset comprises a large number of joints, primarily distributed in two dominant sets: N–S and E–W. Fractures oriented between 170° – 190° (N–S) and 90° – 100° (E–W) display the maximum normalized slip tendency (T_s), with values ranging from 0.5 to 1.0 (Fig. 12a). These are represented in red and constitute approximately 80 % of the total dataset. The remaining 20 % of the dataset, comprising NW–SE and NE–SW oriented fractures, show lower slip tendencies, with T_s values ranging from 0.4 to 0, as shown by blue coloration on Fig. 12a. The dilation tendency in this scenario shows a more variable distribution. The maximum values (0.8–1.0) are observed along fractures trending NW–SE, specifically within the 130° to 150° azimuth range. These comprise approximately 30 % of the total fracture population. The remaining 70 % of the dataset displays lower dilation tendencies under this stress orientation (Fig. 12a).

4.3.4.2. Azimuth of $SH_{max} = 170^\circ$. In Scenario 2, where SH_{max} is oriented at 170° , the fracture analysis at the bed scale exhibits a different pattern. Unlike Scenario 1, where variation was mainly observed in dilation tendency, here the normalized slip tendency values are more uniformly distributed across multiple orientations, without a single dominant trend. The highest T_s values (0.5–1.0) are recorded along NE–SW and NW–SE oriented fractures, which make up approximately 30 % of the dataset (Fig. 12b). Despite these orientations showing higher slip tendencies, the majority of fractures remain in the N–S and E–W orientations. Conversely, dilation tendency values are highest along N–S oriented fractures, particularly those within the 160° – 180° azimuth range, with values reaching 0.8 to 1.0. These are aligned with the SH_{max} orientation. In contrast, E–W oriented fractures display low dilation tendency values, generally between 0 and 0.2, shown in blue on the map (Fig. 12b).

4.4. Fault–fracture connectivity and its segment intensity (P21)

The analysis of fault–fracture connectivity across multiple spatial scales, regional, local, outcrop, and bed, reveals marked differences in network structure, data density, and spatial distribution of segment intensity (P21).

At the regional scale, where the dataset is primarily derived from subsurface observations, the fault network exhibits limited connectivity. The number of nodes ($N_x = 12$) and branches ($N_y = 28$) is relatively low (Fig. 12), while the number of isolated nodes ($N_i = 223$) far exceeds the number of connected branches. The branch-to-link ratio (NB/NL) is 1.41, and P21 values are localized, primarily concentrated in areas where cross-jointed faults are mapped, most notably in the southern part of the Great Orme (Fig. 2). The clustering coefficient (CL) is 0.64, and the betweenness centrality (CB) is 0.74, indicating a sparsely connected fault framework (Table 3).

At the local scale, the connectivity pattern remains similarly sparse. The number of nodes ($N_x = 0$) is absent, with a low number of branches ($N_y = 5$) and links ($NL = 16$). Isolated nodes ($N_i = 27$) remain dominant, and the NB/NL ratio is 1.31, reflecting a simple fault network (Fig. 13). The spatial distribution of connectivity is limited to the central part of the Great Orme, where a principal NW–SE fault segment bisects the structure into eastern and western domains. This zone corresponds to a localized elevation in P21 values. The clustering coefficient (CL = 0.63) and CB = 0.71 are comparable to the regional scale, indicating no significant increase in connectivity. P21 values are confined to a narrow portion of the mapped area (Fig. 13).

In contrast, the drone scale analysis at Penmon Point shows improved fracture network definition due to significantly higher data resolution. A total of $N_i = 719$, $N_y = 238$, and $N_x = 309$ was recorded (Table 3). Both the clustering coefficient (CL = 2.29) and betweenness centrality (CB = 1.46) increased substantially compared to regional and local scales. The spatial distribution of P21 values shows medium to high intensities, particularly in Segment 1 (western Penmon Point), where most of the exposure is well-preserved and fully covered in the dataset (Fig. 13). Although similar intensities may be present in other segments, outcrop limitations at the edges restrict data coverage and visibility.

At the bed scale, the dataset demonstrates the highest level of connectivity of all scales. The number of nodes ($N_x = 821$) and branches ($N_y = 412$) is significantly larger, with isolated nodes ($N_i = 1216$) recorded (Fig. 12). The NB/NL ratio increases to 3.52, and both CL (3.03) and CB (1.58) exceed the values observed at the drone scale (Table 3), highlighting a densely connected fault–fracture system. The P21 values are distributed across nearly all mapped areas, indicating pervasive fracture intensity throughout the outcrop.

4.5. Permeability tensor

The permeability tensor results derived from FracPaQ analysis span four spatial scales: bed, outcrop, local, and seismic are presented in Table 4. The maximum permeability (K_1) at the bed scale is approximately $2.2 \times 10^{-9} m^2$, while the minimum permeability (K_2) is approximately $6.5 \times 10^{-10} m^2$, yielding a K_1/K_2 ratio of ~ 3.4 . The dominant permeability orientation is aligned along 0° – 180° . At the drone scale, K_1 is estimated at $2.2 \times 10^{-10} m^2$, and K_2 is approximately $6.8 \times 10^{-11} m^2$, with a resulting ratio of ~ 3.2 . The dominant orientation remains aligned along 0° – 180° . The local scale shows a K_1 of approximately $1.6 \times 10^{-11} m^2$ and a K_2 of $5.0 \times 10^{-12} m^2$, with a K_1/K_2 ratio of ~ 3.2 . The dominant permeability direction at this scale is recorded as $\sim 330^\circ$ – 150° . At the seismic scale, the K_1 value is $5.0 \times 10^{-12} m^2$, and K_2 is $1.5 \times 10^{-12} m^2$, resulting in a K_1/K_2 ratio of ~ 3.3 , with the dominant orientation again along 0° – 180° .

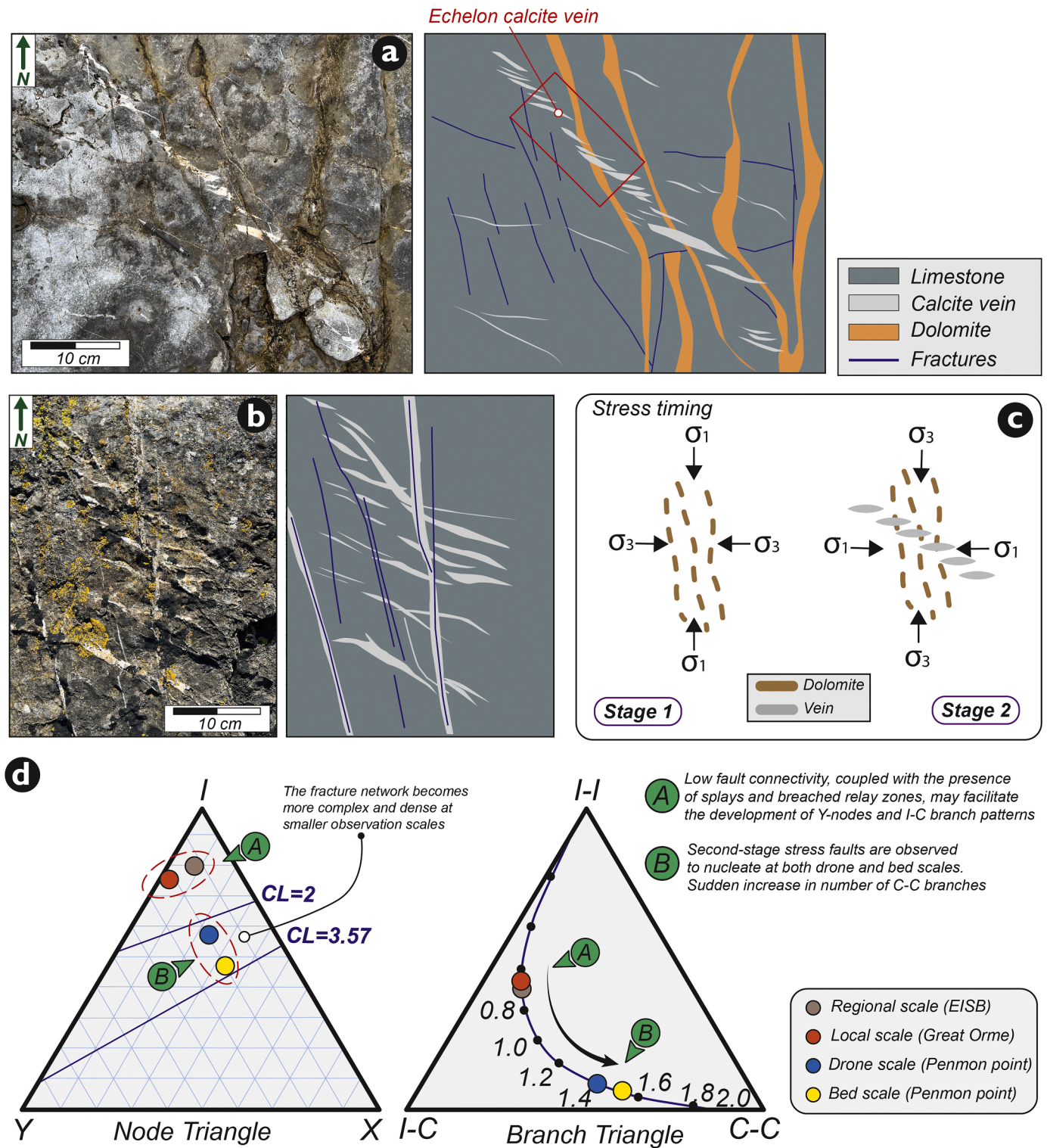


Fig. 14. Bed-scale structural and stress analysis of the Mississippian carbonate platform (MCP) from the eastern coastline of Penmon Point, Anglesey. This scale reveals fracture complexity not captured at regional or local seismic resolution. (a) Field photograph and corresponding interpretation of dolomite-hosted calcite veins cross-cutting limestone, showing both N-S and E-W vein orientations, including an echelon texture indicative of shear. (b) Additional exposure exhibiting dense N-S fractures and calcite veins-oriented N-S and E-W, suggesting multiple fracture opening phases. (c) Conceptual stress evolution model illustrating two principal stress stages: Stage 1 with dominant NE-SW extension forming dolomite veins, followed by Stage 2 characterized by N-S-directed extension and calcite veining. (d) Node and branch topology triangles summarize fracture connectivity evolution across spatial scales. At bed scale, an increase in X- and C-C branches indicate higher fracture connectivity ($CL = 3.57$), as compared to the more disconnected patterns at regional and local scales ($CL \sim 2$).

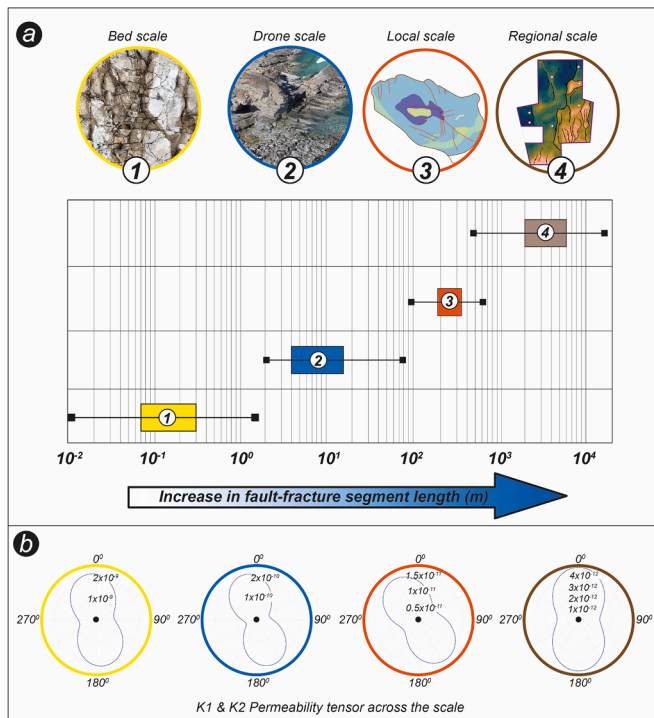


Fig. 15. Multiscale evaluation of fault-fracture segment lengths and associated permeability tensors across the Mississippian carbonate platform (MCP). (a) Box plot of fault-fracture segment lengths across four observation scales: bed scale, drone scale, local scale, and regional scale. The plots highlight a clear increase in average segment length with scale, from sub-meter fractures at bed scale to kilometer-scale faults at the regional level. Datasets at bed and drone scales capture fracture types such as veins, joints, and dolomitized fractures that are not resolved in seismic or regional datasets, which primarily image large-offset faults. This overlap emphasizes the importance of integrating fine-scale observations for complete fault network characterization. (b) Permeability tensor ellipses (K_1 and K_2) for each scale, illustrating principal permeability orientations. Across all scales, N–S-oriented permeability dominates, reflecting the structural anisotropy of the fracture systems. Tensor magnitudes decrease with scale, consistent with increasing fracture spacing and segment length.

5. Discussion

5.1. Structural framework of the North Wales Mississippian carbonate platform

Field observations from the Great Orme and Penmon Point (Figs. 6 and 7) provide valuable insights into the naturally developed structural architecture of the North Wales Platform. These outcrops represent well-exposed analogues that help bridge the interpretive uncertainties in larger datasets such as seismic sections or geological maps (Sanderson, 2016). Both locations exhibit faulted and fractured carbonate successions, marked by localized dolomitization, calcite veining, and jointing, features characteristic of other MCPs across northern England (Fig. 2; Juerges et al., 2016; Manifold et al., 2021).

Our study suggests notable structural variations. In the East Irish Sea Basin (EISB), there is a relatively simple structural fabric dominated by N–S faults, which comprise over 90 % of mapped structures in seismic data (Fig. 8; Jackson and Mulholland, 1993). On the Great Orme both NW–SE and N–S trending faults and fractures are mapped (Figs. 6, 8), while Penmon Point shows a slight clockwise rotation in fracture orientation, with a stronger dominance of NW–SE trends in west segments (outcrop scale) to N–S in East segments (bed scale) (Figs. 7, 8). Fracture sets, both veined and dolomitized, were more easily mapped at Penmon Point due to better exposure, although both sites reveal a consistent cross-joint pattern of N–S and E–W orientations.

On the Great Orme, the predominance of NW–SE to N–S structures suggest a relatively stable tectonic domain during deformation (Fig. 6b). The orientations mimic a deeper structural grain within from older (Silurian and Devonian) strata (Coward et al., 1989; Worthington and Walsh, 2011) (Fig. 6c) suggesting that Mississippian and younger deformation here was likely inherited from pre-existing weaknesses in the underlying basement. This structural inheritance, where pre-existing faults are reactivated under later stress regimes, has been widely recognized in Palaeozoic basins of the British Isles (Coward, 1993; Holdsworth et al., 1997; Moore and Walsh, 2021; Woodcock and Strachan, 2012) and points to a long-lived tectonic framework, potentially rooted in Caledonian or early Variscan structural fabrics (Fig. 5c; Stewart et al., 1997).

In contrast, the clockwise fracture rotation in fracture rotation observed at Penmon Point (Figs. 7, 8) could suggest a strong influence of the nearby Menai Strait Fault System (MSFS). This NE–SW striking sinistral strike-slip zone was active from the Early Ordovician (Schofield et al., 2021) and along with its associated structures, such as the Berw Fault (located ~15 km from Penmon; Fig. 2), has undergone multiple reactivation events, influencing terrane juxtaposition and rotation within the Monian Composite Terrane and adjacent Avalonian units (Brenchley et al., 2018; Gibbons and Ball, 1991). Consistent NW–SE fault trends from the Ordovician–Silurian basement (Schofield et al., 2021; Treagus et al., 2011) through to the overlying Mississippian strata also suggests reactivation of pre-existing fabrics. The proximity of Penmon Point (east segment) to the MSFS likely facilitated local strain partitioning and fracture reorientation (Healy, 2008), underscoring the importance of integrating field-scale observations with broader tectonic frameworks (Bisdorn et al., 2017; Pothier et al., 2015).

Two possible interpretations arise from these structural contrasts: *First*, the NW–SE structures observed in outcrop may reflect inheritance from older Caledonian or Acadian tectonic fabrics (Coward, 1993), reactivated under oblique or transtensional stress regimes during later extensional episodes (as it seen in both Fig. 6b and c). This pre-existing structural grain, coupled with lithological heterogeneity, likely caused strain partitioning at the platform-basin transition, resulting in more intricate fault networks onshore (Cartwright et al., 2000).

Second, the onshore structures may represent the tip-lines or splays of deep-seated N–S basin-bounding faults that accommodated major extension in the EISB. In this view, the platform structures are not isolated but rather the surface expression of fault propagation into shallower levels. Tip-line mechanics predict decreasing displacement and more distributed deformation towards the fault tip, manifesting as veining and fracture networks with lower displacement near the platform surface (Walsh and Watterson, 1987; Worthington and Walsh, 2011). This would explain the more diffuse structural expression onshore compared to the focused faulting imaged in the basin seismic data. If correct, this has implications for predicting fracture intensity and reservoir heterogeneity near fault tips, which could be zones of enhanced fluid flow or compartmentalization depending on the connectivity and aperture of fracture networks (Bisdorn et al., 2017; Watkins et al., 2015).

5.2. Fault–fracture response to the current principal stress

The multiscale analysis of fault and fracture responses under differing stress orientations reveals that both mechanical reactivation potential and mode of failure are governed not solely by the direction of SH_{max} , but also by the inherent geometry and orientation of fault systems across scales (Fig. 8; Table 2). Two modelled stress scenarios: Scenario 1 ($SH_{max} = 140^\circ$) and Scenario 2 ($SH_{max} = 170^\circ$), demonstrate that structural responses vary markedly as a function of scale and dominant structural trend (Figs. 9–12).

At the regional scale, Scenario 1 (140°) yields a high slip tendency (~90 %) across mapped faults, with a notably lower dilation tendency (~30 %) (Fig. 9a). This suggests that the majority of faults in this

scenario are optimally oriented for shear reactivation rather than tensile opening (Röckel et al., 2021). In contrast, under Scenario 2, where SHmax is rotated to 170°, aligning more closely with the dominant N–S fault orientation, dilation tendency becomes overwhelmingly dominant (~90 %), while slip tendency is substantially reduced (Fig. 9b). This reflects a shift toward tensile reactivation and highlights the sensitivity of reactivation style to even minor shifts in stress orientation relative to structural geometry (Ferrill et al., 2020). At the local scale, a similar pattern is observed: faults and fractures show reactivation modes that are clearly dependent on the relationship between SHmax direction and structural trends (Fig. 10a–b).

These trends continue at smaller scales (outcrop to bed scales), although with increasing structural complexity. In the outcrop-scale data, structures are not dominantly unidirectional but instead display cross-jointed networks, with fractures trending ~345°–350° (N–S) and ~240°–250° (E–W) (Fig. 11). Under Scenario 1, both dilation and slip tendencies are moderately developed along N–S sets, with slip tendency being present but not strongly dominant (Fig. 11a). Scenario 2, however, produces a notable increase in dilation tendency due to the alignment of SHmax (170°) with the dominant N–S structures, while slip tendency is substantially diminished (Fig. 11b).

At the bed scale, the influence of proximity to the Menai Strait Fault System at Penmon Point becomes evident. A subtle clockwise rotation (~10°) of structural orientations is observed, likely reflecting localized stress perturbations near the fault system. As a result, under Scenario 1, slip tendency increases, suggesting enhanced shear reactivation potential in this domain compared to the outcrop scale (Fig. 12a). Meanwhile, Scenario 2 continues to show dominant dilation tendency, in line with SHmax being subparallel to N–S fracture sets (Fig. 12b).

These results emphasize that reactivation potential is not scale-independent, but rather emerges from the interaction between stress direction, fracture orientation, and local structural rotation. Even small deviations in structural alignment relative to SHmax can produce significant changes in failure mode, whether favouring tensile dilation or shear slip (Barcelona et al., 2019; Dávalos-Elizondo and Laó-Dávila, 2023; Moeck et al., 2009). This complexity is particularly important in structurally controlled carbonate reservoirs, where fracture connectivity and reactivation behaviour directly influence fluid flow, permeability evolution, and the geomechanical stability of subsurface reservoirs (Burgoa Tanaka et al., 2022; Cappa et al., 2022). Fractures subparallel to SHmax consistently exhibit the highest dilation tendency (seen in Figs. 9–12), promoting tensile opening, while faults oriented obliquely (30°–45°) to SHmax record the maximum slip tendency, reflecting optimal conditions for shear reactivation (Ferrill et al., 2020). This orientation control has critical implications for fluid migration and structural permeability in subsurface systems (Nolting and Fernández-Ibáñez, 2021), namely that the high dilation tendency of fractures aligned to within ~20° of SHmax suggests that they are likely open conduits for fluid flow. This is consistent with previous findings from fractured carbonates and fault zones in geothermal and hydrocarbon systems (Moeck et al., 2009; Morris et al., 1996) where permeability anisotropy strongly governs production and injectivity performance (Glaas et al., 2021).

Slip tendency (Ts) and dilation tendency (Td) are widely used as proxies for fracture reactivation potential and fracture opening, respectively, both of which influence permeability (e.g., Ferrill et al., 2020). In our SHmax = 170 MPa scenario, some fractures show high Td but low Ts, suggesting that dilation dominates over shear reactivation for those sets, which may still contribute significantly to fluid flow. In contrast, fractures displaying high slip tendency, those oblique to SHmax, are more susceptible to shear reactivation. The impact of such reactivation on permeability is complex: it may lead to transient permeability enhancement through brecciation and fracture dilation, or permeability reduction via the development of fault gouge and sealing behaviour (Guglielmi et al., 2021).

5.3. Controls on fault-fracture connectivity across scales

Understanding connectivity across multiple scales is essential for interpreting fracture network behaviour, from regional tectonic structures visible in seismic data to smaller-scale fracture patterns observed in outcrops or drone imagery. Seismic datasets typically only image major fault systems, meaning much of the fracture complexity at outcrop and sub-outcrop scale is not directly captured. Previous studies, such as those by Gutmanis et al. (2018); Strijker et al. (2012), have identified significant limitations associated with data resolution and the scale-dependent spatial distribution of fracture networks. To bridge this gap, our analysis integrates observations across four spatial scales (seismic, local, outcrop, and bed), incorporating scale dependency of fracture lengths using Maximum Likelihood Estimators (MLE) (Rizzo et al., 2017) (Fig. 8). This approach enables quantitative comparison of different fracture length distributions and helps to assess whether fractures at different scales follow similar statistical patterns (Kimbell et al., 1989; Rizzo et al., 2017).

Building on this, we evaluated connectivity using node and branch triangle methods (Sanderson and Nixon, 2015), particularly focusing on increasing fracture intensity. Datasets with higher fracture densities (datasets I, X, and Y) exhibit more distinct and numerous P21 values, indicating enhanced connectivity and more well-developed fracture networks (Fig. 13; Table 3). The linear relationship between P21 values and the number of structures mapped in this study highlights how fracture density increases with scale resolution, particularly as observations move from seismic to bed-scale data (Fig. 12). This trend reflects the fundamental principle that finer-scale datasets capture more discrete structural features, resulting in higher line intensity measurements (P21) (Watterson et al., 1996). As scale decreases, the ability to detect and quantify minor fractures and joints improves, which directly contributes to the increased variability and abundance of P21 values (Odling, 1997). This observation aligns with previous studies suggesting that fracture intensity and network complexity are strongly scale-dependent, and that high-resolution datasets tend to reveal more intricate and well-connected fracture systems than those interpreted from coarse-scale data especially in a carbonate systems (Guerrero et al., 2010).

Critically, our results indicate that small-scale fracture patterns are not isolated features but are structurally influenced by major tectonic features (Table 2). For example, outcrop-scale fractures often align with or propagate from trends consistent with local or regional fault systems (Figs. 8, 12). This suggests that the connectivity at fine scales is at least partially governed by inherited structural fabrics and tectonic stress regimes (e.g., Walsh and Watterson, 1987; Watkins et al., 2015). This is particularly apparent in the bed-scale structural analysis from Penmon Point (Fig. 14a–c). Field evidence of N–S-trending dolomitized fractures, crosscut by E–W-oriented calcite-cemented veins, defines a clear relationship, indicative of at least two temporally distinct stress regimes. This transition, supported by the fracture intensity data (Fig. 12) and connectivity metrics (Figs. 8 and 13), reflects a rotation of the maximum horizontal stress (SHmax) from N–S to E–W, consistent with the regional tectonic overprint exerted by strike-slip reactivation along the MSFS (Bates, 1972; Schofield et al., 2021).

This dual-stage fracture development suggests that dolomitization along fractures occurred during N–S compression, likely associated with the late Variscan deformation or early post-Variscan relaxation (Corfield et al., 1996; Coward et al., 1989; Juerges et al., 2016). The subsequent opening of E–W trending, calcite-cemented veins may represent either a later extensional overprint or strike-slip reactivation-induced tensile fracturing, as has been observed in other carbonate platforms adjacent to regional fault zones (Juerges et al., 2016; Kirkham, 2021). Importantly, the bed-scale cross-cutting relationships provide microstructural evidence of tectonic evolution, capturing a localized expression of regional stress field dynamics. The interpreted stress rotation and fracture overprinting near the MSFS reinforce its role as a long-lived,

reactivated strike-slip system that not only accommodated large-scale terrane movements (Schofield et al., 2021) but also exerted mechanical and hydrological control at the reservoir scale.

This observed rotation in maximum horizontal stress (SHmax), coupled with evidence of fracture reactivation, has significant implications for fracture connectivity within small-scale carbonate systems, where fluid migration and mechanical behaviour are highly sensitive to structural complexity (Salomon et al., 2021). This is quantitatively supported by the node and branch triangle analysis (Figs. 14c, d). The node triangle plots illustrate that both regional and local datasets exhibit comparable connection lengths (CL) of 0.64 and 0.63, respectively. Although the regional CL is marginally lower, this is likely attributable to data resolution limits and the underrepresentation of smaller-scale fractures in fault-scale datasets. Strikingly, the CL values increase dramatically at finer scales, reaching 2.29 in the drone scale and peaking at 3.03 in the bed-scale dataset (Table 3). This more than threefold increase in CL from regional to outcrop scale signifies that fracture intersections and linkages become increasingly complex and abundant as resolution improves. When converted to branch triangle proportions, a similar trend emerges: CB-based branch proportions rise from 0.71 (regional) and 0.74 (local) to 1.46 (drone) and 1.58 (bed-scale) (Table 3; Fig. 14d). These increases suggest that at finer scales, fractures are not only more densely distributed but are also more effectively connected, likely due to multiple fracture generations and reactivation events responding to shifting stress orientations (Duffy et al., 2017; Loza Espejel et al., 2020).

5.4. Implications for geothermal extraction in fractured carbonates

In fractured geothermal systems, especially those hosted within low-matrix-permeability carbonate platforms, the ability to quantify and predict fracture network connectivity becomes central to evaluating reservoir quality (Gutmanis et al., 2018). The assessment of multi-scale fracture connectivity provides crucial insights into fluid flow anisotropy, mechanical integrity, and resource potential (Loza Espejel et al., 2020). Interestingly, earlier research by Nolting et al. (2021) also found that fractures can remain open even at depths of up to 10 km. However, without detailed knowledge of multiscale fracture connectivity and associated structural controls, it remains extremely difficult to predict flow behaviour or assess the potential for any viable fluid flow within these reservoirs. While seismic and regional structural datasets define the broader tectonic framework, they are inherently limited in their resolution. In contrast, sub-seismic fractures are critical to reservoir permeability and flow compartmentalization. In this study, outcrop analogues were used to fill this resolution gap and characterize fracture properties across several orders of magnitude (Figs. 6–8, 14, 15). The analysis reveals that connectivity increases substantially with scale refinement, with bed- and outcrop-scale datasets exhibiting higher connectivity indices (CB) compared to regional fault data (Table 3). This indicates that sub-seismic scale fractures form densely connected networks that may be critical to maintaining vertical and lateral fluid flow in the subsurface (Rizzo et al., 2024; Zheng et al., 2025). Notably, the topological richness of the bed-scale networks, especially where orthogonal joint sets intersect, indicates the potential for enhanced transmissivity in fractured zones that are otherwise invisible in standard seismic interpretations (Faleide et al., 2022).

The distribution of fracture lengths was further evaluated through a multi-scale statistical approach using Maximum Likelihood Estimators (MLE) (Rizzo et al., 2017) (Fig. 15a). Scale gaps arise due to the limited resolution of imaging methods, where resolution is defined by the smallest feature that can be reliably observed and measured within a given dataset (Fig. 15a). Outcrop-based exposure mapping, particularly at outcrop and bed scales, proves valuable for identifying joints and veins (Figs. 6, 14a, b, 15a), capturing features across four orders of magnitude, with fracture branches ranging from approximately 0.01 to 100 m in length (Fig. 15a). Photogrammetry data typically spans two

orders of magnitude, capturing fracture branches from 2 to 80 m in length, and highlights fracture swarms (Fig. 15a). Although cross-joint fractures are clearly observable at this scale, features smaller than 2 m become increasingly difficult to resolve and are highly dependent on the resolution of the drone camera. At Penmon Point, photogrammetry-derived fracture branch lengths commonly range from 3 to 15 m, whereas bed-scale measurements reveal much finer features, averaging between 0.08 and 0.2 m (Fig. 15a). This aligns with previous studies that emphasize the scale-dependent nature of fracture attributes, where sub-seismic features, although unresolved in traditional subsurface data, can govern key aspects of fluid flow, mechanical strength, and reservoir compartmentalization (Palladino et al., 2020; Rizzo et al., 2024).

Quantitative analysis using FracPaQ reveals a strong scale-dependent permeability behaviour across the dataset (Figs. 8, 15a). The estimated maximum permeability (K_v) decreases markedly from approximately $2.2 \times 10^{-9} \text{ m}^2$ at the bed scale (centimetre scale) to $\sim 5.0 \times 10^{-12} \text{ m}^2$ at the seismic scale (kilometres) (Fig. 14b), with all the permeability tensors showing a similar N-S trend, although with a slight deviation from bed scale (170°) to seismic scale (180° ; Fig. 15b). This subtle variation reflects the influence of local structural rotations, likely linked to stress heterogeneity and proximity to regional fault zones such as the Menai Strait Fault System (Schofield et al., 2021). FracPaQ calculates permeability using fracture length and spacing, assuming constant aperture across scales (Healy et al., 2017). Therefore, the reduction in permeability observed at the seismic scale reflects not the true hydraulic potential of large faults, but the reduced structural connectivity and underrepresentation of intermediate and small-scale fractures due to resolution limits. This is evident (see Table 4) in the much lower connectivity metrics at the seismic scale (CB: 0.74; CL: 0.64) compared to the bed scale (CB: 1.58; CL: 3.03). These differences in fracture network complexity directly impact the calculated permeability, emphasizing the influence of data resolution and sampling scale (Odling, 2001). However, despite these localized changes in fracture orientation, the overall impact on the permeability tensor appears to be minor, with a dominant N-S flow direction maintained across all scales.

Whilst the absolute permeability values decline with scale, the anisotropy ratio (K_v/K_h) remains relatively stable ranging between 3.2 and 3.4, across all observation scales (Table 4). This suggests that while connectivity and resolution strongly influence the magnitude of calculated permeability (Vermilye and Scholz, 1995), the dominant flow direction remains aligned with the principal fracture set (N-S) across the offshore Mississippian North Wales carbonate platform. These results highlight that in the EISB, fracture systems aligned along a N-S orientation should be prioritized, as they are most likely to contribute to effective fluid flow, particularly where aligned with the dominant fault trend. This is consistent with the regional structural framework, where the largest faults also exhibit N-S lineaments. In contrast, in central and eastern England, the structural regime transitions to a NW-SE-oriented fault network, which may influence fault slip behaviour and fracture dilatancy differently under the present-day stress field. Understanding these regional variations is crucial for targeting fracture-controlled permeability in geothermal exploration.

6. Conclusion

The Mississippian carbonate platforms (MCP) of the UK have complex multi-scale structural and geomechanical characteristics. Our multi-scale approach, applied to the North Wales Platform and its offshore extension in the East Irish Sea Basin, using sites on the Great Orme and Penmon Point, married with subsurface data from the East Irish Sea Basin. This has generated a comprehensive understanding of how fault and fracture networks behave across different spatial resolutions. These insights are essential for evaluating fracture-controlled fluid flow and thereby optimizing geothermal energy extraction in low-porosity carbonate systems.

1. This study integrates geometrical (orientation, length, and density) and topological (including node type, connectivity, and branch statistics) analyses of fault and fracture networks across multiple observation scales. By combining regional seismic data with outcrop-scale surveys and drone-based photogrammetry, a comprehensive understanding of structural controls on geothermal systems in a Mississippian Carbonate Platform has been developed.
2. Fault and fracture networks in the EISB and North Wales Platform exhibit strong scale dependency in both geometry and connectivity. At the regional scale, faults are predominantly north–south oriented, while at finer scales, fracture orientations become more heterogeneous and complex. By applying Maximum Likelihood Estimators (MLE) to fracture length distributions and connectivity analyses using node and branch triangle methods, we show that fracture intensity (P21) and network connectivity increase with scale resolution. This approach bridges the resolution gap between conventional seismic and surface observations, providing a framework for better predicting fracture-controlled permeability in geothermal reservoirs.
3. The evolution of fracture connectivity across scales reflects a dynamic structural history influenced by regional tectonics, local fault activity, and stress field rotation. The observed increase in connectivity metrics (CL and CB) from seismic to bed scale demonstrates that finer-scale datasets capture a more intricate and better-connected fracture network — a critical control on fluid flow in low matrix permeability carbonate reservoirs. These structurally controlled, highly connected fracture zones are likely to serve as preferential flow pathways and should be prioritized in geothermal exploration and reservoir targeting within the Mississippian carbonate platform system.
4. Fracture reactivation analysis using slip and dilation tendency indicates that fault reactivation style is governed by fracture orientation relative to the maximum horizontal stress direction. Faults aligned with the stress axis tend to dilate and act as effective fluid conduits, while oblique fractures are more likely to slip. Stress modelling results from two scenarios ($SH_{max} = 140^\circ$ and 170°) reveal that even small changes in stress orientation can significantly alter predicted fracture reactivation behavior. Under $SH_{max} = 170^\circ$, dilation tendency is highest in north-south fractures, while slip tendency dominates in oblique sets under $SH_{max} = 140^\circ$.
5. The combined analysis of fracture orientation, connectivity, and reactivation potential under present-day stress conditions provides significant new information for the development of low enthalpy geothermal energy from Mississippian carbonate platforms in the UK. Fractures with high dilation tendencies that are aligned sub-parallel to the maximum horizontal stress (SH_{max}) represent the most favourable targets for fluid flow, as confirmed by multiscale dilation analysis. At the bed and outcrop scales, permeability tensors indicate a dominant flow direction aligned with N–S fracture sets, supporting targeted drilling intersecting these trends.
6. Quantitative analysis reveals that while absolute permeability (K_1) decreases significantly from the bed scale to the seismic scale, the anisotropy ratio (K_1/K_2) remains consistent across scales, suggesting stable directional flow aligned with dominant fracture sets. The enhanced connectivity at outcrop scale (evidenced by high CL and CB values) suggests that these densely fractured zones may offer higher transmissivity, which is essential for sustaining deliverability of geothermal water.

CRedit authorship contribution statement

Maulana Rizki Aditama: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Cathy Hollis:** Writing – review & editing, Validation, Supervision, Investigation. **Mads Huuse:** Supervision. **David Healy:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Maulana Rizki Aditama reports financial support was provided by Indonesia Endowment Fund for Education. If there are other authors, they 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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Data availability

Data will be made available on request.

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